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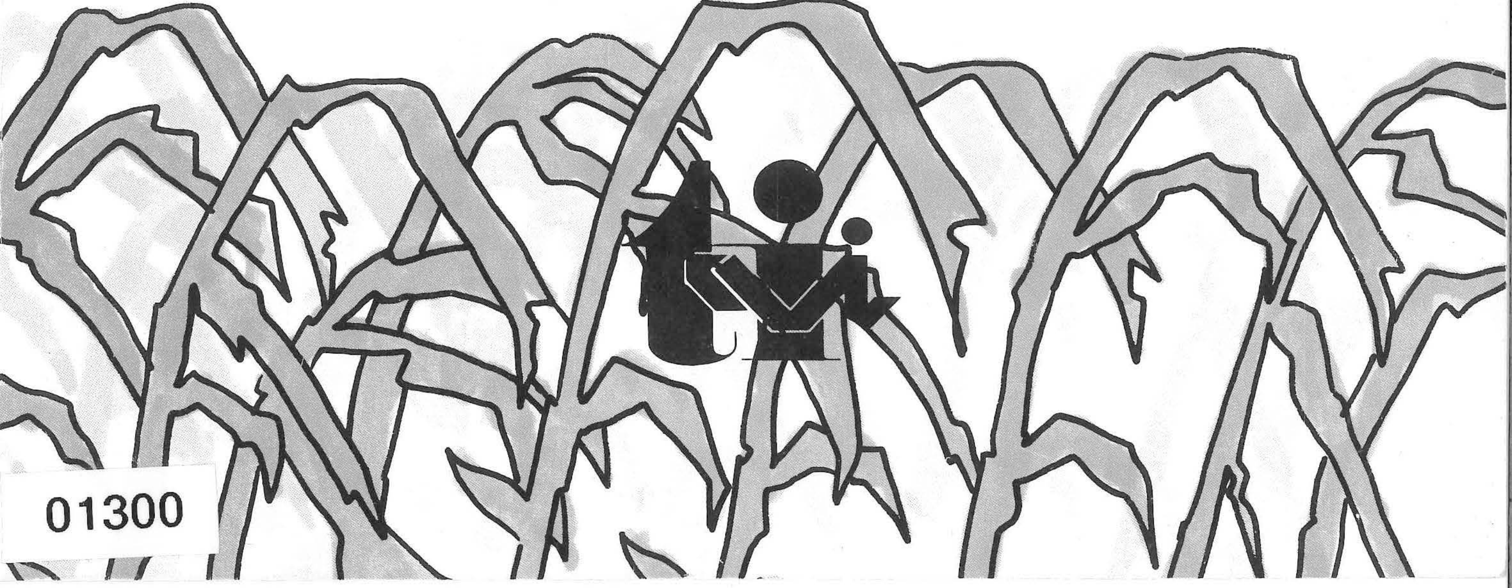

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CONTENTS

PROCESSING TECHNOLOGIES OF DREDGED MATERIALS

CHARACTERISATION METHODS FOR DREDGED MATERIALS

DREDGED MATERIALS AND ENVIRONMENTAL IMPACT

PROJECT STUDIES AND MANAGEMENT

PROCESSING TECHNOLOGIES OF DREDGED MATERIALS

CLEANING OF SEDIMENTS CONTAMINATED WITH ORGANIC MICROPOLLUTANTS

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ABSTRACT

In the Development Program Treatment Processes (1989-1994) research into the cleaning of sediments contaminated with fluorene, phenantrene, chrysene and benzo(a)pyrene was conducted. In this article solvent extraction and biodegradation of these components are discussed. Cleaning of contaminated sediments can be preceeded by hydrocyclone separation. the diluted overflow can be treated by aeratio in a basin with good results. The underflow can be reused without further treatment or, when polluted, treated by extaction with triethylamine. Biodegradation of PAHs in the underflow is possible when the contaminants are not too strongly absorbed to sediment particles. Particles in the underflow tend to contain PAHs that are not biologically available.

INTRODUCTION

Organic micropollutants are a major cause of serious contamination of sediments in the Dutch waters. Especially the polycyclic aromatic hydrocarbons and the PCB's are considered a problem. Disposal of contaminated sediments won't always be possible nor preferred. To reduce the amount of sediment to be disposed of the Ministry of Transport and Public Works set up the Development Program Treatment Processes (1989-1994) for research into treatment techniques for contaminated sediments and the development of integrated treatment processes. The Program includes techniques for dredging, cleaning and disposal.

At present the techniques for cleaning sediments contaminated with organic micropollutants are: hydrocyclone separation, froth flotation, solvent extraction, thermal treatment and biological treatment. The first three techniques lead to concentration of the pollutants, whereas the latter two will destroy the contaminants. Combinations of different techniques are also possible and may lead to better results.

In this paper the results of biological cleaning methods and the extraction of organic micropollutants with solvents is presented as well as the combination of hydrocyclone separation and biological cleaning.

The organic micropollutants that were analyzed in the research projects were the 16 PAH of the EPA and oil. In this paper the fluorene, phenanthrene, chrysene and benzo(a)pyrene will be taken as guide pollutants for biodegradation.

The choice of techniques to be discussed is based on the following considerations. Solvent extraction gives very high removal percentages, with the soil structure being destroyed. The use of energy and chemicals is high and a concentrated contaminant/solvent stream will be produced. Biological treatment techniques in general show higher residual concentrations, but contrary to solvent extraction the soil structure will remain. The use of energy and chemicals can be low and the contaminants can be destroyed. The costs of solvent extraction will probably be higher than for biological treatment. So these techniques have opposite (dis)advantages.

Solvent extraction and biological treatment for cleaning sediments have been tested on laboratory scale. A black-box approach was used to test the techniques. This has the disadvantage that the system is not really understood, but when positive results are recorded, the development and implementation of the technique can progress quickly.

Demonstration scale projects will be carried out for the biological techniques "aeration in a basin" and "landfarming".

SOLVENT EXTRACTION

Methods

Solvent extraction with toluene and triethylamine was carried out with 100 g oven dry sediment solids. The solvent dose was 2 kg/kg dry solids. Toluene was used because of the high solubility of PAH in this solvent. Triethylamine has the very usefull propery of forming one phase with water under 15 °C. At higher temperatures water and amine can be separated.

After one hour of stirring the solvent/sediment mixture stood for ca. 20 hours. The solvents were decanted. Triethylamine had to be heated to 30 °C before decanting. Subsequently the decanted mixtures were treated in a centrifuge. The final concentrations of PAHs in the sediment were analyzed.

Table 1: Solvent extraction of PAHs with toluene and triethylamine

Sediment type ----------- PAH	initial concentration mg/kg d.s.	concentration after extraction and cleaning efficiency			
		toluene		triethylamine	
		mg/kg d.s.	%	mg/kg d.s.	%
Geulhaven (A)					
fluorene	10	2	80	0,3	97
phenantrene	24	4	83	0,7	97
chrysene	13	2	85	0,3	98
BaP	7	1	86	0,2	97
Scheveningen (B)					
fluo	3	0,8	73	0,3	90
phen	17	3	82	0,9	95
chry	22	3	86	2	91
BaP	21	4	81	2	90
Dordrecht (C)					
fluo	120	9	93	5	96
phen	270	20	93	13	95
chry	30	3	90	7	77
BaP	17	2	88	8	53
Dodewaard (D)					
fluo	2	0,3	85	0,1	95
Phen	14	1,3	91	0,3	98
chry	14	1	93	0,2	99
BaP	18	1,5	92	0,2	99

Results and discussion

Table 1 presents the extraction efficiencies for four different types of sediments.

It is clear that the extraction efficiencies are higher for triethylamine then for toluene. Another conclusion to be drawn from table 1 is that the efficiency differences between the PAHs are relatively small; the lighter PAHs are as easily removed as the heavier ones. It seems that the final concentrations in the sediments depend on the height of the initial concentration. Removal percentages of 90 to 99% for PAHs were obtained with solvent extraction. A second or third extraction step might be necessary in order to increase the efficiency.

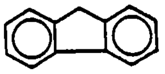
An american company, RCC, developed the B.E.S.T. proces (1) based on extraction of organic micropollutants from wastestreams using triethylamine. They report PCB extraction efficiencies of 99,95% in a multi-stage extraction of sediments. RCC also reported that a high fines content in the sediment can cause processing problems.

BIOLOGICAL CLEANING TECHNIQUES

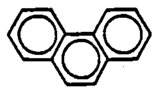
To realize biodegradation of PAHs in soils or sediments sufficient oxygen, nutrients and micro-organisms that can metabolize the contaminants should be available. Besides the presence the mass transport of oxygen, nutrients and contaminants to the microorganism and removal of degradation products is important. The waterphase is the most important transport medium in the soil enough water should therefore be present to make mass transport possible.

Other factors that influence the biodegradation of contaminants are for example the presence of toxic compounds or the temperature.

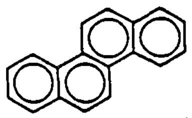
The different polycyclic hydrocarbons show different degradation rates. The general rule is that the more rings the slower the degradation reaction. Reported half lives of fluorene phenantrene, chrysene and benzo(a)pyrene in soils or sediments are (2):



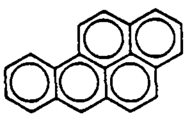
fluorene (fluo): 10 to ca. 300 days



phenantrene (phen): 38 to ca. 300 days



chrysene (chry): 39 to ca. 470 days



benzo(a)pyrene (BaP): 875 days

The increasing half live periods with increasing number of rings is probably caused by decreasing solubility of the PAHs. It is probably due to the use of different laboratory degradation conditions and different sediments or soils that a large variance in half live periods has been found.

In the Netherlands four techniques for biodegradation of PAHs in sediments have been investigated on lab- or demo scale. These research projects were coordinated by the RIZA.

The biodegradation techniques investigated were bioreactors and composting for the treatment of sediment and landfarming and aeration in a basin for the treatment of sediment fractions. In the following section the methods used and the results of these treatment techniques, except composting, will be presented and discussed.

Bioreactor

There are several types of bioreactors for the cleaning of soil. In the Netherlands the Delft University of Technology developed a three-phase reactor based on the Pachuca reactor (3) and TNO investigated biodegradation of organic micropollutants in soils in a rotating drum bioreactor (4).

The research into cleaning of sediments contaminated with PAHs was carried out by TNO. The lab scale bioreactors are 6 litre drums, with four axial baffles to ensure good mixing of the sediment slurry.

The objects of research were to determine whether it would be possible to obtain significant degradation of PAHs within a relatively short period (i.e. one or two months) and, if so, to determine the influence of cost determining factors on the degradation rates.

Methods

The drums are filled with 2.5 litre of sediment slurry (15% d.s.) and rotated continuously. The 3.5 l gas phase consists of pure oxygen and is replaced with fresh oxygen every day. The temperature is about 25 °C and fertilizer (N/P/K) is added. The pH is kept neutral with NaOH. The degradation results of this procedure are listed in table 2.

The procedure for testing varying process conditions was carried out about the same way. The reference test was carried out under above mentioned conditions except that the temperature was lower (ca. 20 °C) and a dry solids content of 30% wt. was used. The rotation speed of the drum was 50 rpm. Several parameters were changed to measure their influence on the degradation rate and the final concentration of PAHs in the sediment. The variables were a higher dry solids content (60 % wt.), a lower rotation speed (10-20 rpm), a combination of the two, no addition of fertilizer, a higher temperature and seeding. Information about these variables is necessary to determine the conditions under wich the reactor should be operated and to determine the operation costs.

At the time of writing the research was not yet finished, so only some preliminary results are presented in table 3.

An experiment with 2% of potasiumazide was carried out to determine the contribution of factors other than microbial activity to the decrease of the PAH concentration.

Results and discussion

From table 2 it can be noticed that, in general, the degradation efficiency decreases from fluorene to benzo(a)pyrene, as expected. Furthermore there is a large difference of degradation rates between the sediments. This is partly caused by differences in initial concentrations.

It has been reported that degradation rates in non-polluted sediments can be a factor 10 to 400 lower (2). And, because the concentration versus time relation is not a linear function, the degradation rate is dependent on the (initial) concentration.

But the figures also show that other factors must play a role. When, for example the chrysene figures of A and D are compared (table 2), a large difference in final concentration is noticed, whereas

Table 2: Biodegradation in a laboratory bioreactor with different sediments

Sediment*	Unit	fluorene	phenantrene	chrysene	Benzo(a)pyrene
A: start	mg/kg d.s.	10	24	13	7
60 days	"	0,3	1	1	3
efficiency	%	97	96	92	57
B: start	mg/kg d.s.	3	17	22	21
60 days	"	1	6	14	21
efficiency	%	67	65	36	0
C: start	mg/kg d.s.	120	270	30	17
60 days	"	7	23	11	12
efficiency	%	94	91	63	30
D: start	mg/kg d.s.	2	14	14	18
60 days	"	1	6	12	22
efficiency	%	50	57	14	0
E: start	mg/kg d.s.	2	3	3	3
60 days	"	1	2	3	4
efficiency	%	50	33	0	0

* A = Geulhaven B = Scheveningen C = Dordrecht D = Dodewaard E = Zierikzee

initial concentrations are approximately the same. One of these other factors can be the matrix structure on wich the PAH are sorbed (see discussion).

Geulhaven sediment (A) shows the best results. Relatively low final concentrations are realized at high rates.

The experiments of varying conditions in the bioreactor were also carried out with sediment from the Geulhaven, but the sample came from another part of the harbour. In this sample concentrations of contaminants are not the same as in the former sample (table 2).

After 56 days all the bioreactors show a removal efficiency for the 16 PAH of the EPA of 70 to 80 %. Although it is very difficult to draw conclusions because the results gained don't have statistical significance, some tendencies could be seen. It seems that addition of fertilizer for this type of sediment is not necessary. Furthermore a higher dry solids content (60% wt) and a lower rotation speed (10-20 rpm) can be used because the figures did not show a negeative influence on the degradation rate of the PAHs.

Seeding and a higher temperature can indeed speed up the degradation of PAHs, but this only seemed significant in aproximately the first ten days.

Whether these results actually lead to lower cost still has to be determined.

Table 3 shows the results of varying processing conditions for the individual PAHs. It seems that the different conditions don't have any influence on the final concentrations of these PAHs within 56 days. The experiment with Na-azide shows loss of PAHs within the 56 days. There was no CO$_2$ detected, so there was no significant microbial activity. Other disappearance processes could have occurred, but these are not known. The result of the other experiments have not been corrected for these losses.

Landfarming

Landfarming is a technique known from soil cleaning. Especially sandy soils contaminated with easy degradable contaminants can be treated with this method.

When soil is treated in a landfarm, the soil is spread out in layers of 0.3 to 1.5 m and the moisture content is usually kept at 80 % wt. Sometimes fertilizer is added to provide nutrients for the microorganisms and the land maybe ploughed in order to improve the soil structure. A loose structure is necessary to make oxygen transport into

Table 3: Influence of variation in processing conditions in the bioreactor on the final PAH concentration after 56 days.

Conditions	Initial and final concentrations in mg/kg d.s. and efficiencies after 56 days			
	fluorene	phenantrene	chrysene	Benzo(a)pyrene
Reference				
start	18	9	4	2
end	1	1	1	2
eff.	94	89	75	0
Without fertilizer				
start	18	9	4	2
end	1	1	0,4	2
eff.	94	89	90	0
60% d.s.				
start	18	9	4	2
end	2	1	2	2
eff.	89	89	50	0
15 RPM				
start	18	9	4	2
end	1	1	1	1
eff.	94	89	75	50
60%, 15 RPM				
start	18	9	4	2
end	2	1	1	2
eff.	89	89	75	0
30°C				
start	4	7	3	2
end	2	1	<0,1	1
eff.	50	86	>97	50
2% NaN$_3$				
start	18	9	4	2
end	4	9	3	2
eff.	78	0	25	0
Seeding				
start	9	9	4	3
end	2	2	1	8
eff.	76	76	75	-

the soil possible.
The landfarming technique was tested on hydrocylone underflow of Geulhaven sediment in order to determine whether this method can be usefull to treat coarse sediment or sediment fractions.

Method

Hydrocyclone separation took place in a Dorr-Oliver hydrocyclone, type PU-25/6. The cyclone has a variable apex diameter of 3 to 6.5 mm. The diameter can be varied in steps of 0.5 mm. The Geulhaven sediment was screened over a 2mm screen and diluted to a dry solids content of 20 % wt. The apex diameter used was that diameter at which the underflow gave a rope discharge. At this point the underflow has a high dry solids content. The cut point of the cyclone, as given by the manufacturer, lies between 10 and 20 μm.
Ten kilograms of the underflow-slurry (the coarse fraction) was mixed with N/P/K-fertilizer. The slurry settled in a 60x40x10 cm container and the water was decanted after 4 days. After 14 days the underflow was dry. The layer of loose, dry (ca. 80 % wt) material was 3 cm thick. This means that the conditions for landfarming were rather optimal and not a simulation of what might be expected in practice. The PAH concentration was measured during six months and the layer was regularly "ploughed". The temperature was about 16°C.

Results and discussion

Results of the landfarming experiment are shown in table 4. Due to the separation in the hydrocyclone the initial concentration is relatively low. The initial degradation rates (after 67 days) can be compared with the rates in table 2 at the same initial concentrations.
After 190 days low concentrations of the lighter polycyclic hydrocarbons can be reached, but benzo(a)pyrene does not show a decrease in concentration.
The results show that landfarming can be a usefull technique to treat contaminated sediment (underflow). But since the experiment only had a orientating character, conclusions for other sediments (with other characteristics and contaminant concentrations) cannot be drawn.

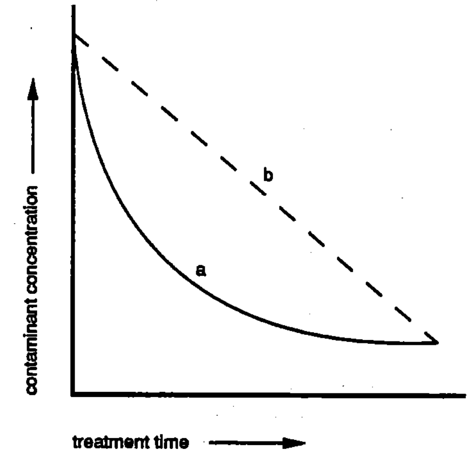


Figure 1:
Hypothetical degradation curves in case of intensive aeration (a) and less intensive aeration (b) of a contaminated sediment suspension.

Aerated basin

The hydrocyclone overflow is a diluted sediment fraction that could be treated in an aerated tank or in a depot or lagoon.
The idea was that it would not be necessary to supply oxygen continuously to the diluted sediment slurry, but to do it intermittently. Figure 1 shows the expected degradation curves. Instead of the initial high degradation rates in the case of intensive oxygen supply (curve a), the degradation rate decreases, but the final concentration of contaminants is expected to be the same (curve b). So this technique could be used on large scale (in a lagoon or depot) with a long residence time. Intensiveness of oxygen supply is determined by frequency and amount of air supplied.
Experiments were carried out to verify the above mentioned hypothesis.

Table 4: PAH biodegradation in Geulhaven underflow under optimal landfarming conditions

PAH	Concentration in mg/kg d.s. after				efficiency %
	0 days	67 days	130 days	190 days	
fluorene	4	3	0,7	<0,2	>95
phenantrene	16*	8	4	0,7	96
chrysene	3	2	1	0,5	83
Benzo(a)pyrene	2	4	3	1	0

* maximum

Table 5: PAH biodegradation in Geulhaven overflow in aerated tanks

PAH	Conditions: (1) = frequency (x times 1 hour/day); (2) = amount of air (l/day)		
treatment time (days) efficiency (%)	A (1) = 4 (2) = 200 concentration mg/kg d.s.	B (1) = 4 (2) = 50 concentration mg/kg d.s.	C (1) = continuous (2) = 60 concentration mg/kg d.s.
fluorene			
0	51	51	51
56	22	27	20
118	10	20	20
190	5	9	7
eff. (%)	90	82	86
phenantrene			
0	96	96	96
56	18	27*	10*
118	9	10	11*
190	7	9	9
eff. (%)	93	91	91
chrysene			
0	34	34	34
56	7	10	3
118	3	4	5
190	2	3	2
eff. (%)	94	91	94
Benzo(a)pyr.			
0	16	16	16
56	12	14	10
118	7	10	14
190	6	9	9
eff. (%)	63	44	44

* maximum

Methods

Hydrocyclone separation of Geulhaven sediment was carried out as described above in the section "Landfarming".

7.5 Litre of overflow was put in a cylindrical beaker with a porous glass bottom. The liquid level was 20 cm. Stirring equipment was used to mix the suspension (11 % dry solids) during aeration through the glass bottom. Fertilizer was added and the temperature was about 16 °C.

Frequency of stirring and aeration and the amount of air supplied were varied in four experiments. The results of three experiments are presented here. It was thought necessary to avoid permanent anaerobic areas in the beaker by aeration as well as stirring. The frequences of aeration and stirring were 4 times an hour per day and contiuous stirring. The amounts of air supplied were: 200 l/day, 50 l/day and 60 l/day.

Results and discussion

The results of the aerated basin experiments are summarized in table 5.

The concentrations of PAHs in the overflow of Geulhaven sediment are much higher than in the total sediment (table 2) or in the underflow (table 4).

In 190 days the absolute decrease in contaminant concentration is relatively high compared to the landfarming and bioreactor experiments with Geulhaven sediment. Especially the decrease of the chrysene and benzo(a)pyrene concentration is striking. But the degradation rates in the bioreactor are higher (when the degradation efficiencies after 60 and 56 days are compared).

Oxygen measurements are not available. It is likely that the overflow-suspension in the intermittent aeration experiments is periodically anaerobic or anoxic (nitrate is available because of the addition of fertilizer).

When the efficiencies over the first 56 days are compared, it seems that continuous aeration gives the best results. After 190 days experiment A (200 l/day) shows the lowest final concentration and therefore the highest efficiency.

Although the figures have to be carefully interpreted because of deviations in sample taking, it seems that the hypothetical figure 1 can be brought in question. The experiment with the lowest frequency of aeration (B), shows the slowest initial degradation rate, but the the same final concentration as in experiment A could not be reached. In terms of final concentrations that can be reached frequency of aeration is probably not an important factor, but the amount of air supplied is.

TABLE 6: Correlation of hydrocyclone separation and biodegradation (5)

Source	E_{PAH} (%)	cleaning efficiency for PAH* (%)
Geulhaven	20	92
Dordrecht	45	82
Schevingen	72	50
Dodewaard	84	20

*PAH = naftalene, acenaftalene, acenaftene, fluorene, anthracene, fluoranthene, pyrene, benzo(a)anthracene

DISCUSSION AND CONCLUSIONS

It was concluded that degradation rates of PAH are dependent of the initial concentration, but not all differences in degratation rates can be explained in this way. Absence of microorganisms or the presence of toxic components can inhibit biodegradation. Furthermore the type of matrix on which the PAHs are sorbed plays a role. Hydrocyclone separation can be used to help characterize this matrix (5). Table 6 shows the correlation between separation efficiency for the 16 PAH of EPA and the biodegradation efficiency for the lighter PAHs. The hydrocyclone separates sediments on grain size and density. In all sediments the concentration of PAH in the coarse screen fraction was the highest. It is generally known that PAHs in sediment are related to the organic material content. The density of the organic matter varies depending on the type of matrix (wood, tar, tar/sand lumps, etc.). Concentration of organic matter is possible in the overflow of the hydrocyclone as well as in the underflow. Table 6 shows that with increasing concentration of PAHs in the underflow (an increasing E_{PAH}) the biodegradability of the PAHs decreases. A plausible explaination for this phenomenon is that, when a sediment contains a large part of heavy or large organic particles (which go to the underflow), desorption of the organic micropollutants is much more difficult. In large, light particles, the diffusion path is relatively long and the desorption from high density particles may be low because of enclosure of the contaminant molecules.

Preliminary results, which were not presented, showed that there are potential cost saving factors for the operation of a bioreactor. The question is whether two months of operating a bioreactor (with a very low capacity) won't be too expensive. Degradation rates in the bioreactor are the highest compared to degradation rates in Geulhaven sediment (in similar periods) in landfarming or aerated basins. This is due to the better conditions (higher temperature, no oxygen limitation, excellent masstransport). Combined with the fact that higher initial concentrations give higher degradation rates, it would be logical to apply bioreactors in case of very high pollutant concentration to remove a large part of the contaminants within a limited time. Removal of the remaining pollution could take place in a less cost intensive treatment as landfarming or aeration. Whether this application of bioreactors can be effective has to be determined by economical evaluation.
Although the experimental results of landfarming were good, landfarming of underflow after hydrocyclone separation will not allways be effective as pointed out above. The fact that biodegradation of PAHs in the underflow of Geulhaven sediment takes place with high efficiencies might be caused by degradation of PAH sorbed on misplaced fines (5). But in other sediments, the PAH in the underflow might be sorbed on particles with a high density or very large particles with long diffusion paths. This type of sorption might inhibit biodegradation of PAHs.
Application of landfarming might be interesting for non-separated sediments more than for underflows, because it will be a relative cheap technique with long possible residence times compared to the bioreactor. Underflow which is contaminated might be treated by froth flotation, gravitational techiques or solvent extraction.

When contaminated overflow after hydrocyclone separation is treated in an aerated tank, it might be expected that biodegradation will progress relatively rapid caused by the above mentioned matrix differences. From the presented tables no comparisons of degradation rates can be made, because of the differences in concentrations and techniques.

The general conclusion from the experiments that were carried out, is that cleaning of sediments is possible by solvent extraction as well as biodegradation. Solvent extraction shows the best removal percentages, but to reach the lowest standards will be difficult.
Cleaning techniques can best be combined with hydrocyclone separation. The diluted overflow can be treated in an aerated basin, depot or lagoon. The underflow, when polluted with PAHs, can be treated for example with triethylamine. Biodegradation of PAHs in the underflow is possible when the contaminants are not too strongly absorbed to sediment particles. Particles in the underflow tend to contain PAHs that are not biologically available through very strong sorption.

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TREATMENT OF PHOSPHORUS AND ARSENIC BEARING SEDIMENTS AND SLUDGES

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ABSTRACT

A method has been developed to remove amphoteric elements like arsenic, phosphorus, chromium, aluminium and others out of sludges and sediments. Thermal treatment at 900°C in presence of alkaline reagents like soda converts the insoluble amphoterics into their soluble sodium salts, which can be easily extracted. The amphoterics are finally fixed as calcium salts in the form of pellets. The solids remaining after extraction of the amphoterics are more amenable for reuse or further treatment. The whole process does not result in additional liquid waste, which cannot be reused.

For two types of sediments the efficiency of the method for the removal of phosphorus and arsenic has been ascertained. Removal percentages of 90% and more are possible in one course.

INTRODUCTION

Due to new legislation in the Netherlands there is a tendency for a shift from dumping of solid waste and sludges to reduction of waste on the one hand and recycling or reuse on the other hand. Most often hazardous substances are present. Removal of these substances is then a prerequisite for recycling or reuse. In other cases materials can be recovered from waste for reuse purposes reducing at the same time the amount of waste and its pollution capability.

For the removal of arsenic compounds from arsenic-bearing iron hydroxide sludges a method has been developed based upon the amphoteric properties of the element arsenic. Due to the presence of more amphoteric elements in solid waste or sludges the method is multi-purpose.

The research reported here has been focussed on the removal of arsenic and phosphorus compounds from sludges and sediments. The arsenic present in the sludges originates both from natural and industrial sources. Disposal of wastes and agricultural run-off result in substantial amounts of phosphorus in ground and surface water. Sludges emanating from water treatment and sediments in surface water contain appreciable amounts of phosphates which can interact with the aquatic environment. Essential in waste reduction or recycling/reuse studies is the avoidance or limitation of additional waste production either in a dissolved or gaseous form.

The impurities themselves must be concentrated as good as possible. The method for the removal of arsenic and phosphorus out of sludges and sediments holds this principle.

OCCURRENCE OF ARSENIC AND PHOSPHORUS COMPOUNDS IN SLUDGES AND SEDIMENTS

In literature only scattered information about the occurrence of arsenic and phosphorus in sludges and sediments is available. Up to now the presence of minor amounts of arsenic or phosphorus in sludges and sediments has not been considered as a problem. Only the occurrence and behaviour of phosphorus in sediments have been investigated in more detail due to its fertilizing character in relation to the water connected with the sediment (1). Much attention has been focussed in the litterature on the removal of arsenic and phosphorus compounds from water.

In the Netherlands the introduction of the Chemical Waste Act resulted in a survey of limiting values of concentrations of toxic metals and metalloids. A selection is presented in table 1.

With respect to the arsenic compounds its occurrence and behaviour in dutch waterworks sludge has been studied in more detail due to the fact that a substantial part of the sludge exceeds the 50 mg per kg d.s.-value. This fact inhibits recycling or reuse of that part and makes dumping of the sludge involved more problematic. Concentration values exceeding 1000 have been registered. In this case arsenic is mostly associated with the iron hydroxide complexes.

Table 1 Some limiting values of concentrations of toxic metals and metalloids (in mg per kg. dry solids) as formulated in the Chemical Waste Act.

Concentration value (mg/kg d.s.)	Elements
50	Arsenic (As), cadmium (Cd), mercury (Hg), antimony (Sb), selenium (Se), tellurium (Te)
5,000	Cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), vanadium (V), wolfram (W)
20,000	Zinc (Zn), barium (Ba)

Within the scope of reuse of iron-rich waterworks sludges attention has been paid to the use of the sludge in the steel industry. One of the main reasons to reject its use is the presence of substantial amounts of phosphorus in the water works sludge. In general 3 up to 15 grams phosphate has been found per kg dry solids, incidentally it rises up to 30 grams phosphate per kg. dry solids. Substantial reduction of the phosphate content of sludges is necessary for possible reuse of iron-rich waterworks sludge in the steel industry.

In sediments concentration values from 1 up to 6 grams P per kg dry solids have been measured, which are in the same order of magnitude as for waterworks sludge.

REMOVAL OF ARSENIC AND PHOSPHORUS FROM SLUDGES AND SEDIMENTS

Several methods have been reported in litterature concerning the removal of arsenic and phosphorus out of solid wastes and sludges (2-11). Most of them are quite complicated, moreover resulting in additional voluminous liquid waste. The method of removal applied here is based upon the amphoteric properties of the arsenic and phosphorus. In presence of an alkali arsenic and phosphorus oxides can behave as acidic compounds resulting in the formation of soluble arsenate and phosphate compounds.

Basic reactions for the dissolution of the arsenic and phosphorus from the solid matrix are:

$$Na_2CO_3 \xrightarrow{800\text{-}900°C} Na_2O + CO_2$$

$$2\ Fe(OH)_3.FePO_4.FeAsO_4 \xrightarrow{high\ T} 3\ Fe_2O_3 + P_2O_5 + As_2O_5 + 3\ H_2O$$

$$P_2O_5 + As_2O_5 + 6\ Na_2O \longrightarrow 2\ Na_3PO_4 + 2\ Na_3AsO_4$$

or as overall reaction:

$$2\ Fe(OH)_3.FePO_4.FeAsO_4 + 6\ Na_2CO_3 \xrightarrow{800\text{-}900°C} 3\ Fe_2O_3 + 2Na_3AsO_4 + 6\ CO_2 + 3H_2O$$

Due to the thermal treatment at 800 - 900°C in an oxic environment organic matter present in the solid waste or sludges is completely oxidized.

Other amphoterics like aluminium, chromium, antimony and vanadium behave in the same way.

Sodium arsenate and sodium phosphate can be easily extracted from the solid phase after heat treatment resulting in a dilute solution.

Precipitation of the dissolved arsenate and phosphate with lime in a so-called pellet reactor results in a very condensed form of calcium arsenate and calcium phosphate (pellets).

The advantage of the method applied is that the chemicals involved are quite common and easy to apply. Moreover the liquid phases are fit for reuse as alkaline agents in water treatment.

REMOVAL OF ARSENATES AND PHOSPHATES IN ACTUAL PRACTICE

For the verification of the method of removal developed two sediments and a model sludge were taken into consideration, namely a river sediment (RS), sediment from a pond-based phosphate removal system (PPRS) and a model sludge of iron hydroxide/iron phosphate (IHP).

The RS-sample was taken from a sludge dump rather dried out, strongly smelling and oily. The PPRS-sample originates from a pond where by iron chloride dosing phosphate is removed to limit the growth of algae in the following reservoir. Finally the IHP-sample was prepared as a reference for the practical samples.

Conditioning of the solids was carried out before the experimentation by heating at 103°C to constant weight. The conditioned samples were analyzed for the composition by instrumental neutron activation analysis. For the remaining analyses the Standard Methods were applied. The conditioned samples are indicated in the tables by the term "without soda, 25°C". Heat treatment of the conditioned samples was carried out in absence and presence of soda. Different weight ratios were applied for the soda-solids mixtures. In tables the 1 : 1 ratios are mentioned giving the best results for these samples.

Table 2. Residual iron content of the sludges in mg/kg d.s. in dependence on the way of treatment.

	without soda		with soda (1 : 1)	loss of ignition (900°C)
	25°C	900°C	900°C	
RS	53	69	46	29
PPRS	364	498	405	28

Table 3. Residual phosphorus content of the sludges in mg/kg d.s. in dependence on the way of treatment.

	without soda		with soda (1 : 1)
	25°C	900°C	900°C
RS	2.8	4.2	0.6
PPRS	4.9	5.8	0.45

Table 4. Residual arsenic content of the sludges in mg/kg d.s. in dependence on the way of treatment

	without soda		with soda (1 : 1)
	25°C	900°C	900°C
RS	46	60	3
PPRS	27	36	<0.1

In table 2 the iron content is presented for the three samples under consideration in dependence of the way of treatment. In tables 3 and 4 the same is presented for the phosphorus and the arsenic content respectively. The method presented here appears to be very effective for the removal of phosphorus and arsenic especially when these elements have been fixed at iron hydroxide complexes.

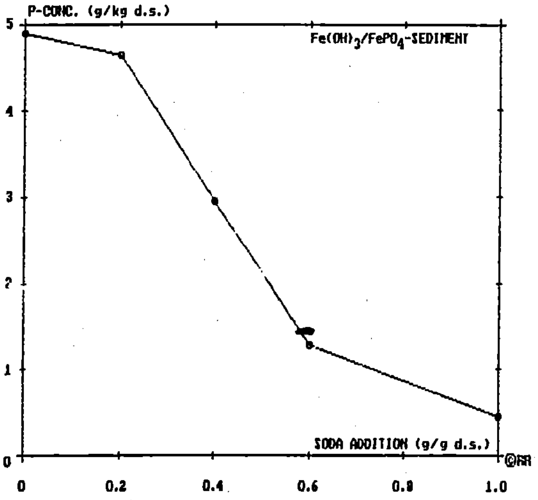

Figure 1.
Reduction of the P-concentration of pond sediment in dependence of the soda - dry solids ratio.

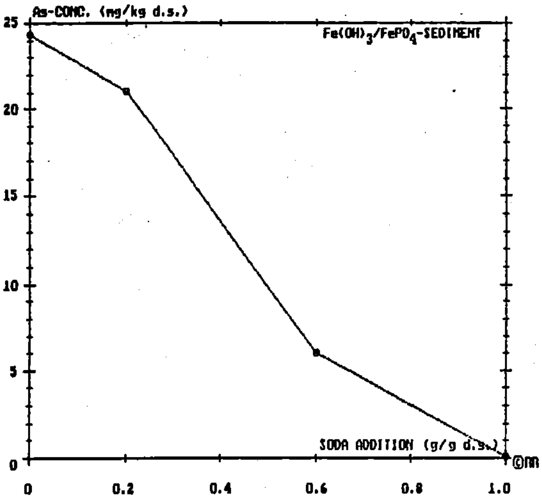

Figure 2.
Reduction of the As-concentration of pond sediment in dependence of the soda - dry solids ratio.

In figure 1 and 2 the residual P and As-concentration respectively are given for the pond sediment in dependence of the soda - dry solids ratio. At 105°C conditioned samples were treated during 1 hour at 900°C. Containing about 4.9 mg P per kg dry solids a ratio of 1 : 1 is needed to reduce the P-content of the dried sludge with 90% and to remove the arsenic nearly completely.

THERMAL ANALYSIS OF THE SLUDGES

In order to gain more insight in the processes going on during the thermal treatment of the sludges thermogravimetric analysis was carried out for the river sediment, the sediment from a pond - based phosphate removal system and a ferric phosphate model precipitate.

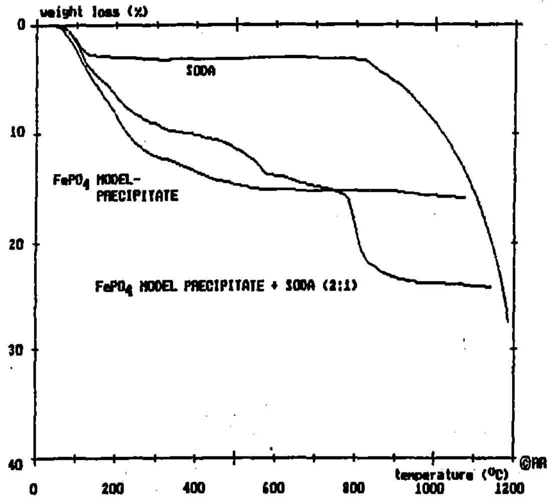

Figure 3.
Thermogravimetric analysis of soda, ferric phosphate precipitate and a mixture of both.

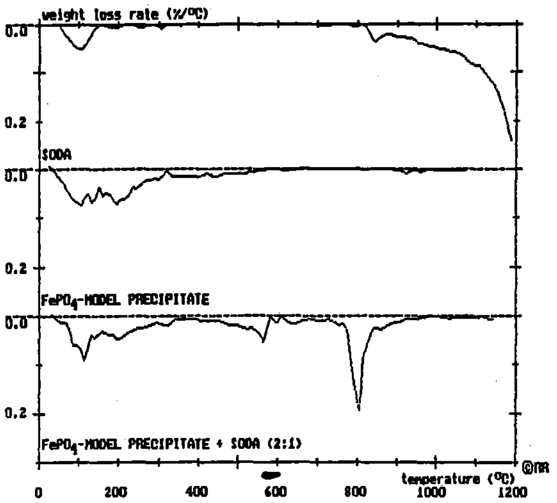

Figure 4.
Differential thermogravimetric analysis of soda, ferric phosphate precipitate and a mixture of both.

In figure 3 and 4 the results of the thermogravimetric analysis of a ferric phosphate model precipitate are presented clearly indicating the temperature sections for dehydration of the sludge and decomposition of the soda added. For the conditions of thermal analysis involved dehydration takes place up to 600°C and the decomposition of soda starting at a temperature of about 700°C is completed at 900°C.

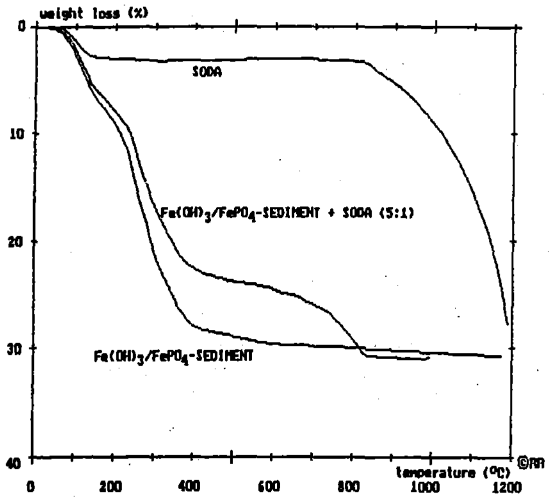

Figure 5.
Thermogravimetric analysis of a P-containing pond sediment and a mixture of soda and sediment.

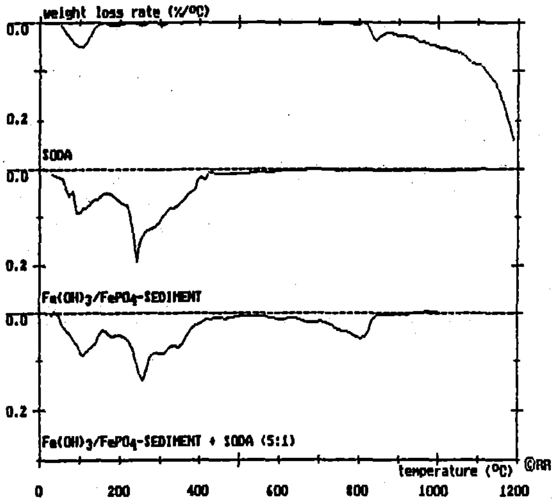

Figure 6.
Differential thermogravimetric analysis of a P-containing pond sediment and a mixture of soda and sediment.

In figure 5 and 6 the results of the thermogravimetric analysis of the P-containing pond sediment show the same tendency as the P-model precipitate although less pronounced.

An example of a more complex behaviour of sediment is presented in figure 7 and 8. Here a sample of river sediment stored in a depot was taken for thermogravimetric analysis. Due to the presence of lots of clay and silt, detritus and other organic matter its behaviour during thermal treatment is far more complex than the rather simple P-sludges. The organic matter however has been oxidized completely before the decomposition of soda starts. So interference with the decomposition is unlikely.

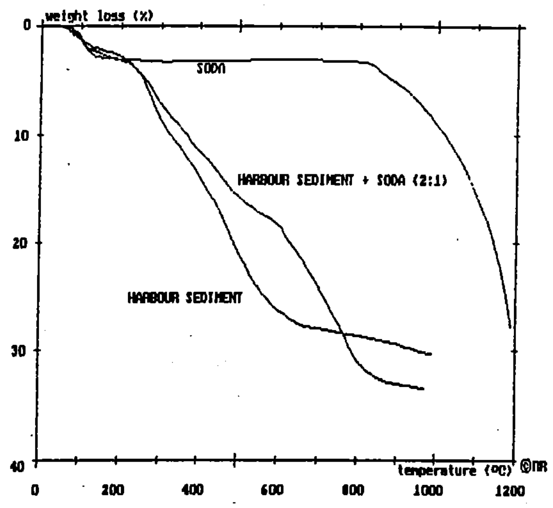

Figure 7.
Thermogravimetric analysis of river sediment and a mixture of soda and river sediment.

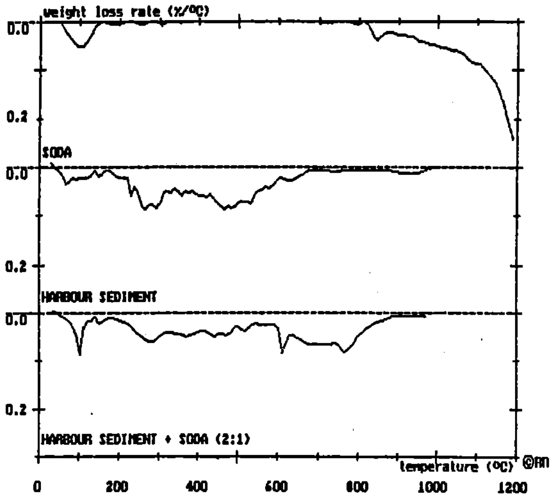

Figure 8.
Differential thermogravimetric analysis of river sediment and mixture of soda and river sediment.

CONCLUSIONS

A method has been developed to remove amphoteric elements like arsenic, phosphorus, chromium, aluminium and other out of sludges and sediments by thermal treatment at 900°C in presence of soda.

The amphoterics present after thermal treatment as sodium salts can be extracted and separated as their calcium salts in the form of pellets.

The method can be easily included in existing sludge and sediment treating systems.

Apart from the presence of the amphoterics as pellets no additional solid or liquid wastes are produced which cannot be reused.

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THE USE OF BIOFIXATION IN THE TREATMENT OF CONTAMINATED SLUDGE

FIRST RESULTS IN BELGIUM

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Abstract

The safe deposition of dredged sludge is becoming increasingly difficult and expensive due to its high content of hazardous organic compounds. For this reason tests were started to treat this sludge with biofixation in situ and ex situ. The first results of these experiments are presented in this text.

Introduction

Within living memory the existense of harbour and river sludge has been a fact of life and until recently it has never been a problem. Permanent dredging of navigable waterways and harbours has always been and will always be necessary. In recent years, however, the deposition of this fertile sludge on the farmers' fields or even on the bottom of the sea has become extremely hazardous since this sludge in some cases has become heavily contaminated.

A first result of this conatmination was the birth of laws that decreed that contaminated sludge should be deposited on land in a controlled way. This controlled deposition includes studies of groundwater flow on the site of the sludge basin, bentonite walls drilled to a certain depth around the basin, HDPE sheets in the basin, a monitoring grid which follows the situation over the years, etc. This, of course, makes deposition extremely costly and in fact, it isn't a solution, only a displacement of the problem. Besides, for a small country like Belgium with a high population density the location of an environmentally sound deposition basin becomes increasingly difficult.

It is for this reason that several dredging firms started studies where the treatment of sludge is considered. Two kinds of treatment could be envisaged here : in situ or ex situ. The decision whether to treat on or not on site depends on a number of factors which will become clearer, we hope, after lecture of this paper.

In situ treatment

The treatment on site of underwater soils is subject to a number of restrictions when one tries to determine the methods to use. In fact at this moment only biodegradation is a feasible way of treating contaminated sludge on site.But even here one has to consider certain limitations which are inherent to an on site biological treatment for which it is not always easy to control what is actually happening in the underwater soil. Firstly, there is the fact that in most cases one has to work in anaerobic circumstances due to the excessive amount of organic contamination. Anaerobic degradation is at this stage still a slow process, even when one works with selected bacteria. Secondly, the exact amount and the kind of pollution play an important role in the decision whether to treat on site or not. Very complex compounds such as PCB's or high concentrations of heavy metals would limit extensively the biodegradation. A third problem arises when there is a continual influx of contamination, which doesn't stop once the treatment has started. This necessarily must lead to an equilibrium situation between the influx and the biodegradation. The question whether this equilibrium will be favourable or not is very difficult to answer in advance since the amount and the kind of discharge may vary in time. Nevertheless, with all these considerations in mind a number of tests are being conducted with biofixation. This product consists of a mineral carrier on which bacteria are fixed together with essential nutrients. The necessary oxygen for the start of the treatment is delivered by this carrier, which is extremely porous.

Oudenaarde - Afleidingsvaart

The first test to be discussed here is being conducted in the city of Oudenaarde, south of Ghent. The canal treated was in fact an old branch of the river Scheldt that is now partially filled up. At one end two sewer pipes discharge domestic waste water of 10.000 inhabitants of Oudenaarde. At the other end of this canal, about 600 m further, the water flows into the river Scheldt. The aim of the treatment was twofold : a reduction of the bad smell (mainly H_2S) and the cleaning of the water. A reduction of the sludge volume was not anticipated, though, of course, it would be welcomed were it to occur.

The treatment started on the 17th of January 1990 when the bacteria were brought into the water. A number of parameters were monitored such as : oxygen concentration, the COD and the concentration of sulfides. Of these parameters the oxygen and sulfide concentrations showed no particular trend towards diminution or increase. The COD, on the other hand already showed a clear diminution after one week : from 473 ppm to 269 ppm (fig. 1).

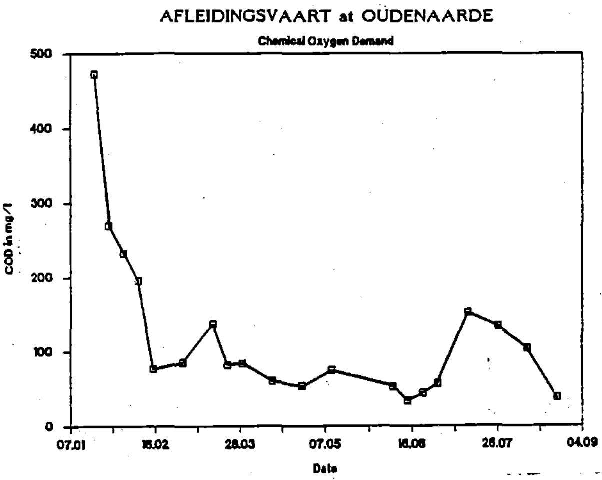

Fig.1 Evolution of the COD in an in situ treatment.

This diminution continued the following weeks until it remained at a status quo of about 75 ppm after a month. On 12 March an increase of the COD is noticed to 137 ppm. This was due to the fact that on 26 February, 5 March and 12 March a treatment with bacteria was started on the sewer pipes themselves. This, in combination with heavy rainfall during that same period, resulted in a sudden downpour of material that had accumulated in the pipes during the previous years. This led of course to the temporary increase mentioned above. Two weeks after the treatment of the sewer pipes however the situation was back to normal, that is, the COD had a value of 82 ppm.

A second treatment of the water was carried out on the 21st of May. This resulted in a further decrease of the COD value to 53 ppm, and even 33 ppm. In July however, an increase of 100 ppm could be established again, which diminished gradually till the end of August, where the values fluctuated again around 70 ppm. The reason for this temporary increase is perhaps due to the exceptionnal warm wheather in July and August which led to a lack of oxygen.

Nevertheless, one can state that the treatment of the water was quite succesful, though the problem of the bad smell was not totally solved.

On the 27th of June a treatment of the sludge was executed. The biofixation used wasn't as fine grained as the one used for the water treatment, which means it would sink instantly to the bottom and work primarily on the sludge itself. Only a 100 m part of the canal was thus treated.
Though it is somewhat early to comment on the results of the echo soundings at the time of writing this paper the measurements are anyhow presented. In August a decrease of about 5 cm could be noticed on the treated part of the canal. The rest of the canal showed a status quo.

Though these results are quite promising, it still is somewhat premature to draw final conclusions. The final results will be presented at the conference itself.

Ghent - Ketelvaart

A second test is being conducted in the city of Ghent. Here a connecting canal between the rivers Scheldt and Leie is being treated primarily to reduce the amount of sludge. The length of the canal is again 600 m, the average width 20 m. A first treatment was executed on the 15th of March 1990. Since the water quality was already quite good (the COD was low) no significant improvement could be expected here. Moreover, since the Ketelvaart isn't a closed basin, there is a continual flow of waters issuing from the rivers Scheldt and Leie. Therefore attention was paid mainly to the sludge. Up to now only a very small reduction of volume of the sludge has been recorded and is perhaps statistically insignificant. A clear reason for this very slow sludge reduction can at this moment not be given. Maybe a delay of 6 months is really to short for any significant evolution to take place.

Nevertheless, a slight reduction of the PCA and PCB concentration is noticeable, but, again, more conclusive results will be presented at the conference.

Ex situ treatment

For several reasons an on site treatment isn't always possible. In a number of cases dredging is the only means of keeping harbours and waterways open to shipping, which excludes a biological treatment as it would take to much time. In other cases the sludge to be treated is to contaminated to be treated on site. In these cases a treatment in a depositary basin becomes inevitable.

A test will be conducted to treat extremely contaminated sludge in a 2000 m^3 basin. At the time of writing this test was planned to start in November 1990. The sludge to be treated has its origin in the Ghent-Terneuzen Canal, which connects the harbour of Ghent with the North Sea. This canal is situated in an industrial area where power stations, tar factories, paper mills, ore refining factories, etc.are located. The dredged material is thus heavily contaminated with organochemical waste and with heavy metals. Since the degree of pollution is of course much higher compared with sludge from less industrialised sites another approach is necessary.

Small scale tests have been and are being conducted in 15 m^3 containers. A small resume of these tests - of which some are still continuing - will now be given. A first group of tests simulated the filling of a basin, that is, every day a small percentage of sludge was brought into the container until it was full. In an ordinary basin everything would stop there. In our simulation however, with every amount of sludge a certain amount of bacteria was added.

Aeration and mixing

Since again these bacteria are aerobic, oxygen was necessary. Because of the high degree of pollution the biofixation wasn't able to provide enough oxygen for a significant degradation to take place. For this reason several aeration systems were tested on a small scale. Due to the high dry matter content however it rapidly became clear that aeration alone was not enough. The sludge at a certain distance from the aerator precipitated and after some time no important degradation could take place here anymore. This resulted in the experimentation with mixing systems to keep the sludge in suspension and eventually, to guide it to the aerator. Two different aeration systems were tested : a surface aerator and tube aeration with compressed air. Two mixing systems were tried : a sub-surface propellor mixer and static mixers. It became clear that all these worked well in water with a low dry matter content. From the moment however that the dry matter content exceeded 10 % a combination of the different systems became compulsary.

The tube aeration consisted of three plastic tubes laid at the bottom of a 15 m^3 container. They worked well but after a couple of weeks the tubes became clogged up at the ends.
The surface aerator sucks in the sludge at the bottom of the basin and throws it out at the surface ensuring thus a perfect aeration. Degradation moved more rapidly than in the tube aeration, but, when the dry matter content exceeded 15 %, the sludge precipitated and aeration stopped. As mentioned before, mixing became necessary. Unfortunately, the static mixers didn't satisfy. Since there are no moving parts the circulation is assured by the aeration. Mixing takes place in a vertical cylinder with a special and complicated configuration of partitions that ensure a thorough mixing. Again, in water this works very well, but with sludge it appeared necessary to have an active mixing system.

The sub-surface mixer worked well and in the end it was decided to use 4 mixers with vertical axes, turning slowly at 37 rpm. Underneath the impellers an open ended pipe with a sparge plate would bring air in the sludge.

Biodegradation tests

Several tests with bacteria and aeration have been conducted. The results of these tests will be discussed now. To have an idea of the weekly evolution of the degradation it was decided to follow the results of a weekly petroleum ether (40°-60°C) extraction. An analysis of a more specific organochemical compound would have given more satisfaction, but because of the cost it was opted to do the inexpensive extraction. The extraction (fig. 2) gives only a rough indication of a positive or negative trend, because one never knows what exactly was extracted. Nevertheless, after consecutive experiments it was decided to use the petroleum ether extraction as a reliable parameter since increases or decreases in the values of the extraction could be correlated with increases or decreases in COD or BOD.

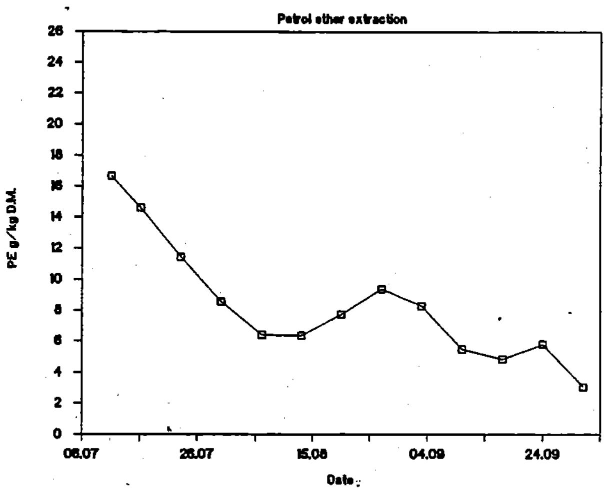

Fig.2 Evolution of the petroleum ether (40°-60°C) extraction.

The initial value of untreated sludge fluctuates around 16.000 ppm and after 15 weeks it is 4.000 ppm, which means there's been a decrease of 75 %. This decrease takes about a month whereafter everything remains at a status quo and there's no further evolution. During each test an analysis was made of the aromatic compounds (phenols, benzene, toluene, xylene,...) PCA's (16 EPA), PCB's, EOX and mineral oils.

The degradation of PCA's and mineral oils results in an increase of toluene and in some tests of phenols. At the writing of this paper about 80 % of PCA's could be degraded in just over three months (fig. 3). The amount of toluene in that same period doubled (fig. 4). Futhermore, small amounts of toluene have been measured in the shed where the experiments take place. This leads to the assumption that a part of the toluene produced in the biodegradation vaporizes and that, in fact, ther's more toluene formed than can be measured.

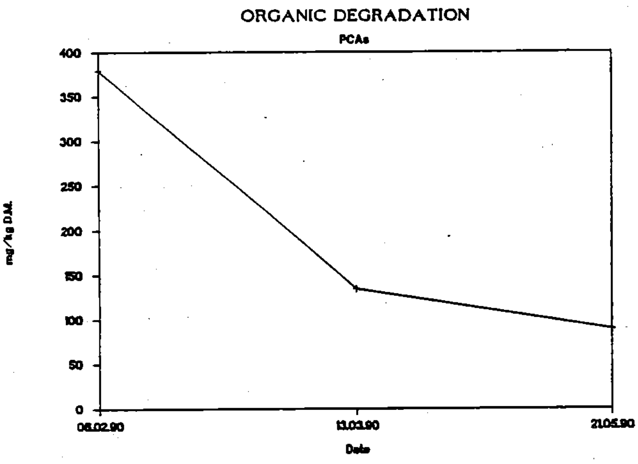

Fig.3 Degradation of PCA's in an ex situ experiment.

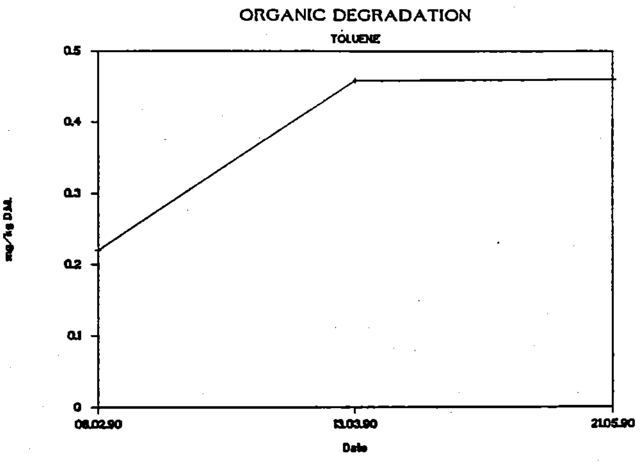

Fig.4 Increase in the toluene concentration during treatment.

Nearly the same is visible with phenols. They show very slow degradation, and after a while even an increase.
PCB's are degraded gradually, but this is very difficult to measure since they are present in very small quantities (0,3 ppm). Nevertheless a decrease of ± 55 % was measured. EOX and mineral oils values diminished with about 60 %.
Summarized, it can be stated - as was to be expected - that the biodegradation of complex compounds such as PCA's has as reaction intermediaries or as byproducts a number of simpler compounds such as phenols and more importantly toluene.

Conclusion

The on-site treatment is still in its infancy. A lot of factors aren't understood yet. The outside influence is enormous and difficultly controlled, but the first results are quite promising : the water in Oudenaarde is of an undeniably better quality and in Oudenaarde as well as in Ghent a (slight) reduction of the sludge could be measured. Therefore on site experiments should be encouraged and followed closely since such a treatment would be a tremendous extension to the arsenal to treat environmental problems.
The ex situ experiments show a biodegradation of 80 % after three months. Further reduction seemed impossible.
Drawing final conclusions on the subject would certainly be premature, since a lot has still to be explained and interpreted, since much more experiments are necessary and most importantly since the large scale tests have not started yet.

EVALUATION OF A SOLVENT EXTRACTION AND BIOTREATMENT PROCESS FOR DREDGED SLUDGES CONTAMINATED WITH OILS AND TARS

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ABSTRACT

Dredged sludges from a steel mill stream to a treatment plant, and pit wastes containing iron fillings contaminated with oil/grease were treated to recover the iron and oil for reuse by a solvent extraction process. The process water,and dredge spoil water containing dissolved organics were biologically treated to organic levels low enough for safe disposal. Solvent extraction with toluene was found to be best for the pit sludge samples. Due to the presence of free fatty acids which originated from microbial activity, aswell as polar compounds used in lubricating oils, a special solvent mixture was evaluated as being best for the stream sludges. The treatment criteria were based on achieving less than 1 to 2% organics in the solid (iron) residue to make it recyclable. The biological treatment for water consisted of a calcium alginate immobilized activated sludge bioreactor. Dissolved organics in water samples were reduced by 91.56% in the bioreactor. Essentially all of the waste sludge can be converted to recyclable fractions, thus providing an environmentally safe and cost effective solution.

INTRODUCTION

The complex nature of sludges makes them difficult to transport, treat or dispose. Van Gemert [1] has outlined various treatment methods for dredged sludges and sediments. Due to strict environmental regulations the disposal cost for sludges is high, and even after safe disposal the generator is liable for any environmental impact which may occur in the future due to its disposal. Dredging costs at $ 10 to $ 40 per cubic yard for 100,000 cubic yards of material at the site in question are by themselves enormous costs, not including the cost for disposal. Analysis of the sludge samples from various locations in the stream, and in the pit indicated solid compositions in the range of 40 to 70 % by weight, of which iron is a major component. By separating and recycling the iron, a substantial reduction in cost can be obtained, and more important is the environmental impact from harmful effects of the sludge can be significantly reduced. The oil fraction remaining after recovering the solvent has a high calorific value, and can be used as a fuel.

Disposal of any sludge in its hazardous form is always risky, and hence if possible the sludge should be treated, either to reduce its volume or separate and recover the harmful constituents. Recovery of the harmful constituents, and recycling of the useful components requires a good separation process. Due to the non uniformity of the samples from site to site, and from location to location within a site, the choice of a good and complete treatment scheme is difficult. Physicochemical and biological treatment has been investigated in this study, because the combination is more cost effective than the separate technologies.

EXTRACTION

Solvent and surfactant extraction processes to remove oils and other organic compounds from soil, sludges and other complex matrices have been used by many researchers [2-5]. Both the solvent and surfactant can be recycled. Surfactant extraction can be more preferable than solvent extraction from the environmental point of view. The drawback with the surfactant extraction process is that the recovering processes are complex and hence the cost of recovering the surfactant can be high. On the other hand, distillation can be a very simple and cost effective process for recovery of the proper solvent. Also, the surfactant cannot be recycled as many a times as the solvent, and this reduces its applicability from the view of cost.

Another important consideration is that most commercial surfactants are specifically designed for solubilizing generic compounds, while an organic solvent can solubilize a large spectrum of organic compounds. This is particularly important in treating matrices contaminated with a wide variety of contaminats as in this study.

BIODEGRADATION

Biological treatment of waste streams containing organic compounds is also an extensive field of research [6]. The biological process is advantageous because it is cheap, it offers a permanent solution by mineralizing the harmful organic constituents to carbon dioxide, water and biomass. The process is also ideal to treat waste streams containing low concentrations of organic compounds.

Biological reactors are best suited for treating wastes in aqueous forms because the liquid phase can be made homogeneous, which allows for efficient transfer of oxygen and nutrients which are essential to the process. The sludge samples can also be subjected to biotreatment without extraction to produce methane under anaerobic conditions which is a slower process. In this particular problem the emphasis was more on recovering the solid fraction for recycling, and a biological process alone would prove expensive. Hence biological treatment was used only as a downstream process to decontaminate process water.

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MATERIALS AND EXPERIMENTAL METHODS

NATURE AND COMPOSITION OF SLUDGES

Sludge samples from two different sites were investigated. Sludge "P" was taken from a pit, and sludge "S" was taken from the stream leading to a treatment plant. Sludge "P" was essentially dry, while sludge "S" had lot of moisture and a different chemical composition from that of sludge "P". This was primarily because of high microbial activity in the stream which continuously changed the chemical composition of the sludge. Table 1 summarizes the average composition of sludges "P" and "S" in terms of oil, solids (iron and other inorganics), and volatiles (light organics and moisture, B.P. 110C).

TABLE 1: COMPOSITION OF THE SLUDGE SAMPLES INVESTIGATED (% W/W)

SAMPLE I.D.	SOLIDS	MOISTURE	OILS AND GREASE
P-01	79.8	6.7*	13.5
S-05	23.3	57.6	19.1
S-06	44.1	30.8	25.1
S-08	52.6	29.7	17.7
S-13	58.4	33.0	8.6

* also contains trace volatiles

EXTRACTION PROCEDURES

Prior to selecting toluene as the extracting solvent, an initial screening was performed with chloroform, ethyl acetate, hexane and toluene to select the appropriate solvent. Two extractions of 1:1 solvent/sludge ratio by weight were performed in the initial screening experiments with each solvent on the pit sludge samples. The decision was made based on visual observation of the organic phase color, and the separation of solids from the organic phase after extraction. From these studies toluene was found to be the best extracting medium for pit sludges.

Extractions with toluene were done with various solvent/sludge ratio (1:1, 2:1, and 4:1 by weight), and various stages of extraction (1, 2, and 4). Known weights of sludge samples were first dried in an oven for 20 to 24 hours at 110C to ensure complete removal of volatiles and the moisture. After determining the loss in weight, the samples were extracted with toluene by vigorous shaking for 1 minute and allowing it to stand for 15 minutes. The final separation of the solids from the organic layer was done by centrifugation. The bottom solids were again dried at 110C for 20-24 hours to remove the entrapped toluene before analysis.

From the stream sludge samples were taken at various locations, and their composition varied from location to location. Initially all samples were screened with toluene after which samples S5, S8, and S13 were used for extensive studies with a solvent system specially mixed from solvents not on the US/EPA priority pollutant list.

All samples from extraction experiments were analyzed by weight. In addition the solid samples after extraction were analyzed by thermal gravimetric analysis and differential scanning calorimetry for organic content.

BIOTREATMENT OF CONTAMINATED WATER

Looking at the entire process it was anticipated that some water (even after drying) would end up as bottoms in the distillation or solvent separation unit after the solvent has been recycled and the oil has been recovered. This water, along with water drained from the dredged sludges, would best be treated in a biological system.

The bioreactor consisted of calcium alginate immobilized activated sludge. The activated sludge was obtained from a wastewater treatment plant in New Jersey, and was acclimated with emulsions of extracted oil in a commercial surfactant. The sludge was then immobilized as described by Sofer et al. (1990) [7]. Experimental setup of the bioreactor is shown in Figure 1. The system consists of a reactor packed with the biocatalyst, and a reservoir operated in batch recirculation mode. Feed from the reservoir is pumped through the reactor back to the reservoir where it is supplemented with additional dissolved oxygen by means of air, oxygen or hydrogen peroxide.

Contaminated water from the stream and the oil extracted from the sludge were treated in the bioreactor. The oil was solubilized in a commercial surfactant and then treated in the bioreactor. The biodegradation process was followed by monitoring the total organic carbon, and the inorganic carbon in the reactor stream on an O.I. Analytical (model 700) TOC analyzer. Biooxidation rates were monitored by an on-line Clarke-type dissolved oxygen probe (Yellow Spring Instruments) and recorded by a chart recorder assembly. The bioreactor system was computer controlled with an IBM compatible PC.

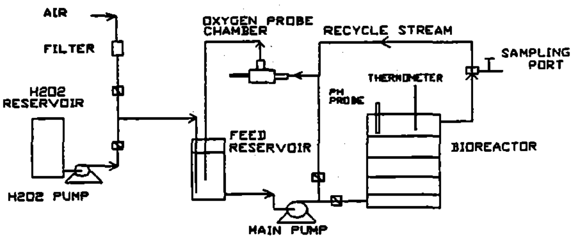

FIG.1 EXPERIMENTAL SETUP OF CALCIUM ALGINATE BIOREACTOR (BATCH RECIRCULATION MODE)

RESULTS AND DISCUSSION

EXTRACTION OF SLUDGE SAMPLES FROM THE PIT

The results expressed as percent oil removed as a function of solvent/sludge ratio, and number of batch extraction stages are tabulated in Table 2 and Table 3. By using a solvent/sludge ratio of 2:1 in a single stage extraction, the organic content of the solids was reduced to 1.6% by weight. Although the reduction was up to 1.2% organics with a solvent/sludge ratio of 4:1, this decrease was not significant enough compared to the increase in amount of solvent. This is because the extraction process at this point is probably limited by either contact time, temperature or solubility in toluene of the organic fraction remaining on the solid.

TABLE 2: EFFECT OF TOLUENE/SLUDGE RATIO ON REMOVAL OF OIL FROM PIT SLUDGE SAMPLE (P-01)

ONE STAGE EXTRACTION

SOLVENT/ SLUDGE RATIO (W/W)	PERCENT OIL REMOVED	PERCENT OIL REMAINING
1:1	78.9	3.5
2:1	90.2	1.6
3:1	93.2	1.2

In the next set of experiments, the number of extraction stages was varied keeping 1:1 ratio of solvent/sludge by weight. The absolute amount of solvent used per unit weight of sludge was same as earlier, the only difference was that the extractions were now done in two and four stages. As seen in Table 3, the two stages of 1:1 solvent/sludge ratio extractions showed better oil removal than one stage of 2:1 solvent/sludge ratio extraction. Much better was the four stage extraction which reduced the organic content on the solids to 0.2% by weight. By doing extractions in more stages the contact time was increased, and the average driving force for extraction was higher as fresh solvent was used in each stage, thus resulting in better extraction efficiency.

TABLE 3: EFFECT OF EXTRACTION STAGES ON REMOVAL OF OIL FROM PIT SLUDGE SAMPLE (P-01)

SOLVENT/SLUDGE RATIO 1:1

# STAGES	PERCENT OIL REMOVED	PERCENT OIL REMAINING
1	78.9	3.5
2	93.8	1.0
4	99.2	0.2

EXTRACTION OF SLUDGE SAMPLES FROM THE STREAM

Unlike the pit sludge, samples from the stream sludge were difficult to extract with toluene or other single solvents. The main difficulties encountered were formation of a very stable emulsion (problem of separation), high moisture to oil ratio (inability of a single component solvent extraction system to provide good removal), and presence of free fatty acids (from high metabolic activity) which were insoluble in both toluene and hexane.

To indicate the presence of high microbial activity in sludge S5, the Lowry protein test, D.O. consumption tests, and the hydrogen peroxide tests were conducted. The Lowry protein determination test indicated the presence of 30 ug protein/ml of sample, the dissolved oxygen consumption rates were on an average 9.4 nmoles/min-ml. These values are high and indicate a high microbial activity in the sample, and hence the liklihood of high polar intermediate constituents.

Among the stream samples tested, sample S5 was found to combine all difficulty points mentioned above, and as a result it was selected for detail experiments to treat the stream sludge. Samples S8 and S13 were used for comparison purposes.

Extraction with toluene and hexane

Since an earlier analysis with the pit samples indicated that 4 times 1:1(solvent/sludge ratio) extraction with toluene leads to nearly 100% oil recovery, the same extraction procedure was followed for the stream sample S5. This time the oil content on solids (dry weight basis) was reduced from 26.2 % to 6.7 %. These results were unexpected, since the extracting solvent recovered after the fourth extraction was nearly colorless, suggesting complete extraction of all oil.

In the next set of experiments sample S5 was extracted four times with equal weight quantities of fresh hexane (4X1:1). Although solvent recovered at fourth stage was nearly colorless the oil remaining on the solids was as high as 9.3 % on a dry basis.

Up to this point the only thing clear was that toluene extraction was slightly more effective than the hexane extraction on wet samples. The difference in the results can be justified based on the difference in polarity of the two solvents. Toluene, being more polar than hexane, removed a larger fraction of polar organic compounds which were high in the stream sludge samples.

Effect of moisture content on extraction of oils

Another major difference between the pit sludge samples, and the samples from the stream was that of moisture content. The poor performance of the solvents could also be attributed to their inability to draw out the organics bound with water. Consequently in another experiment, a part of S5 sample was dried in the oven at 110C for 24 hours. A one stage 2:1 (solvent/sludge ratio) hexane extraction was done with each dry, and wet samples. The solids analysis after extraction showed 4.8% by weight organics on the dried sample, while the organics on wet samples were as high as 15.7 %. Hence it was possible to improve the extraction efficiency by drying the samples and removing the water. The solvent recovered from the dry sample extraction was nearly colorless, and one would expect that all of oil had been extracted. Apparently it seemed that the remaining 4.8 % organics formed a non-extractable fraction (the polar type).

Although the extraction efficency was improoved by removing a large fraction of moisture, the heating process was unable to remove the fatty acid type constituents. An alternate solution was to use the special solvent mixture which would remove both moisture and the free fatty acids, and significantly improve the extraction process.

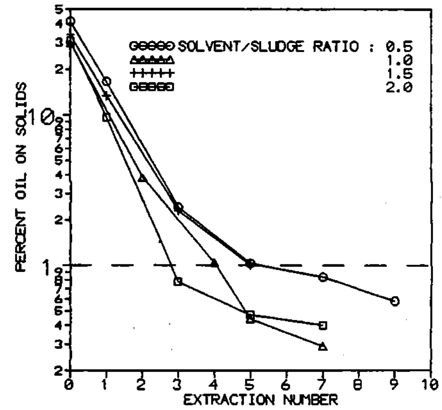

Fig. 2 Extraction of S5 sludge with special solvent mixture: Effect of solvent/sludge ratio on extraction of oils.

Figure 2 shows the effect of solvent/sludge ratio on percent oil remaining on the solid residues with this solvent system. At a solvent /sludge ratio of 0.5, seven extractions were required to meet the specifications of less than 1% oil on solids, while only three extraction stages were required with a solvent/sludge ratio of 2.0.

BIOLOGICAL TREATMENT OF DREDGE SPOILS WATER AND EXTRACTED OIL

To ascertain that in solving one problem (treatment of sludge) another problem (of wastewater) is not created, a biological treatment system was designed and tested for treatment and safe disposal of water fractions. Process water and dredge spoils water formed a major component of this fraction. It was assumed that the recovered oil would meet the specifications for burning as fuel, but in case it failed, an option for biological treatment of the oil was also investigated.

Biotreatment of stream water

Two samples of stream dredge water taken at different locations were treated in the bioreactor. Volumes of 100, 200, and 300 ml of original dredge water were treated in batches in the bioreactor. When compared to control (without biomass), Figure 3 shows that on an average 75% of the total organic carbon removed was due to biodegradation for each injection. The remaining organics were probably removed due to stripping by air from the reservoir, and other abiotic mans. The cumulative removal was 535 ppm TOC in 55 hours.

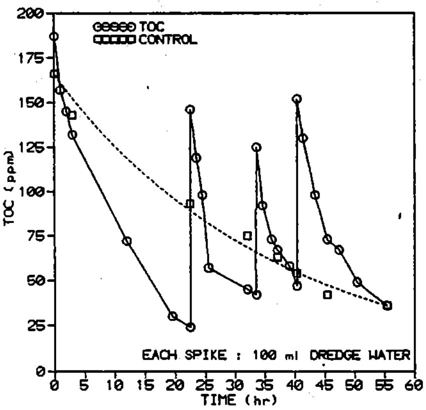

Fig. 3 Biotreatment of stream dredge water in calcium alginate immobilized bioreactor.

Figure 4 shows the variation of TOC and TIC in a series of 300 ml spikes of stream dredge water in the bioreactor. With every spike of stream dredge water the TOC values decrease with time. The concentration of TIC increases initially, and this is probably due to the mineralization of organics into carbon dioxide. After reaching an equilibrium value the concentration of TIC begins to drop because the TOC concentration has decreased, and also due to aeration the dissolved carbon dioxide is being stripped from the reservoir.

The average reaction rates at 100 ml spikes (approx. 150 ppm TOC) of stream dredge water were 10.53 ppm TOC/hr (see Fig.3), while the reaction rates with 300 ml spikes (approx. 300 ppm TOC) of dredge water were on an average 3.83 ppm TOC/hr (see Fig.4). This could be due to inhibition of the microbes at high concentrations or due to the lack of dissolved oxygen.

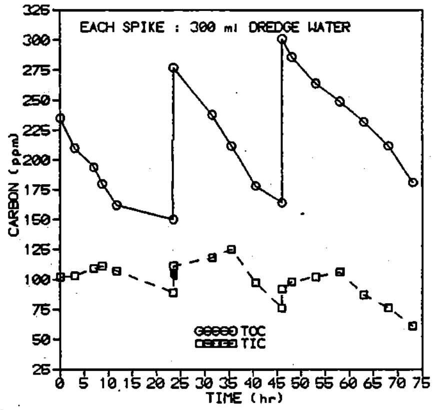

Fig. 4 Biotreatment of extracted oil in calcium alginate immobilized bioreactor with hydrogen peroxide as a DO source.

The combined TOC concentration of the two water samples was 1209 ppm. After treating 1000 ml of this water in the bioreactor (total volume 2000 ml) the combined reactor sample when analyzed showed 51 ppm of TOC. After accounting for dilution, 604.5 ppm of TOC was reduced to 51 ppm, a reduction of 91.56% of which 75% is strictly biological removal.

Biotreatment of extracted oil

As described in the materials and methods section, the extracted oil was emulsified in a commercial surfactant and then injected in the bioreactor for degradation. In this case experiments were conducted with hydrogen peroxide as a source of dissolved oxygen to reduce the physical loss of organics, and to avoid excessive foaming with aeration due to the presence of surfactant.

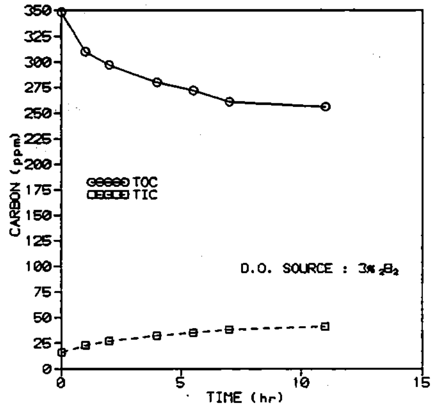

Fig. 5 Biotreatment of extracted oil in calcium alginate immobilized bioreactor.

When compared to control (without biomass) at least 93% of organics removed were due to biodegradation as seen in Figure 5, and hence by using hydrogen peroxide the physical losses were minimized. Of more importance was the change observed in degradation rates which now increased to 8.36 ppm TOC/hr from 3.83 ppm TOC/hr at approximately the same TOC concentration from 300 ml spike of dredge water. This was due to a higher DO level (10.5 ppm) which was maintained with hydrogen peroxide when compared to 6.5 ppm with air in the experiments with dredge water.

Control experiments with surfactant alone (without oil) showed that 15% of the surfactant from a starting concentration of 250 ppm (measured as TOC) was being biologically degraded. Since this observation was done in the absence of oil, it is difficult to say whether the surfactant would be degraded preferentially over oil when the two are together.

From these experiments it was clear that both dredge water and extracted oil could be biologically treated for safe disposal. The TOC concentrations do not go completely to zero (see Figures 2,3,&4) due to background TOC levels from enzymes, surfactants, and other non-biodegradable organics. The enzymes can be filtered out using ultrafiltration membranes, and the surfactant can be recovered and recycled. The resulting water can be safely disposed into receiving waters.

CONCLUSION AND SUGGESTIONS

Laboratory investigation of various sludge samples has indicated that toluene extraction on dry samples, and a special solvent extraction on wet sludge samples can be effective in treating oil contaminated dredged sludges to recover iron and oil for reuse. A first hand economic evaluation based on pilot scale extractions performed on a commercial extractor shows that the process can also be economically feasible when compared to other competing technologies.

The key technical bottlenecks have been the non uniformity of the sludge composition, a high moisture/oil ratio which interferes with the solvents' ability to extract the organics, and the formation of a stable emulsion which creates problems in phase separation. Solvent extraction after preheating the sludge to remove sufficient moisture is recommended to improve both extraction efficiency, and solid-liquid separation. A limiting step is identified as being the polar type constituents which are difficult to extract, and which account for about 10 % by weight of total organics.

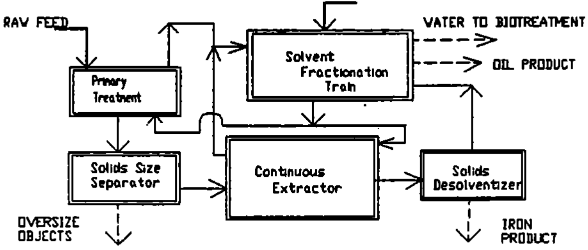

FIG.6 SCHEMATIC PROCESS DIAGRAM

The most important contribution has been one from the environmental point of view. The process reduces essentially all of the waste to recyclable fractions, and significantly reduces both present and future environmental problems that may arise due to improper storage, treatment and disposal of the waste. The water stream was effectively treated in a bioreactor to reduce its organic content below safe discharge levels. Figure 6 shows a conceptual schematic diagram of the overall process which is proposed to treat the contaminated sludges at the site.

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BIOTECHNOLOGICAL LEACHING OF HEAVY METALS FROM THE SILT FRACTION OF DREDGED MATERIAL : EXPERIMENTS USING A MEMBRANE REACTOR

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ABSTRACT

In 1987 the author started with a task force of (micro) biologists to study the possibilities of using biotechnologal methods for the cleansing of sediments and sewage sludge polluted with heavy metals. In 1988 the resulting literature study and design of a possible method, led to a feasibility study by order of DBW/RIZA (department of the Dutch Ministry of Public Works), concentrated on dredged material, which in its turn led to the assignment of the experiments described below in 1989.

It was concluded that decreasing pH is a suitable mechanism to dissolve/desorb heavy metals from the matrix of sediments, and that oxidation of metal sulphides makes them soluble and causes also a further decrease of the pH. The concept of the method is based on the use of two different microbiological processes: the production of lactic acid and the microbial oxidation of sulphur compounds.

Lactic acid can be produced by many bacteria, in high amounts and rather efficiently. Lactic acid is a strong organic acid and a strong chelator of (heavy) metals, which means that resorption and precipitation of the dissolved metals can be prevented. The choice for lactic acid instead of citric acid is made because sediments are very anoxic and lactic acid is produced at a more negative redox-potential than citric acid.

When the bulk of the metals has been dissolved by the lactic acid, oxidation of the persistent metal sulphides starts by *Thiobacilli ssp.* These are chemo-litho-autotrophe, which means that they grow slowly and have a slow metabolism. So they have got a place in the process where all the easier soluble metal compounds have already been removed.

The process technology is 'custom made'. In order to be able to shift balances (e.g. between desorption and resorption) in a programmed direction, a variety of gradients is induced. An important role is fulfilled by the Membrane Reactor®, which has recently been developed by SEC. In this reactor biochemical reactions take place and fluid is separated from solids at the same time.

The results of the first, exploratory experiments show that high yields can be achieved (100% removal of cadmium in one experiment). The test equipment had, however, too many limitations in degrees of freedom to be able to perform a really continuous process. A pilot installation is under construction, in which an integrated cleansing procedure can be carried out, including recovery of the dissolved metals.

Looking at the problem in a different way...

Downstream main rivers, in harbours, canals and estuaries all the dirt man can think of, deposits in thick layers of contaminated silt. This material is rich in valuable metals that are, however, hard to recover.
Leaching metals from ores using bacteria is a well-known method. That's one natural process that can be used, but it has its limitations.
Many (micro)-organisms produce chelators with which they 'mask' hazardous metal-ions to defend themselves. That is another biological mechanism offering possibilities.
Organic pollutants, like oil (products) and polycyclic aromatic hydrocarbons, can be digested by bacteria. That is the third opportunity
(to complete the job).

offers a wide view on Nature's possibilities,

Natural processes tend to find an equilibrium under given circumstances. Man is very inventive in shifting the balance for his own purposes, but looking on the one end he is interested in, he's often blind for the inevitable countermovement at the other end. Looking at it from a less narrow point of view, each countermovement triggers off a second shift in balances, and so on. From a technological point of view we can use these interrelated shifts. It's like milking a cow: keep milking her and she continues producing.

that man can mold to a biotechnological process.

BiMicrobial Metaleaching® is based on the concept of optimizing metabolic circumstances for micro-organisms and keeping them off balance.

A leap in the dark

The research programme was based on a chain of facts and hypotheses found in literature, consults of scientists, assumptions and new inventions, never tested. Actually, nothing was sure. But the ideas fitted together well and the general opinion was that there were no scientific or technical impossibilities, so it was worth trying.

This is probably the right place to extend our thanks to the small group of scientists participating in the organisation of the Dutch Integrated Soil Research Programme and the members of the staff of DBW/RIZA, who granted the monuy for this project.

The experiments had one main purpose:
to explore to what extent the chosen bacteria could dissolve heavy metals from sediment, what conditions they needed and how effective they did their job.

Actually the dark was not so dark at all. The theoretical approach in the feasibility study had provided insight into the interrelations between the possible chemical and physical changes that occur in silt, in both directions: precipitation and adsorption of metal compounds versus dissolving and desorption.
These mechanisms are crucial, because they are equilibria that can be influenced.

Experimental set-up of the experiments

The reader bear in mind that the scientific goals and methodology of the research programme are subservient to the raison d'être of the project: developing a technology dealing with the immense problem of polluted sediments.
And that SEC is a commercial company.

The process was originally designed as a bulk process. To be able to do research and to develop the necessary equipment, the process design was scaled down to manageable dimensions. In this way upscaling problems can, more or less, be avoided.

The research programme has methodically been divided in phases. Phase I was the feasibility study, phase II the experimental programme described here, restricted to the mere proof that the concept works and phase III, now in progress, the trying out of the integral process.

Phase II consisted of three series of experimental leachings of three different fresh water silts.

The main biological processes were, originally:
- producing an efficient lactic acid culture in bulk, using *Lactobacillus helveticus* and glucose;
- producing an efficient culture in bulk of *Thiobacillus thiooxidans* and *T. ferrooxidans*;
- producing a non-defined methanogenic culture in bulk, capable of converting lactic acid to methane;

to be used in the following processes:
- dissolving as much of the metal compounds as possible in a mixed suspension of silt, lactic acid, glucose and lactic acid producing bacteria (*L. helveticus* as well as the micro-organisms present in the silt);
- removing the lactic acid surplus from the suspension by converting it to methane (eventually this part has been left out);
- dissolving more persistent metal compounds using *Thiobacilli* for oxidizing metal sulphides, and other compounds by the sulphuric acid produced.

The main technological aspects were:
- testing of the first experimental model of the membrane-reactor in which both the processes take place as microfiltration, separating fluids from solids, combined with electrophoresis to improve the separation of the charged chelates;
- how to measure and regulate the processes.

We were most curious to find out:
- what metal compounds dissolved at what pH;
- in what quantities;
- how the bacteria reacted on the silt matrix (not a friendly one);
- in what way the silt changed in the process, especially its physical behaviour in view of the repeated dewatering procedures during the cleansing process;
- in general all phenomena we could expect or did not expect.

THE BIOTECHNOLOGY

Biotechnological bulk processes can, if you keep close to the natural conditions of microbial systems, be designed inherently selfcontrolling. On the other hand we need production, so we place the organisms under stress by keeping them off balance.

A biotechnology based on steep gradients

The process-technology developed for the leaching of heavy metals from dredged material consists of series of reactors in which steep gradients are carefully kept; on a macro- and on a micro-scale. Only when a gradient is no longer sustainable, a new cycle is started to impose a new steep gradient, and so on. Even the cycles themselves form a gradient. Starting neutral, the acidity of the silt suspension increases in each cycle, until pH 1 is reached.

In the MembraneReactor® a continuous gradient is kept in dry matter content across the central membrane, in order to carry away the dissolved and chelated metals. This gradient is enforced by an electric field in the same direction, in order to accelerate the transport across the membrane of the positively charged lactate chelates carrying a bivalent metal-ion,.

When the dry matter content allows no further dewatering, a new cycle is started by mixing the silt with fresh (partly recirculated) water with lactic acid and glucose. In this way the bacteria are not hindered by their own metabolite (lactic acid) and are not poisened by an increasing concentration of dissolved metals.

THE EXPERIMENTS

Three different sediments were treated two times each; the first time to get familiar with the material and how it reacted on lactic acid, the second time to quantify the amounts of removed metals. The material of each second treatment is used for the experiments with *Thiobacilli.*

The samples were fresh water silts; two rather mineral (Maas sediment from the harbour of Stein and Rhine sediment from the harbour of Arnhem) and one more organic (Dommel sediment, a tributary of the river Maas). The Dommel and Maas samples were separated by means of a hydrocyclone by particle size > 40 µ, the Stein sample was sieved only.

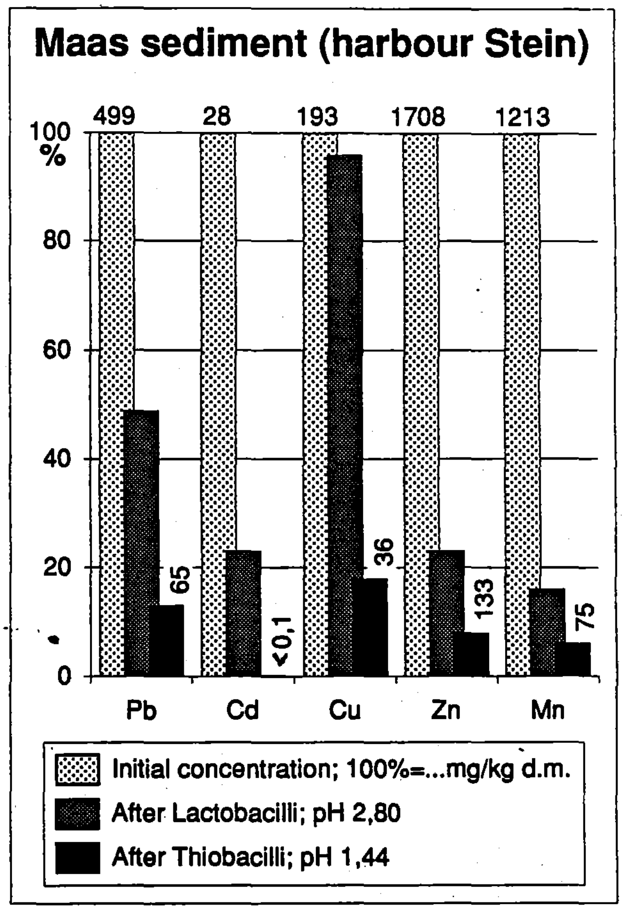
Treatment Stein silt (516 g, second run)

pretreatment	sample	with Lactob.	with Thiob.
dry matter:	40.2%	1.3%	1%
pH start:	8.2	4.02	1.51*
pH end:	4.02	2.80*	1.44

*The lactic acid production by *L. helveticus* was not sufficient for a rapid acidification, so lactic acid was added. The used, high productive strain appeared very sensitive to metals, although later some adaptation was noted.

The treatment with *Thiobacilli* has been carried out in a aerated vessel where the suspension was pumped around for mixing purposes.

The samples have been analysed with flame AAS.



GRAPHIC 1: Three heavy metals and manganese partly removed and cadmium totally removed from Maas sediment (harbour Stein) in appr. 6 days

Reference:

	Dutch A-value (natural background)	B-value (investigation)	C-value (clean-up)
Pb (this silt)	ca 60	150	600 mg/kg d.m.
Cd (this silt)	ca 0,5	5	20 mg/kg d.m.
Cu (this silt)	ca 20	100	500 mg/kg d.m.
Zn (this silt)	ca 60	500	3000 mg/kg d.m.

Treatment Dommel silt

The first test-run with the Dommel sediment showed a spontaneous decrease of the pH after adding glucose, from pH 6.9 to 4.4 in two days.

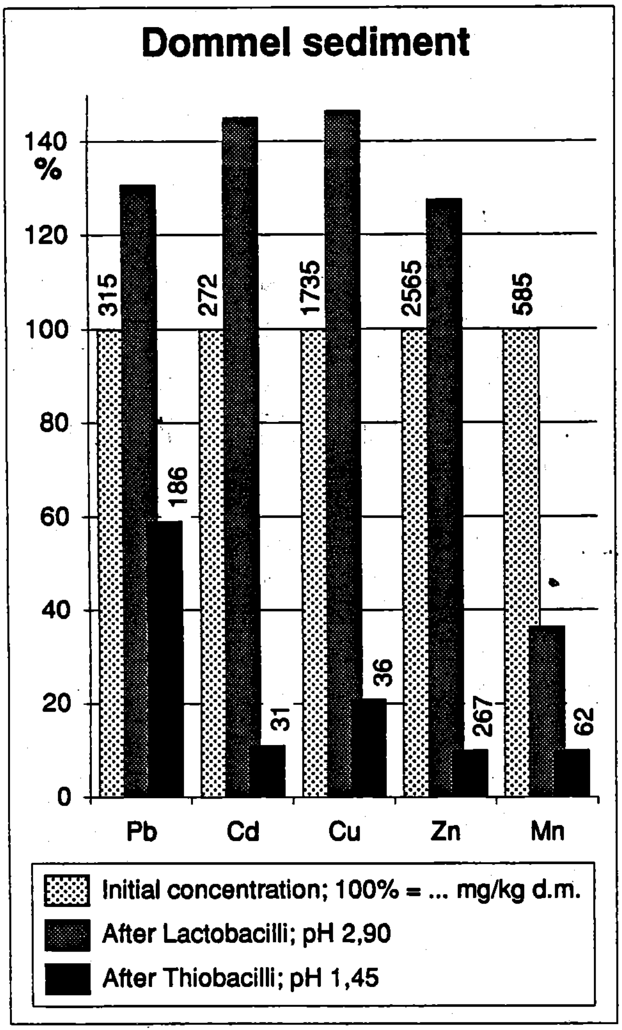
The second run was done with a sample containing 1004 gram dry matter, of which 10.4% organics.

During the acidification with lactic acid a substantial amount of H_2S and CO_2 escaped.

The second run could not be carried out with the membrane reactor because the membrane was damaged. To separate solids and fluid, gravitation separation is used. The dry matter content and pH changed as follows:

	pretreatment sample	with Lactob.	with Thiob.
dry matter:	15.9%	2%	1%
pH start:	6.70	3.70	2.9
pH end:	3.90	3.85	1.45

Despite the activity of Lactobacilli in the suspension, pH tended to rise. Probably some acid and glucose was metabolised by the micro-organisms present in the silt; a lot of CO_2 was formed.

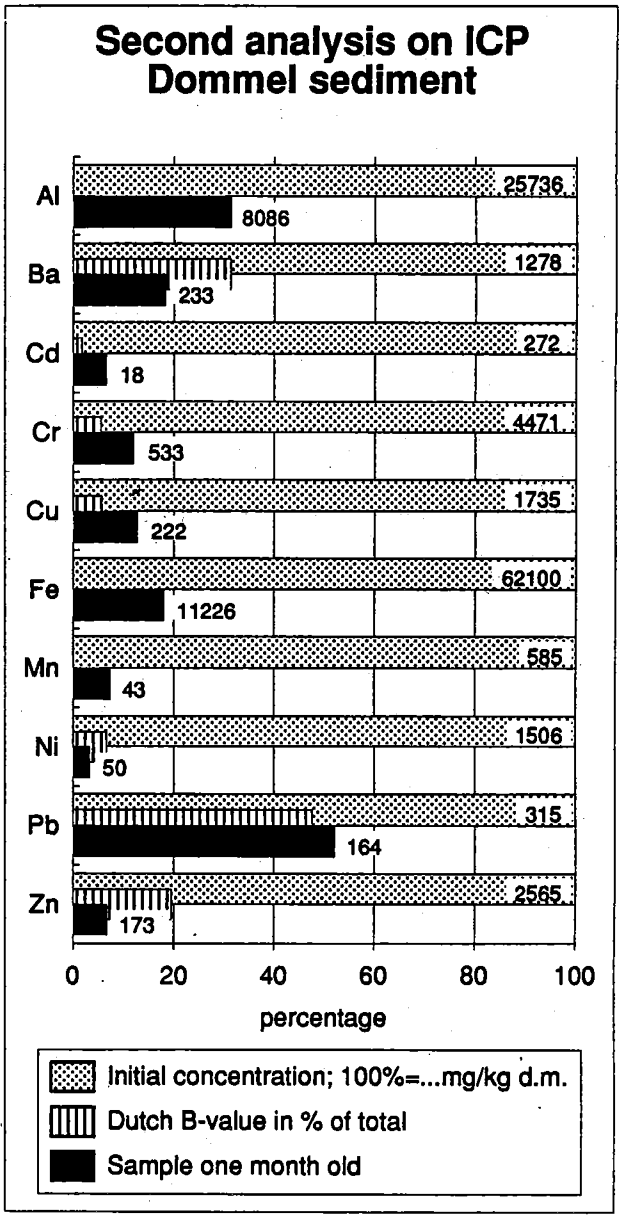


GRAPHIC 2: Four heavy metals and manganese partly removed from Dommel sediment in 5 days

Notes

A particular phenomenon was the initial rise of the concentrations of the four heavy metals after the treatment with Lactobacilli. The fast decrease of the Mn concentration shows that in the first stretch with the Lactobacilli the *relative* amount of persistent (heavy) metal compounds increases initially, due to degradation of organic matter (CO_2 production!) and dissolving of heavy particles like Fe/Mn(hydr)oxides. The total mass loss as dry matter amounts ca 35%.

One month later the treated samples of Dommel sediment could be analysed again on a ICP Emission Spectrometre.



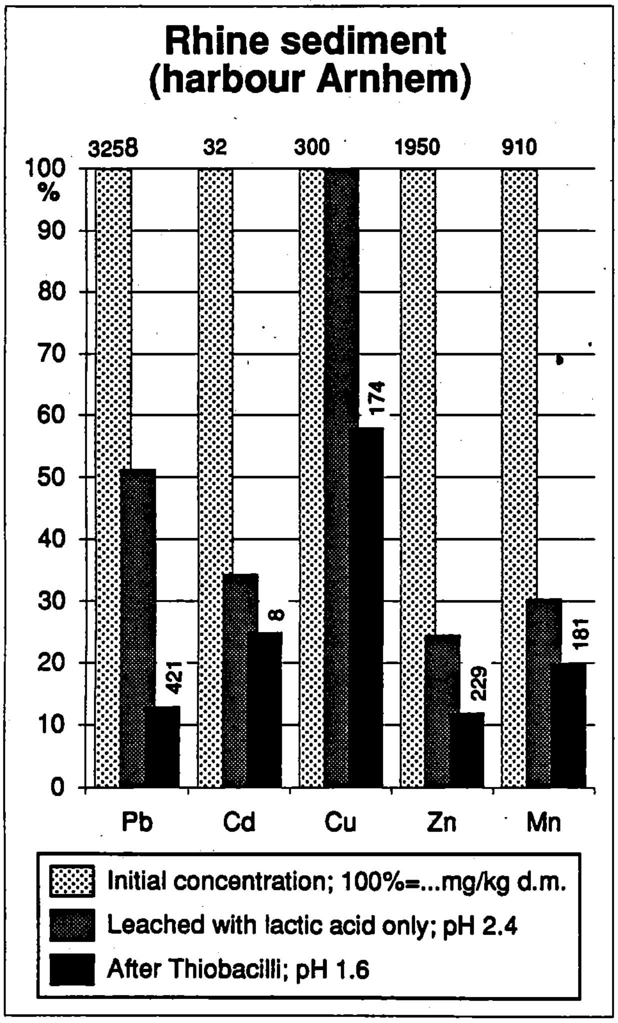
GRAPH 3: Dommel sediment analysed again on ICP

The elements Ag, As, Be, Bi, Co, In, Mo, Nb, Zr showed no integratable emissions. The elements V, W and Y showed present in the initial samples. Ti and Sr concentrations decreased.

The results of the treatment of Rhine sediment (harbour Arnhem)

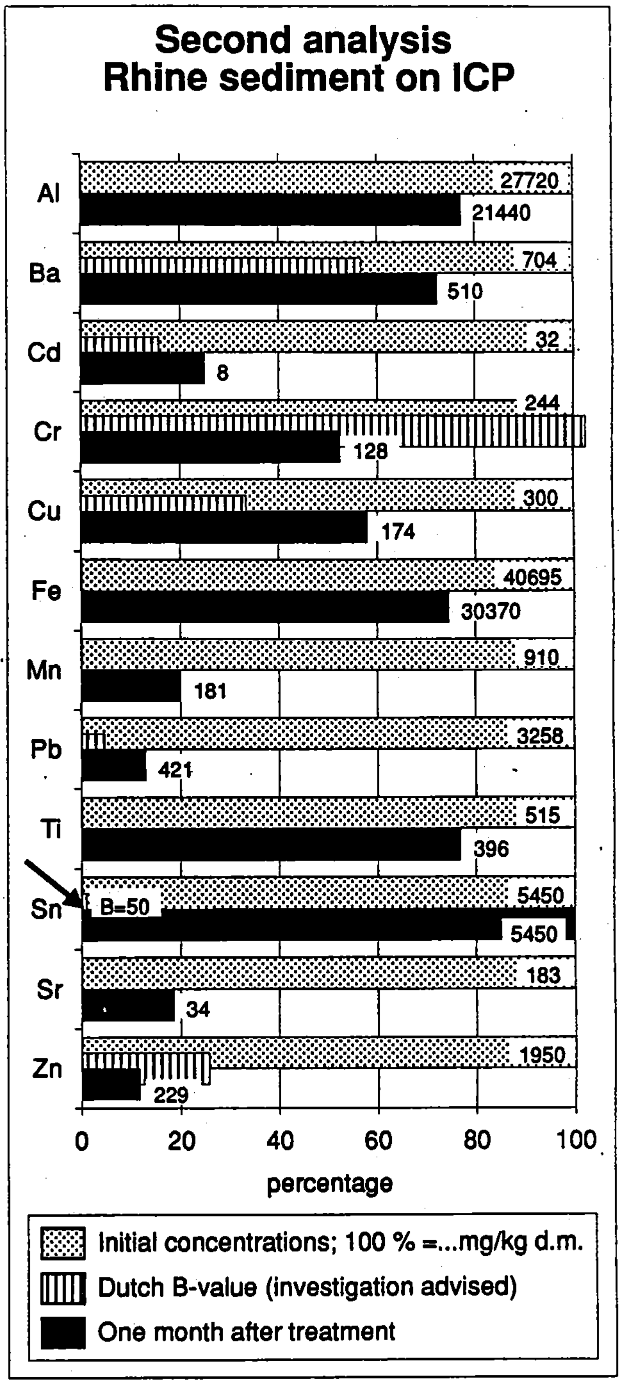
The Rhine sediment sample, polluted by a metallurgic plant, was separated by means of a hydrocyclone by 40 µ. Unlike the previous two samples, the Arnhem silt was only treated with lactic acid. No Lactobacilli were added. Separation of solids and fluid was done through gravitation.

In two cycles pH is lowered from 6.8 to 2.4 using pharmaceutical lactic acid. The sample was pumped around through the Thiobak during 6 days, resulting in a pH of 1.6.



GRAPH 4: Leaching results Arnhem silt

Like the Dommel sample, the Arnhem sample of treated silt was analysed one month later on an ICP emission spectrometre.



GRAPH 5: Second analys of Rhine sediment, one month after treatment

A CLOSER LOOK AT THE MECHANISMS AT WORK

In the following chapter a few more things are said about the pursued close relation between lactic acid producing bacteria, the chelating process and the biochemistry of the oxidation of sulphur and sulphide, catalysed by *Thiobacilli.*

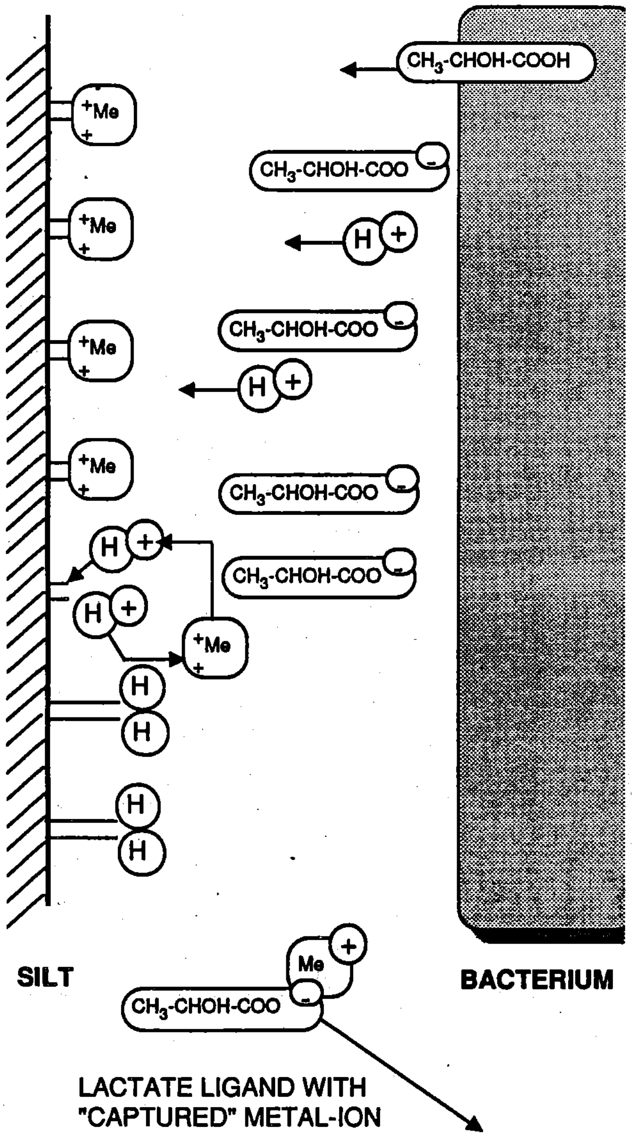


FIG. 1: Visualizing ion-exchange and chelating

That's how they work

On the left the surface of a silt particle with a overall negative charge can be seen. Metal-ions are bonded to the silt-surface in one way or another.

On the right a bacterium produces lactic acid molecules. When excreted, the lactic acid dissociates; the H^+ exchanges with the metal-ions (the hydrogen bonds are stronger than the metal bonds). The free metal-ion normally resorbs immediately to the silt or precipitates when meeting a suitable ligand. The (negatively charged) lactate-ligands, however, 'capture' the metal-ions. These chelates act as carriers for the dissolved metals. By means of combined microfiltration and electroforesis they are removed from the system.

Unbalancing lactate-chelates

When cadmiumcarbonate dissolves in a lactic acid solution, chelates are formed. In time a balance is reached between chelates of one, two or three lactate-ligands according to a specific relation $K_{(25^\circ C)}$ (for Cd):

$$K_1 = \frac{[Cd^{++}(C_3H_5O_2^-)]^+}{Cd^{++} + C_3H_5O_2^-} = 1{,}21$$

$$K_2 = \frac{[Cd^{++}(C_3H_5O_2^-)_2]^\circ}{[Cd^{++}(C_3H_5O_2^-)]^+ + C_3H_5O_2^-} = 0{,}87$$

$$K_3 = \frac{[Cd^{++}(C_3H_5O_2^-)_3]^-}{[Cd^{++}(C_3H_5O_2^-)_2]^\circ + C_3H_5O_2^-} = 0{,}1$$

Lactic Acid, C.H. Holten et al. Stichting ILRA Copenhagen 1971

This balance-seeking, rather slow reaction is forced into one direction, the monolactate chelate, by removing the monolactate chelates by means of electroforesis across a membrane. Thus an accelerated removal of the dissolved and chelated metals is achieved:

$$CdCO_3 + 3H^+ + 3C_3H_5O_2^- \longrightarrow$$

$$\longrightarrow \underline{[Cd^{++}(C_3H_5O_2^-)]^+} + CO_2\uparrow + H_2O + 2C_3H_5O_2^-$$

$$\rightleftarrows [Cd^{++}(C_3H_5O_2^-)_2]^\circ + C_3H_5O^-$$

$$\rightleftarrows [Cd^{++}(C_3H_5O_2^-)_3]^-$$

$$\downarrow$$

electrophoresis

Thiobacilli

In general sediments are very anoxic and show a negative redox-potential. In time micro-organisms reduce all material containing oxygen. Sulphates are reduced to H_2S and sulphide salts, which are very insoluble, even at a low pH.

Thiobacillus thiooxidans is capable of oxidizing sulphide salts to free metal-ions and suphuric acid in order to obtain energy from it. It is a chemo-litho-autotrophic, highly specialized species that only uses CO_2 as carbon source and the oxidation of S° and S^{2-} as energy source. It can be found everywhere.

Thiobacillus ferrooxidans, its brother, is specialized in oxidation of Fe^{2+} to Fe^{3+} besides the use of S° and S^{2-}.

In the conversion of reduced sulphur compounds to sulphuric acid the following reactions, catalysed by *Thiobacilli*, are involved:

$H_2S + 2O_2 \text{---}> H_2SO_4$

$S_8 + 12O_2 + 8H_2O \text{----}> 16H^+ + 8SO_4^{2-}$

$CdS + 2O_2 \text{----}> CdSO_4\downarrow$ (and for Pb, Cu etc).

The oxidation of ferro to ferri, catalysed by T. ferrooxidans, goes for ironsulphate:

$4FeSO_4 + O_2 + 2H_2SO_4 \text{---}> 2Fe_2(SO_4)_3 + 2H_2O$

This enables the following chemical reactions possible, independent of the bacteria:

$2FeS_2$ (pyrite) $+ 2Fe_2(SO_4)_3 \text{---}> 6FeSO_4 + 4S^{\circ}\downarrow$

$CdS + Fe_2(SO_4)_3 \text{---}> CdSO_4\downarrow + 2FeSO_4 + S^{\circ}\downarrow$

(This can be seen as the growing of small cauliflowerlike sulphur precipitations).

When a strong and acid chelator like lactic acid is present, the free metal-ions are immediately captured. No insoluble sulphate salts are formed:

$CdS + 2O_2 + C_3H_5O_2^- \text{--}> [Cd^{2+}(C_3H_5O_2^-)]^+ + SO_4^{2-}$

This is called 'masking' in analytical chemistry. In the BiMicrobial Metaleaching® process, carried out in a newly developed aerobic thin-layer bioreactor, the Thiobak®, it is patented.

STATE OF THE ART

The present state of the development of the BiMicrobial Metaleaching® is experimental.
A pilot installation is under construction. This enables pilot-treatments to be carried out in 1992.

The research is now aimed at improving the yield and deminishing the reaction time. The occurring (bio)degradation of organic pollutants as oil and PAH is being optimized. The problem of upscaling laboratory-scale methods to a full-scale plant is avoided by starting the development on a larger scale than usual.

There was no other way: the bioreactors and membrane filters have one optimal size, so the capacity can only be enlarged by multiplying them.

In 1991 a containerized installation will be available for pilot-treatments, consisting of one or more process containers, one electrolysis container, an energy unit and a control room.
The capacity is dependent on the properties of the dredged material, as are the costs. A preliminary test-cleansing is necessary in all cases to be able to forecast results, price and (im)possibilities.

There is a direct relation between desired results and price. In fact most metals can be removed completely, as can most organics.

The flowchart

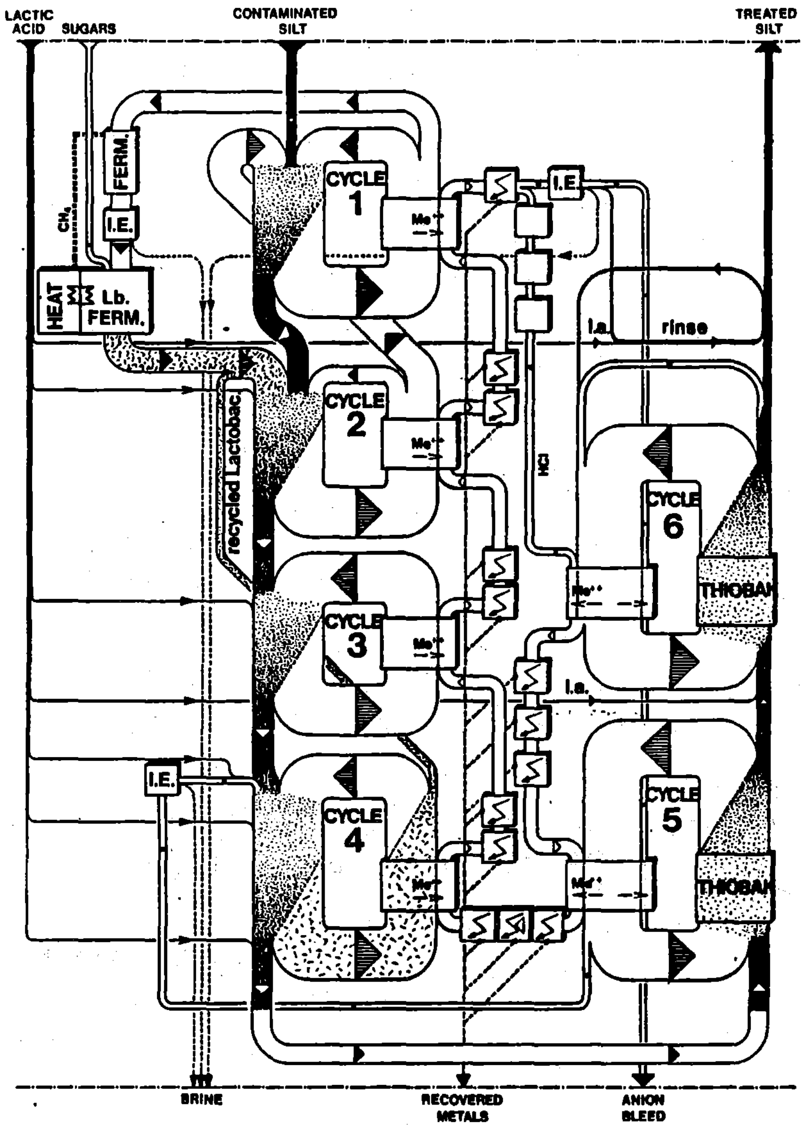
The speciation of metals in sediments is more complex than in ores, and sediments are harder to handle as well. In order to make the metals accessible for bacteria the sediments can be mixed to a sludge with bacteria and the necessary nutrients. In that way the handling-problems are reduced to pumping and separation of fluid and particles.

The flowchart shows a 6-stage cyclic process, in which the sludge is mixed repeatedly with fluid, and drained again. In each cycle a programmed increase in acidity is induced by feeding Lactobacilli with sugar and adding lactic acid.
In the last two cycles Thiobacilli oxidize the metalsulphides. The then dissolving metals are chelated by the still present lactic acid, while the sulphide is oxidized to sulphuric acid. When given time, the Thiobacilli produce a pH of 0,5.

The Thiobak®, a thin layer bioreactor, was especially developed for the aerobic leaching with Thiobacilli. The MembraneReactor® was developed to combine bio-leaching in a slurry with simultaneous separation of fluid from silt-particles and bacteria.

The separated fluid, loaded with lactic acid and chelated metal-ions, is unloaded by means of electrodialysis. The lactic acid is recirculated, the metalions are removed by a secundary circuit of hydrochloric acid. This goes for electrolysis to recover the dissolved metals.

During the process a great deal of organics (natural and synthetic) is being degradated. Whether the cause is biological or chemical, is not yet known. After neutralisation of the sludge leaving cycle 6, bio-degradation can be optimized in a more extensive way.



Flowchart BiMicrobial Metaleaching®

*Storm Environmental Consultancy

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Rijkswaterstaat, WL, IB & TNO-MT Zware metalen in aquatische systemen geochemisch en biologisch onderzoek in Rijn en Maas en de daardoor gevoede bekkens. 6 deelrapporten

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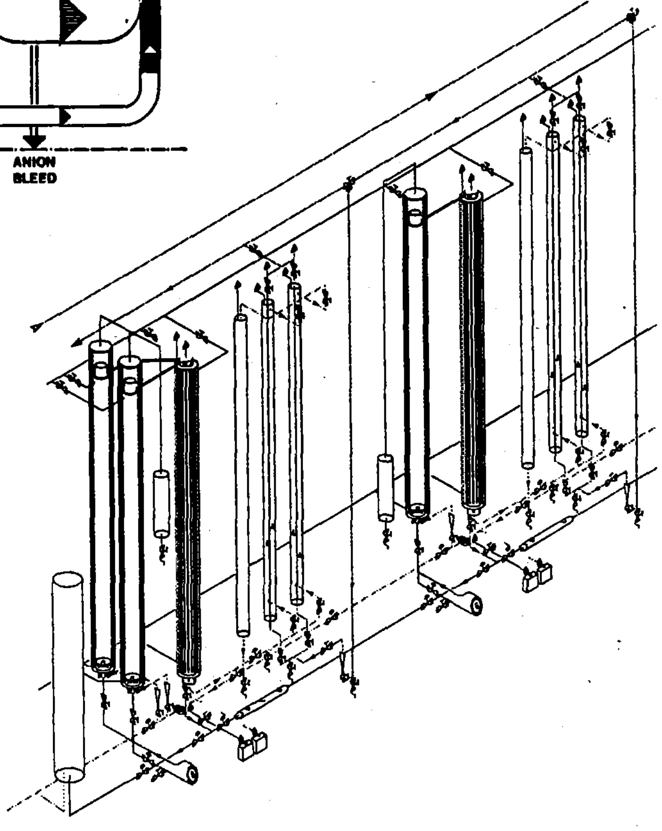
The design ⟶

The isometric design of the pilot-plant shows two of the six cycles of the main process flow. Not showed are the electrolysis system and the control system.

The dimensions are fixed. More capacity means more units.



EXTRACTION OF WEAKLY MAGNETIC PARTICLES FROM SLUDGES ON VGMS

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ABSTRACT

Some mining sludges and tails, industry wastes magnetic particles, which are commercially profitable to process but contaminated with hazardous materials. One of the ecological clean methods of their extraction is magnetic separation, i.e. high-gradient magnetic separation (HGMS) and volume-gradient magnetic separation (VGMS). The latter has advantage over the first in convenient working with abrasive and corrosive materials, and filters. Unfortunately, VGMS is not effective for fine particles extraction. This work purpose was to find out the possibility of superposition of these two processes in order to use advantages of either of them. To do this, an initial working zone was separated by diaphragm into a row of narrower zones. The diaphragm surface was coated by a ferromagnetic expanded metal net with mesh size of 1.5 mm, made of 80 microns ribbon. The process of weakly magnetic particles extraction from "red sludge" was studied in this work. 95% of particles were fine (less than 44 microns size). The field generated by superconducting magnetic system was about 2 T. As a result of experiments, the growth of extraction of weakly magnetic particles and the increase in the degree of purification of sludges from them, as the separation zone got narrow, was obtained.The transformations from VGMS to HGMS took place when the zone number was increasing.

INTRODUCTION

The problem of extraction of weakly magnetic particles from sludges is associated not only with a purification of contaminated materials, but also with an extraction from them valuable components, for example, a weakly magnetic iron, tantalum, manganese, etc. One of ecologically pure methods of purification is magnetic separation. The most widespread are high-gradient magnetic separation with ferromagnetic elements in a working zone, using permanent magnets and electromagnets to generate magnetic fields. With the development of technical superconductivity the possibility to obtain sufficiently high magnetic fields in great volume made its appearance, which makes its possible to increase capacity and selectivity of such a type devices. Besides, new`type separators (VGMS) were developed in which the working is free from ferromagnetic elements and a non-uniform magnetic field is generated by an external magnetic system$^{1)}$. The use of superconducting magnetic separators already starts to be beyond the scope of laboratories, especially this is vital there where the use of usual (electromagnetic) separators is impossible or not cost-effective due to requirement placed upon their dimensions, power and capacity.

THEORY

Let us consider the three-dimensional separation region E containing the extraction surface Γ. Let us assume that a particle penetrated into the region E under the effect of certain forces, travels inside and a particle reaching the surface Γ is regarded as extracted. let us introduce into the region E a set of coordinates and consider in the point $\vec{r}$ from this region a particle which is affected by forces at instant of time $t_o=0$. Under the effect of these forces the particle will move according to the equation:

$$m\vec{r}=\vec{F}, \qquad (1)$$

where m is the particle mass, $\vec{F}$-the resultant of all forces affecting the particles. Let us assume that the solution of equation (1) was found at definite initial conditions, and it was resolved against time, i.e. the time $t(\vec{r},\vec{r}_o)$ during which the particle penetrates from point $\vec{r}$ into point $\vec{r}_o$, was determined. If $\vec{r}\in\Gamma$, then $t(\vec{r},\vec{r}_o)$ is the time of particles extraction from the point $\vec{r}$. Averaging this time over possible initial conditions, we shall obtain a mean time of separation in the considered region E:

$$<t>=\int_E t(\vec{r},\vec{r}_o)d\vec{r}/\int_E d\vec{r}. \qquad (2)$$

Let us discuss collection of points in the region E, for which a time of extraction is constant and equal to t_c. This set of point forms a surface which divides the region E into two parts E_1 and E, so that for any point $\vec{r}\in E$ $t(\vec{r},\vec{r}_o)\leq t_c$, and for points $\vec{r}\in E_2$ $t(\vec{r},\vec{r}_o)>t_c$. For the time t_c all particles will be extracted from the region E_1. If to assume that at the initial moment similar particles are distributed uniformly in the region E, a coefficient of extraction of the given particles for time t_c will be determined as follows:

$$R(t_c)=\int_{E1}d\vec{r}/\int_E d\vec{r}. \qquad (3)$$

VOLUME-GRADIENT MAGNETIC SEPARATION

Let us look upon a wet separation process and neglect an inertia of particles. In the approximation of a laminar flow of spherically noninteracting particles the equation (1) will take the form $\vec{F}_m+\vec{F}_c=0$, where $\vec{F}_m=\pi D^3\varkappa\mu_o J^2\mathrm{grad}(\vec{h}^2)/6$ is the magnetic force and $\vec{F}_c=-3\pi D\eta\vec{v}$ is the Stokes force. The gravity force can be neglected, which is valid unless the condition $v_o>(\rho-\rho_o)D^2g/(18\eta)$. Here D is the particle diameter, $\varkappa$ is the magnetic susceptibility, μ_o is the magnetic constant, J is the density of current through the separator´s magnet system, $\vec{h}$ is the magnetic field strength in the point $\vec{r}$ per unit current density, η is the medium, v_o is the pulp flow velocity, ρ and ρ_o are particle and medium densities, respectively. From solution of this equation, using the formula (2) let us consider a time corresponding to the predetermined coefficient of extraction R:

$$t(R)=18\pi\Phi(R)/(\varkappa D^2\mu_o J^2), \qquad (4)$$

where $\Phi(R)=<\int d\vec{r}/\mathrm{grad}(\vec{h}^2)>$ is the extraction factor depending only on the separation parameter. The pulp comes through the separation zone for the time t L/v_o, where L is the zone length, v_o is the mean pulp velocity. Taking this into account, solving the equation (4) with respect to R, we shall obtain:

$$R=\mathrm{arc}\Phi(\Theta),$$

where $\Theta=\mu\ XJ^2L/(18\eta v\ )$, $X=\varkappa D^2$ is the parameter of particles extraction. The form of separation extraction function $R(\Theta)$ is determined completely by its geometry and the argument Θ depends on a particle properties X, the separator operating conditions $A=J^2/v$ and the separation zone length L. In the above mentioned assumptions the initial material is sufficient to be described by two functions: 1)the density of particles distribution over the extraction parameter W(X) and 2)the dependence of extracted component content upon this parameter $\beta(X)$[2]. Knowledge of $R(\Theta)$, W(X) and $\beta(X)$ functions allows the separation results to be predicted. For instance, the yield of a magnetic product obtained during the separator operation in the mode A and the extraction of useful component is expressed by the ratios:

$$\gamma=\int W(X)R(X,A)dX, \qquad (5)$$

$$\varepsilon=\int W(X)\beta(X)R(X,A)dX/\beta_o,$$

where β is the content of the useful component in the initial product.

HIGH GRADIENT MAGNETIC SEPARATION

An extraction of particles from HGMS comes about by their capture by ferromagnetic elements. In paper[3] it was shown that the thickness of a layer of magnetic particles captured by a ferromagnetic wire depends on the ratio of magnetic velocity $v_m=\varkappa HMD^2/(18\eta a)$ to a mean flow velocity v_o near the wire surface of radius a and magnetization M. A maximum value for captured particles layer q is expressed by the following relation: $q=c_1(v_m/v_o)^{c2}$, where c_1 and c2 are constants. The experiments on fine particles separation on HGMS with a ferromagnetic net indicated similar dependence for the thickness of layer of deposited particles on the net1). In the present paper we assumed that the capture radius depends on the ratio of the magnetic velocity to flow velocity. If the captured particles layer thickness did not reach its maximum value q, then extraction should grow with an increase in the capture radius until the capture cross-section E_1 overlaps all separation region E. A separation time corresponding to the extraction R can be calculated from the formula (3), as well as also for VGMS with allowance for the magnetic and Stokes forces. The HGMS extraction function depends on the radius of capture of a ferromagnetic matrix element, and, consequently, on the magnetic velocity / flow velocity ratio. A parameter characterizing an extracted particle is value $\varkappa D^2$. The extraction function $R(\Theta)$ both for VGMS and HGMS has the form of a smeared step increasing monotonically from 0 to 1. A coincidence of E and E_1 regions corresponds to a full 100% extraction, i.e.the overlap of entire separation zone by the radius of capture of the ferromagnetic net or filter.

DEVICE DIAGRAM

The device diagram is shown in fig.1.

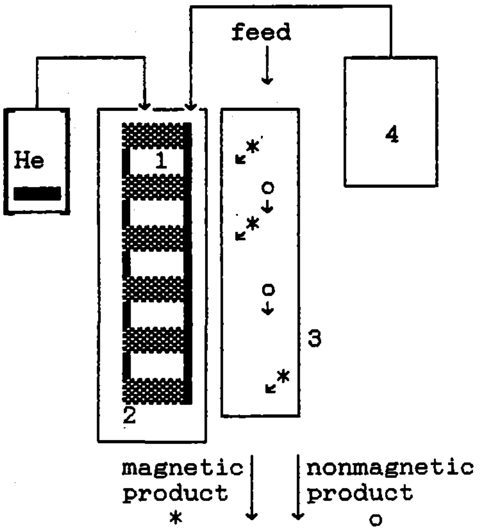

Fig.1 The device diagram.

The base of it the superconducting magnetic system 1 made of NbTi wire. The superconductor is placed in cryostat 2 filled with liqued helium. The highest value for current I supplied from a source, amounts to 300A; the magnetic field induction on the working zone 3 attains 2 Tesla. The separation zone length L=66cm, its depth b=3sm, width - 10cm. Four types of chambers were used (fig.2): A-the chamber with free separation zone; B-the chamber divided into 3 subzones by vertical diaphragms parallel to the magnetic system plane, C-the chamber whose 0.1% volume is filled by the net; and D-the chamber with the separation zone filled by the same net by 3% of its volume.

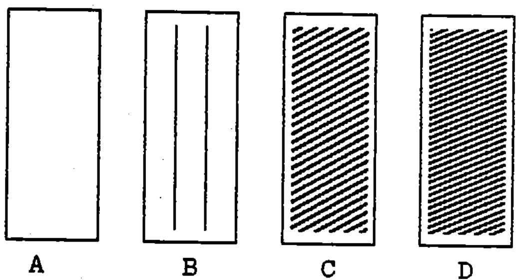

Fig.2 Four type of separation chamber.

The net is made of a magnetically soft stainless steel ribbon with thickness of 80mu. The mesh is 1.5mm.

EXPERIMENTS AND THEIR DISCUSSION

To verify the separation mechanism extraction experiments with hematite Fe_2O_3 were carried out. In the fist place a density of this material particles distribution over the extraction parameter W(X); where $X=\varkappa D^2$, was determined. This can be performed in two ways. Firstly, to calculate W(X) by measuring a granulometric composition of particles. And here it is taken into account that magnetic susceptibility of all particles of an initial material is the constant value: $\varkappa=10^{-3}$. The W(X) dependence measured in such a manner is shown in fig.3 by a dotted line. Secondly, this function can be measured at a separator operating in the VGMS conditions by a repeated repurification of a magnetic product4). The W(X) dependence obtained in the second manner is shown in fig.3 by a solid line. The difference between to plots is that in the second case there is a dip

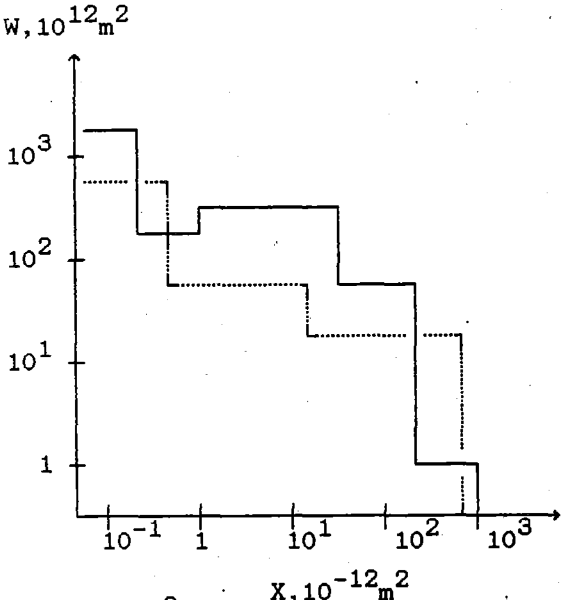

Fig.3 $W(\varkappa D^2)$ dependence for the initial material.

(the local minimum) in the region of low values of the extraction parameter X. This difference seems to be associated with the effect of particles fluctuation in magnetic fields of the order of 1.5-2 Tesla. Exactly at these induction values an extraction of particle fractions with low X parameters took peace. Flocculation results in a decrease in fine particles number and an increase of large-sized particles amount. This increase an extraction of particles. To calculate indexes of magnetic separation products the function W(X) should be measured in the second manner in order to take into account the flocculation. Let us note that in the given case the dependence of useful component content on the extraction parameter is constant value: $\beta(X)=1$.

A narrow class particles size 40 to 80mu was chosen from the same material, to determine experimentally the $R(\theta)$ extraction function for each chamber type. Extraction functions were plotted assuming that the extraction process proceeds in terms of the extraction parameter $\varkappa D^2$. All four function are depicted in fig.4.

One can note that the general shape of extraction functions of all 4 chambers is the same. But $R(\Theta)$ extraction functions of B,C and D chambers are

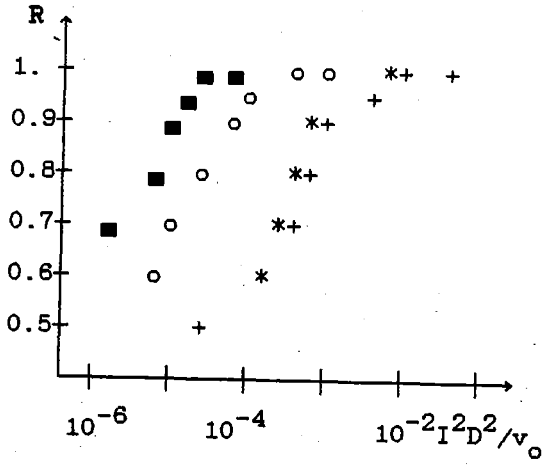

Fig.4 Extraction curves.

displaced about A on the axis of argument Θ by about 20%, one order of magnitude and two orders of magnitude, respectively. Here $A=I^2/v_o$, v_o is average velocity of pulp flow in the chamber. This is explained by a higher level of extracting and the less separation time. One can conclude that in the given case the transition from VGMS to HGMS is expressed mathematically in the presence of cofactor on the argument Θ: $R=R(\alpha\Theta)$, where $\alpha=1, 0.2, 10$ and 100 for chamber A,B,C and D, correspondingly.

Yield of separation products $\gamma(I^2/v_o)$ of all hematite of the size from 0 to 100 mu for each type of chambers were measured and calculated from the known functions $R(\theta)$ and $W(X)$. The results are presented in fig.5,6 and 7.for chamber A, B and C,D, respectively. The experimental and calculated dependencies agreed with an experimental accuracy, the errors amounted to not over then 5%.

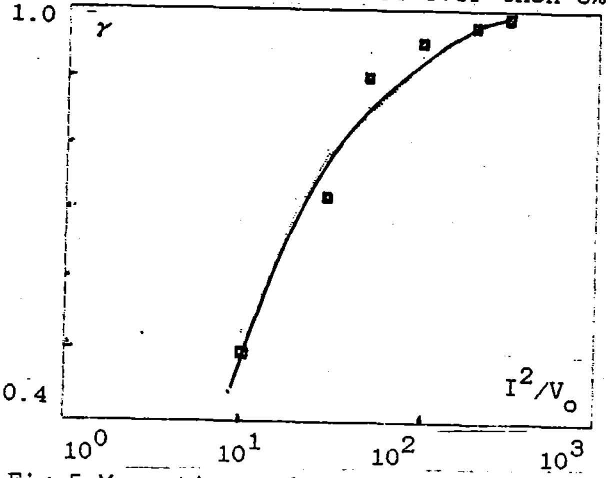

Fig.5.Magnetic product yield, chamber A.

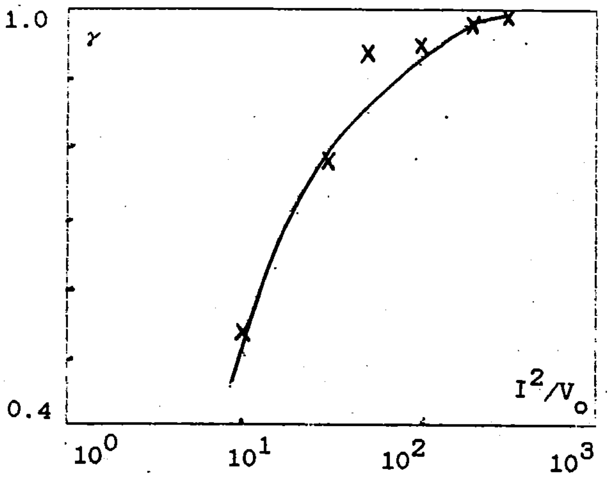

Fig.6. The magnetic product yield, chamber B.

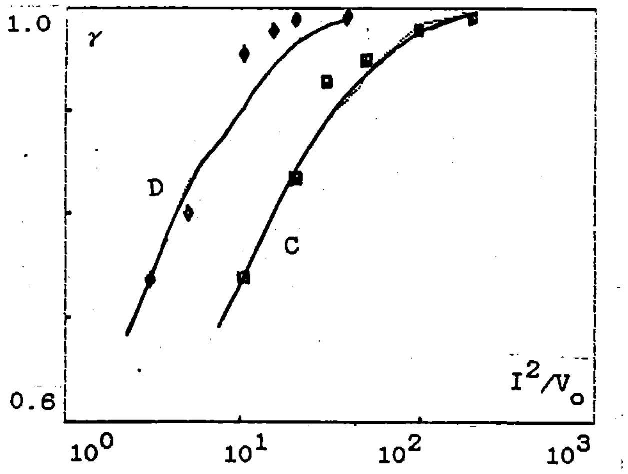

Fig.7. The magnetic product yield, chamber C and D.

A sludge material containing impurities can be presented as a mixture of a sand and impurity components. At the same separator in the same chambers the experiment were run on a extraction of hematite from its mixture with a sand. 85% of particles had sizes not over than 44 μm. The Fe_2O_3 content was β =41%. The magnetic field induction was equal to 1.5 Tesla. The results are placed in Table 1 and 2. It can be seen from Table 1. that magnetic product yield and hematite extraction increase with the transition from the chamber A to D. Table 2 shows that the hematite content in the increment of magnetic product $\Delta\beta_m$ increases with this transition, too. It indicates that more fine particles namely, more uncovered, are extracted in chamber D.

Table 1.

Chamber	γ_m,%	ε_m,%	β_m,%
A	26.4	30.6	48.3
B	40.3	44.7	46.2
C	50.6	57.5	46.6
D	78.2	91.8	48.9

Table 2.
The increment of magnetic product.

Chamber	$\Delta\gamma_m$,%	$\Delta\varepsilon_m$,%	$\Delta\beta_m$,%
A-D	51.8	61.2	49.6
B-D	37.9	47.1	51.9
C-D	27.6	34.3	52.2

To work with sludges of a wide range of size it is worthwhile to use a combined system of chambers. At the beginning of technological chain the chamber of the A or B type (VGMS) should be placed to select more large particles, and then - the chamber of the C or D type (HGMS) to purity sludges from fine particles. In this case a contamination of a matrix with large particles is reduced and the role of mechanical capture of nonmagnetic particles including quartz is decreased.

From the results of the paper one can conclude that the separation process proceeds over the parameter $\varkappa D$ This makes it possible to predict separation results, to calculate indexes of enrichment and purification products. The growth of extraction of weakly magnetic particles from sludges as the zone of separation narrows, was obtained. The transition from VGMS to HGMS results in the increase of extracting forces and the result of the separator's extraction function in the direction of argument's low values. In strong magnetic fields of 1.5-2 Tesla the extraction processes are affected by flocculation processes which increase an extraction of fine particles. The use of superconducting fine particles namely, more uncovered, are extracted in chamber D.

Table 1.

Chamber	γ_m,%	ε_m,%	β_m,%
A	26.4	30.6	48.3
B	40.3	44.7	46.2
C	50.6	57.5	46.6
D	78.2	91.8	48.9

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The increment of magnetic product.

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CONCLUSIONS

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ANALYSIS OF THE TURBULENT TRANSPORT EFFECT ON HYDROCYCLONE PERFORMANCE AND THE DEVELOPMENT OF MORE EFFICIENT CYCLONE-LIKE SEPARATORS FOR THE PROCESSING OF FINE SLIMES

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ABSTRACT

A hydrocyclone has played an important part in industial, agricultural, pharmaceutical and environment protection fields etc. for producing classified or concentrated materials and for removing harmful or hazardous substances. Furthermore, a demand for classification of fine or ultrafine materials has recently been drastically increased in these fields. The material behavior is dominated not only by centrifugal motion and mean medium flow pattern but also by turbulent fluctuating flow structure in the hydrocyclone. The structure of turbulence has been evaluated first by analyzing spatially observed turbulent characteristics and then the effect of turbulence on the separation performance has been numerically analyzed taking into account the propagation of turbulent energy by diffusive mixing. The result of simulation indicates that the separation performance is remarkably deteriorated with the increase of turbulent intensity in the hydrocyclone. In order to improve the separation performance a few types of turbulence-free cyclone-like separators have been developed. One of them has been applied to remove metallic pollutants contained in fine slimes. The result shows that the turbulence-free separator is much more efficient in separation performance than the conventional hydrocyclone.

INTRODUCTION

A demand for classification of fine or ultrafine materials has recently been drastically increased in industrial, agricultural, pharmaceutical and environment protection fields. It has been, however, very difficult to classify sharply submicron and a few micron particles in any wet separation system. Fine or ultrafine particles have only limited inertia and, hence, their behavior is strongly affected by the disturbance generated in the separator. Turbulent energy generated in a wet system decays more slowly than that in a dry system, which owes to the difference in the kinematic viscosity.

Turbulent transport phenomena have been considered as one of the most essential factors affecting on the separation efficiencies and theoretical and/or experimental works[1-9] have been contributed to analyze for some separation processes. Most of these works have discussed only on the separation processes in homogeneous turbulence. Turbulent energy is, however, generally supplied at a localized source and propagated heterogeneously into the working space in a classification vessel. Hence, one has to take into account the locality of turbulent characteristics to analyze for the turbulent transport effect on the classification performance.

In this article turbulent characteristics are observed first in a hydrocyclone by using the electrochemical method and turbulent energy is proved to be propagated by diffusive mixing. Then the diffusion coefficient is identified as a function of the space coordinate in the hydrocyclone. The effect of the intensity of turbulence on the classification performance is numerically analyzed in the next section. Finally, a few types of turbulence-free cyclone-like separators are developed to improve the classification performance and one of them is applied successfully to remove metallic pollutants contained in fine slimes.

TURBULENT CHARACTERISTICS IN THE HYDROCYCLONE

A number of methods, techniques, and instruments have been developed and used for the observation of the structure of turbulence, viz., hot wire or hot film anemometer methods, flow visualization techniques, electrochemical methods, utilization of pressure sensors, application of image analysis by photodiode arrays, utilization of laser Doppler effects, etc.

An electrode reaction method[10,11] was selected for the measurement of turbulent characteristics in the hydrocyclone because spatially distributed characteristics could be detected on a minute scale and in a simple manner. Moreover, the electrode reaction technique can be applied to a system containing not only a continuous phase but also a dispersed phase. The reaction liquid is composed of potassium ferrocyanide, potassium ferricyanide, potassium chloride and tap water. The diffusion current between the cathode made of a platinum wire and the anode made of a silver plate is determined by the flow velocity of the liquid in the vicinity of the cathode. The diffusion current is observed as a sum of the mean component and the fluctuating component because both components exist in the liquid velocity field. The relationship between them can be written as

$$I + I' = a\sqrt{u + u'} + b \tag{1}$$

where I is the mean diffusion current, u is the mean flow velocity, I' and u' denote the fluctuating components, a and b are constants determined by the properties of the electrodes and the reaction liquid. Hence, the fluctuating velocity can be distinguished by

$$u' = \frac{I'}{a}\left[\frac{I'}{a} + 2\sqrt{u}\right] \tag{2}$$

The diffusion current was converted to the voltage and stored in the transient memory. Then the time series of data was transferred to the microcomputer system and the Eulerian time correlation function defined by

$$R_E(\tau) = \frac{u'(t)\,u'(t+\tau)}{u'^2} \tag{3}$$

was calculated. The cylindrical hydrocyclone used in the measurement has the following dimensions : radius of the cyclone R_c=40 mm, radius of the inlet R_i=5 mm, radius of the overflow finder R_o=10 mm, radius of the underflow pipe R_u=7 mm, height of the cyclone H=60 mm.

The Eulerian time correlation functions observed at different points in the hydrocyclone operated with only continuous phase under various inlet velocities are shown in Fig.1. As can be seen, the Eulerian time correlation functions are approximated by

$$R_E = exp\left(-\frac{\pi\tau^2}{4T_E^2}\right) \tag{4}$$

$$T_E = \int_0^{\infty} R_E(\tau)\,d\tau \tag{5}$$

Equation (4) has also been confirmed in a system containing the dispersed phase.

The effect of the inlet velocity on the stochastic mean of the fluctuating velocities is shown in Fig.2. Thus it is found that the turbulent energy varies proportionately with the kinematic energy of the fluid at the inlet level. The dependence of the integral time scale on the inlet velocity also appears in Fig.3. Consequently, following relationships can be deduced from these observations and simple dimensional analysis :

$$\sqrt{u'^2} = K_1 u_1\left[\frac{R_c}{r}\right] \tag{6}$$

$$T_E = K_2\left[\frac{r}{u_1}\right] \tag{7}$$

where K_1 and K_2 are constants. Then another scale of turbulence, or the integral space scale, can be defined by

$$\Lambda_r = u\,T_E \tag{8}$$

Although strictly speaking the integral space scale has to be calculated from the integration of the longitudinal velocity correlation function Equation (8) should be reasonable in the case where the space scale is evaluated in the mean flow direction.

Thus one can imagine the functional form of the longitudinal velocity correlation function from Equations (4), (5) and (8) and conclude that turbulent energy is propagated by diffusive mixing in the hydrocyclone[12]. Therefore, the turbulent diffusion coefficient in the mean flow direction is written as

$$D = K_3\sqrt{u'^2}\,\Lambda_r \tag{9}$$

where K_3 is the coefficient determined by the relationship between Lagrangian and Eulerian turbulent characteristics, which has been recognized as 0.4 in homogeneous turbulence[13]. Consequently, the turbulent diffusion coefficient in the hydrocyclone is rewritten as

$$D = K_4 u\,R_c \tag{10}$$

where K_4 is the constant given by $K_4=K_1K_2K_3$.

The discrepancy in the turbulent behavior between continuous phase and dispersed phase has been theoretically evaluated[12]. As a result it has been found that a solid particle smaller than a few tens of a μm moves along with the surrounding fluid elements. Moreover, the effects of the solids concentration on the settling and diffusion behavior of a solid particle have been numerically analyzed[11]. The result has indicated that both effects cancel each other and, hence, the concentration as well as its distribution have not to be taken into account. Thus the diffusion coefficient for the fluid elements given by Equation (10) will be used instead of that for the solid particles in the following calculations.

FORMULATION OF THE MATERIAL BEHAVIOR IN THE HYDROCYCLONE

The material behavior in the cylindrical hydrocyclone is written in the cylindrical coordinate system as

$$\frac{\partial C}{\partial t} = \frac{1}{r}\left[\frac{\partial}{\partial r}\left(rD_r\frac{\partial C}{\partial r}\right) + \frac{\partial}{\partial z}\left(rD_z\frac{\partial C}{\partial z}\right)\right] - \frac{\partial (u_z C)}{\partial z} - \frac{\partial (u_r C)}{\partial r} \qquad (11)$$

where C is the solids concentration, t denotes time, r and z are radial and axial space coordinates, D_r and D_z are diffusion coefficients in the r- and z-directions, respectively, and u_r and u_z are mean flow velocities in the r- and z-directions, respectively. Assuming that the diffusion transport of solids particles is negligible in the z-direction compared with the mass transfer caused by the mean axial flow and that the axial flow is uniform in the r-direction Equation (11) is rewritten as

$$u_z\frac{\partial C}{\partial z} = D_r\frac{\partial^2 C}{\partial r^2} + \frac{D_r}{r}\frac{\partial C}{\partial r} + \frac{\partial D_r}{\partial r}\frac{\partial C}{\partial r} - \frac{\partial (u_r C)}{\partial r} \qquad (12)$$

in the steady state.

Moreover, the mean flow velocities are assumed to be given by

$$u_r = \frac{Q}{2\pi rH} - v_c \qquad (13)$$

$$u_z = \frac{Q}{\pi (R_c{}^2 - R_f{}^2)} \qquad (14)$$

where Q is the flow rate, R_f denotes the radius of a hypothetical cylinder at the inside of which finer solid particles are recovered as the overflow product, and v_c is the centrifugal settling velocity of a particle given by the Stokes law.

NUMERICAL ANALYSIS

The material behavior in the hydrocyclone has been numerically analyzed by using Equations (12), (13) and (14). The explicit asymmmetric finite difference method developed to solve nonlinear parabolic partial differential equations[14] has been adopted because of the excellent convergence property. The boundary conditions are given by

$$\left.\begin{aligned} r = R_c \ ; &\quad \frac{\partial C}{\partial r} = 0 \\ r = R_f \ ; &\quad C = 0 \end{aligned}\right. \qquad (15)$$

The effect of the intensity of turbulence on the distribution of solid particles in the z-direction in the hydrocyclone is shown in Fig.4. The solids concentration has been calculated in a monodispersed system composed of larger particles than the theoretical separation size and averaged over the r-direction. The solids concentration is normalized by the average concentration on the inlet level C_0. As can be seen from Fig.4, the amount of misplaced materials is increased and, hence, the solids concentration is decreased as the intensity of turbulence is increased.

Then the distribution of the solids concentration in the r-direction has been evaluated on the outlet level of the hydrocyclone in the case where the intensity of turbulence, or the diffusion coefficient, is varied on the inlet level. Some of the results appear in Fig.5, where the solids concentration is normalized by the average concentration on the outlet level C_r. The results also indicates that the turbulent diffusive mixing disturbs the classification behavior and the distribution tends to be uniform as the intensity of turbulence is increased.

The effect of the disturbance on the classification performance has also been evaluated in a gravitational classification system in which the source of turbulence is localized. Some of the results calculated in the case where the disturbance is generated in the vicinity of the underflow discharge level are shown in Fig.6. As can be seen, a little disturbance remarkably deteriorates the performance, viz. the sharpness of separation is decreased and the separation size is increased with the increase of the intensity of turnulence.

Consequently, how to reduce the disturbance, or turbulence, in the classifier is one of the most important problems to improve the separation performance in fine classification.

DEVELOPMENT OF THE TURBULENCE-FREE SEPARATORS

BASIC CONCEPT

The decay process of turbulent energy propagated by diffusive mixing is written as

$$u^2 = \sqrt{\pi}\,\frac{\gamma}{4}\,[2\nu(t+t_0)]^{-5/2} \tag{16}$$

where ν denotes the kinemaic viscosity and γ and t_0 are constants determined by the stochastic mean of the fluctuating velocity and the integral space scale observed in the vicinity of the source of turbulence[11,12]. The generation of turbulence is inevitable in any industrial classifiers and, hence, supplied turbulent energy has to be dissipated as soon as possible. It is found from Equation (16) that turbulent energy is dissipated much more rapidly in a pneumatic classification system than in a hydroclassification system because the kinematic viscosity is above ten times larger in the former than in the latter. Consequently, the generation of turbulence have to be suppressed in the hydroclassifier as possible as one can.

The disturbance should be generated mainly at the point where the velocity changes drastically and the strong shear flow exists. Therefore, the velocity difference between the feed slurry and the rotating slurry has to be reduced first in the centrifugal classification system. Then the velocity difference between the rotating slurry and the wall of the apparatus has also to be reduced. Moreover, it should be efficient for the reduction of the disturbance to simplify the flow structure in the classifier. According to these considerations a few types of turbulence-free cyclone-like classifiers have been developed.

Two representatives are simply illustrated in Fig.7 (a) and (b). The classifier shown in Fig.7(a), called MI-NO CLASSIFIER, utilizes the simultaneous settling of solid particles in the centrifugal force field which is generated by the coaxial rotation of every parts in the apparatus. Thus the solid particles are classified according to the distance in the centrifugal settling direction determined by the particle size. The dispersed settling is applied, on the other hand, in the classifier shown in Fig.7(b), called STATICLONE, in which solid particles are classified due to the velocity difference between the radial flow of the medium and the centrifugal settling of particles. The centrifugal force field is also generated by the coaxial rotation of every parts in the apparatus. Each rotational flow in these classifier is written as a forced vortex and the tangential velocity profile is given by

$$u_t = r\,\omega \tag{17}$$

where u_t is the tangential velocity and ω is the angular velocity of the rotating flow.

CLASSIFICATION CHARACTERISTICS

The separation size can be predicted theoretically for the proposed classifiers, which is given by

$$d_c = \xi\sqrt{\frac{Re}{G}} \tag{17}$$

where Re denotes the axial Reynolds number, G denotes the initial centrifugal coefficient, and ξ is the constant determined by the configuration of the apparatus. It is also derived from Equation (17) that the separation size is in proportion to the square root of the slurry flow rate and is inversely proportional to the rotational speed. Hence, the fluctuation in the throughput has a little effect on the classification performance.

Equation (17) has been verified through a series of experimental works carried out by using calcium carbonate particles. Some of the results observed in the MI-NO CLASSIFIER are shown in Fig.8. As can be seen, the separation size is not so much varied even when the centrifugal coefficient is widely changed except for the range of small centrifugal coefficient and it is accurately predicted by Equation (17). Then one of the conventional hydrocyclones has been used to compare the classification performance. As a result submicron particles could not be classified in the conventional hydrocyclone.

Then one of the turbulence-free separators, or STATICLONE, has been applied to remove a metallic pollutant contained in a fine slime. Copper sulphide precipitated by aeration in the copper sulphate solution was used as a metallic pollutant. Copper sulphide particles were distributed in size less than 2 μm, which were confirmed under a microscope. Calcium carbonate particles were used as a fine slime, whose size was larger than 2 μm. These particles were mixed and suspended in tap water to obtain an appropriate concentration. A series of separation tests were carried out by changing the solids concentration and the copper concentration in the feed slurry. The overflow and underflow products were recovered under the classification condition of the separation size of 2 μm and each product was subject to the chemical analysis to calculate the removal rate of the pollutant.

The effects of the solids concentration on the removal rate and the grade of the overflow product are shown in Fig.9 and 10, respectively, where the copper concentration in the feed slurry is also varied on three levels and a few data observed in the conventional hydrocyclone are plotted comparatively. As can be seen, the overall separation performance is more superior than that of the hydrocyclone though the removal rate shows a little decrease as the solids or copper concentration is increased and though the grade of the overflow product is slightly deteriorated as the solids concentration is increased or the copper concentration in the feed slurry is decreased.

These results have been observed in an idealized system composed of artificial pollutants finer than the separation size of the classifier and artificial slimes coarser than the separation size. There are, however, many cases in practice where metallic pollutants have to be separated from slimes by only density difference since their sizes are similar. The effect of the disturbance on the separation performance is more striking in such separation than in the separation by particle size. Consequently, the turbulence-free separators may be effective to remove any types of pollutant materials and they will play an important part for solving some environmental problems.

CONCLUSION

The structure of turbulence in the hydrocyclone has been evaluated first by analyzing spatially observed turbulent characteristics such as fluctuating velocities, Eulerian time correlation functions, space and time scales, etc. The turbulent diffusion equation with variable diffusion coefficient has been introduced and the effect of turbulence on the separation performance has been numerically analyzed. The result indicates that the sharpness of separation is remarkably deteriorated and the separation size is increased with the increase of the turbulent intensity in the hydrocyclone. In order to improve the separation performance a few types of turbulence-free cyclone-like separators have been developed. The theoretical basis of the separation mechanism has been discussed and one of them has been applied to remove metallic pollutants contained in fine slimes. The result shows that the turbulence-free separator is more superior in separation performance than the hydrocyclone. The developed separators will play an important part for solving some environmental problems.

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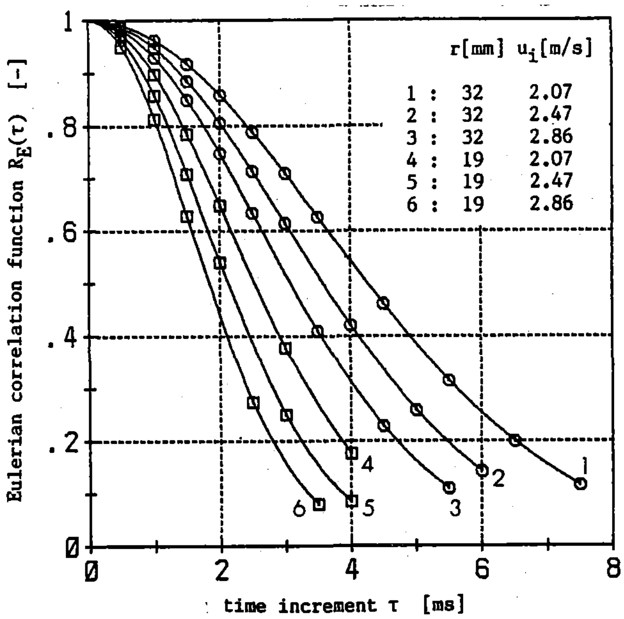

Fig.1
Eulerian time correlation function in the hydrocyclone

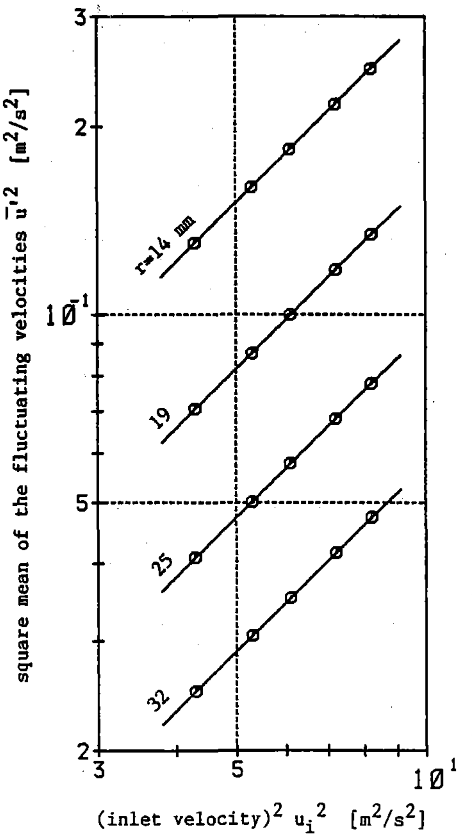

Fig.2
Effect of the inlet velocity on the stochastic mean of the fluctuating velocities

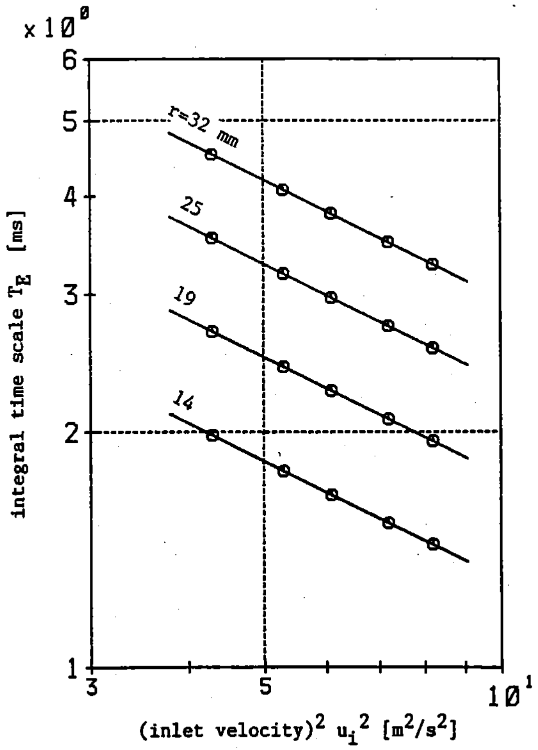

Fig.3
Effect of the inlet velocity on the Eulerian integral time scale

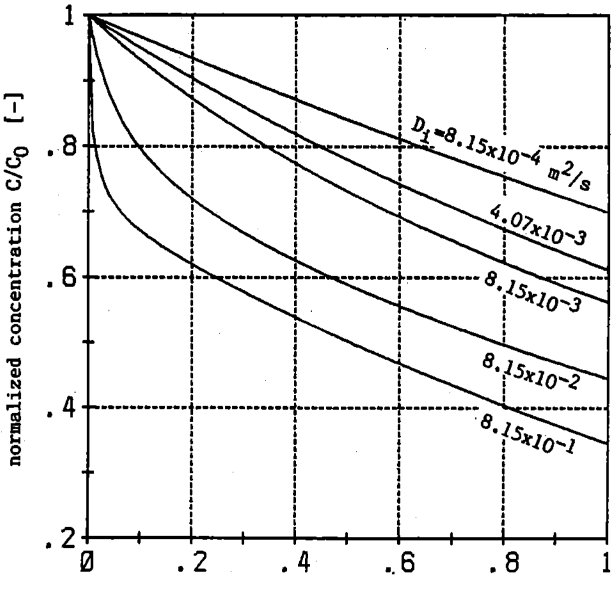

Fig.4
Solids concentration profiles in the *z*-direction averaged over the *r*-direction

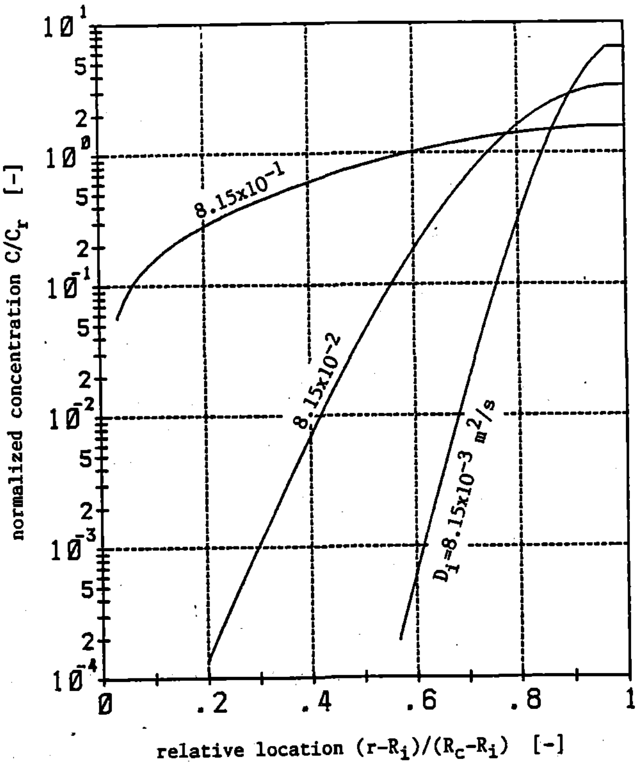

Fig.5
Solids concentration profiles in the *r*-direction on the outlet level for the underflow product

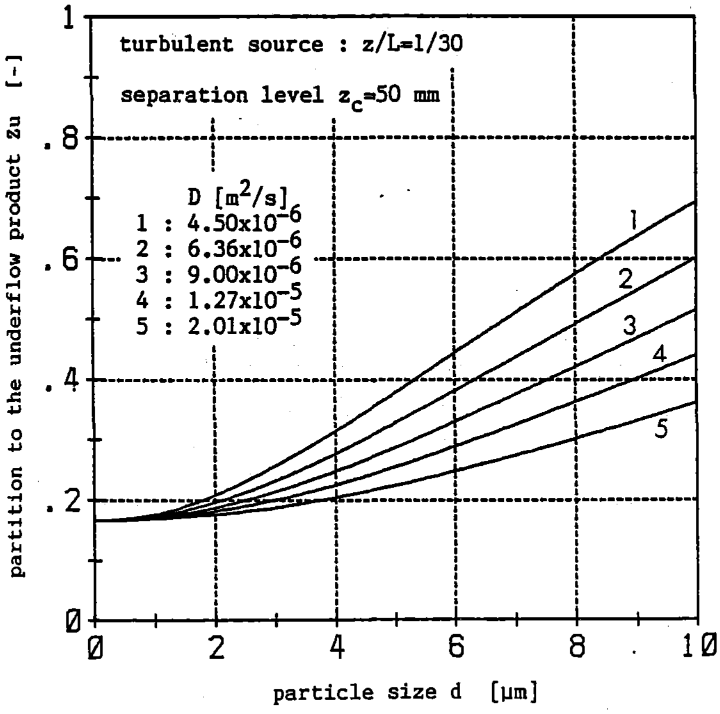

Fig.6
Fractional partition to the underflow product in the gravitational classifier having a localized source of turbulence on the lower level of the sedimentation vessel

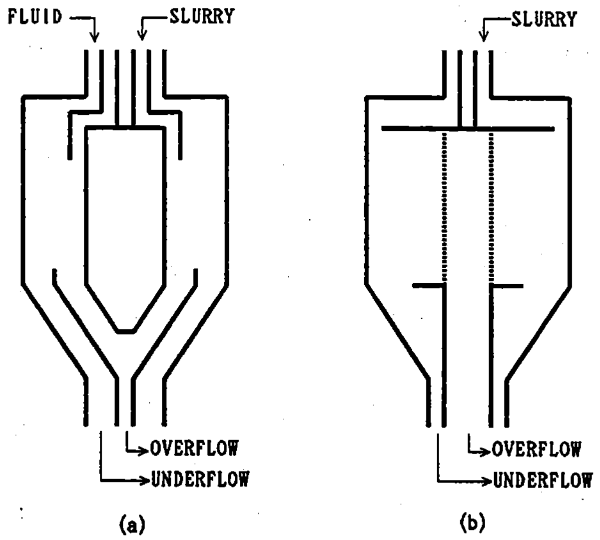

Fig.7
MI-NO CLASSIFIER (a) and STATICLONE (b)

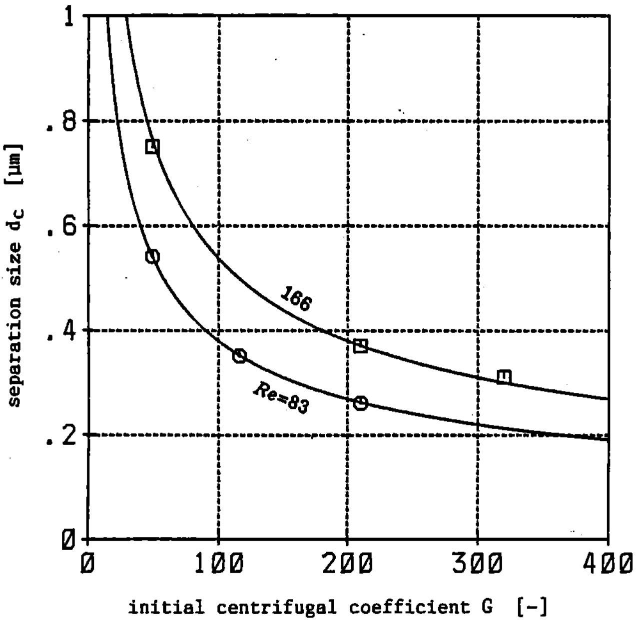

Fig.8
Effect of the initial centrifugal coefficient on the separation size in the MI-NO CLASSIFIER

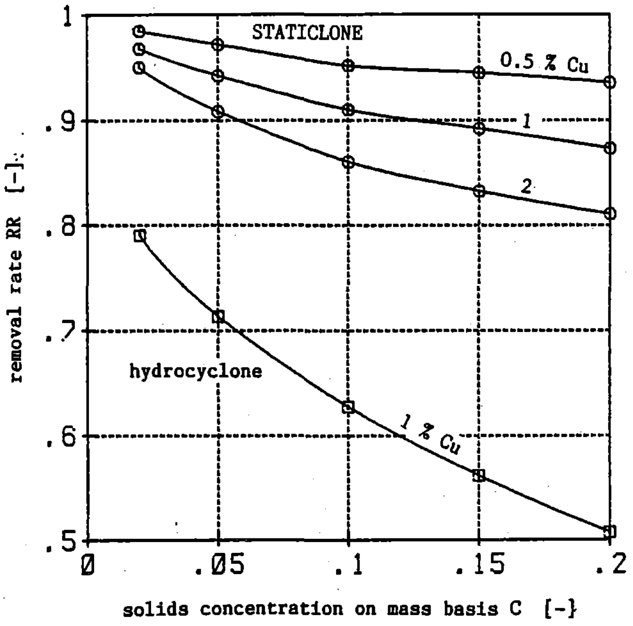

Fig.9
Effect of the solids concentration on the removal rate of the metallic pollutant in the STATICLONE

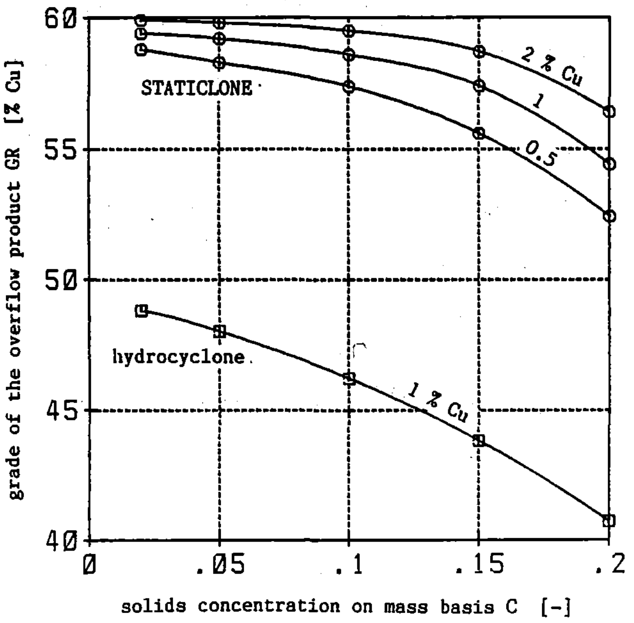

Fig.10
Effect of the solids concentration on the grade of the overflow product in the STATICLONE

PREDICTION OF SETTLING AND CONSOLIDATION OF COHESIVE SEDIMENT

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ABSTRACT

Classic consolidation models, based on soil mechanics, have proven to fail under certain conditions for fluid mud layers. Moreover, when mud is dumped in underwater storage sites, mud is brought into resuspension and the settling has a great influence on the structure of the deposited mud layer. Therefore a model, based on the hindered settling theory, has been developed to solve both sedimentation and consolidation. From experiments an empirical formulation has been obtained for the settling velocity as a function of dry density, generalizing the fall velocity concept, by using the property of characteristic lines of the mass balance equation. The model has been extended to take into account both cohesive and non-cohesive particles. Calculated settling curves and density profiles are compared with experiments.

INTRODUCTION

When modelling high concentration vertical sediment transport the sedimentation or sink term is an essential term in the mass transport equation. On this matter very little work has been published so far.
To develop a semi-empirical formulation of the settling term the mass transport equation has been reduced to a 1-D vertical mass balance equation. This model was used to simulate settling column experiments where gravity is the only force present.

Deposited fine cohesive sediments form a fluid mud layer which consolidates with time. This layer can flow under certain conditions. Therefore it is important for mud flow modelling to take into account not only settling, but consolidation as well. This complicates the formulation of the settling term considerably. It widens however the application of the model to predict settling and consolidation in mud dumping sites, which is of great importance for the planning of maintenance dredging.

The theory of hindered settling provides a simple tool for the prediction of sedimentation. In this paper this model has been generalized to approach the consolidation process in a similar way.

An other reason to use the hindered settling approach is to have a much simpler tool than the classical soil mechanics equation for predicting consolidation. This equation for the void ratio, as derived by GIBSON *et al.* [1], requires several empirical closure equations with many parameters, which are often hard to determine. Some of these parameters even have no physical meaning. Moreover this kind of model does not give good results under certain conditions, even though PANE & SCHIFFMAN [2] have shown that the void ratio equation can be generalized to solve both consolidation and sedimentation. This requires however a relationship for the permeability coefficient as a function of void ratio and therefore makes this method even more complicated. More details and examples can be found in SHIFFMAN et al. [3], as well as a state-of-the-art of consolidation models 6 years ago.
BOWDEN [4] comes to the conclusion that: "*The failure of Darcy's law at specific volumes above seven for natural slurries, compressed under self-weight, is discouraging because it implies that consolidation models which assume its validity are incorrect.*". As a remedy he proposes "*to use some form of a hindered settling model*"(p.166).

HINDERED SETTLING

The hindered settling theory has been introduced by KYNCH [5]. Particles in suspension are subjected to gravity. In their downward movement the chance of colliding with other particles grows with increasing density, what slows down their fall. For an infinitely thin layer the layer density changes with the variation of the sediment flux. This is expresssed by the equation of mass conservation:

$$\frac{\partial\Delta\rho}{\partial t}+\frac{\partial S}{\partial\Delta\rho}\frac{\partial\Delta\rho}{\partial z}=0 \qquad (1)$$

where $S=v\Delta\rho$ is the settling flux, v is the fall velocity and $\Delta\rho$ is the excess density ($=\rho - \rho_w$; dry density $\rho_d = 1.6*\Delta\rho$).
The fall velocity is assumed to be only a function of the density. Under this condition, eq.(1) shows that density propagates as a kinematic wave. Therefore iso-density lines in a settling curve diagram are characteristic lines (fig.1).

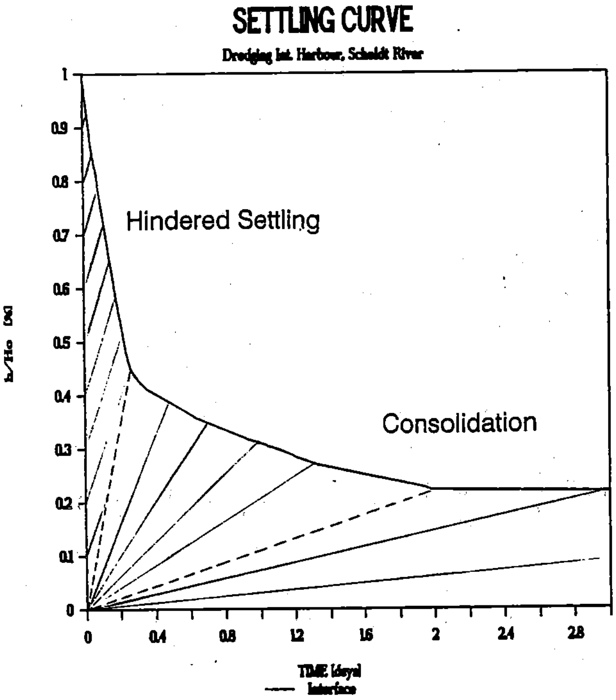

Fig.1: Settling curve and characteristic lines

For any experimental point of a settling curve the fall velocity is found as the slope of the curve, and the density can be calculated from the mass balance over the characteristic line through the point. With curve fitting one can find an empirical relationship between fall velocity and excess density. An expression of the following general form can be found, based on physical considerations:

$$v = v_s(1-\Delta\rho/\Delta\rho_m)F_c(\Delta\rho) \qquad (2)$$

where: v_s is the equivalent Stokes fall velocity (unhindered settling of a particle with equivalent diameter); $\Delta\rho_m$ is the maximum excess density for which the particles have no more possibility to move or deform; F_c is a factor which takes into account the effect of cohesive forces which decrease the fall velocity. The factor $(1-\Delta\rho/\Delta\rho_m)$ represents the fraction of the settling area that is open or the probability that a particle cannot meet another one.

Particle size.

When the initial density is homogeneous and all particles are similar, an analytical solution of eq.(1) is possible. In reality, density profiles do not correspond to an initial homogeneous distribution. The main reason for this is the non-uniform particle size distribution.
This results in high density peaks at impenetrable levels (bottom or interfaces between 2 layers). Larger, heavier particles will fall faster than small ones. Cohesive particles have a smaller equivalent Stokes fall velocity but are also slowed down due to cohesive forces. When the cohesive particles are close enough to each other, coarse particles cannot penetrate those layers anymore [6].

NUMERICAL MODELLING

To take into account the above mentioned non-uniformities the sediment is divided into coarser, non-cohesive material (sand) and finer, cohesive material (clays). Mass balance (eq.1), with substitution of eq.2, has to be solved for these two types of particles. Eq.(2) has to be multiplied with an additional factor to take into account hindering by the other type of particles. Therefore the mass balance equations for both particles are coupled. For the non-cohesive particles the factor F_c has the physical meaning of particles getting stuck between the cohesive material, as described above.
The introduction of a diffusive term into eq.1 however remains a necessity to stabilize the numerical algorithm. Numerical experiments have revealed that only by varying the diffusivity coefficient in the same way as the fall velocity, the model converges to a physically acceptable solution. The diffusion coefficient is found by comparing experimental with calculated density profiles.

A finite element method is used. The settling column is discretised into a certain number of layers in which the densities vary linearly with depth. The densities are calculated in the interconnecting nodes of the layers or elements. Since the fall velocity is a function of density, the flux term is non-linear. To linearize the equations, the fall velocity will be estimated, based on previous calculations, and improved iteratively. The boundary conditions are: zero mass flux at the top free surface and the bottom.

To allow higher accuracy, the mesh is refined where there are high density gradients. Especially the sharp interfaces cause severe numerical problems. To capture the interfaces, grid refinement is needed in particular in those regions. The program locates these levels and adjusts the grid automatically (while the number of elements remains the same).

The Consolidation Function

From settling column experiments the calibration of equation 2 can be performed. For each sediment the corresponding function F_c has to be known. Experimental points of fall velocity versus dry density for 3 settling column tests are plotted in fig.2. (The experiments will be discussed later.)

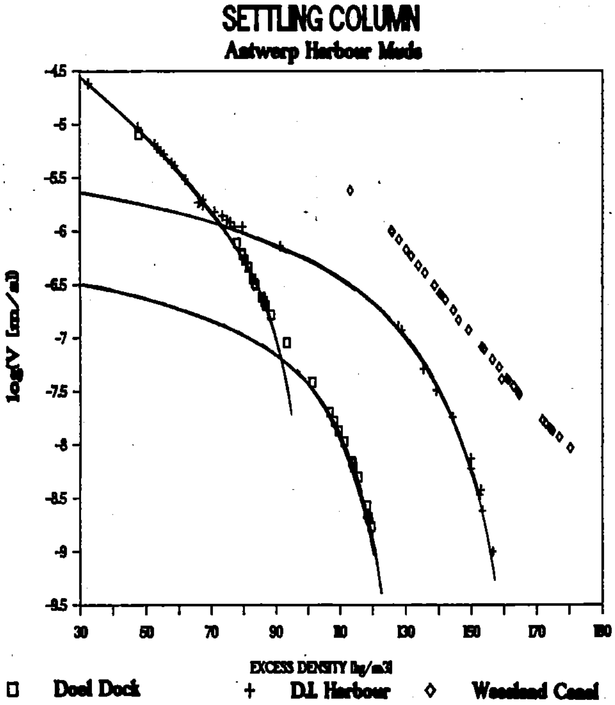

Fig.2: Experimental fall velocities

From fig.2 it can be seen that there seem to be two distinct modes of consolidation. It is suggested that the modes physically represent the compression (expulsion of pore water) and particle deformation respectively.
Each mode can be fitted with a relatively simple fuction, using a least squares method.

For the first mode:

$$F_{c1} = (1-\Delta\rho/\Delta\rho_c)\exp(-\Delta\rho/\Delta\rho_x)$$

with $\Delta\rho_c = 91\text{kg/m3}$ ($\rho_d = 146$ kg/m3)
$\Delta\rho_x = 49\text{kg/m3}$ ($\rho_d = 79$ kg/m3)
$v_s = 0.176$ mm/s

For the second mode:

$$F_{c2} = (1-\Delta\rho/\Delta\rho_m)^n$$

with $n = \pm 2.7$
$v_{s2} = 0.0063$ mm/s
$\Delta\rho_m$ depends on the mud origin (organic matter content, etc.)

From this a set of 5 necessary parameters can be determined:

v_{s1} Stokes fall velocity
$\Delta\rho_1$ max. density for 1st mode
v_{s2} velocity for 2nd mode
$\Delta\rho_2$ max. density for 2nd mode
$\Delta\rho_{12}$ for the transition

There seems to be some indication that the first 3 are not dependent on the mud origin. More experiments are currently carried out to verify this.

For the sand fraction, no detailed investigation has been carried out so far. However it is expected that a similar relationship as eq.(2) exists. When the sediment is pure sand, F_s is expected to be 1, because there are no cohesive forces. However, in the case of a mixture of sand and fine material, the trapping of sand particles in the cohesive sediment has to be taken into account. Therefore F_s will be smaller than 1 and a function of F_c.

FIELD AND LABORATORY OBSERVATIONS

Natural formed mud layers

As a result of the non-uniform particle size distribution, clearly layered mud deposition takes place in tidal mud flats. High density peaks are observed at the interfaces between two layers.

Dumping

Filling of dumping sites is a continuous process over a period of many days. In underwater dumping sites turbulent resuspension takes place during dumping (e.g. with a diffusor). This enables larger particles to fall faster. This can be seen clearly in the very gradual density profiles. Similarly, for settling column experiments, one obtains very different density profiles when mud is dumped versus when it has been inserted as a homogeneous layer (fig.3).

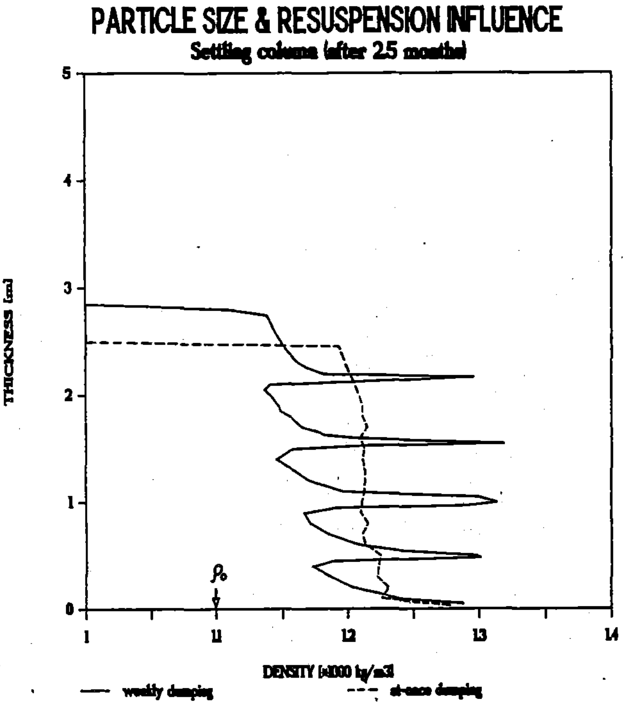

Fig.3: Density profiles

From experiments it is known that the settling and consolidation process is influenced by many parameters: grain size distribution, organic matter, initial layer thickness and presssure, salinity (influences flocculation),... [7,8]
Flocculation is not considered in the present formulation, since the initial densities are higher than the critical density above which flocculation cannot take place.

PREDICTIONS

Muds from different places of the Antwerp Harbour can consolidate at very different rates, depending on the initial particle size distribution and organic matter content. In general, it is possible to calibrate eq.(2) for each mud, and calculate the settling curve under other conditions. A more critical comparison between model and reality is to look at the density profiles.

For low initial densities, this is for $\Delta\rho_0 < \Delta\rho_c$, coarse particles will have the chance to sink to the bottom, and then do not play a role anymore. In that case the fine particles above behave as if there never had been sand.

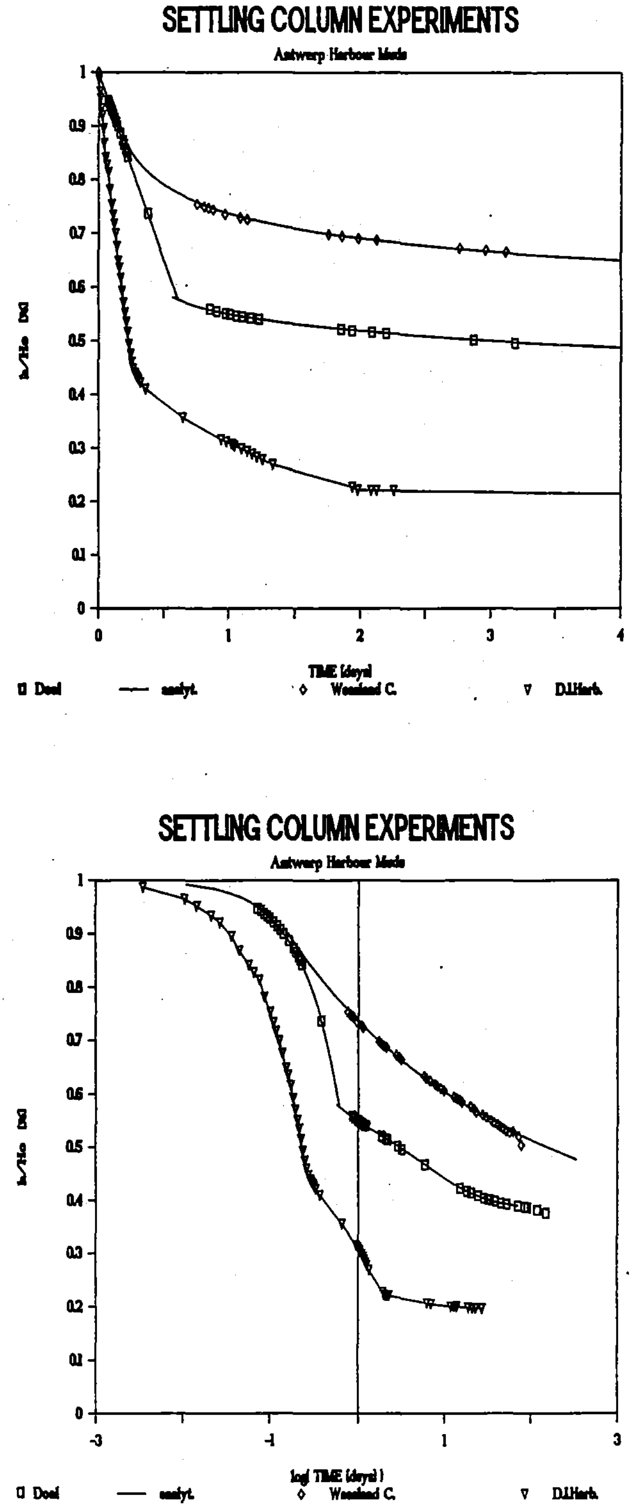

Fig.4: Settling curves

When no particle size distribution is known, a good estimation of the sand fraction is possible from the density profiles, measured during a settling column experiment where $\Delta\rho_0<\Delta\rho_c$, since the density peak on the bottom can be contributed only by this fraction.

<u>Discussion of some settling column experiments.</u>

The results of three experiments are discussed. Details on the experiments can be found in reports to IMDC [9]. Densities are measured with a gamma-densimeter (accuracy 3%).
The evolution with time of the mud-water interface is shown in fig.4. The processing of these data resulted into a fall velocity/excess density graph, seen in fig.2.

<u>Sample 1: Doel Dock.</u>
Initial density = 1053 kg/m^3
Initial height = 1.96 m
Estimated sand fraction = 3.5%

Qualitatively calculated density profiles are in good agreement with experiments (fig.5), also with measurements by BEEN & SILLS [10]. Quantitatively there are some discrepancies, mainly due to inaccurate measurements (what can be easily found out by checking total mass conservation).

<u>Sample 2: Waasland Canal</u>
Initial density = 1100 kg/m^3
Initial height = 5 & 11 m
Estimated sand fraction = unknown

Since $\Delta\rho_0>\Delta\rho_c$, the density profiles never showed a high gradient or density peak at the bottom, what sustains the hypothesis that in this case the sand particles are trapped inbetween the cohesive particles. Therefore it was impossible to estimate the sand fraction without additional size distribution analysis.
Attempts were made to simulate the evolution of the mud-water interface at a dumping site. They proved to be succesful over a time period equal to the duration time of the settling column experiment, which was 3 months (fig.6). However the structure of the mud layer at the dumping site, according to measured density profiles, indicates that the dumped mud had been resuspended before deposition. Calculated density profiles therefore were incorrect. Only with a settling column experiment where $\Delta\rho_0<\Delta\rho_c$ it would have been possible to make an accurate prediction.

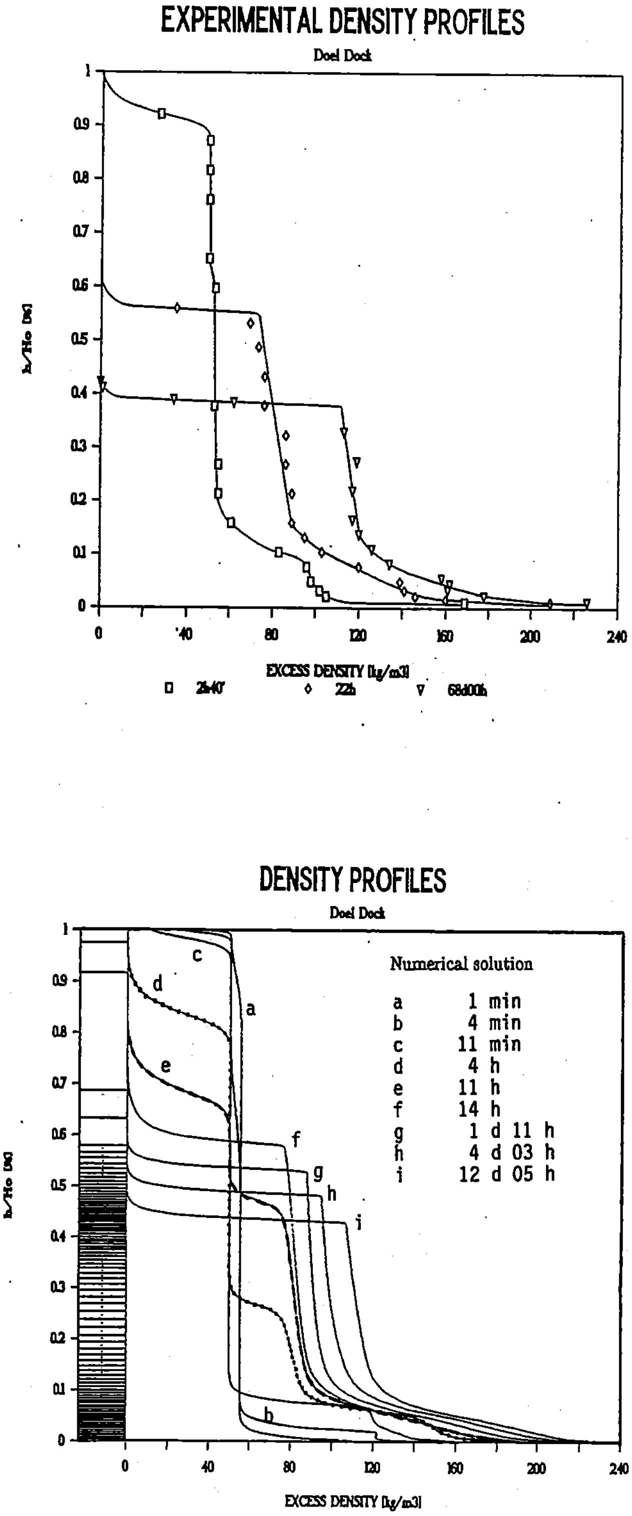

Fig.5: Density profiles

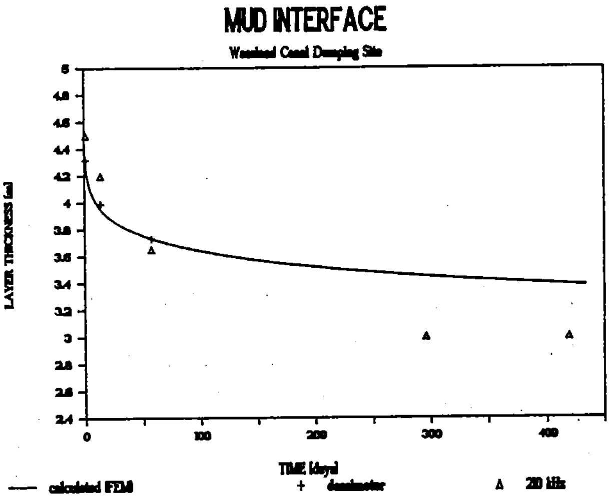

Fig.6: Simulation of a dumping site

Sample 3: Dredging International Harbour
Initial density = 1050 kg/m^3
Initial height = 2 m
Estimated sand fraction = 35%

This mud showed to settle and consolidate at a very high rate. This indicates that the fine material behaves much more like pure (kaoline) clay.

DISCUSSION

Application of the model to a long time experiment, based on calibration in a short time experiment can give a rather large deviation in the long run. This is simply due to extrapolation errors.
More experimental data are necessary to support the above theory. Currently new data are processed and will be presented at the conference.
To obtain the necessary parameters for using the proposed model, it is necessary to know the following information concerning the in situ mud layer: dumping method , initial density and sand fraction for mud dumping sites; a good estimation of the sedimentation rate and partcile size distribution for natural formed mud layers. A settling column experiment has to be carried out with $\Delta\rho_0 < \Delta\rho_c$.
So far, accurate prediction is only possible when a settling column experiment is carried out over a long period, what is not very practical. Further investigation of the second consolidation mode (which physical parameters play a role) is necessary.

ACKNOWLEDGEMENT

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LARGE SCALE SEPARATION AND CONSOLIDATION TECHNIQUES FOR ON LAND DISPOSAL OF FINE-GRAINED DREDGED MATERIAL

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ABSTRACT

The search for reclamation areas of fine grained material from maintenance dredging works becomes increasingly difficult. In order to solve these problems common to most harbours DOLSO has started a large scale testing program of different techniques which can be used to reduce the required surfaces for dewatering and consolidation of the dredged material :

- separation of sand and silt in separation fields or by mechanical devices such as the elutriator;
- accelerated dewatering of fine grained material in dewatering fields.

The paper describes the different methods as well as the monitoring program used to evaluate both physical and environmental advantages and constraints of the methods.

INTRODUCTION

During recent years the amount of fine grained material both from maintenance and infrastructural dredging works is increasing within the Antwerp region. On the other hand the available dumping and reclamation areas are diminishing both on-shore and off-shore especially where fine grained material is concerned because silt requires very long settling and consolidation periods before the reclamation areas can be used for industrial or constructional purposes.

In order to cope with these new challenges the Ministry of Public Works and Traffic has decided to start a series of large scale testing projects in order to respond efficiently to these challenges.

The first series of projects which are executed or are under execution aims to reduce the required surfaces as far as possible for a reasonable price. These projects are :

- separation fields
- elutriator
- consolidation fields
- underwater disposal techniques

Furthermore a second series of much more experimental tests is in the planning and preliminary testing phase. They concern the actual treatment of polluted silt by extraction and/or immobilisation techniques.

This paper will concentrate on the first series with the exception of the underwaterdisposal techniques which are reported in detail in another paper of this congress (ref 1).

SEPARATION TECHNIQUES

General considerations

If the different characteristics of sand and silt are taken into account it is obvious that the separation of both fractions is one of the basic possibilities to reduce the volume of problem generating material.

The resulting sandfraction is a high quality product which can be used for reclamation purposes to create new and valuable industrial areas within the surrounding harbour zone.

The remaining silt with a reduced volume has to be treated further or can be stored in underwater cells in the nearby docks.

In order to realise the separation of these fractions, different techniques have been evaluated and it has been decided to test two of them in a pilot project :

- the separation fields
- the elutriator

Both have been retained because they can handle the large volumes produced by the traditional dredgers working on the Scheldt river. This will lead to the advantage that no intermediate bufferstock will be required for the raw dredged material and an additional pumping set can be omitted.

Hydraulic separation fields

Basic principales

Both from theoretical considerations and practical experience it is well known that a continuous flow of a sand-water mixture results in a selective disposal of the soil particles with the coarser material mainly at the start of the flow and the fine material at the end of the flow. The exact settlement charcteristics vary with flow conditions, water depth, velocities and grain size of the material.
Within the separation fields this natural phenomenon has been utilised under controled conditions in order to realise the desired separation.

Prototype facilities

The separation fields are oblong reclamation fields with a length of approximately 500m and a width of 60m. This small width has been chosen in order to realise a uniform flow over the whole width without secondary flows near the dikes especially in the corners. At the end of the separation fields there is an open connection with a large waterbasin. A series of 4 separation fields of 3,5 ha each has been realised for the pilot project as can be seen on fig.1. Due to the local situation the open connection with the water basin had to be replaced by a normal outlet construction.

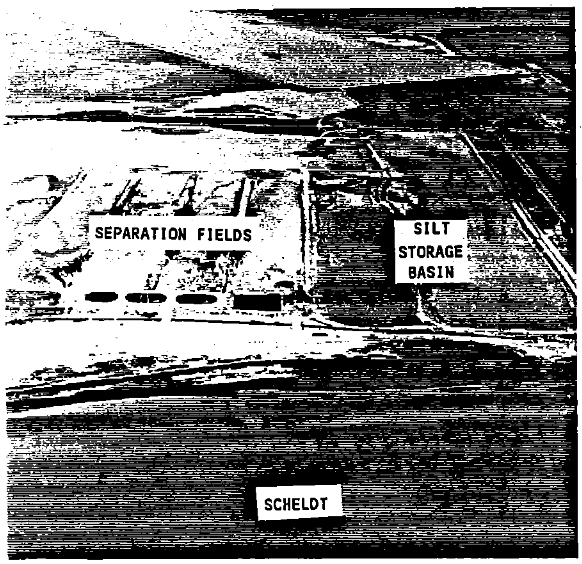

FIG. 1 : GENERAL VIEW ON THE SEPARATION FIELDS

Pilot project

For the final deepening of the access channel to the new Berendrecht lock (spring 1989) a considerable amount of dredging works had to be done. Partly the removal of large volumes of silt accumulated during the construction period of the lock but partly also the final deepening phase of the navigation channel. As a consequence the material reclaimed by the cutter suction dredger was a mixture of fine grained silt and coarser material from the original bottom; an ideal situation for the pilot project.
During the pilot project selective dredging techniques have been used in order to realise a first separation at the dredging site.

- The overlying layers of pure silt have been pumped directly into the underwater cells with the techniques developed by the Ministry of Public Works and Traffic (see ref 1).
- The underlying layers of mixed material, totally 193.820 m^3 have been pumped mainly into the separation fields.

During the reclamation activities efforts were made to reduce the downtimes of the cuttersuction dredger as much as possible in order to realise a continuous flow in the separation fields where the coarser material settles close to the discharge pipe while the finer silt flows through the gates into the waterbasin where it was stored for further treatment.

Monitoring program

The monitoring program has to respond to the following objectives :

- measure the sand volume within the separation fields
- define the efficiency of the technique (grain size characteristics)
- check the environmental quality of both products (sand and silt)
- evaluate the possibilities of this technique for normal maintenance material
- optimise the design of the fields

At the end of the reclamation activities a detailed measurement of the sand volume in the separation fields has taken place. The measuring is realised with normal topographical instruments. A volume of 72.216 m^3 of sand is found in the 4 fields or a recuperation of 37%

of useful material.

The efficiency of the technique was controlled by two sampling campaigns :

- the first one immediatly after the end of the reclamation activities, consisted only of surface samples. As a part of the fields was not accessible at that moment some of the samples are taken at the toe of the dikes. The results (mean grain size of each sample) are given in fig.2.

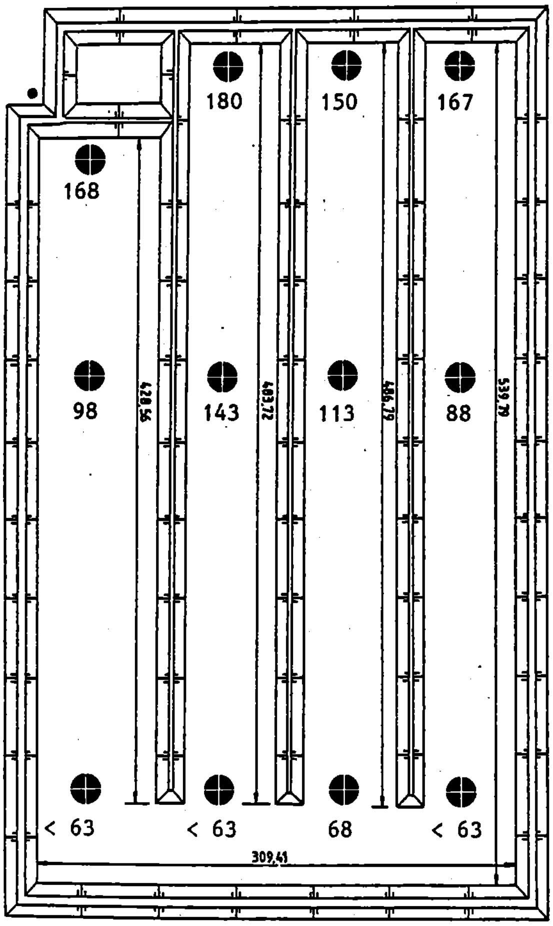

FIG. 2 : AVERAGE GRAINSIZE (μ) IN THE SEPARATION FIELDS

- the second one followed one year later and included a sampling on two levels one at the surface and one approx. 0,5m below at the bottom of the reclaimed material.

From these campaigns a clear separation between sand and silt was found (table 1). The location of the sampling points is given in fig.3.

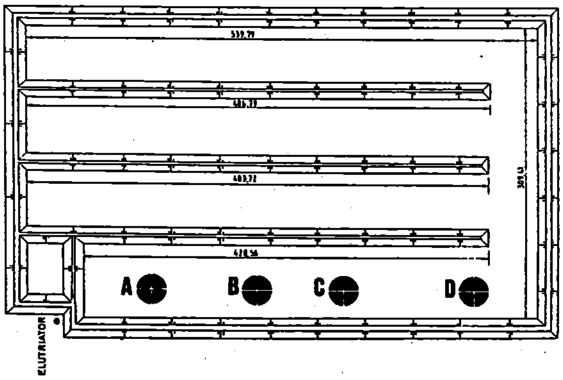

FIG. 3 : SAMPLING SITES

Site	A	B	C	D
Silt layer (m)	0.1	0.3	0.4	0.5
Sand layer (m)	0.4	0.2	0.1	-

Table 1 : layer thickness in the separation field

During the second campaign the same samples have been analysed on their content of heavy metals. The results showed a very strong difference between both layers with very low content in the sand and higher content in the silt, as can be seen from table 2.

Element	Sand	Silt
Cd	<0.4	5.4
Hg	<0.1	0.8
As	3.7	22.8
Pb	5.0	80.0
Zn	15.0	290.0
Cu	4.7	76.5

Table 2 : Heavy metal content (ppm) of both materials

A correlation between grain size and contaminant content has been made for different metals. The Cd relation is given in fig.4.

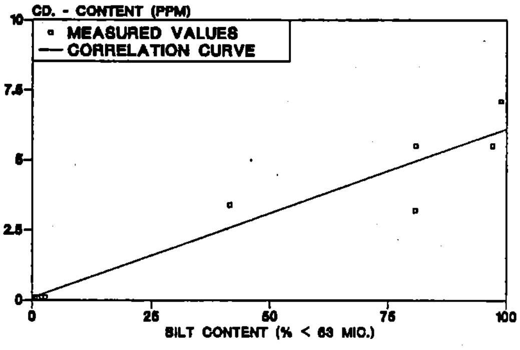

FIG. 4 : INFLUENCE OF GRAINSIZE ON CD. - CONTENT

The possibilities of this separation technique within the treatment procedure of material from normal maintenance dredging activities have been judged based on economic considerations.
Costs are calculated both for a sludge treatment procedure with and without the separation of sand and silt. From these calculations it can be concluded that a separation step is beneficial if 20% of sand is present in the dredged material. If not it is more economical to bring all the material immediately into the following dewatering and consolidation stop of the sludge treatment procedure.
More details about the financial implications of the project are given in ref 2.

Conclusions

- Separation fields can be utilised efficiently for the separation of a mixed dredged material into a sand- and a siltfraction.

- The impossibility to realise an open connexion between the separation field and the waterbassin resulted into a thin silt layer over the whole surface of the field. An industrial installation has to include this open connexion to prevent these problems.

- It is advised to construct the field under a slope in order to limit the stagnant water above the sand during operational stops of the dredging activities.

- The silt fraction contains by far the most important part of the contaminating elements.

- The utilisation of a separation field is economically justified with a sand content of 20% or more in the raw material.

The elutriator

The elutriator is a mechanical equipment developed for the separation of a sand-silt mixture into its components.
Again the functioning of the equipment is based on the same physical laws as the separation fields. This means the different behaviour of sand and silt in a continuous flow.
A detailed description of the elutriator, its functioning and the different pilot tests can be found in ref 3.

ACCELERATED CONSOLIDATION TECHNIQUES

General considerations

One of the most important problems with fine grained dredged material is the very long natural dewatering- and consolidation period even when the layer thickness is limited. Therefore very large surfaces are required for the natural process with a long term cycle for a reasonable dewatering.
These surfaces are no longer available within the Antwerp region (see ref 4).Therefore new techniques have to be developed in order to reduce these requirements. First there are the mechanical means such as hydrocyclones and filterpresses which are still in a pilot testing phase in Genth and in Hamburg (ref 5) with relative high investment and operational costs. Based on these drawbacks it was decided by the Ministry of Public Works and Traffic to proceed in another direction and to start a pilot program to investigate the possibilities to reduce the consolidation time to approximately one year by a special design of the reclamation areas and by the utilisation of specific techniques to accelerate the natural process.

Preliminary study

First a preliminary study has been started in order to define the main aspects which have to be studied during the pilot program. Therefore a first theoretical evaluation has been made of the different possibilities with the mathematical simulation model CONSOL (see ref 6). From this evaluation it was concluded that the following aspects have to be monitored :
- under drainage techniques
- surface drainage techniques
- evaporation enhancement techniques

with the drainage as the most important element.

Design of the pilot plant

Based on the conclusions of the preliminary study and on financial constraints, a pilot plant was designed consisting of 5 different dewatering fields of approximately 4.5 ha each with a width of ca 130 m and a length of ca 350 m. The layout of the different fields is given in fig.5.
Three of the fields are equiped with different types of underdrainage systems each with the

possibility to control the pressure in the system through the outlet level of the water, in order to evaluate their efficiency.
Each of the fields can be filled by hydraulic transport at one of the smaller sides and the dewatering installation is placed at the other end of the field.

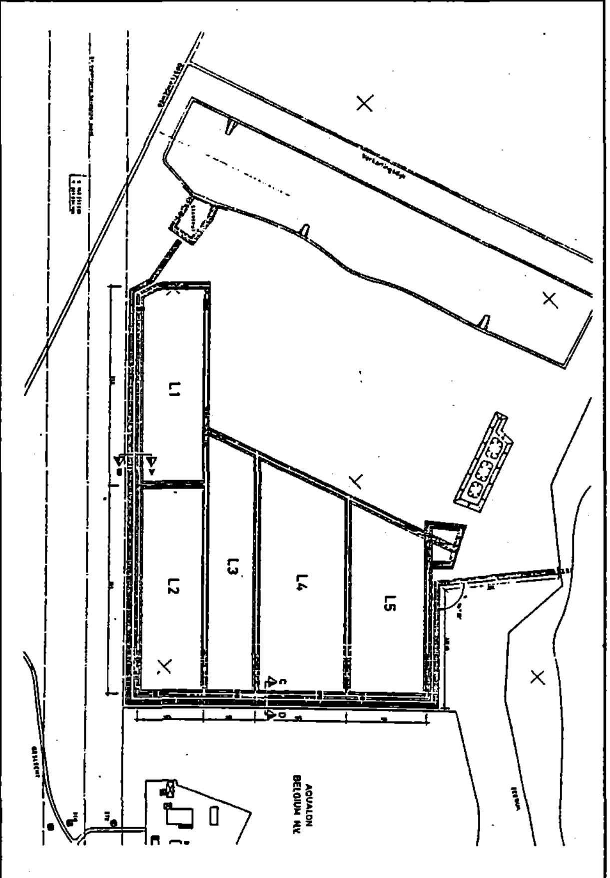

FIG. 5a : LAY-OUT OF THE DEWATERING FIELDS

Pilot program

The pilot plant was filled with silt from the water- and silt basin filled during the pilot tests of the separation fields and other applications. The material is dredged with a small demountable cutter suction dredger and pumped directly into the dewatering fields. The dewatering fields are filled by successive layers.
During the filling the water outlet was closed in order to prevent the loss of the finer parts through these outlets. After an initial settlement period of a few days the outlets are opened to evacuate the water under controled conditions before the next layer was entered.
The final height of mud was chosen at 2m.

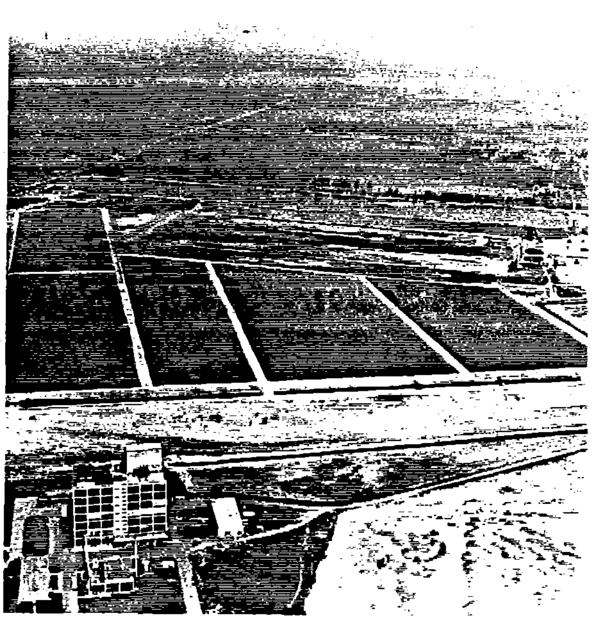

FIG. 5b : AERIAL VIEW OF THE DEWATERING FIELDS

During the complete filling operation the underdrainage system remained closed in order to prevent overpressure and clogging phenomenae in the sand which could damage the system. After the finalisation of the filling the underdrainage has been started gradually.
Between april and june 1990 286.000 m^3 of silt was dredged from the basin and pumped to the dewatering fields where an initial volume of approx. 500.000 m^3 could be measured. From begin july 1990 the consolidation and settlement process started. The following measurements have been taken :

* field n° 1
  - drainage system
* field n° 2
  - vacuum pump on the drainage system
  - vegetation of half the surface (after 3 months)
* field n° 3
  - no drainage system
  - vegetation on half the surface (after 3 months)
* field n° 4
  - no drainage system
  - amphirol and discuswheel for additional surface drainage (after 4 months)
* field n° 5
  - drainage system
  - amphirol and discuswheel for additional surface drainage (after 4 months)

In all the dewatering field a ringditch was created 6 to 8 weeks after the filling procedure. These ditches are maintained and deepened since then.

Monitoring program

In order to be able to make an objective judgement concerning the most efficient methods for an accelerated dewatering; a detailed monitoring program has been started which includes :

- An identification of the dredged material in the dredging area; the following tests have been performed :
  - 8 corings
  - 8 in situ vane tests
  - geotechnical identification of the corings including laboratory tests
  - chemical identification of the silt (contaminant content)
  - An identification of the sub-soil conditions in the pilot area :
  - 5 corings
  - groundwater sampling and analysis
  - monitoring of the groundwater level around the fields
- A follow up of the boundary conditions :
  - a selfregistrating meteo station (rain, wind, temperature, sunshine, etc are contineously registrated)
  - daily control of the groundwater levels around the dewatering fields
- A laboratory testing program :
  - a series of 7 long term consolidation tests with different boundary conditions
  - detailed identification of the silt (grain size distribution, permeability)
  - detailed study of the drainage filter sand by clogging tests
- A continueous follow-up of the silt in the dewatering fields :
  - regular control of water and silt level in the dewatering fields
  - periodic detailed campaigns of in situ density measurements during the first 4 months
  - periodic measurements of the in situ shearstrength during 8 months
  - periodic inspection of the fields
  - chemical analysis of the silt
- Final impact measurements :
  - sampling of the underlying groundwater table to determine eventual contaminant dispersion
  - sampling of the underlying groundlayers with chemical analysis to determine eventual absorption of contaminants.

First results

Most of the before mentioned tests are still under execution at the redaction of this paper. neverthemess some intermediate results are already available.

- In situ density measurements :
  a series of 4 measurements are available over a period of approximately 4 months. An example is given in fig.6. From this figure we learn that density of the dewatering materal is slowly increasing from 1.20 t/m^3 till 1.35 t/m^3 an average.

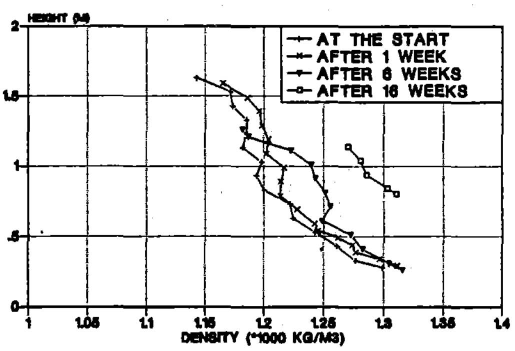

FIG. 6 : DENSITY PROFILE

From a detailed analysis of the measuring results it could be calculated that the average density during the filling was approximately 1.10 t/m^3. After a short first settling period this density increased till 1.22 t/m^3.

- Consolidation control :
  with regular intervals the thickness of the siltlayer in the different basins was measured at 5 locations. From these measurements the consolidation curve can be calculated. A summary is given in table 3 and fig.7.

Basin n°	Initial Height (1/7/90)	3/8/90	14/9/90	31/10/90
1	1.64 100%	81%	67%	65%
2	1.75 100%	76%	67%	66%
3	2.09 100%	89%	77%	76%
4	1.93 100%	86%	76%	75%
5	1.74 100%	75%	64%	64%

Table 3 : Evolution of the heigth in the different basins

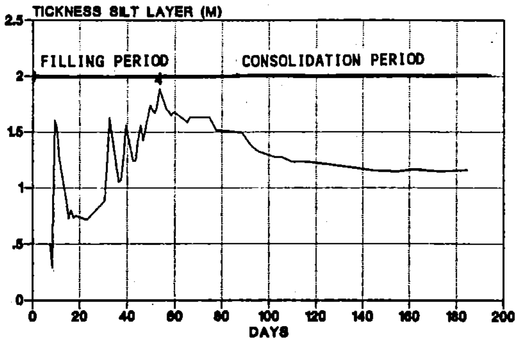

FIG. 7 : LAYER TICKNESS IN A DEWATERING FIELD

Intermediary observations and conclusions

- Within a short delay (4 months) the volume of the silt in the dewatering fields has been reduced by 30%.
- Visual inspection as well as the first measuring results leads to the conclusion that the fields with underdrainage facilities are sligthly in advance compared to the two others.
- Evaporation becomes important only after a few months. During the first months the pore water volume which sort at the surface exceeds the evaporation capacity even during a very hot summer like 1990.
- It is advised to plan the filling activities very early each year in order to take full advantage of the evaporative capacities of the summer.

FINAL CONSIDERATIONS

- Both the separation and consolidation fields are promising tools for a short term solution of the problems within our country where a shortage of reclamation areas exists especially for the fine grained material.
- Both techniques can be used on an industrial scale within very short delays.
- The application of these techniques is an important but an intermediate step towards a global solution as they are only methods to produce a useful product (ref 7). Additionally it is necessary to look for projects where these products can be applied. Different solutions are suggested. Some of them are actually tested on laboratory or semi-industrial scale:
  - utilisation as fill material for landscaping projects (see ref 3)
  - utilisation to improve poor quality soils
  - mixture with night soil for agriculture application
  - utilisation as a raw material for the construction industry

  The selection between these alternatives will depend on the level of contaminant content of the material.
- It has to be mentioned that the annual production will be very important. Therefore large scale utilisation projects will be required.
- Another drawback for the utilisation of the dewatered material is the contaminant load of the maintenance dredged material. Although the final solution lies outside the dredging world with a better implementation of the water purification programs we have to cope with this problem in the meantime. Therefore pilot tests have been started within the Ministry of Public works and Traffic to find techniques for the extraction or immobilisation of the contaminating elements.
- Finally the described techniques as well as the different utilisation and cleaning procedures are part of a global approach which is given schematically in fig.8.
- To implement this scheme an industrial silt treatment system has to be created which will be run by an industrial company. For the redaction of this objective the Ministry of Public Works has reserved exclusively for this purpose important areas within the industrial harbour area . This area has been integrated in the structure planning of the new harbour area on the left bank of the river Scheldt.

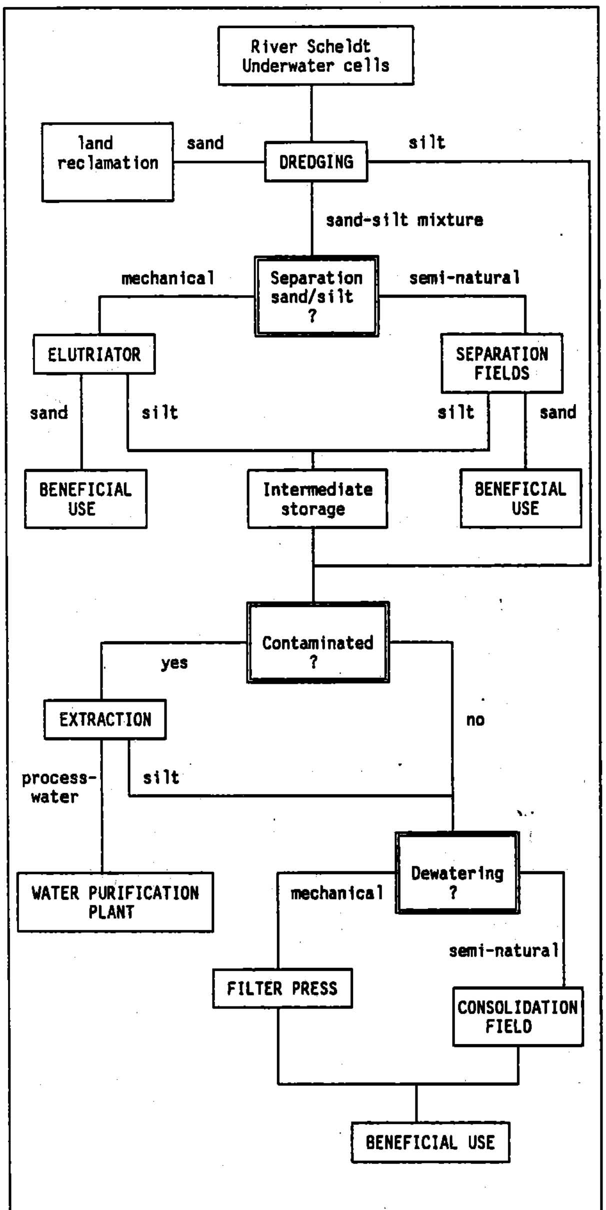

FIG. 8 : SILT TREATMENT SYSTEM - GENERAL SCHEME

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CONSOLIDATION BEHAVIOUR OF DREDGED SLURRIES

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ABSTRACT

Consolidation is an important phenomenom if polluted dredged material has to be deposited. A new computer model has been developed at Delft Geotechnics to handle this process. The model, named FSCONBAG, is based on the state-of-the-art Finite Strain Theory. In this paper attention is focussed on the parameter determination, using a non-standard laboratory test. Furthermore, some calculated results are presented to illustrate the various ways the model can be used for decision making.

INTRODUCTION

The Netherlands are located in the low lying delta area of the rivers Rhine and Meuse. Along these rivers very important chemical industries are situated. Mainly due to these industrial activities the bottoms of rivers and harbours in this delta are highly contaminated with a broad range of pollutants, such as PAK´s, PCB´s, heavy metals, etc. These sediments must be dredged for nautical or ecological reasons. Depending on the concentration and kind of contamination, these sediments will be placed in various disposal sites, wich must all be acceptable for the environment. Since the Netherlands are a densely populated country, the number of suitable locations for such disposal sites are very limited. Therefore, it is necessary to utilize every square inch of space. To realize this, a model is needed with which the disposal sites can be optimised, the ultimate storage capacity can be predicted and the flux of the expelled water can be estimated. In addition, the model should be used for decision making and disposal schemes.

Since the sediments of the rivers mentioned consist for a substantial part of silt and clay, the ultimate settlement after disposal is large and the standard Terzaghi theory cannot be used. Therefore, use is made of the state-of-art Finite Strain theory, developed by Gibson et al.,1981. Starting from this theory, several programs have been developed, see Townsend and McVay,1990. Our program, named FSCONBAG, uses a material coordinate system, is based upon a implicit finite difference approach and uses the relations between permeability and void ratio and between effective stress and void ratio.

PARAMETER DETERMINATION

The determination of the relations between the void ratio **e**, the effective stress σ and the permeability **k** are essential for accurate modelling. In the case of slurries with high water content, standard laboratory tests, like oedometer tests, cannot be used. There are two suitable tests available for the determination of these relations, viz. the "constant rate of deformation method" (CRD, Pointexter, 1988) and the "hydraulic consolidation test" (HCT, Imai, 1979). We chose the latter test, since the sample can be tested regardless the water content and the test is rather simple, so little supervision is needed. A disadvantage is the interpretation of the test, wich is rather complicated, but the same is true for the CRD-test. To solve this problem a special program has been developed, with which hundreds of consolidation calculations can be done within one hour, until a fit to the measurement is found. Fig. 1 shows a schematic representation of the HCT device, as used by Delft Geotechnics.

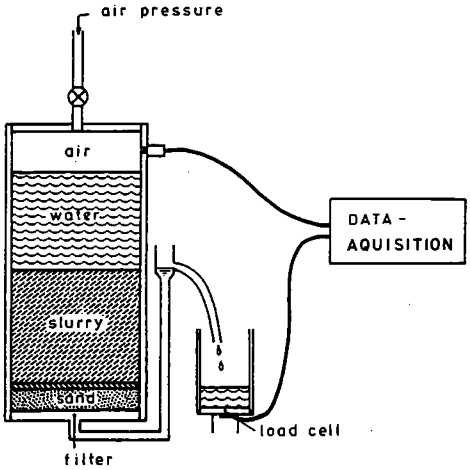


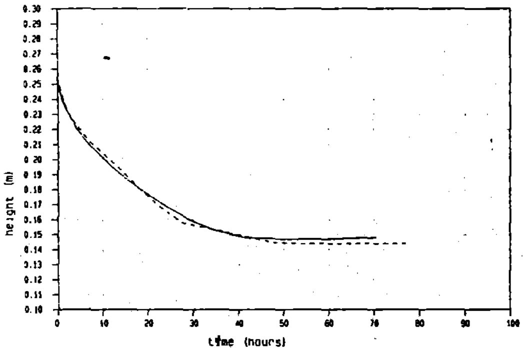
Fig.1 Hydraulic Consolidation Test (HCT) Set-up

Since in the Netherlands it was the first time this method was applied, tests were performed to determine the accuracy. It appeared that the method gives acceptably accurate consolidation parameters, while the costs of the test are relatively low.

In the following two examples are given. The first is a test on a slurry made of commercially available kaolinite powder. During the HCT test an hydraulic load of about 50 kPa is set on a sample of about 30 cm thick.
During the test the height of the sample and the flow through the sample decrease with time. Both quantities are recorded. In figs. 2a and 2b measured results are shown together with the calculated fit.

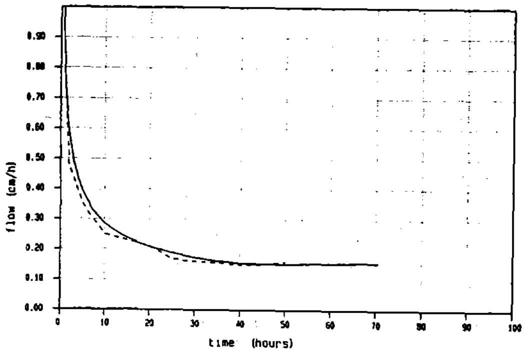
The relations $\sigma(e)$ and $k(e)$ are aproximated by exponential functions. In this case these functions were found to be:

$\sigma(e) = \exp(6.45 - 1.46e)$ ... [kPa]
$k(e) = \exp(-19.84 + 0.65e)$ ... [m/s]



kaoline HCT test

Fig.2a ---- measurement
—— calculated fit



kaoline HCT test

Fig.2b ---- measurement
—— calculated fit

The second example concerns a dredged slurry from the Botlek harbour near Rotterdam. The HCT test results for this material are given in Fig.3. The determined parameters are:

$\sigma(e) = \exp(8.08 - 1.64e)$ ... [kPa]
$k(e) = \exp(-23.76 + 1.14e)$ ... [m/s]

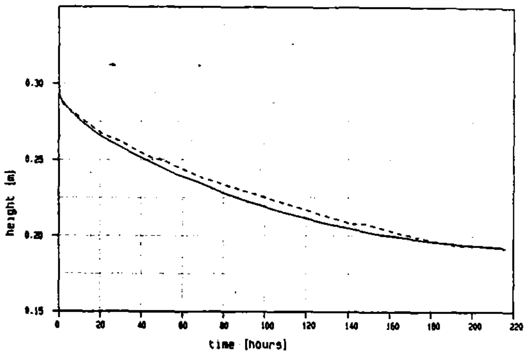


Fig.3a Botlek slurry
---- measurement
—— calculated

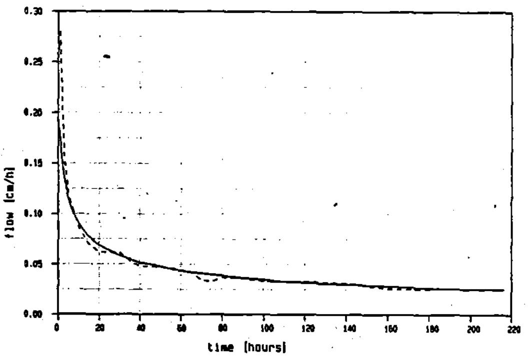


Fig.3b Botlek slurry
---- measurement
—— calculated

FEATURES OF THE COMPUTERMODEL FSCONBAG

The consolidation program includes the effect of creep. Creep causes a time dependent settlement, even if the effective stress in the soil remains constant. The creep model applied is a simple one, based on (Bjerrum, 1967) and provides only a first approximation of the secular effect.
Other features are: loading with a hydraulic gradient, deposition of more than one layer and partial drainage.
The **hydraulic gradient**, e.g. the effect of a seepage force on the consolidation is useful in practical situations in the field, as it has been shown that hydraulic consolidation can accelerate the rate of settlement in a disposal site (Hammer, 1981).
The **multi-layer option** is used when one kind of material is deposited with a waiting period between two dump periods or when different materials are deposited on top of each other.
Partial drainage should be used when a layer with low permeability is situated at the bottom of the deposit (for instance a clay

liner). At forehand, it is often not possible to know how low the permeability of a bottom layer should be to have a significant effect on the outflow of polluted pore water. This depends on the dredged fill properties and on the thickness of both the fill and the bottom layer.

For an accurate calculation of the consolidation in a disposal site on land the transport of pore water may be influenced by an unsaturated top layer. The transport of water in this unsaturated zone cannot be calculated with the consolidation model, since the relations between pore pressure, permeability and water content are totally different. Therefore, an additional program is under development, which incorporates the mentioned top layer effects. Another problem that has not been solved up till now is the effect of gas production, especially methane, which is determined by the concentration of organic material and the presence of oxygen, nitrate, iron, manganese and sulphate.

CALCULATED EXAMPLES

Three examples will be presented here:
A. The effect of a clay liner;
B. The effect of the deposition rate;
C. The effect of a hydraulic gradient.

All the calculations have been carried out with the parameters found for the Botlek slurry, see section 2.

A. Effect of a clay liner.

A clay liner is a man-made densified clay layer on the bottom and often also on the sides of a slurry deposit. The function is preventing the pollution in the slurry to reach the groundwater by absorption of pollutants and by reducing the downward flow. In the example we compare a deposit without clay liner to a deposit with a clay liner of 1 m thickness and a permeability of 10^{-9} m/s. The deposit is assumed to be filled to 9.6 m height in 100 days and the consolidation is calculated until 8000 days (about 22 years). Fig. 4 shows the settlement for both cases.

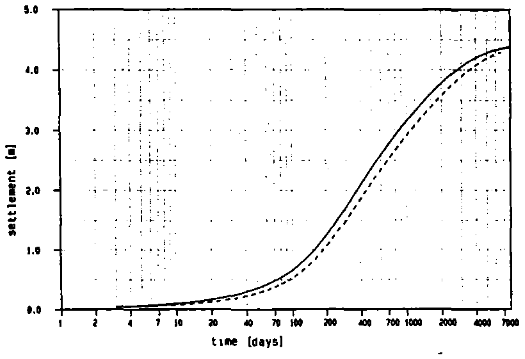


Fig.4 Effect of clay liner (CL)
on settlement
—— without CL
---- with CL

After 8000 days the settlement is practically finished at a value of about 4.4 m. Fig. 5 shows the cumulative downflow with and without clay liner. It appears that the effect on the settlement is minor, but the downflow is significantly reduced. It should be noted that a major part of the expelled water flows upward. The liner causes about 50% reduction of the downflow after 8000 days and a strong retardation. However, still 33 cm of pore water will be expelled through the liner. Furthermore it must be realized that in practical situations the quality of the liner will often be worse than assumed here. Indeed, a liner with a 10^{-8} m/s permeability will hardly reduce the outflow.

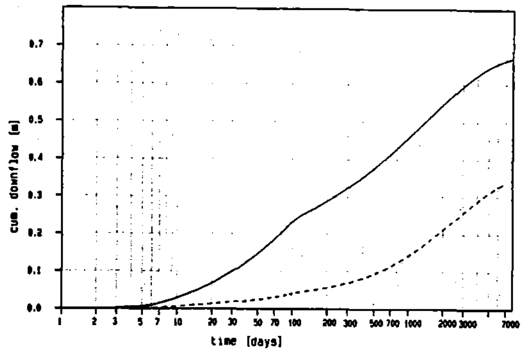


Fig.5 Effect of clay liner (CL) on downflow
—— without CL
---- with CL

B. Effect of the deposition rate.

In a study, performed in order of the Dutch Public Works, one of the questions was if a five year's filling followed by 15 years of additional supply would result in an increased capacity, compared to a continous 20 year's deposit. The reason behind this increase should be the longer time that the self weight of the sludge can act as a driving force for the consolidation. Both deposition schemes have been used in a number of situations. Fig. 6 shows an example of a 31 m deep deposit. It appeared that the 5 year's

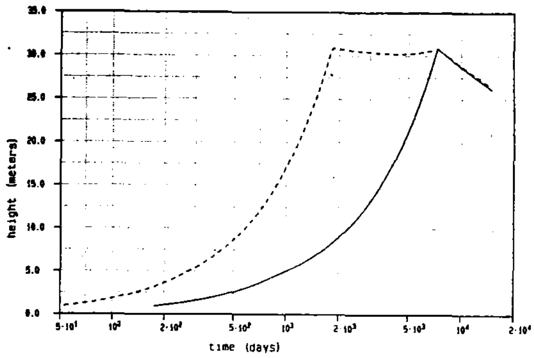


Fig.6. Effect of deposition rate
continuous curve: 20 year's deposition
broken curve: 5 year's deposition

filling scheme increases the total capacity from 40.2 m to 41.2 m (this means that in 20 years the settlement is about 10 m). In the other situations the difference was even smaller. We conclude that increase of the filling rate has only a minor effect on the capacity.

C. Effect of a hydraulic gradient.
In the study mentioned above, also the hydraulic gradient has been varied, from 50 kPa downward to 10 kPa upward. In the latter case the hydraulic gradient counteracts the self weight consolidation. As to be expected, the downward gradient results in a capacity increase compared to the upward gradient; for the 31 m deep depot this increase is about 2 m. The downward flow is affected only during the deposition period (5 years = 1825 days), as can be inferred from fig. 7. In this figure the lower curve corresponds to zero gradient and the top curve to 50 kPa downward.
The reason for the minor effect after deposition is the very low hydraulic conductivity of the thick sludge layer. Most of the flow is controlled by consolidation. It is noted that the consolidation has not ended after 40 years (about 15000 days), where the calculation stops.

SUMMARY

The consolidation model FSCONBAG is a step forward in the prediction of the behaviour of a dredged slurry during both deposition and subsequent consolidation. Effects of various conditions, like presence of a clay liner, different deposition schemes and presence of a hydraulic gradient can be modelled and have been discussed.
A difficult and very important aspect is the determination of material parameters, which describe the consolidation behaviour. In the paper a a new procedure is described, based on hydraulic consolidation and on forward iterative modelling.

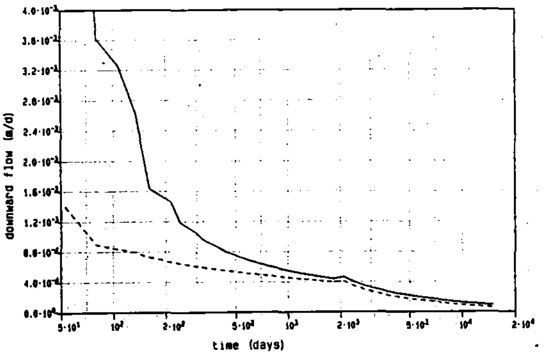


Fig.7. Effect of hydraulic gradient
continuous curve: 50 kPa gradient
broken curve: zero gradient

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FLOTATION AS A DECONTAMINATION TECHNIQUE FOR DREDGED MATERIALS

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1. INTRODUCTION

Flotation is a process for particle-separation of a liquid/solids mixture frequently used in industry and is a technique that promises to show good results in environmental applications.

The dredging company Jan DE NUL n.v. started up a research programme to investigate the possibilities of using flotation techniques for the decontamination of polluted dredged materials.

The following chapter briefly overviews the technique itself. In the third chapter, an overview is given of the most important characteristics of contaminated dredged materials. Starting from these characteristics, the fourth chapter explains why flotation can be considered as a possible decontamination technique. The advantages -in comparison with some other techniques- are given, as well as some important difficulties, arising from the specific nature of the dredged materials to be treated. The fifth chapter describes the experiments that have been carried out. The results are discussed and compared with those, obtained by another separation technique (hydrocycloning). The sixth chapter gives some general conclusions.

2. FLOTATION : THE TECHNIQUE

Flotation is a common technique for the separation of certain phases from an aqueous multi-phase mixture. These materials, by their hydrophobic character, are more likely to stick to air than to water. By air bubbles, they are carried to foam a layer, which can readily be skimmed off. This way the foam layer is providing a concentrate of the hydrophobic particles, after destruction of the foam.

There are a lot of materials which can be separated by flotation on an industrial scale :

- ore minerals ;
- charcoal ;
- industrial minerals such as talc or fluorspar;
- sludge of waste water purification (this is only a solid-fluid separation) ;
- even bacteria and viruses can be separated by flotation.

To make a flotation possible, a number of chemicals are generally used :

- frothers, to create a solid foam layer ;
- collectors, to make particles more hydrophobic ;
- activators, to aid the flotation of certain particles ;
- depressants, to prevent some particles from floating ;
- pH-regulators.

An optimal flotation is only possible when certain conditions are fulfilled : a certain concentration of chemicals, an optimal concentration of solids in the pulp to be floated, a grain size distribution of the solids,...

Before starting an industrial flotation, an important number of physical parameters and chemical conditions need to be determined during intensive labscale testing.

3. IMPORTANT CHARACTERISTICS OF POLLUTED DREDGED MATERIALS.

3.1. General characteristics

An important property of contaminated dredged materials is the grain size distribution : the problem materials are usually silty, containing more than 50 % of fines (fraction smaller than 63 μ).

Where fine and coarse minerals are mixed up, it is generally the fines fraction that contains the contaminants.

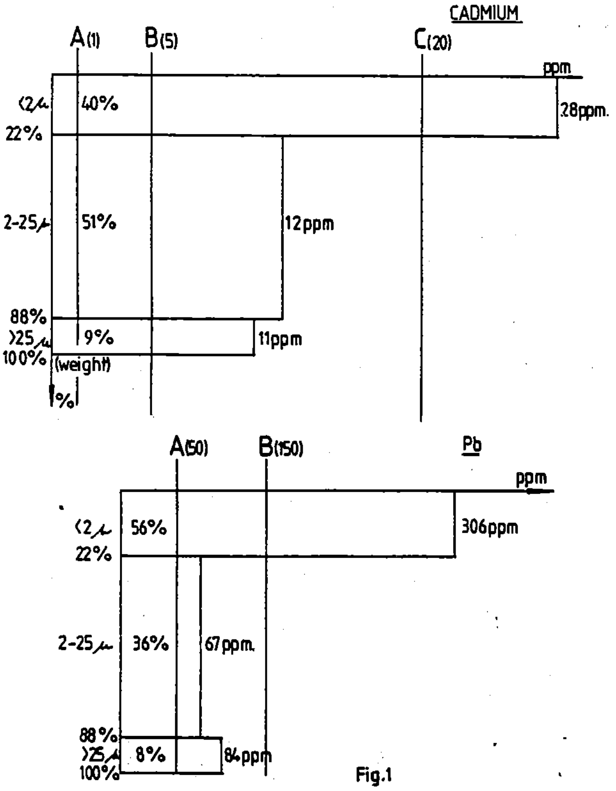

Fig.1

However, it is not the grain size but the mineralogical composition of these materials that makes them sensitive to contamination and difficult to cope with. The clay minerals, that are generally present in amounts from 5 to 50 %, have important electrical surface charges. Interactions between their surfaces and charge-compensating, so called "exchangeable" cations turn the suspension of solids into a fluid of high viscosity. Dredged materials, rich in fines, are usually also rich in organic materials.

These organic materials also exhibit an important exchange capacity for cations.

A typical contaminated mud is usually coloured black, when fresh. It is slightly basic and is formed in a reducing environment under anoxic conditions.

3.2. Contaminant characteristics

Because flotation is a phase-separation technique, contaminants are considered that are not present under dissolved form.

Three groups of pollutants that are very important are : heavy metals (Cd, Zn, Cu, Pb, Ni, Hg, As,...), mineral oils and organic micropollutants as organochlorines (PCB, HCB,..) and polyaromatic hydrocarbons (PAH's).

Heavy metals can be present in different forms: as exchangeable cations, bound to organic materials, bound to Fe- and Mu (hydr-) oxides, as carbonates or phosphates, under sulphatic form.

Ref. 1.

In the reducing conditions, present in a black mud, sulphides are chemically stable. Black muds, treated with acid, release hydrogen sulphide-originating from the decomposition of metal sulphides. A microprobe investigation of silt of the Scheldt could detect the two most abundant heavy metals : Zn & Cu.

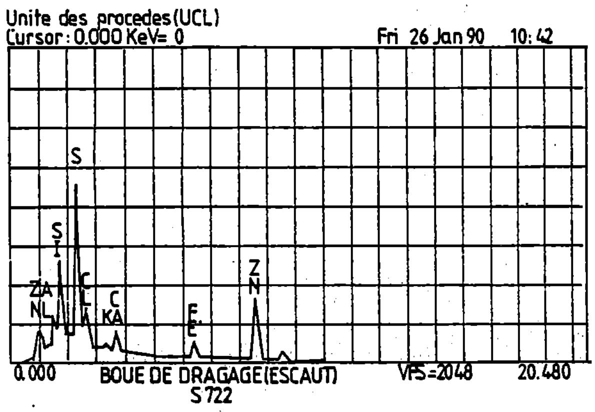

Fig.2 MICROPROBE SPECTRUM OF A SILT-PARTICLE FROM THE SCHELDT-ESTUARY

Both were only found in iron-sulphide (stoechiometric approximately Fe : 1, S : 2) concentrations in an order of magnitude of 1-10 µ. Mineral oils and the organic micropollutants, named above, are not miscible with water and are therefore present as a different phase. These components are also hydrophobic and lipophilic. They are dangerous because they are quite persistent and because of the risk for bioaccumulation.

Ref. 2.

4. FLOTATION AS A DECONTAMINATION TECHNIQUE

Flotation can be useful to decontaminate polluted silt because :

- many organic pollutants are naturally hydrophobic and are easy to float ;
- heavy metals, under particulate form, can be floated if the particles are hydrophobic or can be made hydrophobic. In the mining-industry there is extensive experience in sulphide flotation ;
- flotation is already in use to clean up contaminated soil (Rulkens, 1985)

Ref. 3.

The technique is capable of handling huge deliveries in relatively small installations and it is well-developped in mining-industry.

Compared with some other treatment techniques, one can say that :

- flotation is as fast and rugged as hydrocycloning, but it is more selective and the concentrate volume can be smaller. On the other hand, the use of chemicals is necessary ;
- flotation is faster than a biological treatment for organic contaminants and it needs smaller installations ;
- flotation needs less chemical reagents than acid leaching or complexation, because only the surfaces of the contaminants are involved. It is also not necessary to dewater all of the silt for a separate water-treatment. On the other side the chemical conditions for a flotation are far more difficult.

5. EXPERIMENTAL RESULTS

5.1. Short description of the test

The experiments were carried out in a conventional 2.5 l flotation cell, in a batch process.

Different chemicals were tested with different concentrations and with different pulp-densities.

The experiments were carried out with dredged materials coming from :

- the Scheldt estuary (Berendrecht-lock), lightly contaminated with heavy metals ;
- the river Lys (Menen), lightly contaminated with heavy metals ;
- the sea-canal in Brussels, contaminated with heavy metals, locally with oil and PAH.

After flotation, both concentrate and tailings were filtered and dried.
Afterwards, they were analysed for :
- heavy metals ;
- organic material ;
- oil and fat (some of the samples from Brussels and Menen) ;
- PAH (some of the samples from Brussels)

From time to time, grain size was analysed to control the entrainment.

5.2. Discussion of the results

A definition for the separation - efficiency of a flotation is given as follows :

$E = R_c - R_s$ (Tils,1990) with

- E = efficiency.
- R_c = recovery of contaminant (percentage of contamination in concentrate).

R_s = recovery of solids (percentage of solids in concentrate).

In figs. 3,5 and 6, the efficiency "E" is expressed as the vertical distance between the plot of the result of a certain test on the line $R_c = R_s$. In these graphs, data points, connected with each other are different stages in one flotation test.

Fig. 3 represents the results for copper. In general, the differences between the behaviour of the different heavy metals are small. Following conclusions can be made :

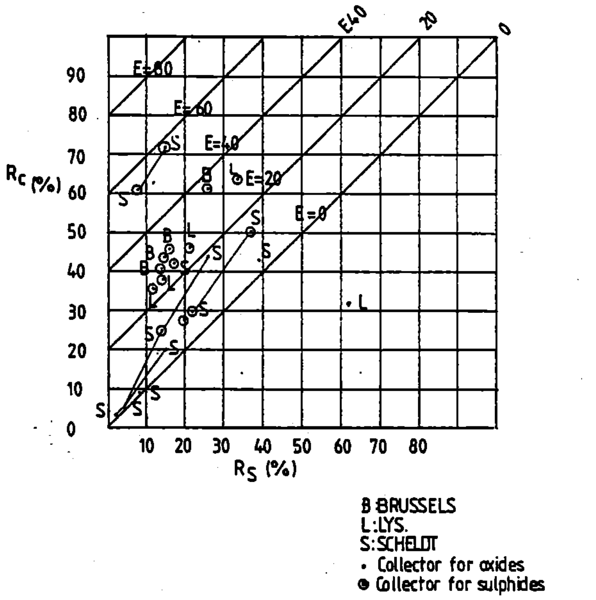

Fig.3 FLOTATION RESULTS FOR Cu

- collectors for sulphide minerals give better results for heavy metals than collectors for oxides ;
- flotation shows better results for silt from the river Lys and the sea-canal in Brussels than for silt from the Scheldt estuary (with exception of the tests with very diluted Scheldt silt, plotting at. R_c = 61-72 % ; Tils, 1990)

The bar chart, fig. 4, represents the recoveries of O.M. (organic materials), Zn, Pb, Cu and total mass of dry material per size fraction. Data are given for flotation of silt of the river Lys.

Here, efficiency is expressed as the difference in height between the mass-bar, and the bars for O.M., Zn, Pb and Cu.

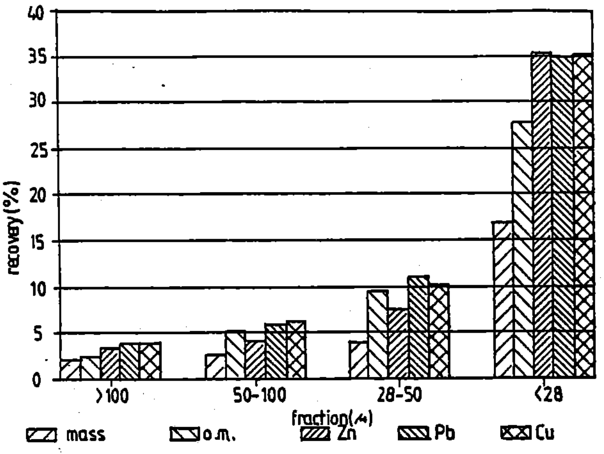

FIG.4 RECOVERIES PER SIZE FRACTION

We can see that :

- the organic materials float better than the bulk mineral mass ;
- the heavy metals float better than the organic materials, but this is restricted to the fraction < 28 micron ;
- for the fines fraction, there is an important entrainment of particles, containing no heavy metals. This phenomenon badly influences selectivity.

In fig. 5, results for PAH and oil are represented. It is obvious that flotation of PAH and oil is more predictable and gives better results than flotation of heavy metals. It is easily possible to obtain recovery up to eighty percent.

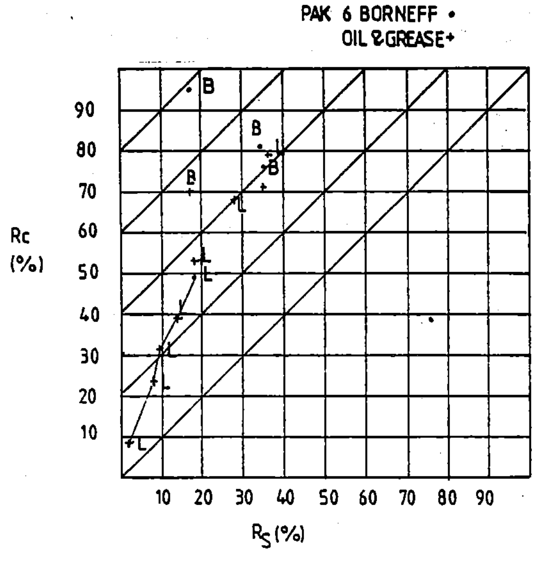

Fig 5 FLOTATION RESULTS FOR PAH (6 BORNEFF) • AND OIL+

Fig. 6 gives the results of separation by hydrocycloning in the Netherlands (de Waay & van Veen, 1988). Our flotation tests result in comparable efficiencies for heavy metals in fine grained materials and slightly better results for organic pollutants. Results for coarse materials are better, but we did not try out any comparable material.

The results of a flotation are located more to the low-recovery end of the graph than the results of hydrocycloning.

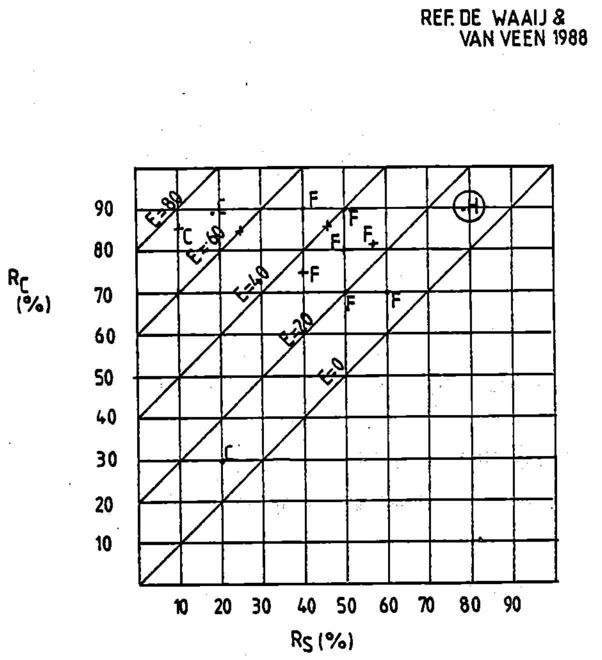

FIG.6 HYDROCYCL. SEPARATION RESULTS (ref. DE WAAIJ & VAN VEEN 1988)

• Organic pollutions
+ Heavy metals
F Fine grained
C Coarse grained

6. CONCLUSIONS

Entrainment of "clean" particles to the concentrate is less important for coarse grain sizes.

Better results can thus be expected for sandy dredged materials that are polluted.
However, most contaminated dredged materials are fine grained.

Flotation is an interesting technique for the removal of naturally hydrophobic, organic pollutants from fine grained dredged materials.

Test results are promising for the possibilities as a decontamination technique for heavy metals, but further research is necessary.

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PROCESSING OF CONTAMINATED SEDIMENTS PRACTICAL EXPERIENCE AND PLANS FOR THE FUTURE

M. CARPELS, SCK, Mol
W. GOOSSENS, Herbosch Kiere, Kallo, B

ABSTRACT

The problem of disposal of contaminated sludge can essentially be reduced to a spatial and economical problem. In our opinion, remedial action w.r.t aquatic sediments concerns in the first place of a reduction of the total volume of sludge to be disposed off.

Since more than two years we have a broad experience in fractionation and on line mechanical dewatering of dredged spoil. With respect to the decontamination techniques, important research was carried out towards a treatment technique with micro organisms.

INTRODUCTION

Until recently dredging activities were only characterized by the lowering of the underwater bottom after dredging. For conventional maintenance dredging this vision was sufficient to calculate a realistic price. When environmental awareness grew, dredging sludge had to be identified by other parameters, i.e. pollution with heavy metals and organic contaminants.

Most dredging companies became confronted with a completely new strategy for handling sludge. Indeed not only physical, but chemical and biochemical features became of great importance. SCK and HERBOSCH KIERE are working together on a methodology to counter the problem practically.

In the following discussion we will firstly give a bird eye view on some possible reclamation techniques and the critical characteristics to be measured. In the second part we will illustrate some of those techniques with a few of our realizations.

RECLAMATION TECHNIQUES

1. GENERAL

Soon it became clear that dredging sludge cannot be treated along established lines. Some sludges are clean and consequently do not need any further treatment. Other sludges can be separated into two fractions i.e. a clean and a more contaminated part in this producing a considerable volume reduction and a way of lowering dumping costs. More complex sludges have to be treated, if possible, by biochemical or chemical processes.

The most important factor in the whole problem is by consequence a good characterization of the sludge. Understanding this point Public Works initiated the foundation of a consortium wherein SCK (Studie Centrum voor Kernenergie), RIG (Rijks Instituut voor Grondmechanica) and WLB (Waterbouwkundig Laboratorium van Borgerhout) are doing research on the so called MEP (Milieu effect procedure). In this approach attention is given to probable environmental effects at the dredging and deposition site.

2. TECHNIQUES

2.1. Dumping without any treatment

Dredging sludge with such physico-chemical properties that no significant environmental effects are to be expected, can be discharged without any treatment, or if possible reused.

2.2. Physical separation

Due to the intrinsic properties of the sediment, pollution is not homogeneously distributed among the sludge particles. In essence, this means that there are particles which are thoroughly contaminated and others with almost no contamination content.

There exist a few conventional physical separation techniques, making it possible to separate those heavily contaminated particles from the other particles. In addition a volume reduction of the discharging quantity is obtained. Physical separation techniques are consequently valuable techniques which are as well for financial feasibility as well for purification efficiency in many cases of more interest than chemical and biochemical processes.

2.2.1. Separation on grain size

Most sludges are composed of organic matter, sand and clay particles. These three fractions have different physico chemical properties and have other affinities towards possible pollutants. Sand principally is completely inert, in contradiction to clay and organic matter which can accumulate huge amounts of pollutants by means of adsorption and binding reactions. Physical separation processes can be based on grain size difference. To separate organics from sand the density difference can be taken into account. Some suitable techniques:

- sieving
- up-streaming
- separation in lagoons
- centrifugation
- hydrocyclonation

2.2.2. Separation of ores

Most waterways are used for transportation of raw materials, in that case contamination of dredged sludge can result from those ores. Grit of that kind cannot be separated by means of grain size based separation techniques. A useful process for this kind of pollution is flotation.

2.3. Chemical treatment

When it is impossible to apply a separation process or whenever a further purification is feasible, a chemical purification process can be employed. Such a process is based on an extraction step, wherein through chemical agents pollutants are eliminated from the sediment phase. A wash step is needed to separate the contaminated water phase from the purified sludge. The last step tackles the water purification problem; chemical agents are used to precipitate the impurities. To determine the most suited chemical agents for the studied sludge, SCK uses a sequential extraction technique.

2.4. Biological treatment

Biological reclamation techniques are based on two principles; organic pollutants are broken down into less hazardous components, while inorganics are placed into more mobile phases so they can be removed more effectively. The immediate advantage of biological incubation is that aggressive chemical reagents are not used so that the underwater bottom can preserve its multifunctional properties.

CHARACTERISATION OF DREDGING SLUDGE

1. GENERAL

As mentioned before it is necessary that a characterization has to lead to a useful treatment proposal. It is not astounding that conventional dredging companies initially had the ambition to tackle the problem using mechanical processes. Nature did help them a hand because an average dredging sludge contains its pollutants only on the grain size fraction less than roughly 60 microns.

Some dredging companies, using this premise, have built grain size separating installations. The first experiences were not always very fortunate. The cause can be found in a lack of knowledge of the sludge and the used technique.

SCK with its department environmental technology started a cooperation with N.V. HERBOSCH KIERE with the purpose to elaborate a scientific programme for the characterization of dredging sludge concerning physical, chemical and biochemical properties. The characterization has to lead to a well- founded choice between possible treatment techniques.

2. IN SITU DENSITY

To estimate the feasibility of a certain technique, it is important to measure the dry matter content of the sludge as it is in situ. The collection of an undisturbed sample is not simple in practice. For densities smaller than 1.3 ton/m3 it is possible to become accurate measurements with a gamma-densimeter probe. Note that using this technique it is impossible to attain other characteristics because no sample is actually taken. The measurement of more dense parts of the underwater bottom can be approximated by sampling with a so called beeker sampler. It constitutes of a tube that has to be pushed into the bottom. At the desired depth a bellow at the end of the pipe prevents loss of material.

3. GRAIN SIZE DIFFERENTIATION

With the purpose in mind of the application of eventual separation techniques one has to look at the economical feasibility. Therefore a sample has to be divided into several different grain size classes and each one is analysed for contaminants. The "granular differentiation" has to be favourable, i.e. the coarser the grains, the lower the contamination load, in order to operate the separation technique successfully.

The conventional method to investigate granular differentiation is by sieving the sample on a sieve shaker and subsequently analyse each fraction. However, we have experienced that this method is not very useful for selecting a convenient industrial process. Indeed, a sieve shaker separates on the physical dimensions of the grain and not on its hydrodynamic diameter or whatever characteristic on which the technique intrinsically separates.

4. GRAIN SIZE

From the above considerations it becomes clear that grain size measurements are very important. There are different techniques to measure grain size distributions but almost every method gives information about another characteristic diameter. Optical methods commonly measure surface equivalent diameters, while hydrodynamic methods give Stokes diameters. By consequence it is important to choose a method that is based on the same physical law as the separation technique is based on.

But this is not the only problem in the evaluation of the grain size distribution. The measuring method probably does not differentiate between agglomerates, density differences and so on.

5. CHEMICAL CHARACTERISATION

A discussion on the possible contaminants in dredging sludges is not the purpose of this contribution, however it is important to look at the chemical interactions between pollute and sludge.

Because knowledge of the chemical state of the pollute determines the type of extraction to be functional, it is significant to applicate chemical extraction techniques.

5.1. Inorganic sequential extraction

Pollutants can be found in fast exchangeable fractions. In that case a simple acid extraction could do the job. But contaminants can also be found as hydroxides, sulfides, adsorbed onto organic matter or even fitted into the crystal matrix of the particles themselves. To eliminate the impurities from those fractions it is sufficient to use specific reactants, economic feasibility however has to be tested afterwards.

5.2. Organic sequential extraction

When contaminants are concentrated in organic matter, then it is critical to investigate how good those binding components are biological recalcitrant. If the binding components cannot be broken down by biological activity, then one can expect that (1) dumping without treatment will not be dangerous for the environment because pollutants are bound on stable places and (2) biological techniques will not be feasible. In the opposite case the use of biological solubilization and removal techniques can be favourable.

EXPERIENCE

1. HYDROCYCLONAGE

Sludge treatment techniques, beside efficiency, have to be economicaly feasible in the first place. For this reason the first technique to be considered is to find a suitable mechanical volume reduction technique. Whenever the granular differentiation permits physical separation techniques the solution will be cheap and simple. We propose to use hydrocylonage above other comparable techniques, such as flotation, up streaming or lagoon separation, because they do not offer the same flexibility, compactness, speed and operating confidence.

In the following realizations and studies we will give a survey of the problems and facilities encountered by using this technique.

1.1. Aggregates

With the project for dredging and treatment of sludge from the canal Brussels-Charleroi at Anderlecht we have encountered the problem of cemented, heavy metal contaminated clay particles. The presence of aggregates can give problems by characterization and interpretation of the grain size distribution analysis. At the time hydrocyclonage activities were initiated granular differentiation was obtained by using sieve shakers. On a sieve shaker it was impossible to break up the aggregates. So the granular differentiation was rather negative. Using light acid incubation combined with an ultrasonic bath it was in the first place possible to show that the agglomerates existed and secondly that a granular differentiation with the crushed agglomerates showed a much more interesting picture. A hydrocyclone test with broken agglomerates showed that it was possible to obtain a good heavy metal separation efficiency (table 1). This data together with data from literature (Svarovsky 1980) lead to the idea that the shear stress in a hydrocyclone is high enough to break up agglomerates.

mg/kg ds	**underflow**	**overflow**	**feed**
As	1	25	9
Hg	.28		.6
Cd	3	21.5.	8
Zn	310	2250	1100
Cr	19.7	115	50
Pb	63	370	200
Ni	8.6	50	<10
Cu	34	205	90

table 1. Hydrocyclone test of sludge without aggregates

After the industrial process however, the results varied day by day and were never as good as at the moment of the test run (table 2). The reason for the lowered separation efficiency can be found in the accumulation of contaminated clay aggregates in the "clean" underflow. This could be shown by electron microscopy.

This brought us to the insight that an adequate prediction of the behaviour of the individual grains under industrial circumstances only can be attained by operating a characterization process which is based on the same entities.

In cooperation with HERBOSCH KIERE we have decided to characterize dredging sludge on a hydrocyclone test rig. Beside pure mechanical fractionation of the sludge, it is possible to use the unit as a pilot cyclone to test the process for efficiency after all properties are investigated.

mg/kg ds	**underflow**	**overflow**	**feed**
As	5	12.5	10
Hg	0.3	0.5	0.9
Cd	5	15	10
Zn	1060	1240	1065
Cr	38	64	55
Pb	145	275	258
Cu	64	105	95

table 2. Hydrocylone run with incomplete aggregate break up

In this way it is not only possible to find a hydrodynamicaly based granular differentiation, but to test the results in realistic circumstances, leading to a more reliable overall mass balance.

1.2. Density differences

An advantage of hydrocyclonage is that separation not only is based on grain size but on density too. This effect can be measured (table 3). Those two effects usually work cooperatively.

density			
kg/m3 ds	**feed**	**overflow**	**underflow**
run 1	2700	2659	2738
run 2	2862	2852	2866

table 3: examples of density separation on a hydrocyclone

This feature can be used when a sludge contains huge amounts of contaminated organic matter. Organic matter has no specific grain size range. In some cases it can be very coarse material e.g. larger than 2 mm, in other cases it can be under 5 microns. But because of its uniform low density in comparison with sand, the hydrocyclone actually "sees" the organic matter as very small and by consequence it will separate the contaminated organic overflow phase from the clean sand underflow. The effect was clearly seen on hydrocyclone tests performed on a heavy metal contaminated sand bottom from a site in Limburg.

After analysing, it was found that the ground was heavy contaminated with Zn and Cd and that the contamination was highly correlated with organic matter. The organics were very coarse and consequently sieve experiments showed a disappointing picture concerning granular differentiation (fig 1). The coarse fraction contained high amounts of Zn and Cd.

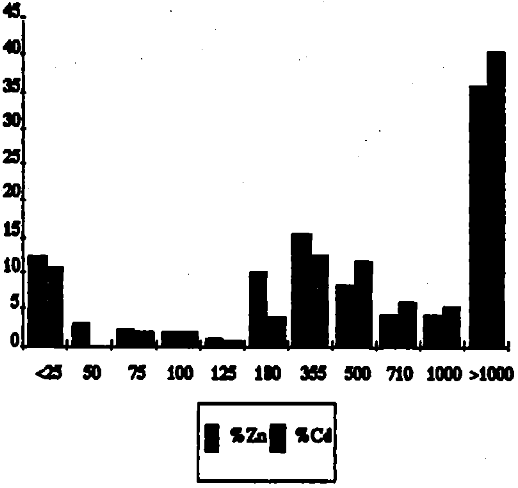

fig 1: granular differentiation on a sieve shaker

A pilot scale experiment was performed wherein the material was firstly conducted over a 2 mm sieve and afterwards put through a rig of cyclones with cut sizes of 50, 20 and 5 microns (for standard material: sand with density= 2.7 kg/l). The sieve took 71 % Zn and 50 % of the Cd contamination, an additional 15 % of Zn and 15 % of Cd could be eliminated in the finest fraction at the cost of roughly 2 % mass extra to be dumped (table 4 and fig. 2).

Remarkable was the fact that the efficiency could only be obtained by the density difference effect and not by the grain size distribution effect.

fraction	% m/m	Zn ppm	Zn %	Cd ppm	Cd %	%glow
> 2mm	23.55	1722	71.29	18.75	50.01	-
underflow 1	40.02	45	3.16	0.8	4.35	0.2
underflow 2	34.55	180	10.9	4.3	20.24	2.8
underflow 3	1.86	4495	14.59	60	15.16	32.9
overflow 3	0.02	1915	0.06	90	0.24	-

table 4: granular differentiation obtained with hydrocyclones

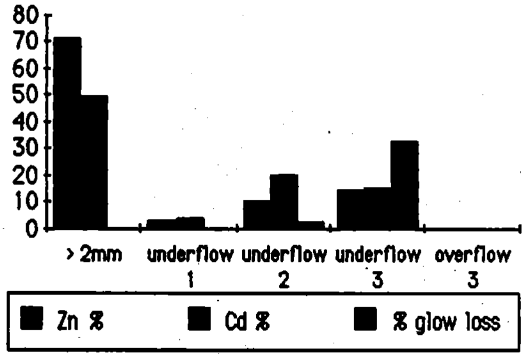

fig 2: granular differentiation obtained with hydrocyclones

1.3. Discrete metal particles

The applicability of hydrocyclonage however, is, like every technique, limited. At the Laak, Limburg, no good results (table 5) could be obtained because discrete iron oxide particles, containing unleachable heavy metals kept contaminating the underflow because of their high density.

Test 1	Feed	Under	Over		test2	Feed	Under	Over
Hg	55	35	85		Hg	95	42	128
As	1100	840	1175		As	1180	475	1310
Cd	185	39	238		Cd	215	30	275
Cr	115	70	125		Cr	140	60	180
Zn	1140	365	1425		Zn	1205	375	1750
Pb	835	545	1535		Pb	1255	335	1700

table 5: Results of hydrocyclone separation of Laak sludge

It can however be seen that hydrocyclonation had a marked effect on the up concentration of metals towards the overflow. The problem of discrete metal particles in the aquatic sediment could probably be tackled with a flotation step.

1.4. Importance of the type of dredging material

1.4.1. Dredging material from Geuzenhoek site

Because the material in this project consisted of unleachable metals, it was impossible to use chemical or biochemical techniques to tackle this problem. The use of hydrocyclones gave successful results.

By using a suitable combination of cyclones it was possible to produce the following underflow (table 6).

mg/kg ds	Feed	Underflow
As	35	4
Cd	10	<1
Cu	85	40
Cr	206	10
Ni	40	25
Pb	565	<5
Zn	2500	<5

table 6: Laboratory results for Geuzenhoek sludge

At the pilot installation on Geuzenhoek site, the results were comparable (table 7). The installation consisted of two cyclones with the underflow used as the feed for the second cyclone. The second cyclone functions here as a wash step combined with the additional removal of the fines from the first underflow. The mass efficiency was about 60% (m/m) underflow.

	feed1		**under1**		**under2**	
	Zn	**Cd**	**Zn**	**Cd**	**Zn**	**Cd**
1	**5398**	**27**	469	1.6	**68**	**0.1**
2	**4758**	**26**	175	0.6	**50**	**0.1**
3	**4945**	**24**	415	1.6	**78**	**4**
4	**5997**	**18**	226	<1	**72**	**<1**
5	**5390**	**16**	321	5	**62**	**<1**
6	**8025**	**15**	541	<1	**55**	**<1**

table 7: Pilot run results on Geuzenhoek site

1.4.2. Dredging material from the Antwerp area

A heavy metal contaminated underwater bottom, gave good results with the preliminary experiments. The granular differentiation seems to give a smooth picture and a high volume and mass reduction (table 8, table 9, fig 3, fig 4). It can easily be seen that with a cut size of 45 microns the underflow is containing more contaminants in comparison to a cut size of 63 microns. The quality gain always goes at the expense of mass reduction.

	cut size µm				
mg/kg ds	**total**	**< 45**	**>45**	**<63**	**>63**
As	8.5	19.6	6	16	5.8
Zn	4800	12321	3060	10536	2851
Cr	250	750	168	654	149
Pb	118	309	73	269	66
Cu	4.5	9	3.8	7.5	3.5
Cd	5.2	14	3.2	12	2.8
Hg	0.5	0.6	0.21	0.52	0.2

table 8: Contamination distribution with two cut sizes

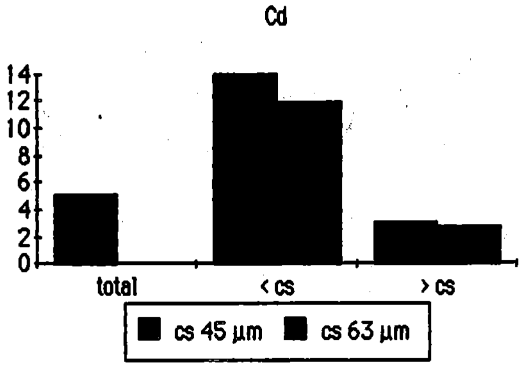

fig 3: A view of Cd distribution with two cut sizes

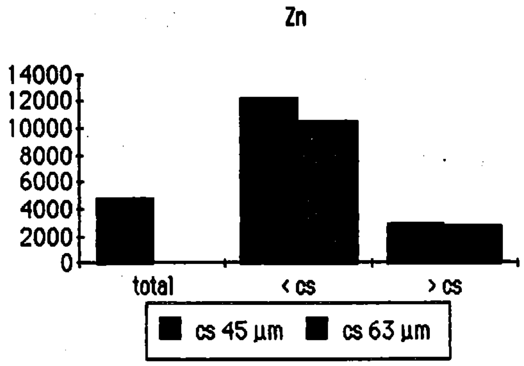

fig 4: A view of Zn distribution with two cut sizes

		cut size µm	
% m/m	underflow	81	74
% v/v	underflow	43	40

table 9: Mass and volume balance at two cut sizes

From the above discussion it will be evident that hydrocyclonage is a technique, with its limits, but because of its simplicity, interesting in practice. However, it is of critical importance that before the start of a reclamation project an applicability study has to be done on a sample, because a ready-to-use, universal solution does not exist.

1.5. Further treatment after hydrocyclonation step

After hydrocycloning, the underflow is, after dewatering, ready to reuse. The overflow can be extracted, if feasible or dewatered.

2. PERSPECTIVES

Because dredging sludge, considering its heterogeneity, is impossible to purify by using only one technique, SCK and HERBOSCH KIERE are doing further research on the usefulness of other techniques.

2.1. Chemical precipitation

Sequential organic and inorganic extraction can give an answer to the most suitable extractants to be used for the sludge under consideration. There has been built a laboratory scale fluid bed reactor for modeling of the following water purification problem.

2.2. Flotation

Flotation is a technique with a highly specific interaction capacity. With this property it is possible to eliminate discrete particles from a sludge suspension. We have successfully used flotation to eliminate sludge foreign micro organisms from suspension (table 10).

flotationexperiments **frother**	**kinetics (min-1)**	**efficiency %**
NaCl 5% pH 7.5	0.304	95
NaCl 5% pH 8.5	0.344	95.7
NaCl 5% pH 7.5 A27	0.303	94.9
NaCl 5 % pH 8.5 A27	0.721	99.5

table 10: removal of foreign micro organisms from a suspension

2.3. Biological two-stage systems

A two-stage system specially for the elimination of heavy metals is developed at laboratory scale. It consists of a chemical extraction, (metal solubilization) followed by a precipitation (metal removal) step executed by microorganisms. The results of the system are pointing out that elimination of heavy metals from an extracted suspension is possible. The parameters affecting the efficiency are intensively studied. A few figures (fig 5 to fig 7) give insight in the elimination capacity. The principles on which the process is based, will be compared with some pure chemical elimination systems.

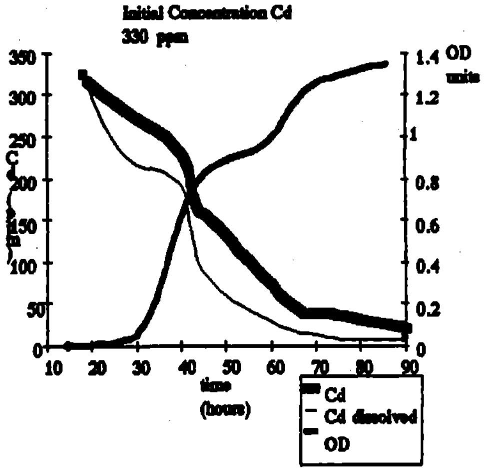

fig 5: elimination of Cd in a batch culture

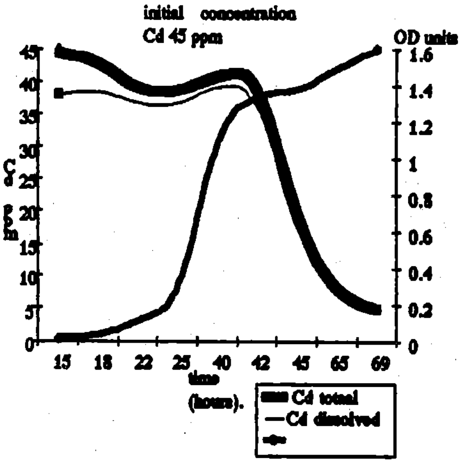

fig 6: elimination of Cd in a batch culture

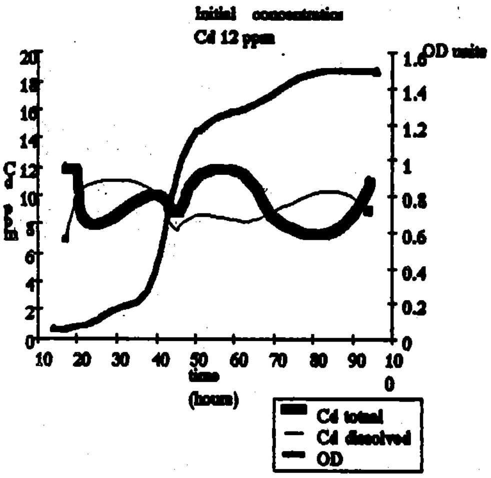

fig 7: elimination of Cd in a batch culture

2.4. Biological one-stage systems

An ideal biological elimination system consists of the suspension of micro organisms with sludge, removal of organic pollutants and bringing inorganic contaminants into more removable positions. This system has been run on laboratory scale already with some results given here (fig 8 to fig 10). The elimination of the biological sludge can be mediated by means of flotation as it is explained above.

An advantage of the one-stage to the two-stage process is that the extraction step is eliminated. As with every chemical extraction method, the sludge becomes completely sterilized and unusable for reuse in agriculture.

A drawback clearly is the incomplete removal efficiency. This has not to be considered as a fundamental shortcoming, though, because we come here onto the property of the discussion of bioavailability.

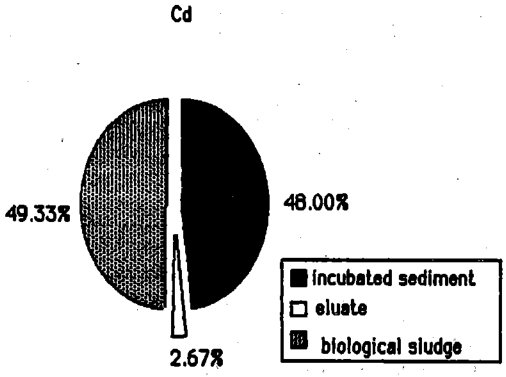

fig 8: Cd distribution after a biological one-stage process

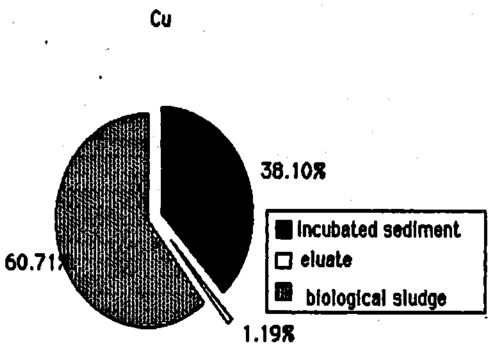

fig 9: Cu distribution after a biological one-stage process

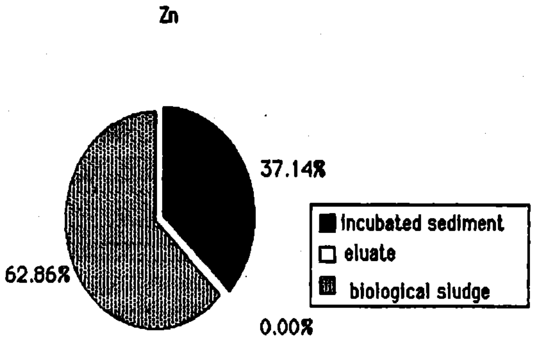

fig 10: Zn distribution after a biological one-stage process

ACCURATE DREDGING OF THIN LAYERS OF POLLUTED MUD

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ABSTRACT

To find an adequate solution for the accurate dredging of thin layers of polluted mud a research programme is carried out. Severe requirements with respect to accuracy of dredging, with respect to generation of turbidity and with respect to mixture concentration have to be met.
Two dredging principles have been selected which have a high potential for meeting these requirements. One solution is based on the principle of a disc bottom cutter and the other solution is based on the principle of a dustpan type dredge.
In order to verify assumptions being made and to optimize both solutions a model test programme has been carried out at the Delft University of Technology. The test results are very promising, high mixture concentrations together with a low generation of turbidity are achievable.

INTRODUCTION

In Holland many of the recent sediments in rivers, lakes and especially harbours and closed sea branches are contaminated. The thickness of these contaminated sediment layers may vary from one tenth of a metre to several metres. For nautical reasons and in order to restore the quality of these waters dredging of polluted muds is necessary.

At this moment several dredging methods are used for the removal of polluted muds. Especially in case of heavily contaminated materials mostly grab dredges in combination with silt screens are used. Less contaminated materials are dredged with trailing suction hopper dredges. To improve the efficiency of the dredging cycle with a trailing suction hopper dredge the so called recirculation system was developed [1].

Since 1989 a research program is being carried out by Boskalis in order to find out and develop an optimum method for the removal of thin layers of polluted mud. The polluted nature of these muds imposes special requirements with respect to the resuspension and spill of dredged material and affects the way in which the most economical dredging operation can be performed. The assumption is made that the dredged material has to be transported in barges over large distances and then stored in deposits. At these deposits, in case the muds contain a large sand fraction, separation in a clean sand fraction and a polluted fine fraction might be considered in order to reduce the amount of material to be stored in the deposit [2].
For selection of the most appropriate dredging method the following criteria, in relative order of importance, are used:

- resuspension and spill of dredged material must be avoided.
- the dredging method must be accurate and selective.

When a certain layer is identified as being polluted one must be able to remove this layer completely without the admixture of other non polluted materials. This has a great impact on the costs of transportation and on the costs of storage of the dredged material.

- the concentration of the material being dredged, in terms of the volumetric ratio between dredged material and material to be transported in barges, must be as high as possible.

This has a great effect on the costs of transportation and on the short term storage costs of the dredged material.
This paper describes the dredging methods we have selected and the model tests we have performed to optimize and evaluate these methods.

SELECTION OF DREDGING METHOD

The dredging action can be divided in dislodging and pick up of the material to

be dredged by means of a dredge head, followed by transport of this material into a barge. The mentioned selection criteria can be met by using the following principles.
The criteria for dredging of polluted mud are used to formulate requirements for the dredging system.
The first criterium can be met by using an as closed as possible dredge head for dislodging and pick up of the dredged material. Furthermore it is essential that all material encountered by the dredge head is being picked up. Deformation and displacement of soil in front of the dredge head, which occurs for instance at a dozer blade, is not allowed.
The second criterium can be met by using an accurate system to measure and control the position of the dredge head.
The third criterium can be met by using a method to pick up the dislodged material which is fairly independent on the mechanical properties of the materials to be dredged. Also the mixture flow rate has to be a function of the amount of material being dislodged.

This leads to the following specifications of the dredging method:
- the height of the opening of the head, through which the soil has to enter the dredge system, has to be adjusted to the thickness of the layer to be removed.
- the dislodged material has to be picked up in a controlled way over the whole width of the dredge head.

This can be realised mechanically, by cutting and displacing the material into the dredge head, or by means of a jet system which jets the dislodged material into the dredge head.
- controlled suction flow rate as a function of the amount of dislodged material.
- no dilution of the dredged material by jet water

Given these specifications two dredge methods have been selected. One method is based on a dustpan type dredge combined with a recirculation system (recirculation head); the other is based on the disk bottom cutter principle (environmental disk cutter).

The principle of the recirculation head is depicted in figure 1.

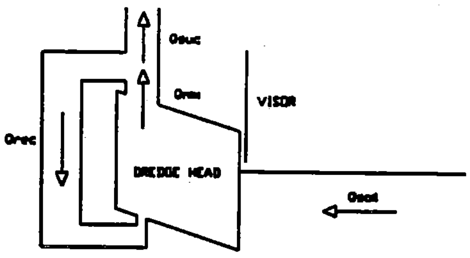

Fig.1 Principle of recirculation head

The soil material entering the dredge head is directly jetted further into the head by means of a slit jet acting over the total width of the dredge head. Due to the jet no suction action is needed to help the soil further into the dredge head. In this way unwanted dilution of the dredged material is prevented. For a slit jet acting over the total width of the dredge head a large flow rate of jet material (Qrec) is needed. By using a part of the mixture formed in the dredge head (Qmix) dilution by jet water is avoided. In the ideal situation the flow rate of material delivered to the barges (Qsuc) is equal to the cutted soil flow rate entering the dredge head (Qsoil) and no soil material is spilled. The visor in front of the dredge head adapts the height of the opening of the dredge head to the thickness of the layer to be dredged.

The principle of the environmental disk cutter is depicted in figure 2.

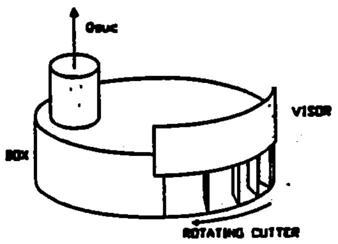

Fig.2 Principle of environmental disk cutter

The cutter has a flat closed bottom. Its axis of rotation is vertical. The cutter is, except from where the soil has to enter the dredge head on top and along the circumference, enclosed by a box to prevent spillage of material and the entering of water into the dredge head. Again a visor is used to adjust the height of the opening through which the soil enters the dredge head to the thickness of the layer to be dredged. The cutter reduces the strength of the soil by remoulding and displaces the cutted material to and into the suction mouth which is situated inside the cutter.

DESIGN OF MODEL TEST

The model tests should enable us to verify our assumptions being made and must give information to optimize both dredging methods and to select the best dredging method. As in the prototype situation thin layers of mud have to be dredged and the dredge head will only be partially submerged these situations have to be investigated.
A test facility of the Technology of Soil Movement Department of the Delft University of Technology was available to perform dredge tests with scale models. A picture of this facility is given in figure 3.

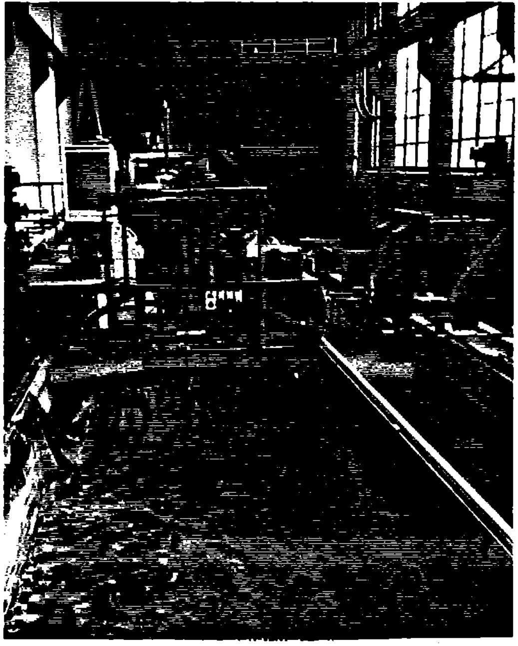

Fig.3 Test facilities at Delft University of Technology

A length scale (nl) 1:3 was chosen being a compromise between staying as close as possible to reality and the need to limit the amound of mud which has to be prepared for the tests. The test models are scale models (geometrical conformity with the prototype). As the soil behaviour when entering the dredge head is thought to be the dominating process, the velocity scale is chosen equal to the length scale. In this way strain rates in model and prototype are equal. The soil strength should be scaled down with the length scale squared to model the effect of the jet in the recirculation head and the mixture forming process in the suction mouth of the environmental disk cutter. In prototype conditions a soil shear strength in the range from 1 to 10 kPa is expected.
As the model soil should have enough strength to allow steep slopes to remain stable we aimed at a shear strength in the range from .5 to 1 kPa for the model soil.
Bottom profiles which can be encountered in reality are schematised to the 4 profiles depicted in figure 4.

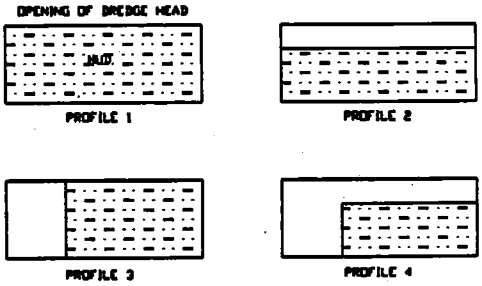

Fig.4 Dredged bottom profiles

At profile 1 the profile to be removed in one cut is just equal to the opening through which the soil has to enter the dredge head. At profile 2 the height of the profile is 70 % of the height of this opening, at profile 3 the width of the profile is 70 % of the width of this opening and profile 4 both the width and the height are 70 % of the corresponding dimensions of this opening.
The sensitivity of the test results to the following parameters is investigated:

-the ratio between Q and Qsoil
-the ratio between the height of the opening of the dredge head (hhead) and the height of the profile to be removed (hsoil)
-the influence of Qrec and the jet pressure (Pjet) in case of the recirculation head
-the revolutions per minute of the cutter
-the presence of an external shield around the cutter

An extensive monitoring program was designed.
In addition to the measurement of flow rates, mixture densities and pressures water samples have been taken at selected points around the dredge head to obtain an impression of the amount of suspended material. Furthermore video pictures have been taken, both with an under water camera and with a camera above the water level, of the dredge heads during the dredging proces.
For the execution of our testing programme we needed an amount of 20 m3 mud as homogeneous, in terms of density and to a lesser degree of strength, as possible and with a strength between .5

and 1 kPa. We made this mud by taking dredged material, mud, out of the well of a trailing suction hopper dredge and mixing this mud with bentonite to give the mud the required strength. The properties of the thus obtained mud are:

shear strength : .5 kPa
density : 1270 kg/m^3

The dimensions of this artificial soil are 12*3*.7 (length*width*height) m^3. Each trial consisted of a track of 12 m. A water level of .2 m is maintained on top of the mud. After a layer has been dredged the water is drained and the surface of the mud is smoothened and spilled material, if any, is removed by means of a plough blade acting over the total width of the test pit.

TEST RESULTS

The test results will be discussed in terms of the mentioned criteria.

Spill and resuspension.

With bottom profile 1 for the recirculation head the jetpressure in combination with Qrec has a large influence on the spill and resuspension. When the jetpressure is too low only part of the material encountered by the head is picked up. At the corners of the head the mud is pushed aside thus creating spill. However no suspended material leaves the head. When the jetpressure is too high the material entering the head is destructed to easy and jetwater together with suspended material leave the head.
With the other bottom profiles, and especially the profiles 3 and 4, the part of the recirculation flow which is not shielded by soil entrains water.
As the suction flow rate Qsuc is related to the amount of soil entering the head most of the entrained water, after mixing with the recirculation flow, leaves the head thus taking suspended material out of the head.
For all bottom profiles the environmental disk cutter hardly created any suspended material, even when the circumferential speed of the cutter was increased to prototype level, provided the cutter was enclosed along that part of its circumference through which no soil enters by means of an external screen. Although very limited, typically less than 10%, some spill occurred in the under cutting mode due to break out of material to the free surface created by the previous cut (figure 5).

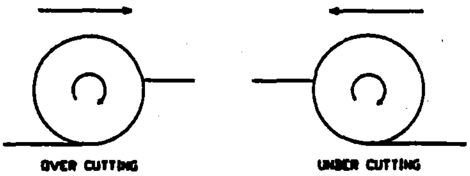

Fig.5 Over and under cutting modes

Accuracy and selectivity.

The geometry of both dredge heads enables the realisation of a flat bed. Provided the positioning of the heads is accurate an extremely accurate bottom level can be realised.
At the recirculation head above a certain jet pressure no detectable deformation of soil in front of the head occurs. Thus the soil one intends to remove is removed and the dredging method is selective.
For the environmental disk cutter a minimum circumferential speed is required, to prevent pushing of the backside of the cutting blades against the soil in front of the cutter. When this requirement is fulfilled no detectable deformation occurs.

The concentration of the material being dredged.

With both dredge heads a very high mixture concentration, better than 70%, could be realised. The mixture concentration depends on the ratio between the cutted soil and the mixture flow rate. For the environmental disk cutter an example is given in figure 6.

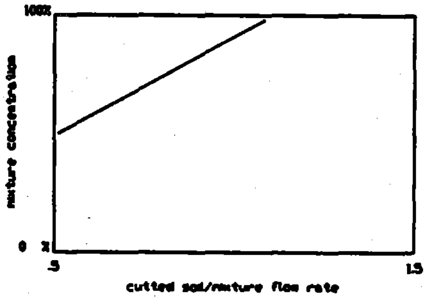

Fig.6 Mixture concentration as a function of the ratio between the cutted soil and the mixture flow rate

When this ratio is one a mixture concentration of about 90% is realised. To prevent spill the mixture flow rate should be about 10 to 20% larger than the cutted soil flow rate. The worst results are obtained with the recirculation head dredging in the bottom profiles 3 and 4.

Though the mixture concentrations are still better than 60%, which, compared with the current dredging methods is quite a good result for these soil profiles, most of the material spilled is suspended which is unacceptable when the material being dredged is polluted. For the environmental disk cutter the mixture concentration proved to be quite independent on the shape of the bottom profiles. Evidently the cutter pushes the cutted soil into the suction mouth thus displacing water, if present, out of the suction mouth.

CONCLUSIONS

The model tests proved the environmental disk cutter to be the most promising dredge head for selective dredging of thin layers of contaminated mud. Under laboratory conditions all criteria, with respect to spill and resuspension, with respect to accuracy and selectivity and with respect to mixture concentration could be met. Shielding of the cutter from the water, above the soil to be dredged, proved to be essential to limit resuspension of dredged mud. The mixture flow rate should be adapted to the cutted soil flow rate. The best results, in terms of resuspension and mixture concentration, are obtained when the mixture flow rate is some 10 to 20% larger than the cutted soil flow rate. Given these promising test results we decided to design and execute a prototype test programme to investigate to what extent these results could be realised in practice. The prototype tests will be performed in november 1990.

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EXPERIENCES IN SEPARATING OF POLLUTED DREDGED MATERIAL WITH HYDROCYCLONES

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ABSTRACT

In the port of Rotterdam, since 1984, tests have been carried out in which hydrocyclones are used to separate contaminated dredged material into coarse (less contaminated) and fine (more contaminated) fractions. The aim of separation is to reduce the volume which must be disposed of.

The results of the investigation into the separation of moderately contaminated sediment that is usually placed in land depots indicate a rise in the total cost. The fine, more contaminated sediment that has to be disposed of has poorer consolidation characteristics than the original dredged material. This means that the volume which must be disposed of, does not or hardly decrease as a result of the reduction of the dry matter content. Because of the large volume of material produced by maintenance dredging, mechanical dewatering is not an attractive proposition.

During recent remedial dredging projects which have been carried out in the Netherlands it has appeared that after using a single hydrocyclone phase to separate heavily contaminated sediment, the coarse fraction from the underflow was not sufficiently clean to be disposed of in a depot for moderately contaminated sediment.

Evaluation of the above mentioned investigations showed that in these cases use of a single hydrocyclone stage did not provide a satisfactory result.

Additional techniques, such as using hydrocyclones in series, flotation etc. are necessary in order to achieve the desired result.

INTRODUCTION

In the Netherlands it has been traditional to dispose of material produced by maintenance dredging at sea or in landfill sites. The inland disposal sites were on low lying areas behind the riverine dikes. In the nineteen-sixties people became aware that in many cases the silt was contaminated by heavy metals which appeared to be mainly bonded onto the fine mineral fractions of the fluvial sediments. Later it was found that the silt was also contaminated by organic micro-pollutants, so since 1985 only sediment from the river mouth and the harbours may be disposed of at sea. The remaining silt must be placed in depots which have been specially constructed for this purpose.

In the beginning of the nineteen-eighties there were almost no more land sites available for the moderately contaminated sediment. This material was therefore placed in a temporary depot on the Maasvlakte until the construction of a large disposal site extending into the sea was completed. The moderately contaminated sediment dredged over a period of fifteen years can be placed in this depot, "the Slufter". The use of the Slufter was partially determined on the basis of a consolidation model which was specifically developed for this site. The consolidation parameters were derived from a large number of consolidation tests in the geotechnical laboratory of the Public Works Department of Rotterdam. [Ref. 1]

During the construction phase of the Slufter the idea arose that this site would have a longer useful life if the contaminated fraction of the dredged material only was placed in it. On the basis of the idea that the contaminants are bonded onto the fine fraction, the government and the two industrial partners Esmil and Hydronamic commissioned the Research Institute for Applied Physics "T.N.O." to investigate the possibility of separating dredged material into a coarse relatively clean and a fine relatively contaminated fraction by using a hydrocyclone. Hydrocyclones are pre-eminently suited for the separation of large quantities of sediment into the desired sub-fractions

THE WORKING OF THE HYDROCYCLONE

Firstly, a short description of the working of the hydrocyclone, together with a short explanation of the parameters which influence the size of the particles at which separation takes place and the sharpness of classification.

The material to be separated, consisting of a mixture of water and sediment particles, is introduced tangentially into the upper part of the hydrocyclone [Fig. 1]. The mixture acquires a rotational downward movement so the particles which are in the liquid are driven to the wall by the centrifugal force. According to Stokes law, the heavier particles approach the wall more quickly. The particles which reach the wall before the mixture reaches the opening on the underside leave the hydrocyclone via the underflow. In the heart of the cyclone a vortex forms in which the flow is upwards. The water with the particles which have not reached the wall leaves the hydrocyclone via the overflow.

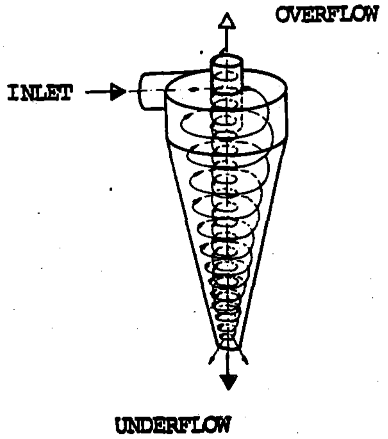

Fig. 1 Working of the hydrocyclone.

The most important process parameters are the dimensions of the hydrocyclone, the pressure difference over the cyclone and the concentration of the mixture that is fed into it. The result is a separation into a coarse fraction and a fine fraction. The choice of a particular hydrocyclone depends on the particle size at which separation is required. The dimensions of the various parts play an important part in determining the sharpness of the separation. The grain size distribution of the sediment introduced into the selected hydrocyclone determines the efficiency E_T. E_T is the relation between the dry matter that leaves the hydrocyclone via the underflow and the total amount of dry matter which was introduced.
The dimensions of the inlet-, the underflow-and the overflow opening and the height of the hydrocyclone are closely related to the diameter of the hydrocyclone. The capacity and the particle size at which separation takes place depend to a large extent on the diameter of the hydrocyclone. With a larger diameter, the inlet opening and the openings of the under-and the overflow are also larger so bigger through flow is possible. With a larger diameter the particle size at which separation takes place is also larger.
The sharpness of separation is determined by the relation between the diameters of the under-and the overflow, the height of the hydrocyclone and the solids concentration of the feed. By sharpness of separation in classification duties is understood the ability to separate one solid from another based on its dimensions.

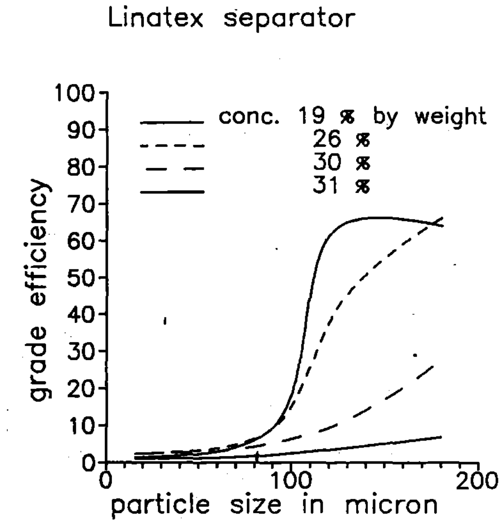

Fig. 2 Sharpness of separation at different solid concentrations.

Experiments with a Linatex separator demonstrated, that at solid concentrations over twenty percent by weight the sharpness detoriated. [Fig. 2]
Figure 3 shows an example of an ideal separator such as a sieve, for example, and a less satisfac- tory separator such as a hydrocy- clone. The x-axis shows the particle size, while the y-axis gives the separation efficiency per fraction. In this case the d_{50} is the fraction of which 50% leaves the hydrocyclone via the overflow and 50% via the underflow. The d_{50} in this case is at 60 micron. The thick vertical line through this point gives the separation efficiency per fraction for a sieve. None of the particles of a dimension smaller than the sieve openings remain behind with the coarse fraction.

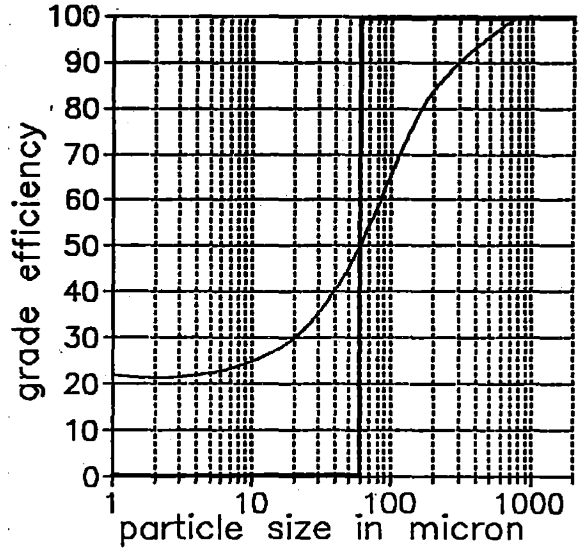

Fig. 3 Separation efficiency per fraction of a sieve and a hydrocyclone.

The value R_f in figure 3 gives the underflow-to-throughput ratio. With hydrocyclones an appreciable and relatively dilute underflow can occur. The total efficiency E_T includes the effect of flowsplitting.
Because of this the solids are devided in at least the same ratio as the underflow-to-throughput ratio and as a result an amount of fines goes through the underflow. The amount of fines through the underflow is called misplacement. Reduction of fines can be obtained by diluting the underflow and separate this with a second hydrocyclone stage.
Once the particle dimension at which separation must take place has been determined the correct hydrocyclone must be found. At this stage product information from various manufacturers and the possible associated expertise are very important.
Other hydrocyclone configurations are considered later.

SEPARATION OF MODERATELY CONTAMINATED SEDIMENT

The investigation into the size of a hydrocyclone installation which might possibly be constructed at the Slufter was carried out on pilot plant scale.
In addition to the investigation into the cleaning efficiency of the pilot plant research was also carried out into the consolidation properties of the material leaving the overflow of the installation.
The results of the consolidation investigation indicated, that owing to the poor consolidation properties of the fine fraction, using a hydrocyclone without further mechanical dewatering would not extend the useful life of the depot. Moreover the useable sand fraction was too small to make recycling viable. In addition to the cost of a hydrocyclone installation and the additional installation for dewatering the under-and overflow and its exploitation, the transport of the cleaner fraction to the sea would increase the cost quite considerably. For this type of dredged material the use of a hydrocyclone was not considered feasible.

SEPARATION OF HEAVILY CONTAMINATED SEDIMENT

In addition to moderately contaminated sediment there are also a number of locations where heavily contaminated sediment occurs. The placement of such material requires exceptional care in the construction of the depot. Furthermore it is almost impossible to find sites for storage depots for heavily contaminated sediments. If the contaminants occur in specific fractions, reduction in volume by means of separation may be useful.
One of the first remedial dredging projects in the Netherlands in which separation of the contaminated sediment was used was carried out in the Arkervaart (1986). When a new lock came into use the canal had to be deepened. The canal bed consisted of sand overlain by a layer of silt which was contaminated with PAC's. The layers which had to be excavated were dredged and then, with the aid of Linatex sand separators, divided into sand and silt fractions.
After mixing with a flocculant, the silt fraction was placed in a depot lined with sheeting. The effluent from the depot was returned to the suction head to dilute the dredged mixture.
The Linatex sand separator is a modified hydrocyclone. To ensure that the misplacement in the underflow is as little as possible, this is provided with a rubber valve; the opening of which is influenced by the weight of the mixture to be discharged. If there is not enough coarse material in the lower part of the cyclone, this valve remains closed so no water (contaminated with fine particles) escapes. At the side of the overflow is a siphon which is to some degree adjustable. With the aid of this, the particle size at which separation takes place can be influenced. For coarser separation the efficiency is lower; less material passes through the underflow and more through the overflow so there is a greater amount of fine conta- minated material leaving via the overflow. The quality of the material from the underflow, however, is generally better. On the one hand a product which is as clean as possible (thus coarse) is desired while, on the other hand as small as possible an amount of contaminated material. Responsible consideration of these two conflicting interests is essential.

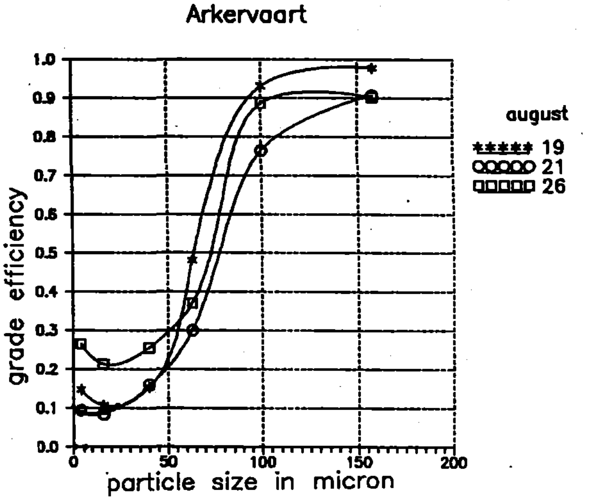

Fig. 4 Separation efficiency per fraction of the Linatex separator for the work in the Arkervaart.

Rijkswaterstaat D.B.W./RIZA [Ref. 2] made observations of the installation over a period of three days. In addition samples were taken from the inlet, the underflow and the overflow of the separator. The samples were used to determine the grain size distribution. Research was also done to determine the degree of contamination with heavy metals and organic micro pollutants of the three discharges.

From the grain size distribution of the inlet, the underflow and the overflow the total efficiency E_T and the separation efficiency for each fraction can be deter-mined.
From the y-axis in Figure 4 it can be observed that the flow rate of the underflow varies between 10 and 30 percent.
The PAC content that went through the underflow on these days amounted to 5, 19 en 41 percent. On the basis of these three observations the conclusion may be drawn that the increasing PAC content with an increasing rate of underflow discharge is caused by the fine particles that are carried in this underflow discharge. The sand satisfied the norms and was considered suitable for utilization.
The sand that was recovered comprised 70 % of the dry matter content of the total amount of dredged material.

In 1989 some remedial dredging projects in which the coarse and fine fractions were separated with the aid of hydrocyclones were carried out. The sand fraction was considerably smaller than in the case mentioned above. After separation it appeared that the sand did not satisfy the norms then valid for recycling and, owing to having too high a content of PAC's in two cases, it was not even suitable for placement in a depot for moderately contaminated dredged material.
There are a number of factors which may account for things going wrong. In contrast to the remedial dredging of the Arkervaart, the sand and silt fraction formed a homogenous mixture. The sediment involved had been deposited over a long period. During the sedimen-tation phase contaminants from local sources taken up into the silt layers were in contact with each other over a considerable period of time. The contaminants in the sand were indeed reduced after one hydrocyclone stage, it did not meet the standard set for placement at the disposal site for moderately contaminated silt. In this case it was advisable to find out how the contaminants came to be in the sand. If the contamination was the result of misplacement in the lower discharge, washing the material from the lower discharge once or twice with the same type of hydrocyclone would probably have been sufficient. In this context "washing" means the reduction in volume of an undesirable fraction of a sediment which has already been separated into subfractions. If the contamination had been the result of the occurrence of PAC's in a highly molecular form, separation at a coarser fraction level would probably have provided the solution. For the latter case separation of sand samples into sub fractions is necessary. If it appears that the contaminants occur in only one of the sub- fractions, a suitable separator must be found for this fraction.

In order to clarify what is meant by washing the under- and the overflow, for a random type of silt from the port of Rotterdam, the particle size ditributions of a hydrocyclone configuration given in figure 5 are calculated.
The results and illustrations in figure 5 were determined by using the mathematical model "Hydrocyc" of Rotterdam Public Works Department, that is based on the empiric relations found by Plitt [Ref. 3].
The input of the model comprises hydrocyclone parameters such as diameter and height of the hydrocyclone and the diameters of inlet, under- and overflow, solid concentration of the feed, pressure difference over the hydrocyclone and the grain size distribution of the sediment to be separated.
With the hydrocyclone parameters, the pressure difference and the solid concentration the

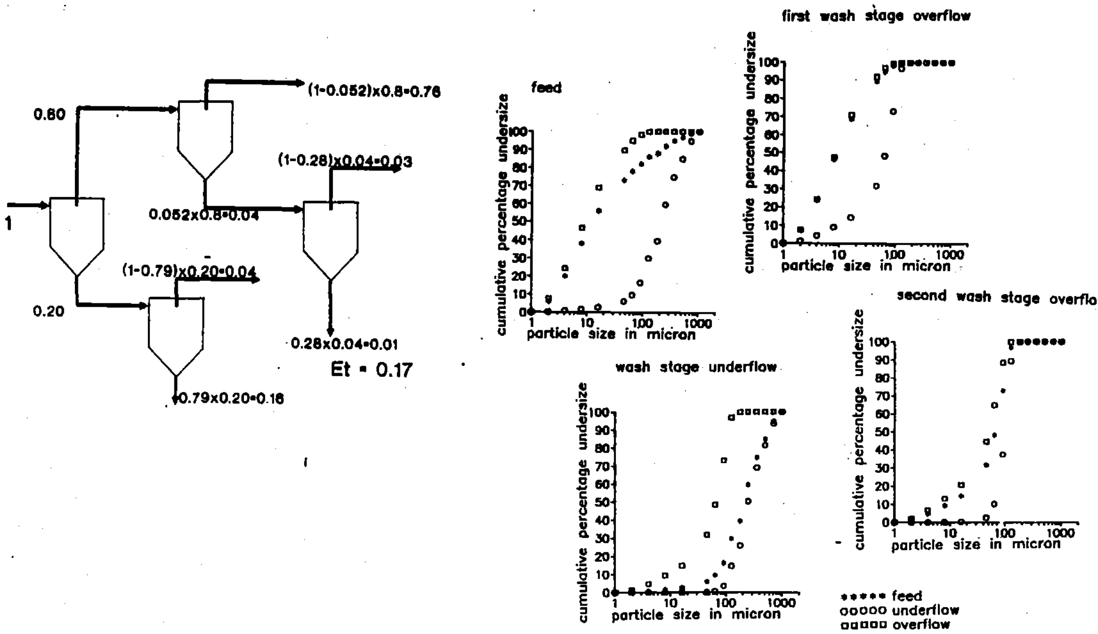

Fig. 5 Hydrocyclone combination with efficiency and grain size distribution

capacity, grade efficiency and underflow-to-throughput are calculated. With the grade efficiency and the grain size distribution of the feed the grain size distributions of the under- and overflow and the total efficiency can be calculated. The grain size distributions of under-and overflow can in the same computerprogram be used as input for a next hydrocyclone stage.

In figure 5 the hydrocyclone configuration and the grain size distributions of the several flows are given. The results of the calculation in the flowchart give the relative amount of dry matter in the flows in question.

As a result of this washing stage, which provides a cleaner product, the efficiency is reduced from 20 to 16 percent.

In some cases the overflow is also given an extra wash in order to recover the coarser particles which have been carried through the overflow of the first stage. In Figure 5 the effect on the increase in the efficiency of the total installation when the overflow of the first stage is washed twice is also shown. This will give only one percent more reduction in the total amount of contaminated sediment to be disposed of. In the above example the total reduction amounts to 17 percent. In case of such a low efficiency, separation with the object reduction of the volume which must be disposed of, is inremunerative. The costs and the exploitation of such in installation are considerably higher than the cost of dredging and transport. The removal of the coarser fraction also has an adverse effect on the consolidation properties.

Figure 6 shows the particle size distribution and the PAC-contamination as a function of the particle size for a sample from the Geulhaven in Rotterdam. From this it appears that most of the contaminants are in the fraction smaller than 20 μ ann some in the fraction greater than 110 μ. The part between 20 and 110 μ is relatively clean.

In order to adequately remove this part from the total sediment a hydrocyclone configuration such as is shown in Figure 7 can be used. In figure 8 the separation results of the various stages are given. The cleanest fraction is ca. 30 % of the total amount of sediment. Assuming that the contaminants occurrence in the finest and coarser fractions differ, then this will mean that for further treatment of these two fractions different supplementary separation or cleaning techniques must be used.

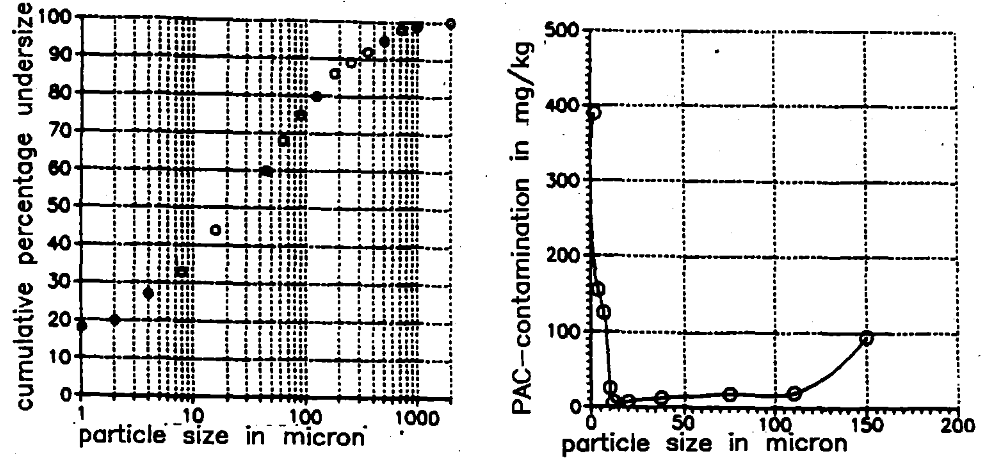

Fig. 6 Particle size distribution and PAC contamination plotted against the particle size of a sample from the Geulhaven.

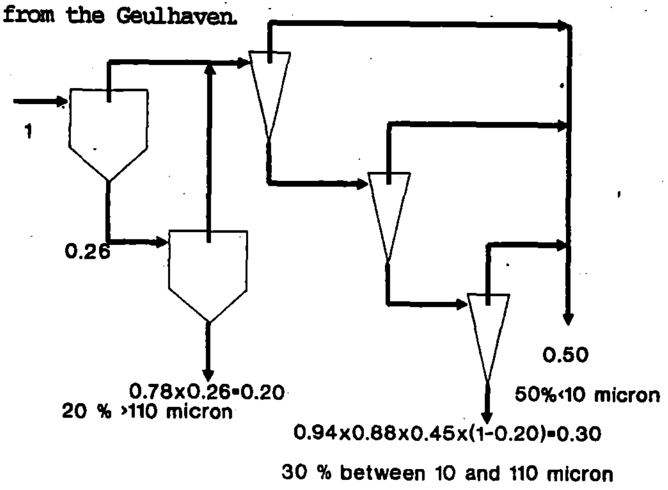

Fig. 7 Hydrocyclone arrangement for the separation of a Geulhaven sample

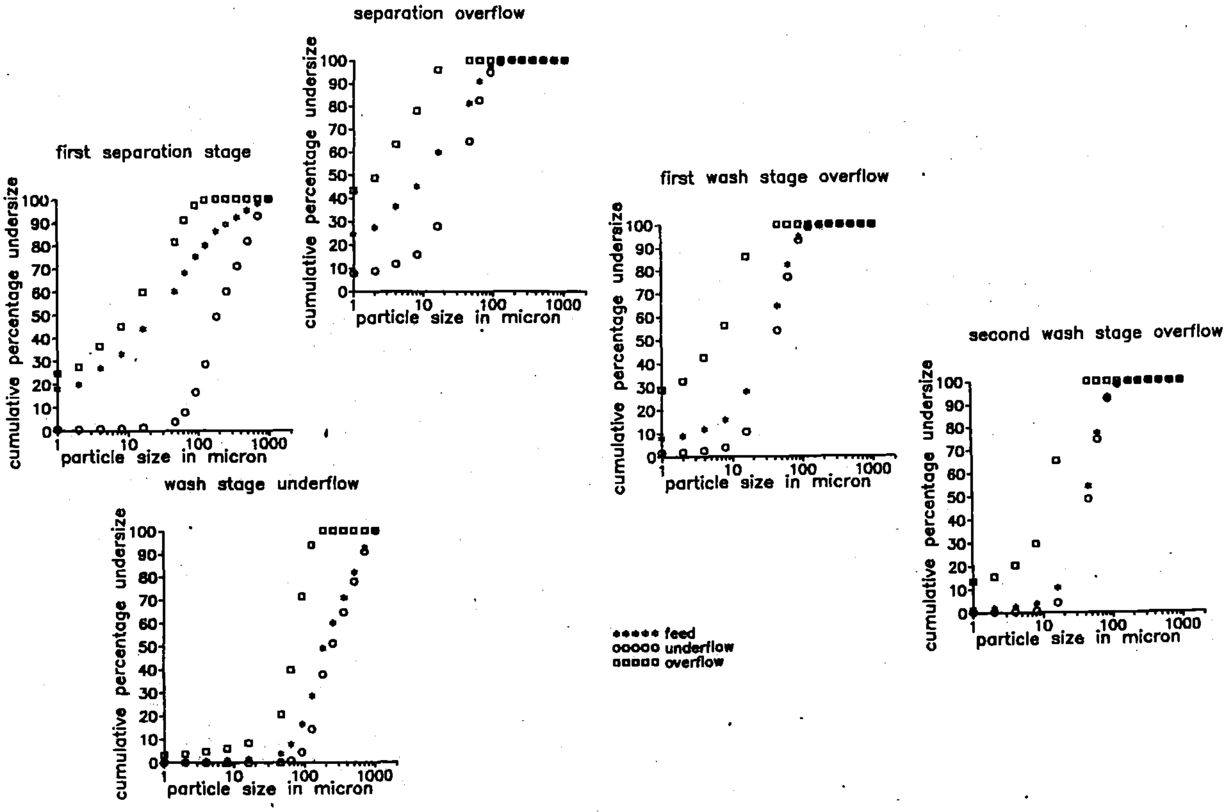

Fig. 8 Separation results for the combination shown in Fig. 7

DISCUSSION

Experience gained in recent years has shown that the use of a single stage hydrocyclone is usually not adequate to create sediment fractions which satisfy the required norms.
The message of this paper is to clear that the preparation for the cleaning of an aquatic sediment belongs to a totally other order than that which has been customary to date.
Before starting remedial dredging it is necessary to know in what form and in what fraction the contaminants occur. At a remedial dredging site the particle size composition can change greatly owing to the hydraulic conditions. The contaminants at a site can also vary. On the basis of the particle size distribution of the location in question and the mode of occurrence of the contaminants it is necessary to find out whether separation is worth while. If the separation efficiency is acceptable, a method of separation must then be investigated.
Usually the coarsest fraction (for example larger than 4 m is sieved off). Next a hydrocyclone configuration must be determined. This is done with the aid of a laboratory test rig. A preliminary estimate can also be made with the mathe- matical model. mentioned earlier.
Only when it is known in which fractions the contaminants occur and whether selective treatment is possible, can a good insight be gained into the efficiency of a separation operation.

On the bass of the previously mentioned possible differences, it is obvious that a separation instal-lation must be sufficiently flexible to create the desired fractions. It must be possible to create various hydrocyclone configurations with the installation. The success of a good design stands or falls on the expertise of the personnel using it. For this part of the remedial dredging more attention must be paid to recruiting staff with training in process technology rather than dredging.
Because the use of hydrocyclones usually goes together with the admixture of considerable quantities of water, good dewatering methods for the upper discharge are very important to be able to obtain a real reduction in the volume of the fraction which is to be placed in the depot.
To prevent that large quantities of polluted water from the process will be drained off into the surface water, it is necessary to recirculate the process water as much as possible. Superfluous process water must be drained off by way of a clarifier.
In addition to separation, it is probable that the contaminants may be removed from a specific fraction by other means; a number of methods used in the mining industry may be considered. One of these techniques, froth flotation is already used successfully in cleaning soil on land sites.

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DEWATERING AND WASHING OF INDUSTRIAL AND MUNICIPAL WASTE SLURRIES WITH AUTOMATIC PRESSURE FILTERS

P. RANTALA, Larox Oy, Lappeenranta, SF

ABSTRACT

When talking about industrial effluents, the main problem always is how to separate liquid from solid matter. Usually, the liquid is returned to the process and the solid matter in a confined area, the volume of the solid being only a fraction of the effluent. The solid matter may also be forwarded to a hazardous waste disposal plant for further treatment. Sometimes the poisonous substances are washed off the solid matter, after which the poisons are returned to the process.
Pressure filtration technology creates new possibilities for the treatment of industrial and municipal sludges. Due to improved solid/liquid separation handling of filter cakes is easy ! An extra bonus is efficient cake wash which means that harmful substances do not get into the environment.

THE LAROX AUTOMATIC PRESSURE FILTER TEHCNIQUE TODAY

GENERAL

The Finnish company, Larox Oy, has manufactured and delivered a number of automatic pressure filters since 1976. The first automatic pressure filter Larox PF was supplied for concentrate dewatering in 1979 and the first automatic chamber filter Larox CF in 1982.

Increasingly, the pressure filter technique is adopted by users. Pressure filters can replace existing vacuum filters and drying drums because of lower operating costs. Centrifuges and bandfilters are also used in many cases, where the residual moisture of cake or cake washing efficiency or fully automatic operation are not the main points. In cases, where these three points are important, a noteworthy alternative is the automatic pressure filter.

AUTOMATIC PRESSURE FILTER TECHNIQUE

The pressure filter technique involves filtration under pressure. In the Larox technique the maximum of 16 bar is used.

Pressure filters have been used for thousands of years, but only came into general use after the first energy crises and when the fully automatic pressure filter technique was developed.

What does it mean to dewater using a fully automatic pressure filter ?

It means that all operations of the filter are automatic as well as the movement of the filter cloth. Both CF and PF filters have constantly moving filter cloths.

The automatic pressure filter Larox PF and automatic chamber filter CF are batch operated filters. The operating principle is as follows:

- closing of the filter
- filtration
- cake pressing
- options: cake washing and cake pressing II
- air blowing
- opening of the filter
- cake discharge

In total one cycle takes 7 - 20 minutes depending on the characteristics of the suspension and the required cake moisture.

INDUSTRIAL AND MUNICIPAL WASTE SLUDGES

In the separation of mechanical liquids and solids there are the following four different methods or combination of these methods to be used:

- gravity
- vacuum
- centrifugal force
- pressure

In all these methods the question is: What is the pressure difference on both sides of the filtermedia ? If the material is still uncompressed, the cake can be theoretically pressed as long as the own molecular construction of the solids gets broken.
The liquid remained between solids can be removed only by air blow, vacuum or by thermal drying.

The situation is still more critical, if some liquid has to be washed away from the cake.

CAKE WASHING

In many chemical or industrial waste water processes, achieving efficient separation is very important to

- remove soluble impurities from solids or
- obtain maximum recovery of dissolved material contained in the liquid phase.

Total removal of liquid from filter cake can be done by drying but dissolved solids in the liquid phase remain in the dried product.
The best way to achieve good separation is by cake washing whereby the liquor retained in the filter cake is displaced by another liquid.

There are two ways of doing cake washing in solid/liquid separation:

A. Displacement washing of the cake on the filter.
B. Washing by repulping the cake and refiltering.

In practice several washing stages are usually employed and to save wash liquor counter-current washing is often used.

Figures 1 to 5 depict typical washing flow sheets.

Figure 1) Combination of displacement washing on filter and counter-current repulping washing using three stages of vacuum drum filters.
Figure 2) Counter-current displacement washing on a horizontal belt vacuum filter.
Figure 3) Multiple repulping system using three stages of rotary vacuum drum filters.
Figure 4) Co-current washing on a horizontal belt vacuum filter.
Figure 5) Counter-current decantation washing using thickeners and a rotary vacuum filter.

All these washing systems are widely used in various processes. Control of washing is reasonably easy and fairly good washing efficiency is obtained.

However, wash liquor consumption is often very high, resulting in too much dilution of filtrate.

WASHING IN LAROX PRESSURE FILTERS

The essential feature for maximum washing efficiency is that replacement of the liquor retained in the filter cake by wash liquor must be as complete as possible.

Cake washing can be carried out efficiently in a pressure filter, where the whole process happens in a closed chamber. A pressure filter is especially suitable for cake washing, when the chamber is in horizontal position. The automatic pressure filter is a good example of this kind of a filter.

The initial filtration stage is followed by diaphragm pressing at up to 16 bars pressure. This ensures that

1. The cake has a very low residual moisture content and
2. There is an empty space between the rubber diaphragm and the cake surface.

(See figure 6)

This empty space can be filled with wash liquor which is then forced through the cake by diaphragm pressing. Because the diaphragm presses uniformly across the full cake surface the liquor contained in the cake is uniformly displaced.

The "WASH RATIO (N)" is defined as the volume of wash liquor divided by the volume of liquor in the filter cake.

Figure 7 shows the theoretical maximum washing efficiency for a washing ratio N = 1.

It can be seen that the Larox Pressure Filter comes very close to achieving the highest theoretical washing efficiency, because diaphragm pressing gives almost complete dicplacement of entrained liquor in cake.

In spite of this, depending on cake porosity there will always be some mixing of entrained liquor and wash liquor, but washing efficiency can be further increased by a second wash.

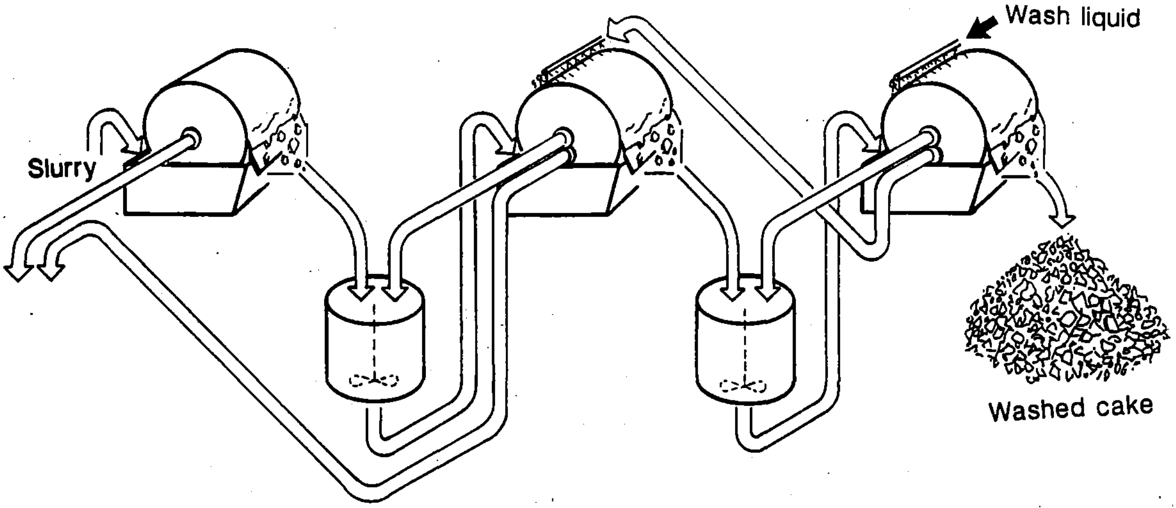


Fig. 1
Combination of displacement and counter-current repulping washing

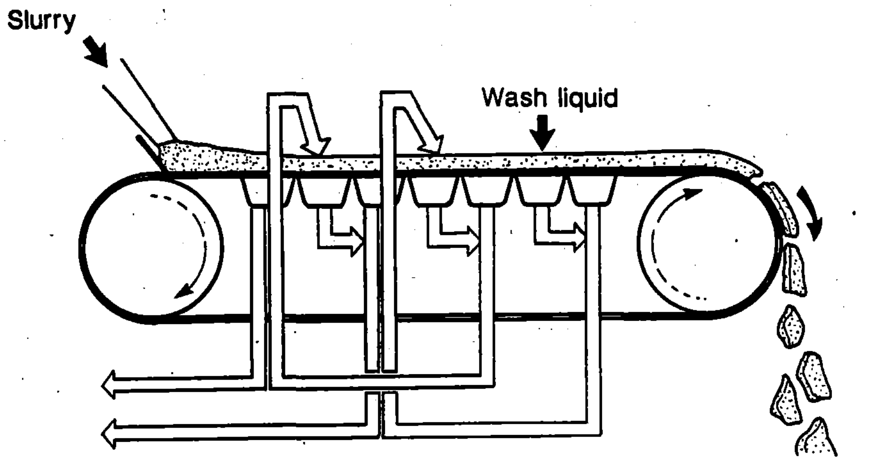


Fig. 2
Counter-current displacement washing

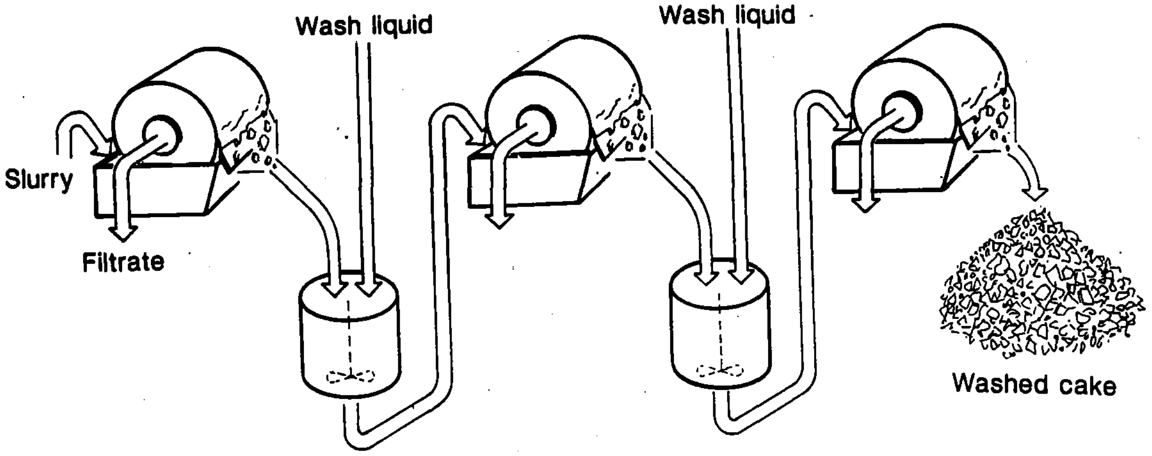


Fig. 3
Multiple repulping system

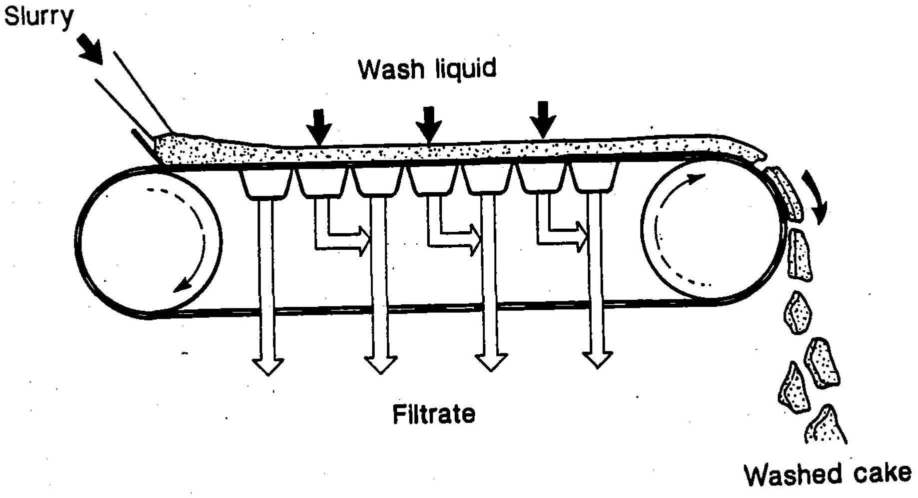


Fig. 4
Co-current washing on a horizontal belt vacuum filter

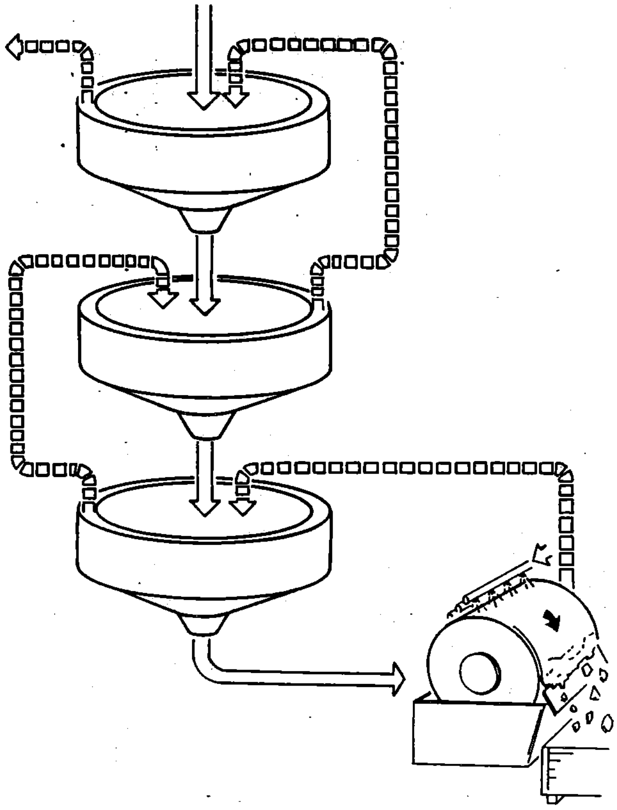


Fig. 5
Counter-current decantation washing using thickeners and a rotary vacuum filter

WASHING PRINCIPLE IN LAROX FILTER

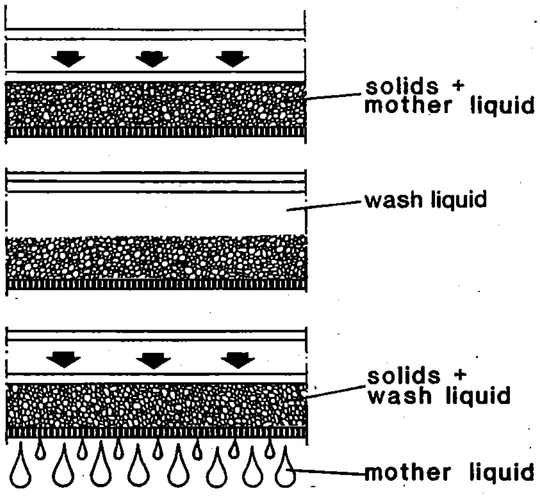


Fig. 6

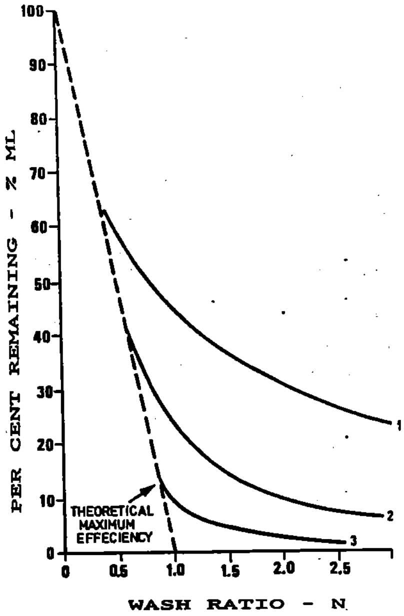


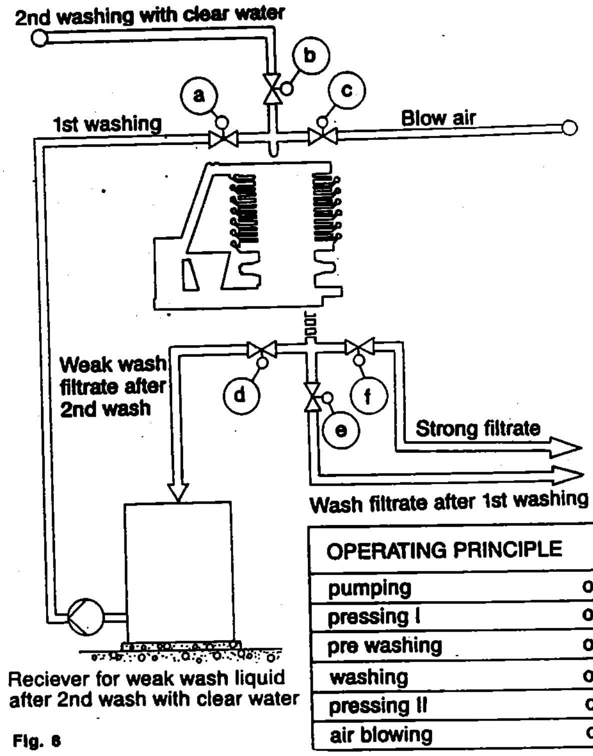
Fig. 7

1 DILUTION IN SEDIMENTATION TANKS

2 COUNTER CURRENT IN VACUUM FILTRATION

3 MECHANICAL DISPLACEMENT IN LAROX PRESSURE FILTRATION

LAROX PF COUNTER – CURRENT WASHING



OPERATING PRINCIPLE	
pumping	open f
pressing I	open f
pre washing	open a and e
washing	open b and d
pressing II	open d
air blowing	open d

Fig. 8

In theory a horizontal Pressure Filter achieves 50 - 60 % better washing efficiency than a vacuum filter.

EXAMPLES OF INDUSTRIAL AND MUNICIPAL WASTE SLUDGES

Industrial waste sludges can be divided into three different groups:

a) Waste sludges which can be easily stored (e.g. gypsum)

b) Special storage areas (soluble heavy metals)

c) Wastes which have to be taken to a hazardous waste disposal plant.

The first group includes materials which can easily be filtered such as gypsum compounds e.g. different kinds of combustion gas washing processes. Normally the separation of liquids and solids is carried out by using band filters.

The second group consists of different wastes from metallurgical and chemical processes. They are mainly in sulphide or hydroxide form. Very often heavy metals are problematic, because they must not be let into ground-water. The aim is to produce a dry, compact waste cake.

The third group is the most problematic one. The aim of the process is to get the waste sludge in such form that it can either be stored or only a small fraction of the cake needs to be taken to a hazardous waste disposal plant.
A good example of this kind of project is the hazardous phenol waste from Neste Chemicals Hamina. The sludge needs an efficient inorganic flocculation as well as efficient cake washing. The soluble phenol can be washed only by using displacement washing method in a pressure filter.
By using this method the phenol content decreases under 0.05 % from the output level of 5 % when wash water ratio of 1.5 is used.

A more precise description of the above can be found in the Larox Application Guide "Waste Treatment".

MUNICIPAL WASTE SLUDGES

THE TREATMENT OF MUNICIPAL WASTE SLUDGES IN THE LAROX AUTOMATIC PRESSURE FILTER

Approx. 100 g/inhabitant/day of treatment sludge is produced in a normal industrialized state. The treatment plants in Finland produce about 1 million m3/year or 150.000 T (D.S.) of sludge. (In Norway 60.000 T/year and in Germany 3.5 million T/year).

In Finland two thirds of this sludge is treated as raw sludge and one third as digested sludge.

During September and October 1990 Mr Reiner Weidner (as part of his diploma work) conducted a series of 300 tests on raw sludge in Lappeenranta at the sewage disposal works of Toikansuo and on digested sludge in Helsinki at the sewage disposal works of Kyläsaari.

The aim of the tests was to find out how the fully automatic pressure filter is suited for the dewatering of the above sludges in the way that the slurries are inorganically conditioned or conditioned by using organic polymers.

The raw sludge in Lappeenranta consisted of chemical or biological sludges. The dry solids content of the sludge varied between 2 - 5 %.

The following characteristics are typical of this sludge:

1. Without using any filter aids:

- filtration of biological sludge without any aids is impossible -> no cake will form
- filtration of chemical sludge without any aids is possible, but this results in high cake moisture and low capacity
- filtration of the mixture of biological and chemical sludge from the treatment plant without using any aids is also possible -> no cake will form

2. With using anorganic filter aids:

- if only $Ca(OH)_2$ is used, without any other material, the results will be much worse than with using Fe^{3+} salts together with $Ca(OH)_2$
- the best filter aids will be together with $FeCl_3$, by an amount of about 30 % $Ca(OH)_2$ and 5 % $FeCl_3$ calculated to the amount of dry solid in the sludge
- if less than 25 % $Ca(OH)_2$ and 3 % $FeCl_3$ is used, the results will rapidly worsen
- using $Fe_2(SO_4)_3$, instead of $FeCl_3$ shows that the filtration is still possible, but not with the same results as with using $FeCl_3$

- using $FeCl_2$ instead of $FeCl_3$ gives almost the same results as the use of $Fe_2(SO_4)_3$
- using FINNFERRI ($FeClSO_4$) instead of $FeCl_3$ gives nearly the same results as when using $FeCl_3$. A very high amount of Finnferri is needed, because it contains only 12 - 13 % of Fe^{3+}.
- it is impossible to filter only biological sludge with $Ca(OH)_2$ and $FeCl_3$ -> no cake will form
- it is possible to filter only chemical sludge with $Ca(OH)_2$ and $FeCl_3$.
- the best results will be obtained, if you filter a mixture of one volume part of biological sludge and four volume parts of chemical sludge
- good results will be also obtained if the mixture slurry from the treatment plant is used (even you do not know the amount of biological and chemical sludge)
- if the chamber volume is reduced to 2/3 of the original one, in order to obtain a thicker cake, you can get more dry solid in cake by about the same capacity with a chamber volume of 4.5 litres
- usually the cake is very easy to remove from the filter cloth
- data:
  - moisture in cake: 55 - 80 %
  - capacity 7.5 - 5.0 kg/m2h D.S.

3. With using polymeric filter aids

- an amount of at least 200 g of flocculant per cubic meter of sludge is needed to obtain good flocks
- if you stirr very slowly and pump very gently, you can handle the sludge easily and you get only a little amount of dry solid in the very first filtrate
- there is no big difference between using Zetag 53, Zetag 57 or Zetag 63 (Alloid Colloids)
- the reduction of the chamber volume effectsin the way that the dry solid in cake will rise, but at the same time the capacity decreases
- data:
  - moisture in cake 71 - 86 %
  - capacity 14.0 - 4.0 kg/m2h D.S.

In Helsinki the dry solids content of digested sludge varied between 2 - 3.5 %.

The following charasteristics are typical of the sludge in question:

1. Without using any filter aids:

- filtration of digested sludge is possible, but no real cake is obtained

2. With using organic filter aids:

- you can reproduce the results of Lappeenranta treatment plant. This means that you need an amount of at least 25 % $Ca(OH)_2$ and 5 % $FeCl_3$ to obtain good results
- if $Fe_2(SO_4)_3$ or FINNFERRI is used, the filtration is possible, but you cannot reach the same dry solid amount in cake or even not the same capacity, as when using $FeCl_3$
- the cake is usually very easy to remove from the filter cloth.
- data:
  - moisture in cake: 55 - 70 %
  - capacity: 4.8 - 3.0 kg/m2h D.S.

3. With using polymeric filter aids:

- an amount of at least 200 g of flocculants per cubic meter of sludge is needed in order to obtain good results
- the flocculant Zetag 63 seems to be the best, because it makes the best flocks which are very stable
- the cake is usually easy to remove from the filter cloth
- data:
  - moisture in cake 72 - 85 %
  - capacity 12 - 5.0 kg/m2h D.S.

SUMMARY

In the future the automatic pressure filter is excellently suited to the filtration of both raw and digested sludges as far as the conditioning of polymers will be developed correct and the formation of flocculation can be properly controlled. In this way the dry solids of the cake is 30 - 35 % and the capacity 10 - 14 kg/m2h and all this happens fully automatically including the cake discharge without operating personnel.

SLUDGE DRYING WITH WASTE HEAT UNDER ECOLOGICAL CONDITIONS

W.R.A. GOOSSENS, Seghers Engineering, Willebroek, B

ABSTRACT

Intensive dewatering of dredged mud up to 95 % dry solid content is possible by applying a multi stage tray dryer after preliminary mechanical dewatering. The indirect contact
dryer known as Seghodryer is heated with low temperature energy (waste heat) and odour release is reduced to zero by condensation of the sludge vapours and thermal destruction of the few persisting aromates. The dry product consists of pathogen - free granules the size of which is controlled by operating this multi stage tray dryer in combination with a dedicated mixer at the sludge feed point.
In this way, the granules obtained are free flowing and thus suitable for further in-line processing or for disposal.

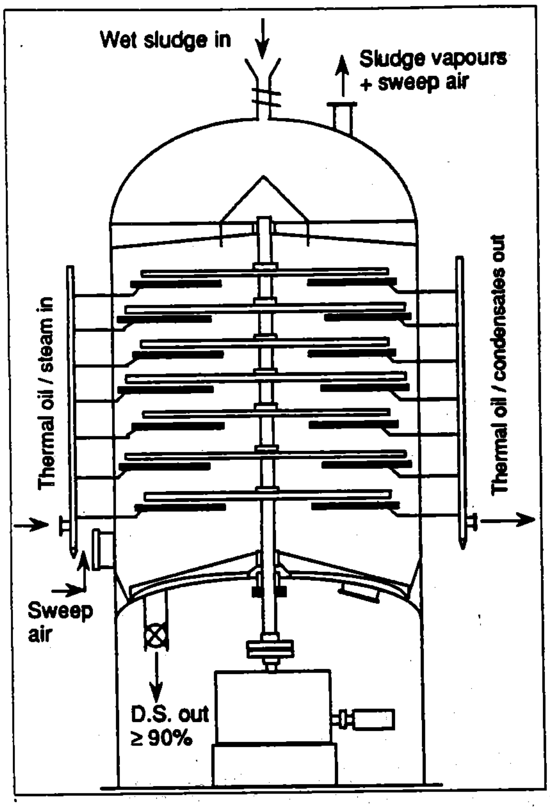
The excellent performance of this Seghodryer has been demonstrated during six years at the scale of 415 kg dry substance per hour for sludge from a municipal waste water, treatment plant equivalent to a through put of 20.75 m^3 per hour of fine-grained dredged material at 2 % DS.

1. INTRODUCTION

Storage and landfilling of dredged mud becomes questionnable as soon as the contamination with hazardeous substances reaches critical levels. Immobilisation or destruction of the contaminants in question is thus required. In both cases, the large fraction of water present in the sludge has to be removed to a high extent under economical and ecological conditions. Mechanical technics are available to dewater the sludge to a certain degree, in general up to about 30 % dry solid content. More intensive dewatering is only possible by thermal treatment called drying. To this purpose, a multi stage tray dryer has been developed with waste heat as energy source. Its trade name is Seghodryer.

2. CHARACTERISTICS OF THE MULTI STAGE TRAY DRYER

As shown in Fig. 1 the multi-stage tray dryer Seghodryer is an indirect contact sludge dryer-pelletizer which largely reduces the initial sludge volume and produces spherical sterilized sludge pellets particles in a one-step operation. The pathogen-free pellets particles, containing less than 10 % moisture and less than 1 % fines are suitable for further in-line treatment or for disposal.



The SEGHODRYER is a vertical, multi-stage tray dryer, requiring minimal floor space. The modular design allows the evaporating capacity to vary from 1000 to 3600 liter of water per hour and per unit, depending on the number of trays and on the cross section of the dryer.

The trays are heated either with steam or with thermal oil in a closed loop at a temperature of about 200°C giving the way to use waste heat. A central shaft with raking arms ensures even distribution of the sludge over the trays and displaces the sludge from one tray to the other. The raking arms of the SEGHODRYER are equipped with specifically designed ploughs turning the sludge on each tray in such a way that free flowing dry granules are obtained.

This indirect drying process is optimised by putting a dedicated mixer on top of the dryer. In this mixer, the recycled part of the dry granules are coated with the incoming wet sludge. In this way, the indirect multi-stage tray dryer handles granules with a dry kernel and a wet boundary resulting in an excellent heat transmission coefficient. Moreover, this propriety combination allows to avoid any operation problem encountered in other drying systems due to glue phase phenonema.

The gentle and low-friction raking motion results furthermore in a low torque and hence in a low specific power consumption, in comparison to conventional sludge drying systems.

3. DESCRIPTION OF THE DRYING PROCESS

Fig. 2 gives the flow-sheet of the various streams around the multi-stage dryer.

In this flow sheet, thermal oil at a temperature of 200°C is providing the heat needed to evaporate the water of the sludge. The thermal oil itself is heated in a oil boiler or in a waste heat recovery system. As alternative, also low pressure steam can be used.

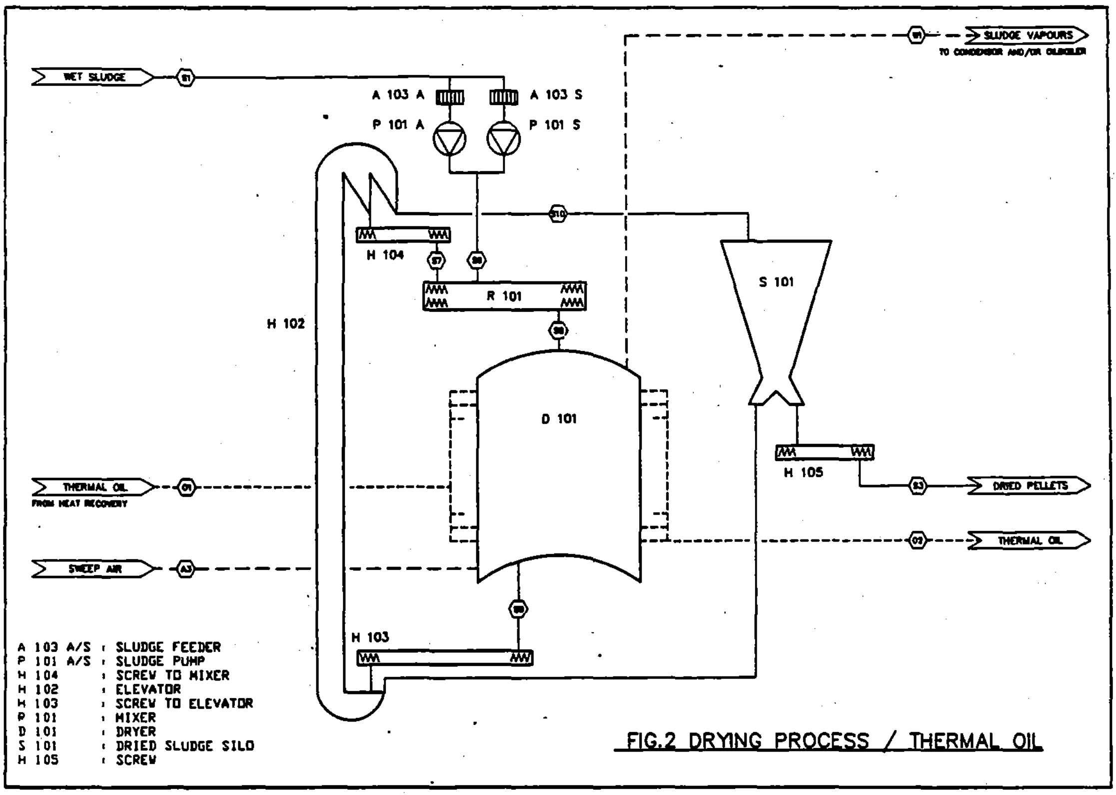


FIG.2 DRYING PROCESS / THERMAL OIL

The mechanically dewatered sludge is pumped by a volumetric sludge pump to the mixer. The two sets of mixing paddles in this mixer are constructed in such a way that the incoming wet sludge is coating the recirculated dry granules. The coated granules have an overall dry solids content between 60 and 70 % giving the possibility to avoid glueing problems encountered during the operation of other types of sludge dryers. They are centrally fed on top of the vertical multistage tray dryer. The ploughs of the dryer scrape them in a rolling movement over the different heated trays in turn outwards and inwards. The dried granules collected at the bottom of the dryer are screwed into a chain conveyor or bucket elevator to be partly recirculated by the mixer and partly transported to the dry product storage silo.

The drying process is indirect by using sandwich type trays consisting of two sheets with thermal oil (or steam) flowing in between. The granules with a dry kernel and a wet outside layer roll over the heated tray by the action of the scraping ploughs causing simultaneously an efficient renewal of the granules in contact with the upper sheet of the tray. This renewing pattern combined with the specific composition of the granules guarantees a very high drying efficiency.

4. STAGE OF DEVELOPMENT

Theoretical considerations on the heat and mass transfer of this drying process are only partially available (1). Therefore, SEGHERSengineering had set up in the past a long term development programm in order to gain practical experience giving the design values of this efficient drying pelletizing process.

At present, a demonstration unit has been operated more than 6 years at a full-scale through-put of 435 kg dry substance per hour. This unit is integrated in a full-scale wastewater treatment plant where the sludge is mechanically dewatered to 25 % dry substance. The Seghodryer unit thus treats 1750 kg of incoming wet sludge at 25 % DS and dries it to a dry solids content of more than 90 % by evaporating 1200 kg of water per hour.

The reliable and virtually maintenance-free operation of this demonstration unit has proven the high quality of the construction of the Seghodryer. The operation data has given the information for a careful design of units in the range of 1000 tot 3600 kg water evaporation per hour. Consequently, when appropriate mechanically dewatering is preceeding the dryer, the largest unit of Seghodryer-Pelletizer can handle an equivalent of 68 m^3 per hour of fine-grained dredged mud at 2 % DS (or 27 $m^3.h^{-1}$ at 5 % DS). This unit gives as product about 1,350 kg per hour of free flowing granules.
The resulting weight reduction is roughly a factor 50 and the resulting volume reduction is roughly a factor 25.

These free flowing dry granules are excellent feed stocks for firing processes to manufacture gravel substitutes under ecological safe conditions with a minimal energy consumption.

5. CONCLUSION

A dryer-pelletizer is technically available to dry sludge material up to 95 % dry substance under ecological conditions. The dried sludge is a free flowing product ready for disposal or for further on-line treatment such as firing into gravel substitute with a minimal energy consumption.

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SLUDGE SEPARATION AND DEWATERING PLANTS

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Technische Maatschappij Bergmann bv and her sister company sistercompany Linatex (Nederland) bv have designed and supplied complete installations to separate and dewater contaminated dredged sludges.

On the poster, reference-installations will be shown with mentioning of the separation and dewatering capacities.

A general flowsheet gives an impression of technologies used to compose an operating installation that can process high capacities of dredged sludge.

From this flowsheet the following crucial components will be highlighted.

The Linatex separator, a modified hydrocyclone, to separate sludge into a clean sand fraction (particle size > 60 micron) and a sludge fraction with concentrated contaminants (particle size < 60 micron).

The Linatex dense medium separator, to remove coal and wood from the underflow of the Linatex separator. Separation at s.g. of 1.6 - 1.8.

The Bergmann gravity thickener, a specially designed pre-dewatering tank to increase the dry solids content of the sludge and so reduce the amount of sludge to be dewatered.

The Andritz belt press to dewater sludges to 40 - 65% d.s. Dewatering capacities and results are related to the amount of organic material in the sludge.

Depending on the characteristics of the sludge and the contaminants, other equipment can be incorporated in the proposed solution, such as: hydrocyclones with a cutpoint down to 10 microns and secondary dewatering machines.

RECENT ADVANCES IN SLUDGE PROCESSING - CENTRIFUGES

F.A. RECORDS, Alfa-Laval Sharples Limited, GB

SUMMARY

This paper briefly describes the main types of centrifuges and describes in more detail the continuous discharge decanting centrifuge, the main centrifuge used in sludge processing.

Some of the theories of the decanting centrifuge are discussed. These include clarification, compaction, dewatering, conveying, power consumption and their effect on scale-up. Some useful techniques in performance assessment and data correlation are described. Specific data is provided.

A brief description of the range of Alfa-Laval decanting centrifuges, installed worldwide, and their performance levels achievable on the various applications are given.

This paper concludes with a discussion of the various instruments, controllers and control programme for partial and full automatic control of centrifuge sludge processing plants.

CONTENTS

1. INTRODUCTION

The continuous decanting centrifuge has been used for a wide range of industrial applications for more than 40 years. it is for only about 20 years that it has found wide use in the treatment of effluent sludges. It has been the introduction and development of polyelectrolyte flocculants which has enabled consideration to their use. Initially only a few models of about 350 mm in diameter were in use whereas today there are many thousands installed world-wide from just 150 mm diameter to over 1250 mm diameter, and there are well over 100 types and sizes from which to choose.

During the 20 years, the decanter has undergone considerable development as have the techniques used to optimise it. These developments have enabled, for instance, digested municipal sewage cake to be discharged at over 30 % and even as high as 45 % solids instead of the mere 18 % achieved 5 years ago. On some secondary sludge thickening applications the need for flocculant has been eliminated.

Instruments and controls have been developed to fully automate centrifuge plants, to maximise performance and minimise costs. The need for operator attention is now minimal and many plants now operate for long periods of time without anyone in attendance. The development of the decanter centrifuge for sludge processing is ongoing at Alfa-Laval Sharples.

2. Classification of centrifuges

There are two main types of centrifuge, those that separate solids from a liquid by filtration and those that utilise a sedimentation type which can perform a liquid/liquid separation function and also a 3 phase separation, liquid/liquid solid.

Each of the two main types can be subdivided into machines which discharge continuously, batchwise or semi-continuously (see diagram 1). Within these subdivisions will be different types according to the methods of discharge. The size, shape and axis of orientation of the bowl will vary as will the g-level employed.

A. Filtration

1. Batch discharge

These machines are generally large diameter, up to 1300 mm and more, vertical axis and relatively long process cycle time. At the beginning of the cycle the bowl is accelerated to feed speed, a fraction of the full speed when process is admitted over a timed period and mother liquor filters through settled cake and through a cloth mounted on the perforated wall of the bowl. The bowl is accelerated to speed, when mother liquor is drained, rinse applied if necessary, and the cake spun dry. The g-level used is about 1000. After spin dry the bowl is decelerated and the cake discharged. The cake discharge is by removable filter bag after the bowl is stopped or by a hydraulic knife while the bowl is rotating at 50-100 rpm. The latter type in Sharples jargon is known as a Tornadomatic.

2. Semi-batch discharge

This machine, known as the 'peeler' centrifuge, or Sharples Super-D-Hydrator is horizontal axis working at a little over 1000 g. It is similar to the operation of the Tornadomatic except that feeding, rinsing and discharge are all conducted at full speed. Cycle times are generally much shorter, sometimes under 1 minute, and hence it is considered semi-batch or semi-continuous.

3. Continuous discharge

Sharples supply two machines that can be fitted in this category. There is the pusher (CD) centrifuge which is a horizontal axis machine with a cylindrical bar screen and a conical rear screen which reciprocates axially pushing the cake that falls from the conical screen onto the bar screen over the end of the bar screen. The pulse rate of the pushing can be up to say 90/minute thus making a virtual continuous solids discharge. The g-levels will be below 1000.

The second machine, the Sharples SuperScreen, is a vertical axis conical perforated bowl in which is fitted an Archimedean screw type scroll for conveying the solids. A small differential between the scroll and the bowl is effected by a gearbox at the end of the bowl. The g-levels of these machines are up to 1800 g. These machines can also be mounted horizontally.

B. Sedimentation

1. Batch discharge

This machine, known at Sharples as the Super Centrifuge, is a tubular bowl vertical axis centrifuge running with 62.000 g for the laboratory sizes. This machine has been in use for over 50 years on a wide range of applications from vegetable oil refining to oil/water separation. Solids are removed from the bowl after stopping and dismantling the machine and are thus used in solids liquid separation as polishers.

2. Semi-batch

These types of machine are not commonly sold currently, having been superseded by developments of the decanter. They are similar in size and design to the 'Tornadomatic' but have an imperforate bowl where clarified liquid decants over a lip ring at the top of the bowl. When the bowl is full of compacted solids, a skimmer pipe is introduced which forces the cake of toothpaste - salad cream consistency up the tube for discharge at the full speed of the bowl. On some designs the bowl will be slowed to introduce a knife to cut out hte hard heel.

3. Continuous

This is the subject of this paper, the continuous scroll discharge decanting centrifuge. This is known in Sharples as the Super-D-Canter or in Alfa-Laval as the NX range of centrifuges. The high pressure high temperature machines for chemical applications will be vertical axis. Effluent machines have a horizontal axis. This is described more fully in the next section.

3. The effluent decanter centrifuge

The Sharples effluent decanting centrifuge has its rotating assembly mounted horizontally between two main bearings supported in pillow blocks mounted on a bedplate. The bowl, the main part of the rotating assembly, is enclosed in a casing from which the clarified liquor, the centrate discharges at one end and the dewatered solids, the cake, discharges at the other. Affixed to one end of the bowl, outside the main casing and outboard of one of the main bearings is a two stage epicyclic gearbox which effects the differential between the bowl and an internal conveyorin the form of an Archimedean screw. At the other end of the bowl is mounted the drive pulley through which ispositioned the feed tube admitting the feed along the centre line into a feed chamber in the hub of the conveyor.

At one end of the cylindrical bowl is a conical or tapered section, the beach, up which the cake is scrolled out of the pond, the liquor trapped in the bowl. At the opposite end to the beach adjustable weirs or dams are fitted into the bowl over which the clarified liquor or centrate discharges. Adjusting the dams alters the depth of the pond. In this design the separated phase flow counter-currently. There are co-current designs. Some designs are fitted with cyclo gearboxes instead of epicyclic.

With high-g and effluents good wear protection is of critical importance. Wear protection is applied to the solids discharge area of the bowl, at the feed inlet, and on the conveyor flight tips. on the more abrasive applications with Sharples, our patented tungsten carbide tiles are used.

The g-level used on decanters for effluent are generally in the 1000-2000 g range. Sharples use 2000 g as standard and where necessary increase this to 3000. On non-effluent applications decanters at 5000 g have been used while 10.000 g is now on offer.

Some of the important parameters of the decanter, which affect process performance, include - the bowl spped, pond depth, bowl length and diameter, beach angle, conveyor pitch, number of conveyor leads and conveyor differential. On top of this, how the feed is admitted, where the flocculant is admitted, flocculant concentration type and rates all affect the result.

One of the critical parameters is the conveyor differential and in modern decanters this parameter can now be adjusted and controlled while the machine is in operation. The differential is controlled by a brake, which is generally directly coupled to the pinion, can be adjusted remotely. Numerically, differential is the difference between bowl and pinion speed, divided by the gearbox ratio.

Some Alfa-Laval decanters have a very large aspect ratio, bowl length to diameter ratio and on these machines the gearbox is further supported on the outboard side with a bearing assembly. The main bearing assemblies are uniquely spring loaded.

See diagram 2 for the main features of the decanter.

4. Decanter theories

The performance limitation of the decanter (see diagram ") will generally dictate the scaling formulae used to determine the necessary size of another machine. It will be useful, therefore, to study some of these scaling formulae and associated theories. The derivation of these formulae is given in more detail in the 'overheads' used in the presentation which are reproduced in diagrams 4-10.

A. Clarity Limitation

The main limitation to decanter capacity has for a long time been centrate clarity. This scale up has generally used the theory known as the sigma theory: viz

$$Q = \Sigma V_s \longrightarrow 1$$

$$\text{where } \Sigma = \frac{2\omega^2 L}{g}\left(\tfrac{3}{4}r_2^2+\tfrac{1}{4}r_1^2\right) \longrightarrow 2$$

$$= \frac{2\omega^2 L r_2^2}{g} \longrightarrow 3$$

Q	is the feed rate to the centrifuge
V_s	is the Stokes terminal settling velocity of the smallest particle to be separated.
Σ	is the sigma value of the centrifuge, purely a function of physical parameters of the centrifuge, g-level times bowl diameter times clarification length.
ω	is the angular velocity of the bowl
r_2	is internal radius of the bowl
r_1	is the radius of the pond surface
L	is the clarification length of the bowl, the axial distance from feed inlet to centrate discharge.
g	is the acceleration due to gravity

When comparing the capacities of Q1 and Q2 of machines 1 and 2 respectively, then the ration of these capacities will be the ration of the respective sigma values of each machine.

$$\frac{Q_2}{Q_1} = \frac{\Sigma_2}{\Sigma_1} \longrightarrow 4$$

B. Hindered Settling

The sigma theory assumes discrete particles settling unhindered. With many effluent systems, particularly municipal, hindered settling ultimately occurs and for the driest cake some solids compaction must occur, which is the final stage of hindered settling. The degree of settlement and thus compaction and cake dryness falls off exponentially. The derivation of the formula for hindered settling is similar to that for sigma and the hindered settling sigma is given by equation 5 below.

$$\Sigma_H \,\alpha\, \frac{\omega^2}{g} L r_2^3 \longrightarrow 5$$

Note in this case has units of volume whereas has units of area. Again

$$\frac{Q_2}{Q_1} = \frac{\Sigma_{H2}}{\Sigma_{H1}} \longrightarrow 6$$

C. Scrolling Capacity

The maximum scrolling capacity (S max) will be proportional to the volume between the conveyor hub (diameter D C) and the smallest diameter of the bowl, which will be the diameter at the beach discharge (D B). It will also be proportional to conveyor pitch (P) and differential (N). Thus

$$S_{max} \propto PN\ (D_B^{\,2}-D_C^{\,2}) \longrightarrow 7$$

D. Scrolling Torque

On most standard applications virtually all measurable torque occurs on the beach, and the conveyor torque level (T) over and above the heel torque (T o) is a function of the solids rate (M), differential (N), the bowl diameter (D), the centrifuge relative g force (G c) and the wet (A) and dry (A D) beach areas. This is given by equation 8 below.

$$(T-T_o)\ \propto\ \frac{Mg_c}{ND}.\Psi(A\omega,A_D) \longrightarrow 8$$

The function (A ,A) is genrally an empirical function, taking into account the extra friction on the dry beach compared with the wet. the factors can vary from process to process.

As previously stated

$$N = \frac{S-S_p}{GBR} \longrightarrow 9$$

where S is bowl speed
S_p is pinion speed
and GBR is gearbox ratio

also

$$T = T_p \times GBR \longrightarrow 10$$

where T_p is pinion torque

Heel torque is experienced throughout the length of the bowl and is proportional to the g force at the wall times the diameter of the bowl times the total scrolling surface area within the bowl (A T).

$$T_o \propto A_T\ g\ D \longrightarrow 11$$

E. Cake Dryness

The calculations for cake dryness limited applications can be quite complex. They will depend upon the mechanism of dewatering, whether it is by filtration, decantation or compaction. To reproduce the cake dryness achieved on a decanter centrifuge many factors could be involved, such as the total residence time within the bowl, residence time on the dry beach, g-force and solids throughput. In the absence of the reliable scale-up information, one will set parameters such as to ensure the same residence times in the appropriate parts of the bowl, maintain the same cake thickness when solids capacity (M) will be given by equation 12 below.

$$M \propto PND \longrightarrow 12$$

Thus scaling from machine 1 to 2

$$\frac{M_2}{M_1} = \frac{P_2}{P_1}\ \frac{N_2}{N_1}\ \frac{D_2}{D_1} \longrightarrow 13$$

In effluent treatment with a 'dry solids' machine, dryness will be proportional to scrolling torque and thus scaling from one size of machine to another one will endeavour to have the same torque per unit volume.

F. Power Consumption

The power absorbed by the main motor of a decanter centrifuge comprises three components of power; the power to overcome windage and friction, the power to accelerate the process (flowrate M) to the discharge diameter (D D) and the power required to produce the scrolling torque.

While the windage and friction power may be calculated with difficulty this will be obtained from practical data obtained by the centrifuge manufacturer. Process power (P P) is given by equation 14 below.

$$P_P = 6.837 \times 10^{-16} S^2 {D_D}^2 M \quad \text{kw} \longrightarrow 14$$

and similarly scrolling power P_S by equation 15

$$P_S = 1.045 \times 10^{-4} S x T_p \quad \text{kw} \longrightarrow 15$$

If in equation 15 one substitutes (S-S) for S one obtains the actual power necessary to scroll the solids. If instead one substitutes S for S one obtains the power absorbed by the brake. With some types of brake a fraction of this latter power can be regenerated, although not all regenerative brakes will generate power as 'clean' as is desirable.

5. Useful techniques

The size distribution of solids of most natural slurries conform to a logarithmic probability distribution (see diagram 11). Despite the mathematical complexity of such a distribution it is readily manipulable (more so than a linear probability) and so is useful in the correlation of centrifuge data. A cumulative distribution may be plotted to give a straight line on log-probability graph paper, where the y axis is logarithmic (of the size) and the x axis is an inverse error function (erf$^{-1}\left(\frac{P-50}{50}\right)$)

where P is the percentage undersize. Referring to diagram 12 it will be seen that it is a simple step to show that plotting centrifuge throughput against percentage capture of solids on logarithmic probability graph paper will also produce a straight line with most natural process materials. Dividing the y axis flowrate by the constant sigma for the centrifuge produces an operating line for all centrifuges of similar geometry.

Understanding the mechanism of scrolling (see diagram 13) is an important consideration in decanter technology. It enables better optimisation of some of the special features within this type of machine such as the hard surfacing on the conveyor flights and bowl, parameters which are fixed at the design stage such as beach angle and flight pitch, and also parameters adjustable within the field such as conveyor differential and pond depth. The mechanism is shown with the use of a vector diagram. It will be seen that if scroll friction is too high or the beach angle is too large or perhaps if the beach friction is too low then the direction of travel of the solids will be greater than 90° to the bowl axis. In other words there will be no positive transport of solids. One can also appreciate that due to the buoyancy effect, problems can occur as solids emerge from the pond. When this does happen, particularly with some effluents, then by special design (the Alfa-Laval Sharples patented BD feature), scrolling can be aided by using the hydraulic head of the liquor in the bowl, fixing this above the solids discharge level. The BD feature is a plate, disc or cone which dips into the pond somewhere in the bowl to the rear of the feed zone and under which the solids have to be conveyed. The solids form a dam or plug under the BD to prevent washout of the liquor from the deep centrate side of the BD to the shallower solids discharge. In the thickening of secondary sludges, one commonly uses the BD feature, and the art of optimising performance is in controlling differential to maintain the plug of solids under the BD, without plugging the bowl itself.

Basically in BD operation one has to ensure that the rate of solids scrolling is equal to the input rate of solids. To a certain extent the system is inherently self compensating. If scrolling is inadequate, cake dryness increases and centrate clarity decreases and vice versa and the control, manual or automatic, will adjust to compensate. Often in BD systems a good correlation is obtained if solids recovery and cake solids are plotted against the ration of solids scrolling rate to solids feed rate, sometimes known as the BD factor . The thicker the cake the more sticky it becomes and the more difficult it is to scroll and therefore empirically scrolling rate S is given by

$$S_O \alpha \frac{N}{X_S} \qquad \longrightarrow 16$$

where X_S is the cake solids content.

The solids input rate is S_I where

$$S_I = Q.X_F \qquad \longrightarrow 17$$

where X_F is the feed solids content and Q is the feed rate
Thus

$$\Psi = \frac{S_O}{S_I} = \frac{N}{Q.X_F.X_S} \qquad \longrightarrow 18$$

Thus plotting recovery and dryness against various operating lines will be obtained for different polymer dosages and different pond depths. See diagram 14.

6. Polymer and the decanter

Flocculation is a subject on its own and as a seperate paper is being presented, this will only be discussed briefly.

For the decanter there are quite a number of parameters to be fixed. Polymer type, polymer concentration, polymer rate and admission point all can and often do affect ultimate performance.

Within the decanter, the process material can be subjected to considerable shear stresses. it is therefore important to choose a polymer resistant to shearn, often a high molecular weight and high ionic charge although not always. The admission point is chosen to allow time for flocculation to occur and complete immediately after admission to the centrifuge to minimise chances of shear after flocculation.

Theoretically the best flocculation is achieved with the most dilute polymer; often 0.1% to 0.2% is chosen. However, if dilution makes the polymeer flow an appreciable fraction of the total feed rate then this can reduce the capacity of the machine. Moreover, when feeding polymer in line, the thicker the polymer the further upstream the polymer can be added. The thicker polymers are able to counteract the adverse shear forces within the centrifuge. On a large number of larger installations polymer concentration has been increased to over 0.5% and even 0.7%.

On municipal sewage generally cationic polymers are chosen. Those sludges which contain inorganic materials such as waterworks sludges will usually use an anionic polymer. Cationic polymers are generally fast acting and are therefore invariably admitted within the centrifuge while anionic polymers are more slow and sometimes are added upstream. With the latest techniques of producing extra dry solids, a new type of polymer is used; instead of single long chain molecules it has partially cross linked polymer chains. This polymer often itself enhances cake dryness several percentage points, sometimes as much as 5%.

7. Applications

Standard decanters in the Alfa-Laval Sharples range are being used for the dewatering of most primary and mixed primary and secondary municipal sludges; e.g. digested, raw, mixed, cosettled primary plus secondary, whole aerated, oxidation ditch, heat treated and water works sludges. Polymers are invariably used. Sometimes these decanters are also used for the dewatering of secondary sludges.

Industrial sludges are also processed on standard decanters although special applications can require special designs. Common industrial applications are paper mill and de-inking processes.

A modification of the standard design enables efficient thickening of secondary sludges such as secondary activated, humus and biological sludges. On many of these sludges which have a low settled volume index (SVI) little or no polymer is required.

A range of decanters has recently been developed which allow enhanced dewatering where, particularly on digested and more drier than from a standard decanter. The use of this design is being expanded to other processes such as waterworks sludges.

Dual purpose decanters can also be supplied which can be used for both standard dewatering and thickening.

TABLE 1

No.	Machine	Location	Sludge Type	Sludge Processability	Feed Concn. % w/w	Throughput M^3/hr.	Cake Solids % w/w	Recovery %	Polymer Addition Kg/ton d.b.
1	AVNX7040	UK	Digested	Normal	2	70	7	95	2.5 - 3
2	AVNX7040	UK	Digested	Difficult	3	70	10	96	3.5
3	AVNX7040	UK	Digested	Difficult	3	50	20	97	6
4	DSNX7040	UK	Digested	Difficult	3	20	29	98	12
5	XMNX7040	UK	WAS	Easy	1	70	4	89	0
6	XMNX7040	UK	WAS	Easy	1	50	5	93	0
7	AVNX4230	Holland	Digested	Normal	5	20	20	95+	4.5
8	DS506	Holland	Digested	Normal	4.4	20	33	>>99	6.5
9	AVNX6050	UK	Deep Shaft	-	1.1	50	5	94	3.5
10	AVNX7040	UK	Deep Shaft	-	1.3	70	5	94	3.3
11	AVNX4250	UK	De-inking	Normal	1.3	25	46	95	1.0
12	AVNX4050	UK	Primary	Normal	4-5	10	24	95	3
13	DSNX4230	Holland	Ferric Waterworks	Normal	4.2	5	29	99.7	8
14	DFNX9040	USA	WAS	Normal	0.8	70	5.5	80	0
15	XMNX9040	USA	WAS	Normal	0.9	180	7	80+	0
16	DSNX4230	UK	Primary Digested	Easy	5-8	10	40	>98	6
17	DSNX4230	Belgium	Cosettled	Difficult	3.6	5	29	>99	10

TABLE 1 Contd.

No.	Machine	Location	Sludge Type	Processability	Feed Concn. % w/w	Throughput M^3/hr.	Cake Solids % w/w	Recovery %	Polymer Addition Kg/ton d.b.
18	DFNX4230	UK	Humus	-	3	5	23	99	9.5
19	DFNX4230	UK	Humus	-	3	10	20.5	99	7
20	XMNX4230	Holland	WAS	Easy	0.8	10	18	99.9	0
21	XMNX5060	UK	WAS	Normal	0.5	60	5+	95	3
22	AVNX4230	UK	Ferric Waterworks	Normal	2.2	12	16	98	5
23	AVNX4230	UK	Ferric Waterworks	Normal	3	12	22	99+	1.9
24	AVNX4230	UK	Alum Waterworks	Normal	1.8	20	13	99	12
25	AVNX4230	UK	Alum Waterworks	Normal	2	20-30	18	99	8-12
26	DFNX4045	UK	WAS	Normal	0.3	8-12	6-8	90	0
27	XM4055	UK	WAS	Normal	3	5	6	96	0

8. Alfa-Laval Decanter Range

Since the amalgamation of the Sharples Company into the Alfa-Laval company the two ranges of decanters, for waste streams, have been incorporated into a common range with a unified nomenclature.

There are four product lines on offer. The standard range, designated the AVNX machines, contain the best features from the original designs. For thickening the XMNX design is used, which will incorporate the patented BD feature and will normally be fitted with a steeper beach than the AVNX machines. The DSNX line is specially designed for dry solids production utilising the full torque capability of the gearbox and fine process control. The fourth line the DFNX machines are the dual purpose machines which can be used for both thickening and dewatering.

In terms of sizes a machine of 150 and 250 mm diameter is available. Several machines approximately 350 mm diameter are available of various lengths. A number of machines in the diameter sizes 420-480 mm are used. For the larger capacities decanters of approximately 640, 740, 1000 and even 1270 mm diameter are available and have been supplied. Not all sizes are in the four product lines. For fuller details refer to the sales literature in the handout.

9. Decanter process Data

As has been said earlier many thousands of Sharples and Alfa-Laval centrifuges have been sold and are operating world-wide on a wide range of effluents. it would be unhelpful to generalise on performance as performance level not only depends on the type of sludge but also the quality of the sludge. A well run sewage works without any industrial effluent will generally produce exemplary performance while a poorly run works overloaded with difficult industrial effluents can cause low capacities and high polymer demands.

Nevertheless some data will be given from production plants and machines on test to give some idea of typical performance levels but they should be viewed in the light of the foregoing. This data is shown in table 1 at the end of this section.

Some graphs are included herein to show the effect of some of the variables and to demonstrate some of the techniques discussed. All this data comes from operational plant or full-scale test installations.

Graphs 1-4 show data from an AVNX7040 installation thickening digested sludge from 2% to 7% solids. These graphs show the effect on centrate clarity of feed rate, polymer dosage, a small change in pond depth and polymer type and concentration.

Graphs 5-6 show data from another AVNX7040 thickening and dewatering digested sludge. These graphs clearly show the good correlation with BD factor ( ) and its effect on solids recovery and cake dryness.

Graphs 7 and 8 also show the use of the BD factor with data from an XMNX 4230 thickening WAS. Graphs 9 and 10 show data from the same plant and demonstrate the good use to which the logarithmic probability function can be put allowing a linear regression analvsis.

On graph 11 is shown some data from a DSNX 7040 plant dewatering a difficult digested sewage. It will be seen that in choosing the right parameters nearly 30% solids in cake is achieved whereas an AVNX 7040 produced less than 20% cake on the same sludge.

10. Decanter Instrumentation and Control

Obligatory instruments and control are limited on decanter installations but more efficient and reliable operation is obtained from fully instrumented and controlled plants except the simplest.

On the larger and faster centrifuges forced oil lubrication is employed and therefore on these it is necessary to monitor oil flows, pressure and temperatures incorporating appropriate safety alarms. In modern times and modern countries where the need for the safety of personnel is recognised vibration alarms and interlocks are obligatory to shut down the machine should out-of-balance above recognised limits occur. In a well run plant the flow rate of the feed and the polymer will be monitored and controlled, probably by eddy current or ultrasonic flow meters and mono type positive displacement pumps. The polymer make-up will be by one of the many proprietary automatic make-up systems.

On all but the easiest sludge the centrifuge will be fitted with a back drive system enabling alternation of the conveyor differential. This can be a fixed speed system or a variable speed system, either hydraulic, inverter drive, variable speed induction motor or an eddy current brake. The last mentioned system is the one mostly used on Sharples plants. Thus bowl speed and pinion speed or differential speed indicators will be seen, as will brake or conveyor torque. Small purpose-built controllers developed by Sharples now control conveyor differential. These are able to control very accurately to a constant pinion speed, differential speed, brake current, conveying torque or by modulating differential control to a fixed external signal such as a dryness meter.
Similar controllers have been developed by Sharples for controlling pump speeds and the centrifuge bowl speed itself. A data unit has been developed for marshalling and archiving 16 channels of data which can be used for record purposes or for some form of supervisory control.

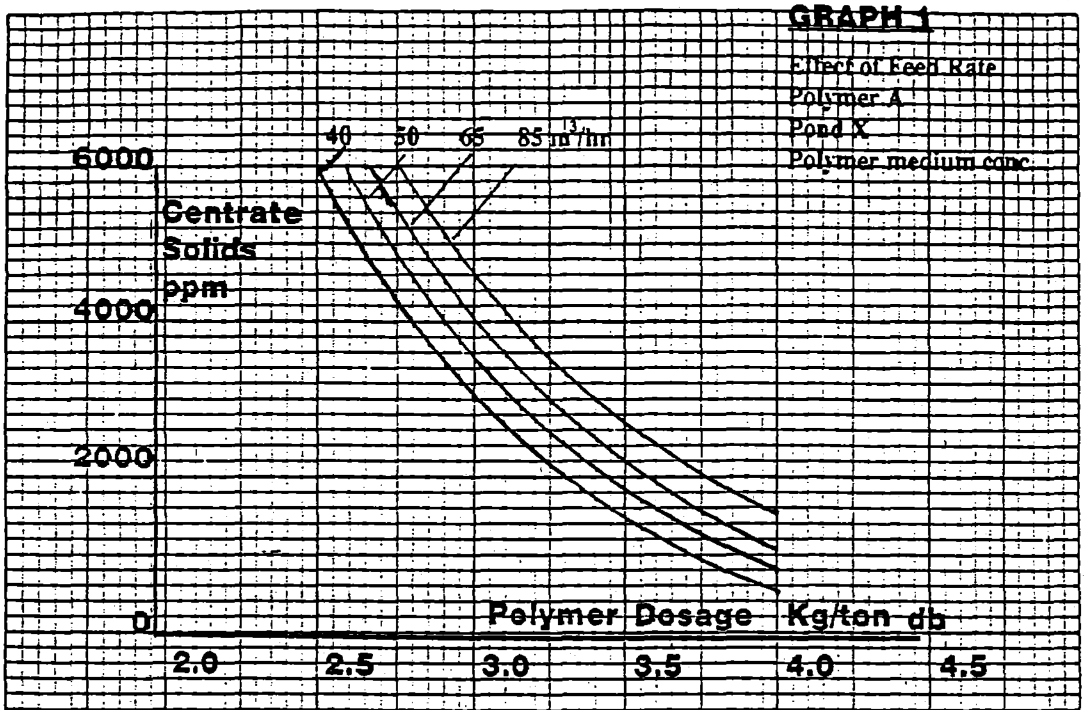
The automatic control of centrate quality has also been the subject of Sharples' attention. Proprietary turbidity meters have been used to monitor centrate quality and through a PID controller modulate flocculant addition rate. Decanters processing most effluents particularly municipal sludges will, with polymer, cause some foaming of centrates. On all proprietary turbidity meters tested this foam is read as solids. This has necessitated a centrate sample having to be deaerated before passing through the meter. Moreover with many centrates dissolved salts tend to precipitate out on the meter lenses. To overcome this the sample has had to be metered together with a metered diluent. While such a system has been developed and used it tends to be equipment intensive and thus expensive if it is to have minimal attention and efficiency. In consequence Sharples has developed its own centrate quality indicator and controller which needs no metering, no diluent and no deaeration. This is subject to a patent application.

All the Sharples' controllers mentioned can be coupled to recorders; they can be communicated with over the telephone system via an IBM compatible computer. In fact we at Camberley communicate with a plant 35 miles from our office every week down-loading the week's data from each of the controllers mentioned for the previous week. In one instance a controller in America has been programmed from the U.K. by telephone.

All the controllers are compatible and capable of being incorporated in a supervisory control system. Several hundred of these controllers have been installed throughout the world in the past 3 years, from China to Africa and from Europe to America.
Diagrams 15-20 are copies of the overheads displayed during the controls part of the talk.

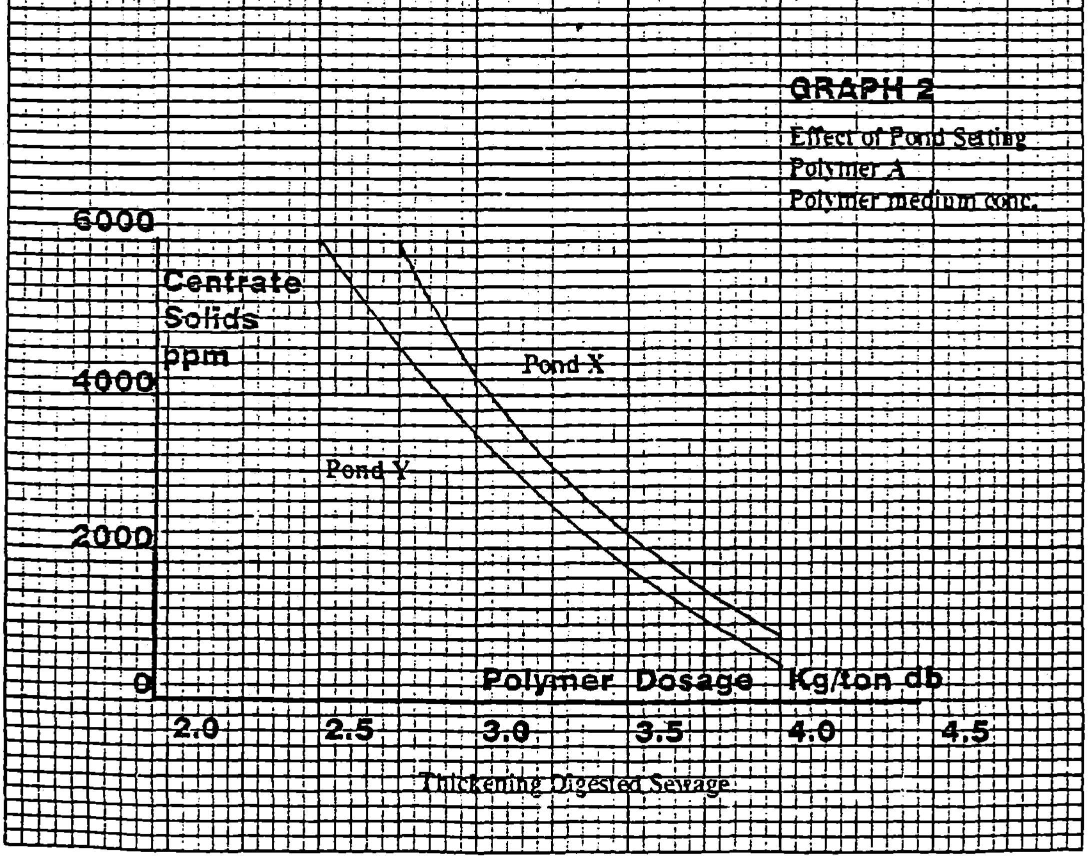
An example of data transmitted over the telephone line and graphed by computer at Camberley is shown in diagram 20.

ALFA-LAVAL SHARPLES



GRAPH 1

Effect of Feed Rate
Polymer A
Pond X
Polymer medium conc.



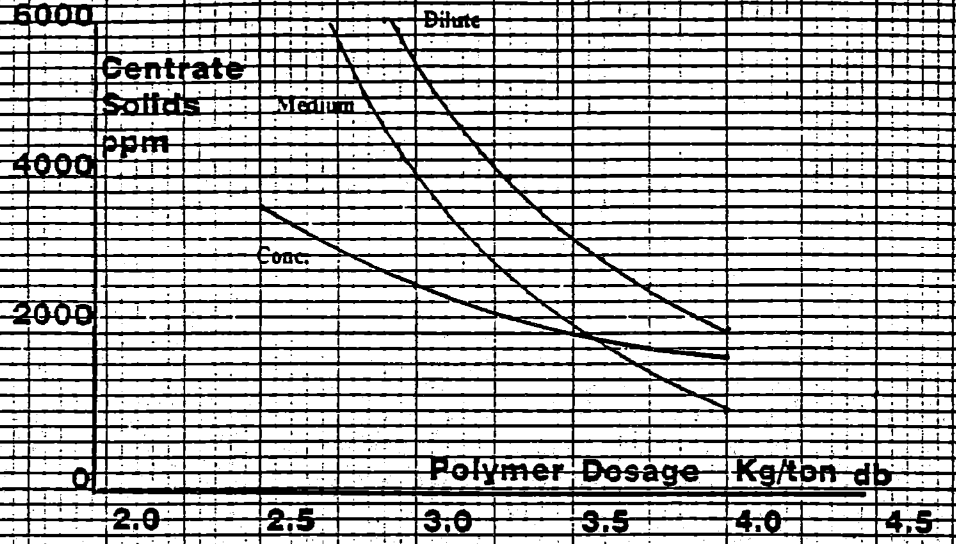
GRAPH 2

Effect of Pond Setting
Polymer A
Polymer medium conc.

Thickening Digested Sewage

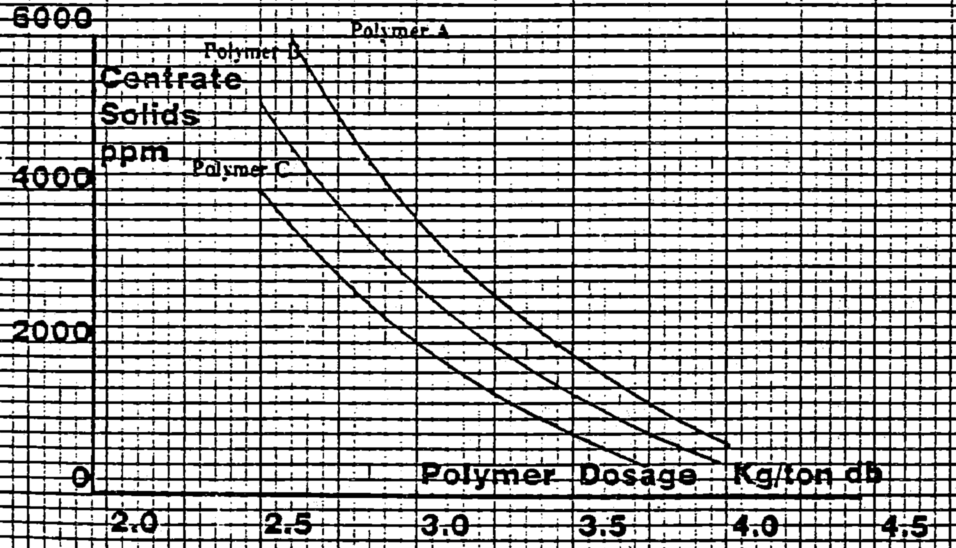
GRAPH 3

Effect of Polymer Conc
Pond X
Polymer A



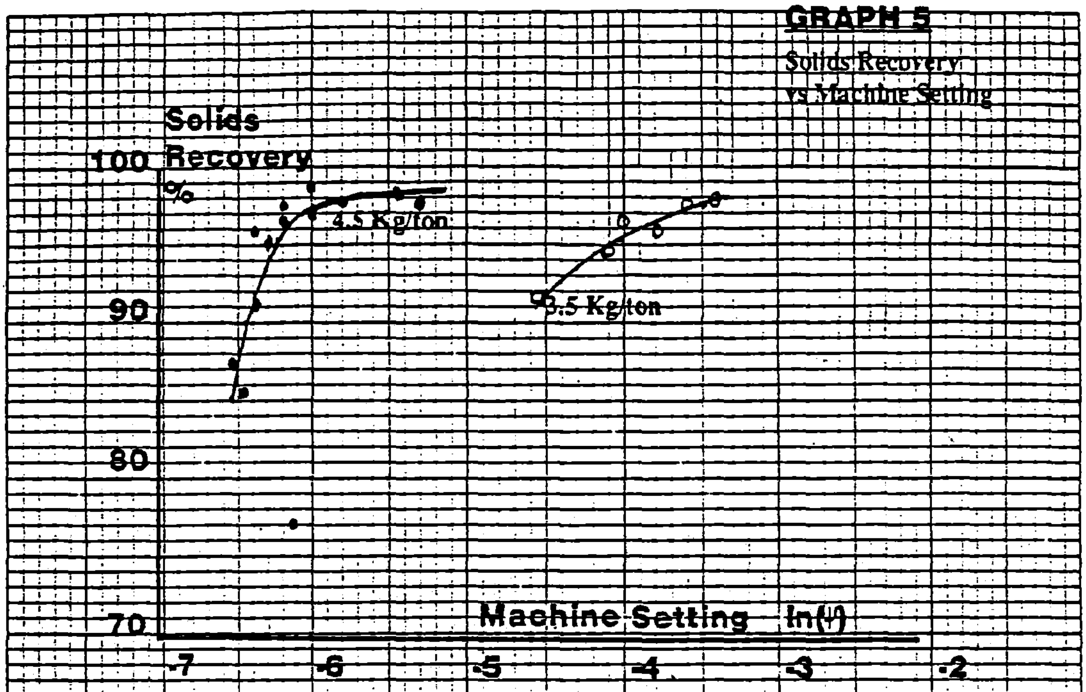
GRAPH 4

Effect of Polymer Type
Pond Y
Polymer medium conc.



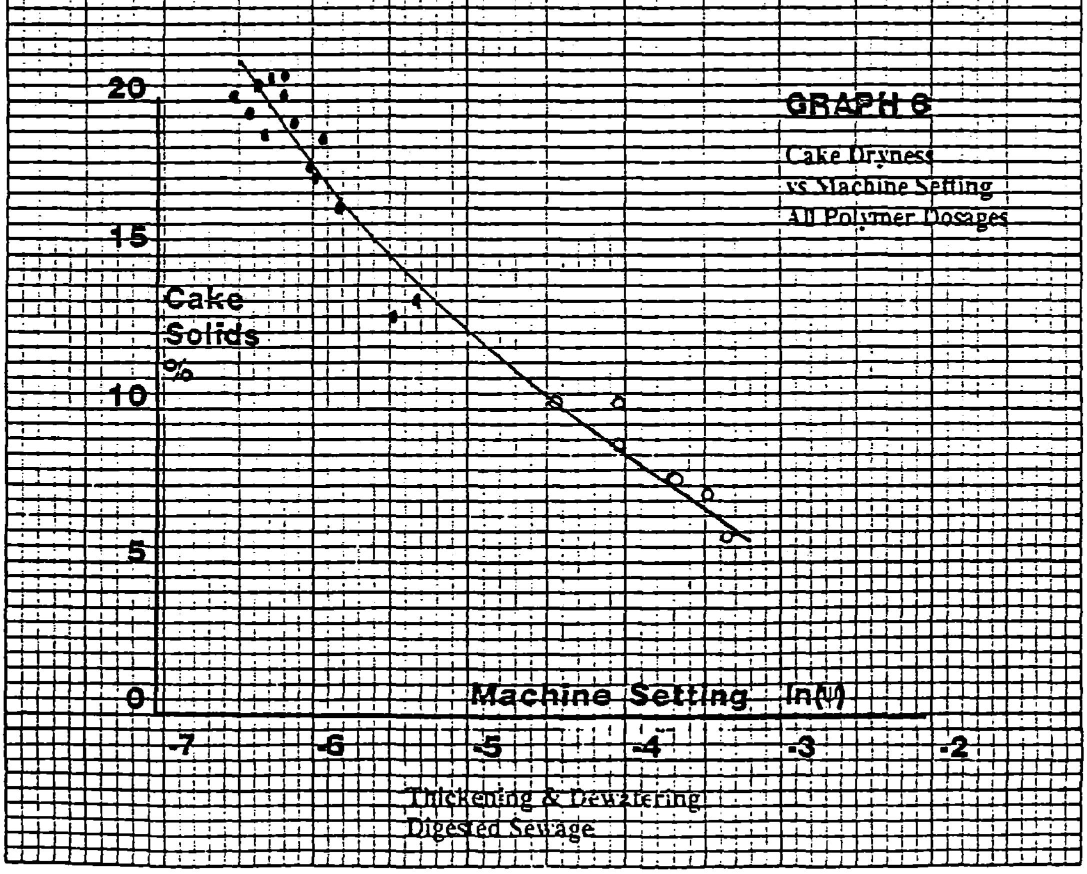
Thickening Digested Sewage

α ALFA-LAVAL
SHARPLES



GRAPH 5

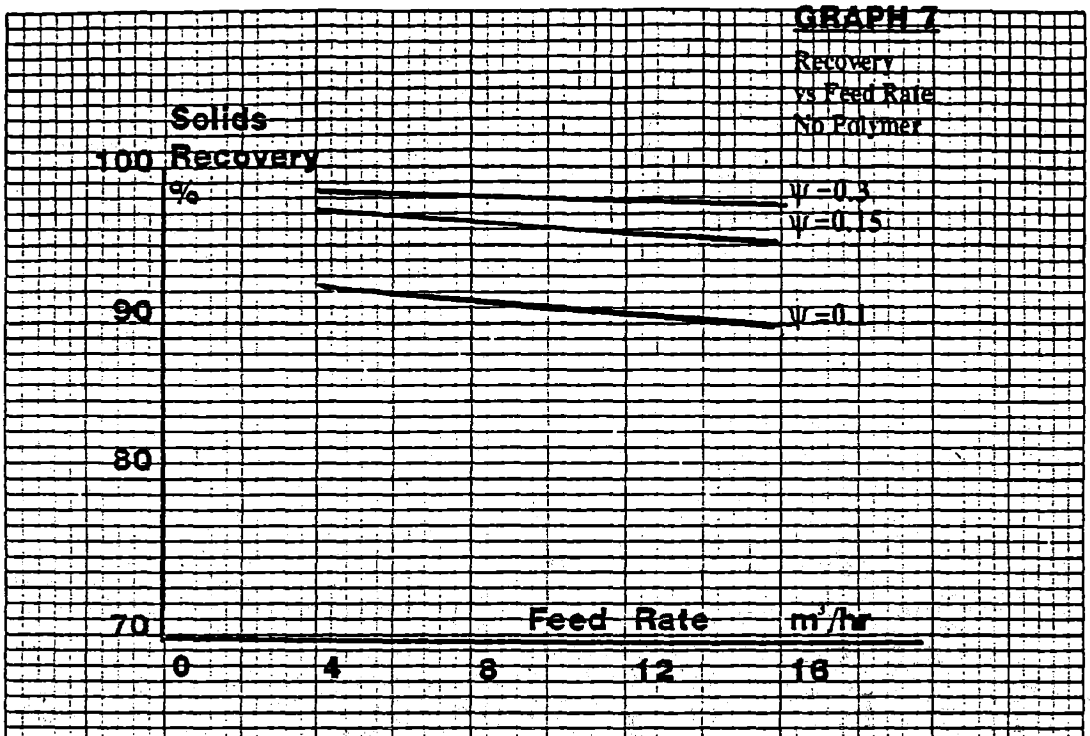
Solids Recovery
vs Machine Setting



GRAPH 6

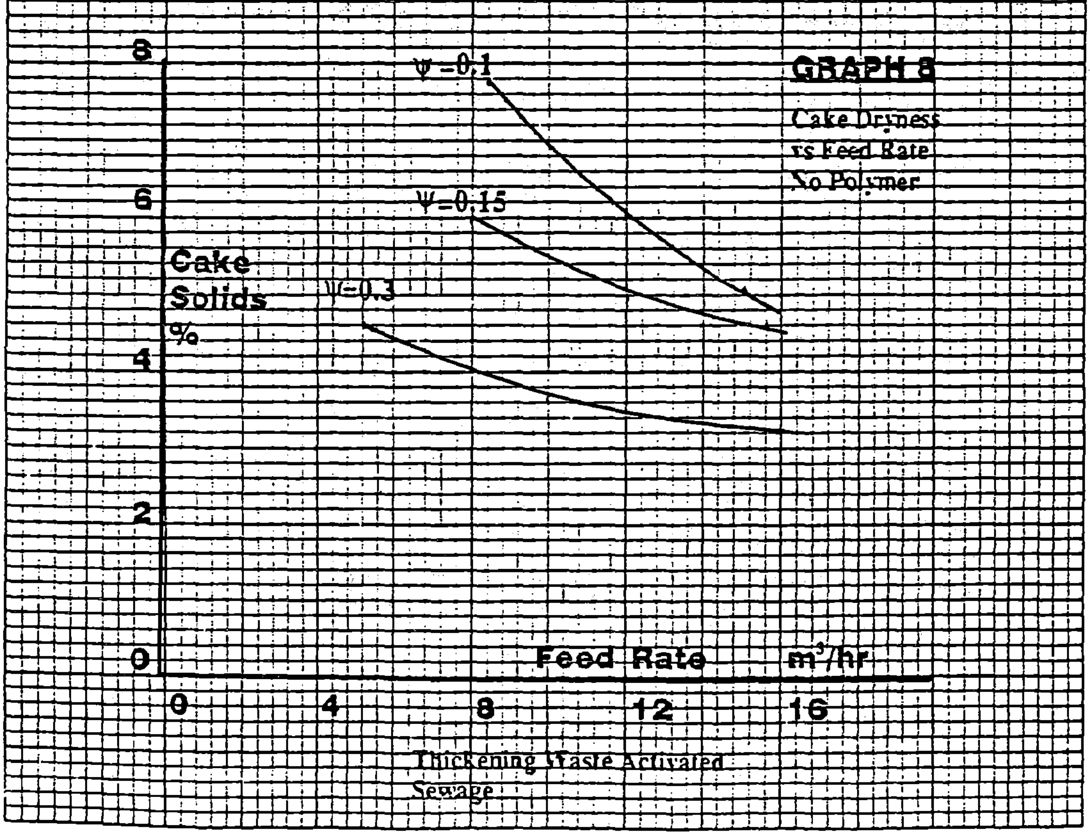
Cake Dryness
vs Machine Setting
All Polymer Dosages

Thickening & Dewatering
Digested Sewage



GRAPH 7

Recovery
vs Feed Rate
No Polymer



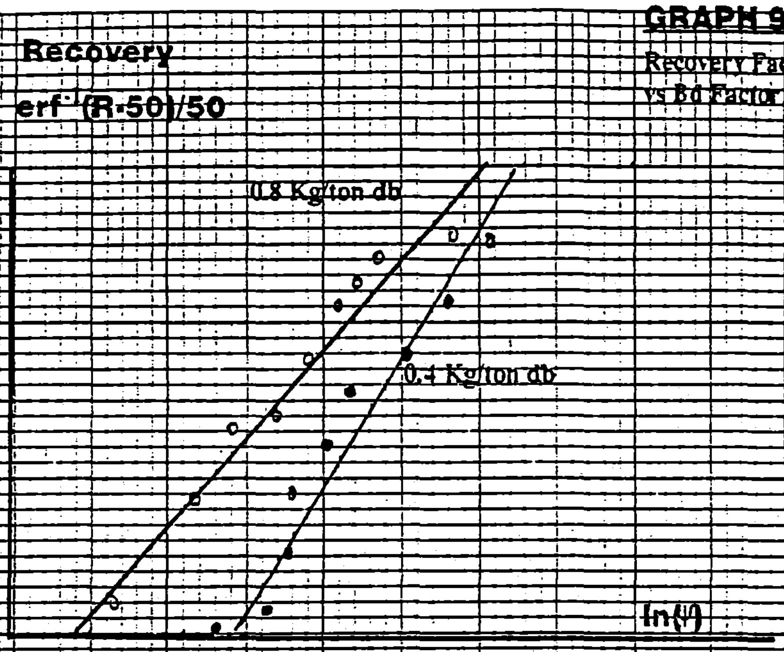
GRAPH 8

Cake Dryness
vs Feed Rate
No Polymer

Thickening Waste Activated
Sewage

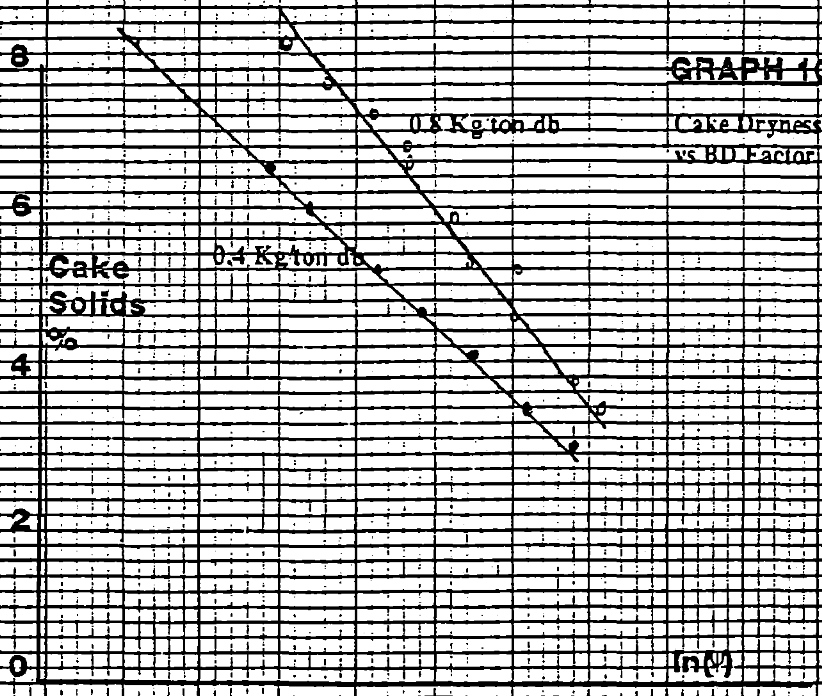
GRAPH 9

Recovery Factor
vs Bd Factor



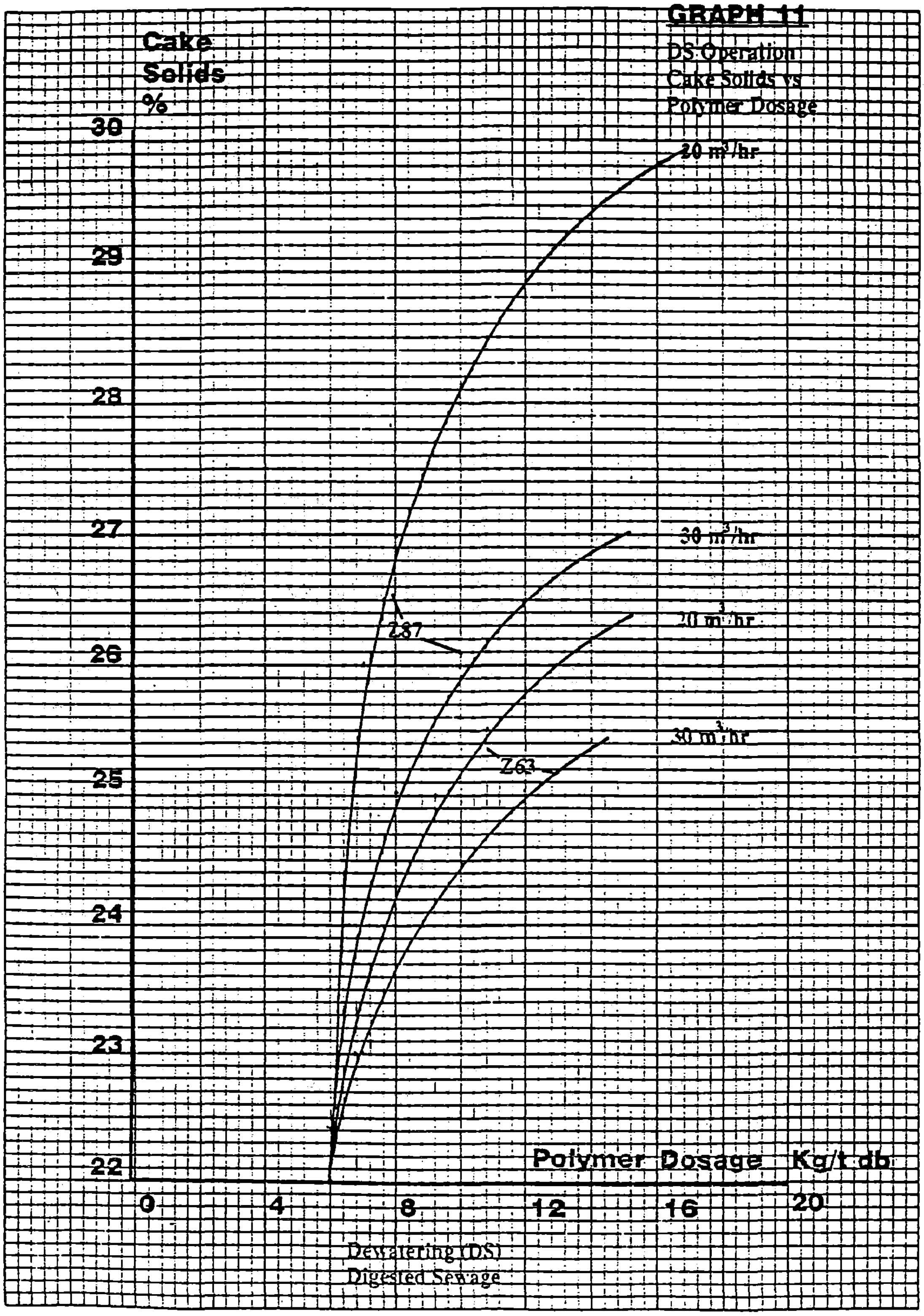
GRAPH 10

Cake Dryness
vs BD Factor



Thickening Waste Activated
Sewage

ALFA-LAVAL
SHARPLES



GRAPH 11

DS Operation
Cake Solids vs
Polymer Dosage

ALFA-LAVAL DECANTER CENTRIFUGES FOR WASTE WATER APPLICATIONS

AVNX = Standard program for conventional sludge dewatering and thickening duties utilising polymers.
Performance as standard Decanters.

CAPACITIES UP TO 150 M^3/H.

DSNX = Execution for high dry solids content in dewatered sludge (5-10% higher than standard program).

CAPACITIES UP TO 60 M^3/H.

XMNX = Thickening centrifuges for waste activated sludge with small or no addition of polymers.

CAPACITIES UP TO 200 M^3/H.

DFNX = Decanters for dual purpose operation
- Dewatering with polyelectrolytes
- Thickening without polyelectrolytes

Typically this is required for capacities up to appr. 20 m^3/h. Machines can, however, be delivered also for higher capacities.

DIAGRAM 24

ALFA-LAVAL
WASTE WATER DECANTERS

Machine Type	Dia. mm	Length mm	Product Line			
			AVNX	DSNX	XMNX	DFNX
3040	230	700	X			
4030	353	860	X			
4035	353	860			X	X
4040	353	1160	X			
4045	353	1160			X	X
4050	353	1460	X			
4055	353	1460				
4230	425	1264	X	X	X	X
4250	425	1772	X	X	X	X
4540	450	1460	X			
4545	450	1460			X	X
5050	478	1984	X		X	X
5060	478	2448	X		X	X
6050	630	2635	X		X	X
7040	737	2337	X	X	X	
7050	737	3048	X	X	X	
9040	1016	3556	X		X	X
9050	1016	4470	X		X	X

DIAGRAM 25

THE SELECTIVE REMOVAL OF THIN LAYERS OF CONTAMINATED SLUDGE

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1. Introduction

River sludge and survace water sludge frequently consists of a mixture of inorganic clay minerals, calcium compounds and organic material and detrital matter. Sludge from the River Rhine, for example, consists, in terms of orders of magnitude, of 2/3 inorganic material and 1/3 organic material. The organic material in suspended river sludge consists for the main part of active living bacterial matter.

The sludge in rivers and other surface waters often consists of a mixture of clay minerals, chalk, inorganic matter, bacteria, and cellulose fibres in which are entrapped all sorts of solid particles and colloidal materials. These may or may not be physico-chemically bonded to flocculant sludge.

The mixture of inorganic clays and organic material forms an ideal location for the binding of both inorganic and organic molecular and colloidal compounds of the most divergent nature, structure and composition. Heavy ionogenic metals and insecticides having ionogenic groups bind well to the adsorption complex of clays and organic material; aromatics, polycyclic aromatics, etc., EOCl's, PCB's and insecticides dissolve well in the aliphatic oil pollutants.

The main components of sludge may be accompanied by :

- the clays; charged particles in the form of heavy metal ions, polar pesticides;
- the organic fraction; oleaginous components contain dissolved chlorinated hydrocarbons, PAH's and insecticides;
- the dead and living microbial and organic matter contain carbohydrates, phosphates and Kjeldahl nitrogen.

River and detrital sludge is, both chemically and physico-chemically, an excellent binding and accumulating matter for all kinds of dipolar and apolar pollutants.

In practice the chemical composition of deposited sludge gives a clear picture of the condition of surface water pollution. When analysing a layer of sediment the state of pollution and, with thicker layers, the pollution "history" may be clearly discerned.

2. Sludge Sedimentation

In both flowing and stagnant waters all kinds of sludge are naturally formed as detritus sludge. The sludge layer formed in the system itself has a thickness of 3-4 mm (25 m3/ha annually) to several centimeters annually (approximately 500 m^3/ha annually) depending on the degree of eutrophication.

Whether this sludge is carried away depends on the hydrological conditions as well whether there is any flow. The hydrological conditions also play an important role in sedimentation.

- In naturally formed ecosystems with little flow the detritus sludge is usually deposited annually on the water bottom in thin and distinguishable layers having a thickness of a few millimeters to centimeters, depending on the degree of eutrophication (several mm to cm annually).
- In aquatic water systems the situation is totally different. Here one may speak of a more or less continuous flow of sludge. The production of sludge in a river system is globally similar.
  In dry years there is relatively more sedimentation in the system; in wet years more sludge will be carried away. Precipitation of riversludge depends entirely on the density and size of the sludge floc.
- River sludge itself has very good coagulation properties. Eddying continuously reduces the particle size of the coagulating sludge. The flow maintains the balance between the coagulation process of flocculation and floc reduction by scouring stress. This process prevents sedimentation.

If the flow velocity is reduced this results in :

* immediate coagulation of sludge flocs. The sludge floc increases in size and thus in sedimentation velocity;
* an immediate increase of the sludge concentration close to the water bottom. This increased sludge concentration in its turn activates coagulation once again.

Depending on the flow conditions, a large part of the river sludge thus precipitates in a limited area. There are thus two processes that activate each other, with the result that the suspended river sludge precipitates more or less instantaneously.

In riverine harbours and estuaries extensive sedimentation can occur locally, being of the order of many centimeters to decimeters annually.

3. Relation between Bottom Sludge and Water Quality

An abundance of research results has shown that the bottom sludge in surface waters greatly influences both the quality of and the ecological processes occurring in the waters above. One may consider here the recycling of P, NH4, and heavy metals, the supply of suspended matter, sulphides, CH4, CO2, N2, etc.

Besides this, bottom sludge offers a home to all kinds of insect and wormlike larvae and acts as a biochemical reactor, reducing sulphates and engaging in denitrification, methanation, etc.

Whan taking vertical sludge samples "hisorical" pollution can often be traced, as well as explained in terms of discharges, in a great number of cases.
Specifically, the upper sludge layers, of the order of some centimeters to decimeters thick, may be polluted by high concentrations of P, N and C and all kinds of heavy metals and xenobiotic compounds. Particularly around discharge points sludge appears to be greatly polluted by heavy metals and P and N compounds.

Besides cleaning up discharges the water bottom needs to be cleaned. Sludge appears to be a large potential source for the prolonged and extensive supply of the pollutants contained in it.

4. Selective Removal of Thin Layers

The selective removal of thin sludge layers (some millimeters to approximately 20 to 30 centimeters) occurs in cases when polluted top layers need to be removed. Examples of the selective dredging of top layers are :

a) cleaning of polluted water bottoms close to the discharge points of sewage systems and industrial companies after discharge has been suspended;

b) removal of eutrophic P and N containing sludge in surface waters,
  - rural areas
  - vulnerable nature preserves
  - waters with a high quality demand, such as drinking water, fishing water, swimming water, recreational water.

c) specific cases
  - dredging of top layer of a water bottom polluted by disasters and shipping accidents
  - removal of thin sludge layers near bathing beaches
  - removal of thin layers from drinking water filtration basins
  - removal of sludge from settling tanks in waste water treatment plants.

The problem of the selective dredging of thin layers came into prominence qhen devising an extensive classification system for dredging deposits. It became clear at that time that a given deposit of sludge may often be classified vertically and horizontally into different classes.
This has great consequences for the technical aspects of dredging and storage as well as, mainly, for cost.

Selective removal of thin layer polluted sludge means that the amount to be stored will be significantly reduced. Storage locations can thus be used for a longer periode of time. The costs of dredging, too, will be lower.
In many cases it appears that only a part, and usually only the top layer of a sludge deposit has been polluted. In terms of water quality, the problem would be solved to a major degree if the polluted sludge layer, with a thickness of some millimeters to approximately 20 to 30 cm, could be selectively removed from the water bottom.

This is a difficult problem in terms of dredging technology. Depending on the local situation one could be dealing with a relatively uniformly consistent sludge to a very gradual change in the consistency of a sludge deposit. The top layers of the sludge deposit commonly may be described as a more or less heavy "liquid". This is the case in lakes and ponds.

From a technological point of view such thin liquid layers are difficult to remove. The current dredging techniques, for various reasons, are not capable of the selective removal of thin layers of muddy sludge.

5. Defining the Problem

The Netherlands have witnessed a turbulent development in terms of standards, the storage of dredging deposits in relation to the quality of the depots and the associated costs. Dredging and the cleaning up of water bottoms is very expensive. From this, besides a qualitative investigation, the question arises of how the sludge layers may be removed as selectively as possible.

When managing surface waters which either have to comply with high quality demands or which are vulnerable, it appears that the water quality still does not meet the required standards, even after cleaning. Subsequent supply of pollutants from bottom sludge in these waters, too, appears to be a severely disruptive factor. In such waters the existing sludge will have to be selectively removed. In many cases the water quality envisaged by the water quality managers, as well as their ecological objectives, can be achieved only when the polluted and often thin upper sludge layers, having a thickness of some cm to dm, are removed from the water bottom.

In regard to dredging technology, selective removal of thin sludge layers is a very recent problem which, up to a few years ago, had not been particularly relevant.

The problem of the selective removal of thin layers of sludge may best be described by the following concepts :

- that upwelling disturbance be prevented as far as possible;
- that mixing with surface water will either be reduced or prevented;

- that separation of those layers that are to be removed and those that need not can be accomplished;
- that undulations in the sludge layer and the water bottom can be absorbed;
- that a large yield in terms of surface coverage can be achieved;
- how this may technically be accomplished.

In other words, how can a dredging technique be outlined for the effective and selective removal of such almost liquid sludge layers of the required thickness without disturbing the remaining layer.

6. Developing a Thin-Layer Dredging Method (The Sludge Slicer)

All kinds of techniques are available to remove sludge; however, there are virtully no operational techniques that are based on the removal of thin layers under strictly retrained conditions.

The selective removal of thin-layer sludge will have to meet the following prerequisites :

6.1. Preliminary Testing and Specification of Dredging Work

* The principal will need to clearly specify by means of analysis which sludge layer of which consistency and thickness will need to be removed.
* Information is required as to the specific density, the dry matter content, the rheological behaviour, the scouring stress resistance at the separation level and the chemical composition.
* The layer to be removed will need to be detailed three-dimensionally in a two-dimensional diagram.
* At the same time, the logistics of dredging, transportation, storage of the sludge and discharge of return water will have to be computed as well as the type of equipment to be used.

6.2. Preconditions and Premises of Thin-Layer Dredging

* In terms of dredging technology one is now confronted with the problem of removing the specified sludge layer either selectively or as selectively as feasible.
  For this purpose the following preconditions will have to be met :

1) mixing with the above water will need to be restricted to a minimum. The sludge layer will need to be delivered to a totally enclosed space qithin seconds, from which it will be drained and pumped to a depot or an intermediate hopper.

2) A separation will have to be achived above, below, on both sides as well as at the front and back. In other words, achieving the physical separation between the sludge layer to be removed and the lower layer that need not be removed will be problematic.

3) This complete screening off is necessary to prevent water flowing in as fas as possible. After all, every m3 of sludge mixture will need to be treated (dredging, transport, storage in demot, dewatering, physicochemical treatment, etc.).

4) The system should in principle also be capable of adapting to undulating water bottoms as well as to occasional accumulations of thicker layers that need to be removed. It therefore needs to be :
   * flexible in resect of reaction to changes in the horizontal (undulating) separation level
   * flexible in respect of reaction to sudden thickening or thinning of the sludge layers (reaction to changes in thick ness).
   * flexible in capacity; m2/h <—> thickness sludge layer.

5) The separation system needs to be relatively insensitive to obstacles on the water bottom.

6) Furthermore, the system needs be relatively insensitive to obstructions caused by such large objects as tree branches, cables, pipes, wood, bricks, etc. The mechanical part of the separation system may not contain any rotating parts apart from the compressor.

7) In principle the system will need to treat large areas every hour. After all, it is not the cubic quantity of sludge (m3) which is relevant, but rather the area (m2/H) covered in relation to an often thin liquid sludge layer (m).
   In short, it is often an area of production which will have to be accomplished, rather than a voluwe of production. Minimizing the water/sludge ratio as far as possible is an important precondition for this.

8) Working rapidly is also necessary in order to prevent a treated area from being backfilled from an untreated area.

9) In short, we are presented with a technically major dredging problem with requirements that are difficult to surmount and one which demands a large degree of flexibility.

6.3. Technical Requirements

The sludge slicer will be required :

1) to remove thin liquid layers of 1 mm to 20-30 cm, if necessary in two to three passes;
2) to function in both forward and reverse modes and where required in a flat plane;
3) to have a speed of 20-30 cm/sec or approximately 700-1000 m/h;
4) to be propelled by means either of winches from the shore, in the davit of a hopper dredger or to have its own underwater traction;
5) to work in a depth of up to 50 m or more;
6) to have a working breadth of approximately 2.5 to approximately 10-15 m;
7) to be insensitive to obstructions and large debris;
8) to be insensitive to undulations in the water bottom;
9) to allow a check to be made on the density of the matter removed;
10) to allow for dosage of flocculants;
11) to be simple to operate;
12) to be transportable by road.

7. The Practical Interpretation of the Sludge Slicer

Work has been going on for years to develop a dredging technique that is capable of meeting the conditions outlined above to a large degree. This has resulted in the SLUDGE SLICER. (fig. 1 top view; fig. 2 side view; fig. 3 front view).

- Sealing of the Top
  The sludge slicer consists of a more or less flat box of 10-30 cm height (a), depending on the thickness of the sludge layer to be removed. On top of the box are a suction mump/compressor (b) together with the pipes which also serve to make the construction sturdy.

- Sealing of the Sides
  If the equipment is to be propelled in a line or in an arc along the water bottom the metal sides may be fitted with runners (c). The sides will cut through the layer to be removed and will prevent sideways overflow in a one-dimensional direction.

- If the equipment is to operate stationary or in a plane the sides are flexible rubber flaps and the equipment is controlled from a davit. In this case it can be operated in a two-dimensional plane.

- Sealing of the Front and Back
  On both the front and the back there are rubber flaps (d) that are hinged and can be retracted. The front flap slides over the sludge layer and prevents the free flow of water. The back flap fits closely to the sludge for the same purpose.

- Sealing of the Bottom
  In between front and back flaps there hangs a curtain of parallel but separate chains (e). The chains cut through the sludge layer to be removed and finally form the closed separation layer between the sludge to be removed and the layer which is to remain.

- Adjusting the thickness of the sludge layer
  Cutting through the sludge will depend on the weight of the chain curtain and on the degree to which it hangs down. Each chain moves in a pendulum fashion to cut through the sludge.

- With a forward motion of approximately 20-30 cm/sec the chains will reach the previously indicated separation plane in 6-10 sec, i.e. after 2-3 meters.

- Taking up the sludge layer
  The sludge is sucked up via a coarse dirt screen placed in the last 1-2 meters of the sludge slicer to the pump mounted on top of the box. If necessary jets (f) can be used here. Usually the sludge is fluid enough to be pumped away without difficulty.

- Prevention of blickage by coarse dirt
  The watery sludge is pumped up after passage through a coarse dirt screen (g) in the upper cavity. These cavities (h) run towards each other to the suction/compression pump. There is a slide shutter (i) mounted in each conduit, one slide being open and one closed.

- Symmetry
  The sludge slicer has a symmetrical construction. Should the suction equipment travel in another direction the flaps retract and only the opening of the shutters has to be reversed.
  In circumstances where the suction equipment travels in only one direction, for instance when cleaning ditches, one can work with only one half of the complete sludge slicer.

8. Treatment of the Sludge Mixture

After the completion of dredging operations, the uppermost detrital or sludge layers in surface waters and spillways is commonly unconsolidated, or only to a limited degree. This implies very water-rich mixtures.

The mixture has to be carried away to a basin with a surface loading of 0.01-0.1 m3/m2.h. In many cases, in particular under circumstances where space is limited, organic flocculants will have to be added in order to achieve a reasonable precipitation of 10-30 mg/l.

For a sludge that is rich in phosphates an intermediate, separate dephosphating step can be added, consisting of the addition of iron (III) chloride. This treatment technique also removes a great deal of the sludge, toghether with the associated bound and dissolved heavy metals, from the water stream.

The depot will have to be equipped with partitions in order to optimise the precipitation.
Large areas of surface water will require a complete set up designed for the minimization of sludge formation and the concentration of the detrital sludge in precipitation gullies specifically designed for the purpose. Here the sludge can be selectively trapped and removed from the water system. Besides these, separate, landscaped sludge depots will have to be constructed for the storage of the detrital sludge formed in the water system. The sludge slicer is also intended for the maintenance dredging of such water systems.

9. Discussion

- Patent protection has been sought for the (on paper) seemingly simple dredging method (No. 88.0129). Discussions are underway with dredging companies in the Netherlands on the technical engineering of the method presented.

- This has not, at the present time, resulted in the actual construction of the equipment, nor in its testing.

- I would emphasize to you that, at present, in 1991, it is still paper solution.

- In view of the fact that the problem of thin layer dredging is a universal one, I believe it is a good thing to lay before you how this bothersome problem can be tackled in such an apparently simple manner.

10. Conclusions

1) The selective removal of thin, pre-defined layers of sludge is technically of the utmost complexity.

2) The methodology presented here on paper is fundamentally extremely simple, yet it nevertheless offers the possibility of removing thin sludge layers in a flexible manner.

3) The method of operation, even though it is known throughout The Netherlands, still has to undergo a technical engineering phase.

4) I anticipate that the SLUDGE SLICER will be operational as a selective dredging technique within a few years.

5) The technique may be utilized in :
- the cleaning up of water bottoms after the major cleansing dredging,
- the regular dredging technique used for maintenance of large, sensitive surface waters and the control of sludge housekeeping in such waters,
- regular ditch maintenance and the maintenance of bathing beaches,
- selective dredging after accidents,
- removal of polluted surface layers close to sewage discharge points,
- in the precipitation tanks of waste water treatment plants.

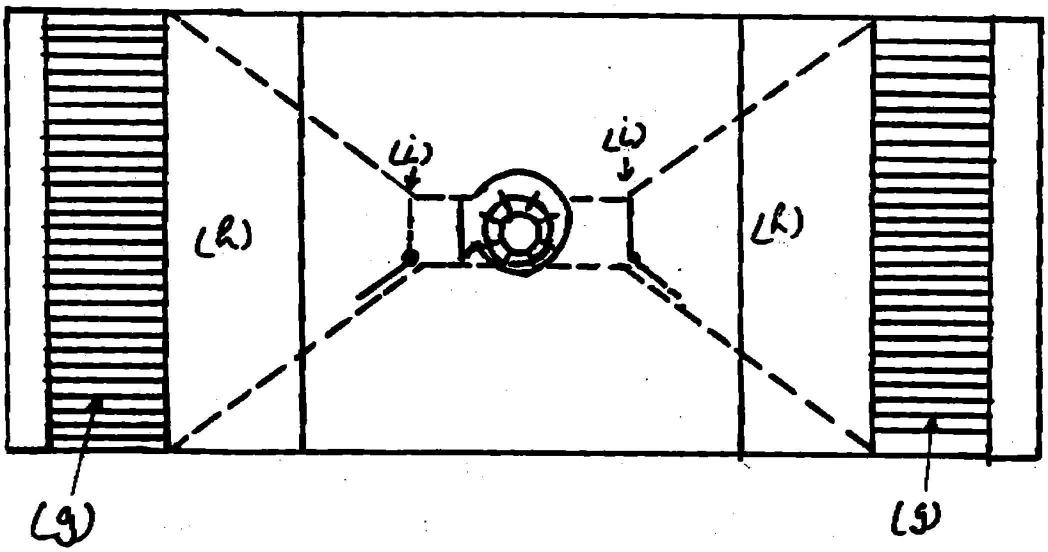

fig 1

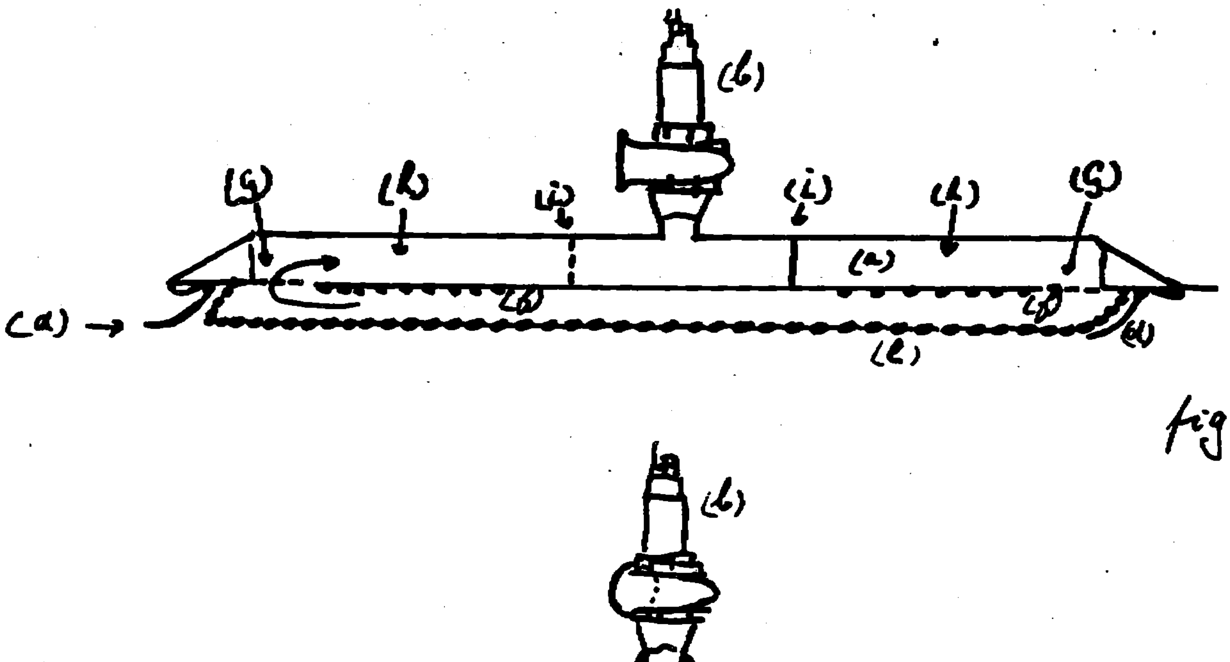

fig 2

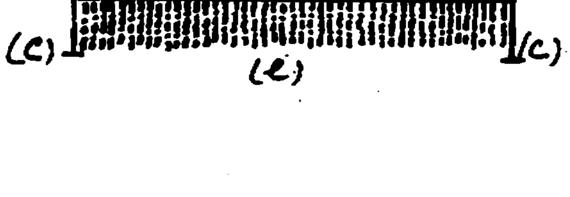

fig 3

MAKING A CHANGE FOR THE BETTER.

Rehabilitation: redevelopment and improvement of the landscape and our 'living environment' is important.

Today it has become particularly vital as work patterns, life styles and attitudes to the natural environment change.

Take neglected docklands for example. Recently they have become the focus of extensive rehabilitation. In place of the dirty silt, debris and dilapidated buildings we are seeing fresh water and attractive landscaped grounds where people can live, work and enjoy themselves.

As the world's foremost dredging and land reclamation contractor in the private sector, Boskalis has confronted this problem of rehabilitation on a worldwide scale.

And not just in docklands. In North Africa the company helped to bring new life to a stagnant lake that was previously an eye sore and gave off an unbearable stench; and in the Middle East an unsightly lagoon was deepened to create an appealing waterfront development.

Cleaning up the canals and inland waterways of Europe frequently has the added problem of pollution. Dredging contaminated silt in the conventional manner will only increase the pollution. Boskalis, though, has developed special techniques for dealing with this, either by dredging the silt or containing it beneath a suitable material.

Just one example of Boskalis' innovative approach which has kept the company at the forefront of the dredging industry for more than 75 years.

But it's not only dredging waterways that Boskalis is known for. The company has reclaimed and improved vast areas of land around the world, converting water-logged areas into prime development sites for industry, housing and recreation.

Boskalis is changing the world... for the better.

BOSKALIS
International Dredging Contractors

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CHARACTERISATION METHODS FOR DREDGED MATERIALS

PARTICLE SIZE CHARACTERIZATION OF SEDIMENTS

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ABSTRACT

The knowledge of the particle size distribution within sediments is important with respect to their physical and chemical properties as there are the reactivity of the material in its environment and the fate of the heavy metals in contact with it.
At the moment the Fraunhofer diffraction method is the best suited one to determine the particle size distribution in heterogeneous materials like sediments. This method will be compared with the sedimentation and sieving techniques.

INTRODUCTION

Sediments form heterogeneous systems with a solid, a liquid and a gas phase. With an average of 95 % most of the solid phase is composed of minerals, the remainder makes up the organic fraction. The particles within these solids have sizes ranging from a few nanometers up to several millimeters.

When heavy metals are dispersed in such a system, they are subject to numerous physical and chemical reactions.

The type of process depends largely on the interactions between the particles and the surrounding solution as well as between the particles themselves. These interactions are defining the chemical form of the pollutants binding to the particles.

On the other hand the interaction between particles leads to the formation of much larger aggregates.

The bound pollutants are therefore incorporated in these large grains.

The correct knowledge of the particle size distribution within a bottom is an important parameter for :

1. the study of the interactions and reactions of heavy metals in watersediment systems
2. the selection of a treatment or clean-up procedure.

Before entering a discussion on the different methods for the measurement of a particle distribution we will pay some attention to the reactions and interactions mentioned above.

The mutual interactions between particles and between particles and the surrounding solution (1,2,3,4,5)

The dimensions of a particle are important for its ion exchange properties. The process of ion exchange is a consequence of the charges on the surface of the particle. In natural sediments these have normally a negative sign. The electro-neutrality of the particle is guaranteed by picking up cations out of the solution. Heavy metals which are present in the soil solution can be exchanged for cations bound to the particle.

A typical reaction between Cd and a particle can be written as :

$$\{[R]^{2-} - M^{2+}\} + Cd^{2+} \longleftrightarrow \{[R]^{2-} - Cd^{2+}\} + M^{2+}$$

$[R]^{2-}$: a clay particle for instance
$\{\ \ \}$: the solid phase of a bottom
M^{2+} : a normal counter cation such as Ca^{2+}

The ion exchange reactions are the basic cause for the binding of heavy metals to colloidal particles with sizes from 50 nm up to 2 µm.

Larger (sand) particles show a much more inert character.

For a contaminated soil this gives rise to a uneven distribution of pollutants (heavy metals or others) between the size fractions. The soil shows granular differentiation of contaminants.

On the other hand there are mutual interactions between the colloidal particles. The most important ones are :
- coagulation - floculation,
- sticking together.

Colloids in suspension show stability, this means that the particles stay in solution as a consequence of the mutual repulsion between the individual units which have the same sign of surface charge. An ion exchange process is neutralizing these charges, the colloidal particles will come together. Larger aggregates will be formed as a result of hydrophobic interactions. The formation of aggregates follows a distribution of probability so that a whole range of dimensions will be the result of it.

But there will be also reactions between the components which are purely dissolved in the soil solution.

This can result into the formation of precipitates, co-precipitates and crystal formation. A typical example is the formation of amorphous oxides of iron. These precipitates can be formed around colloids which serve as nucleation centres or the oxides precipitates between particles in the sediment sticking them together. As in the case of coagulation-floculation the growth of a precipitate around a colloidal particle or between particles in the sediment gives rise to a distribution of probability for the dimensions of the aggregates.

The processes of aggregation and precipitation, mostly reduce therefore a clear granular differentiation of contaminants.

In our laboratory we have measured the particle size distribution as well as the granular differentiation of heavy metals of a great number of different types of sediments. As an example we discuss three different systems, namely :

- the ditch of Fort III at Borsbeek which stands for a semi closed system
- the river Laak, a natural waterway
- the canal Ghent-Terneuzen, an artificial waterway.

For reason of simplicity we have decided to split up the particle size distribution into three main classes :

- 0-45 µm : clay + silt
- 45-63 µm : silt
- > 63 µm : sand

With regard to the particle size distribution one arrives at the following general conclusions :

1. Within the same system, even in a semi closed one, the particle distribution is different from one site to another.
This is clearly shown in the case of Fort III for the sites 1 and 2. (Fig. 1)
2. In natural systems the flow of a river leads to a classification of the particle distribution. The fines are transported much more downstream.
This can clearly be seen in the case of the river Laak. (Fig. 2)

With regard to the granular differentiation one can draw some general conclusions.

1. Within the same water-sediment system there can exist a difference in the distribution of pollutants between the size classes from different sites in the system.
In site 1 of the ditch of Fort III the heavy metals are bound to the fines while in site 2 they are found in the fraction above 63 µm as well. The reason for this can be a more pronounced sticking between the fine particles of site 2. (Fig. 3 and Fig. 4)
2. Not all of the different types of heavy metals bind to the same particle size. As shown for the river Laak (Fig. 5) for instance cadmium is concentrated into the fines. On the contrary arsenic is found evenly in all the particle classes.
Arsenic exists in natural systems in anionic form, mainly as arsenate and arsenite. These forms bind strongly to the iron hydroxide precipitates which form particles in all size classes. Precipitation can also occur on grains of silt and sand. This is the reason why arsenic is found in each size class.
3. In the sediment of the canal Ghent-Terneuzen one can see (Fig. 6) that the heavy metals have the same range of concentrations in all size classes.
This is because the fines make up nearly 86 % of the dry solids. Larger particles are formed by sticking together of the fine and by the process of coagulation-floculation. There are no inert sand particles in the sediment.
This leads to a nearly equal amount of each size-class in the sediment.
4. As indicated for the river Laak (Fig. 7) the concentration of the pollutants follows the natural classification of the particle sizes.

As discussed before the particle size distribution and the related granular differentiation show a rather pronounced variation within a sediment system. So the first step in the examination of such a system has to be a detailed analysis of these parameters.

The result allows :

1. To make some predictions about the reactivity. For instance, the more fines the material contains, the greater its chemical reactivity.
2. To decide wether a physical treatment of a contaminated soil or sludge is meaningful or not to separate it in different size fractions with a different degree of contamination.
3. To select the technical means to be used in the treatment (flotation, hydrocyclonage, etc.).

It is clear now that the method to measure the particle size distribution has to be the best suited for the material under consideration.

<u>Particle size distribution comparison of methods in use</u> (6,7)

Larger particles can in part been built up by sticking together of fines.

This sticking is the consequence of the precipitation of salts like $CaCO_3$ or organic macromolecules between the particles.

A sediment that has to be processed by mechanical means is normally subject to shear forces which can split up the aggregates.

If this is the case the grains have to be desintegrated before a particle size measurement can be practisized.

This means that the cementing components have to be dissolved.

A typical pretreatment is a two step process. First of all the carbonates and oxi-hydroxides of iron are dissolved by treating the sediment with HCl. The next step consists of the oxidation of the organics with H_2O_2 at low pH.

The resulting particle size distribution of a sediment with and without pretreatment is shown in fig. 8.

We now come to the subject of the methods in use for the determination of the particle size distribution.

1. Sieving.

The material is placed onto a series of sieves with decreasing mesh sizes.

In our laboratory we use the ISO standard sieves with mesh sizes which varies with a constant factor of $\sqrt{2}$.

The proces of sieving consists of two phases. The chance that a particle goes through the sieve depends on :

- the particle size distribution of the given material
- the charge loaded onto the sieve
- the amplitude of the sieving vibration
- the shape and size of the particle
- the ratio between the open- and total surface of the sieve
- the angle between the particles traject and the plane of the sieves.

Sieving is a dynamic process and theoretically the time necessary to realise a separation of 100 % would be infinite.

We in our laboratory have defined the limits between which a separation efficiency of 95-99 % can be attained.

- type of sieving medium : water
- smallest sieve opening : 63 µm
- charge on the sieve :
    minimal : 25 g of dry solids
    maximal : 50 g of dry solids
- time of sieving : 9 minutes

Figure 9 shows the results of sieving a sediment on 45 µm and 63 sieve openings. One can clearly see why a 63 µm sieve opening is the minimal useful one. The curves give the particle size distribution of the material retained by the sieve.

2. Separation of particles into size classes by means of gravitational forces.

The gravitational force can be due to the earth's gravitational field or it can be the result of a centrifugal force.

We will discuss the problem for a sedimentation particle sizer which relies on the earth's gravitational field, although the same principles hold for the centrifugal method.

A sedimentation method makes use of the Stokes law for solid particles falling with a constant speed in a given medium.

The particle sizer uses this law to calculate the size distribution and the result is an equivalent Stokes diameter.

To get the correct result out of it one must satisfy the following requirements :

1. the suspending medium must show a laminar flow around each particle. This means that the Reynolds number must be 0.2 or less. For particles with a dry solid density of 2600 $kg.m^{-3}$ the maximum measurable particle size is 61 µm.
2. there may be no mutual hindrance of the particles. Therefore the dry solid concentration is limited to less than 1 % on a volume basis.
3. the particle size limit downwards is about 1 µm.

Otherwise the Brownian movement will resuspend the fines and this fraction will be underestimated.

4. the particles may not be porous.
5. the density of the dry solids has to be the same for all the particles. This is normally not so in the case of a sediment where sand has a density of 2600 $kg.m^{-3}$ while iron rich substances have values of 3600 $kg.m^{-3}$ or more.

Figure 10 gives a clear demonstration of the influence of the upper limit of the particle size in the sedimentation process.

For particles with a density of 2600 $kg.m^{-3}$ and a maximum size of 140 µm, curve 1 gives the true distribution, while curve 2 gives the distribution as measured by sedimentation. The coarse particles sweep the fines out of the solution. By this the number of the small particles is strongly underestimated.

3. Measuring the particle size distribution from the interaction of the particles with an electric field. (Coulter counter)

The particles which are suspended in an electrically conducting solution are passing through an electric field which is set up between two electrodes. The passage of a particle causes a change in the current between the electrodes. This change is registered as a voltage pulse. It can be shown that the extent of this pulse is proportional to the volume of the particle.

Although the method is very good it is normally not useful with sediments which contain ferro magnetic materials or components which are electrically conducting. In this case the change of the value of the current is no more proportional to the volume of the particle.

4. Determination of the particle size distribution by means of the interaction between a particle and electro-magnetic radiation. The Fraunhofer diffraction technique.

Introduction

The optical techniques have some advantages over the other methods used in the determination of the particle size distribution.

There are :

1. the time to complete a measurement is very short, typically 5 minutes
2. the suspending medium must not have special features and can even be changed at will
3. the particles are not subjected to shear forces.

One of the optical methods in use is the Fraunhofer diffraction technique.

This method has some supplemental advantages:

1. one doesn't need to calibrate the equipment
2. the method is based on well-known, theoretically firmly funded principles.

The theoretical basis of the Fraunhofer diffraction.
If electro-magnetic radiation interacts with a particle and if the wave length of the radiation and the size of the particle are of the same order of magnitude then the radiation shows simultaneously absorption, transmission and scattering.
If the particles are opaque and if they are not absorbing any energy then we have to account only with scattering.
In this simple case we can write down the relation of Lambert-Beer

$$\frac{I}{Io} = \exp\left[-N.\alpha_{se}.1\right]$$

$\frac{I}{Io}$: fraction of the incoming radiation left after scattering
N : number of particles per unit of volume [m^{-3}]
1 : path length [m]
α_{se} : effective cross-section of a particle for the scattering process. [m^2]

Starting with the equations of Maxwell for the electro-magnetic field and the Lorenz-Mie theory for scattering one can define the relation between

- the product $N.\alpha_{ex}$
- the relative refraction index of the particles in a given medium
- the scattering angle θ
- the characteristic length x of the particle.

x is related to the physical dimension as

$$x = \frac{\pi.d}{\lambda}$$

λ is the wave length of the interacting radiation
As the Lorenz-Mie theory leads to the correct answer for the problem the analytical solutions are not straight forward and normally very complex.
Depending on the ratio between the dimension of the particle d and the wave length λ of the radiation one can introduce some simplifications. There are two possibilities each with its own theories
$d << \lambda$: Rayleigh scattering
$d >> \lambda$: diffraction theory
It is that last case which allows to make use of the Fraunhofer theory. This can be used if $d > 4 * \lambda$.
With the diffractometer in use in our laboratory working with radiation at a wave length of 632,8 nm this means that the method is suited for particles greater than 2,5 µm.
The incoming radiation will be diffracted at a certain angle θ.
This angle will be greater the smaller the particle is (fig. 11).
A schematic presentation of the particle sizer is given in figure 12.

To apply the Fraunhofer theory correctly one needs some supplemental requirements.

1. the projected surface of the particle must be much smaller than the product of the wavelength times the distance between the source of the radiation and the plane of diffraction. In practice one uses a laser source producing a plane wave front.
2. the projected surface of the particle must be much smaller than the product of the wavelength times the distance between the detector and the plane of diffraction.

In practice this requirement is met by placing the detector in the focal plane of the lense. This positioning has an extra advantage. The particles moving through the diffraction plane give a stationary image.

The basis for calculating the particle size distribution in the domain of the Fraunhofer diffraction is the Airy equation.

$$I = I_o\left[\frac{2\,J_1(x)}{x}\right]^2$$

where : I : the intensity of the diffracted radiation
I_o : the intensity of the diffracted radiation in the centre of the diffraction pattern
x : the characteristic length of the particle

$$x = \frac{2\,\pi rs}{\lambda F}$$

r : the physical radius of the particle [m]
s : the distance from the optical axes to the point of observation in the plane of detection [m]
F : the focal length [m]
λ : the wave length [m]
J_1 : the first-order Bessel function in spherical coordinates.

In practice one doesn't measure the intensity of the energy distribution within the diffraction pattern. In stead of it one measures the energy falling on a limited surface of the detector. This can be done by integrating the Airy equation between the limits 0 en s. The fraction of the energy on a detector area with radius s is then given by:

$$P = 1 - J_o^2(x) - J_1^2(x)$$

J_o en J_1 are the zero- en first-order Bessel functions in spherical coordinates. In the particle sizer in use, the detector is composed of a number of concentric rings. For a given focal length, each ring accords with a well defined diffraction angle. The energy falling on a ring with an inner and outer radius s_i and s_j is then measured.
Each of the rings in a detector stands for a size class.

After summation of the energy over K size classes for N_r particles of radius r one can calculate the particle size distribution within the population.

Practical considerations in using the Fraunhofer diffraction based particle sizer.

1. As it follows from the complete Lorenz-Mie theory the relative refraction index of the particles in a given medium is an important parameter defining the lower limit of particle size that can be measured.
Van Hulst has defined a parameter p which tells us if it is allowed to make use of the Fraunhofer theory.
This parameter takes into account the relative refraction index and is given by the relationship :

$$p = \frac{2\ \pi d\ |m-1|}{\lambda}$$

d : diameter of a spherical particle
m : relative index of refraction
λ : wave length of the incident radiation
| | : absolute value

The Fraunhofer theory can be used without limits p ≥ 30.
This allows to calculate the lower limits of d for some naturally occuring inorganic materials.

component	relative index of refraction in water m	d_{min} µm
goethiet	1,810	4
calcite	1,278	11
kaolinite	1,173	17,5

For values of p between 10 and 20 one has to consider errors of about 15 % on the distribution of sizes smaller than d_{min}.

2. In making use of the diffraction theory one supposes that there is no multiple diffraction. A diffracted bundle of rays doesn't meet the requirement of parallellity anymore.
This leads to an enlargement of the angles of diffraction.
This results in a displacement to the side of the fines as it was that there were more fine particles in the population.
In the modern equipment the correct optical density to avoid multiple diffraction is automatically indicated.
If this is not the case one has to adjust the concentration of the suspension so that the extinction of the incident light is limited to 50 %.

3. The response of the instrument corresponds to the product of the cross-section of the particle times a complex function of the diameter of the particle, i.e. $\pi . d^2 * f(d)$.
This means the response is proportional to d^m with m ≅ 3.
One measures an equivalent volume diameter.

4. No one of the existing instruments covers the whole range of particle sizes of a given sediment. If one has to measure over a large interval, one has to change the optics of the instrument, or to prepare size fractions by sieving.
In our laboratorys we split the sample into two parts by sieving on a 125 µm sieve. The fraction below this size is measured by the diffraction technique, while the coarse fraction is further classified by sieving.

CONCLUSIONS

1. There exists no technique that is totally convenient for the determination of the partical size distribution of a given sediment
- sieving is limited to particles above 63 µm
- gravitational classification is limited by the heterogenity in the density of the materials in the sample
- the interaction of particles with an electric field can not be used if there are particles which are electric conductors as is usually the case for sediments.
- the diffraction technique suffers from the heterogenity in the index of refraction of the materials, which leads to errors of about 10 tot 20 % in the distribution of the particles below 20 µm.

2. Apart from these disadvantages the Fraunhofer diffraction technique is the best suited for sediments.
The reasons therefore are :
- the method is non destructif, there are no shear forces on the particles.
- the system is independent of the heterogenity of the density of the particles.
- the system is independent of the electrical characteristics of the particles.
- the result is directly an equivalent volume diameter.
- the method is very fast, typically 5 minutes for a complete run.

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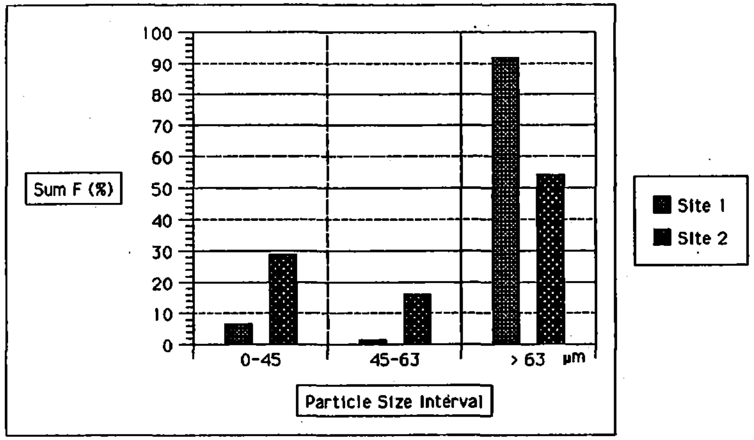

Fig. 1: Borsbeek Ditch FORT III. Difference in particle size S1 vs S2.

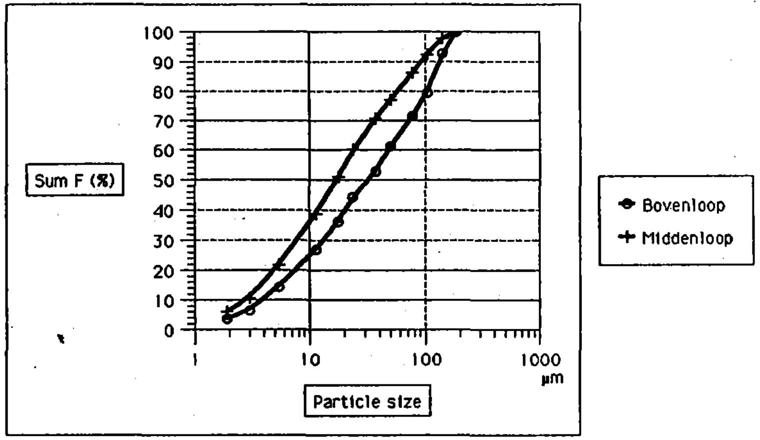

Fig. 2: Particle size distribution LAAK. Natural distribution.

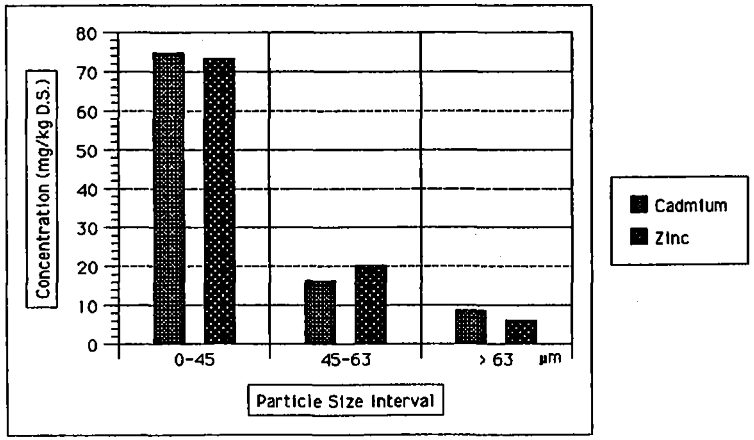

Fig. 3: Borsbeek Ditch FORT III. Granular differentiation Site 1.

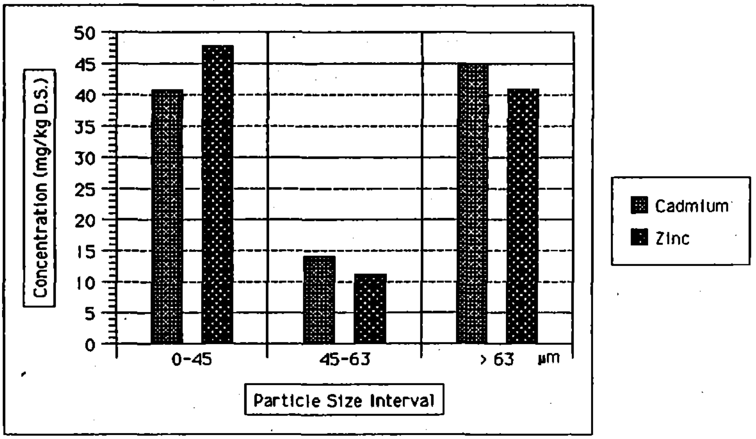

Fig. 4: Borsbeek Ditch FORT III. Granular differentiation Site 2.

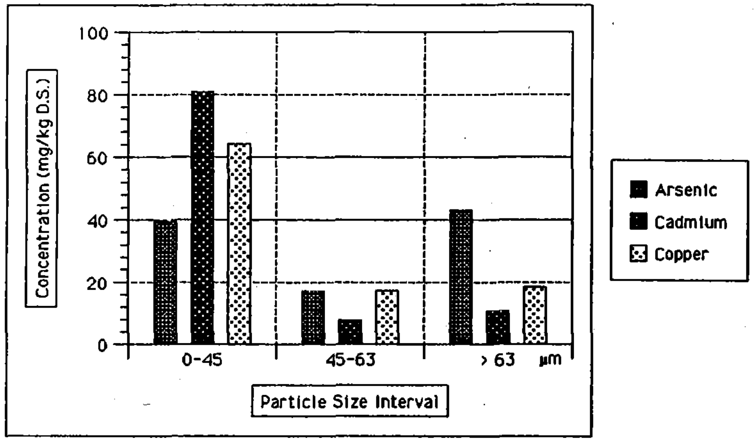

Fig. 5: The river LAAK. Granular Differentiation.

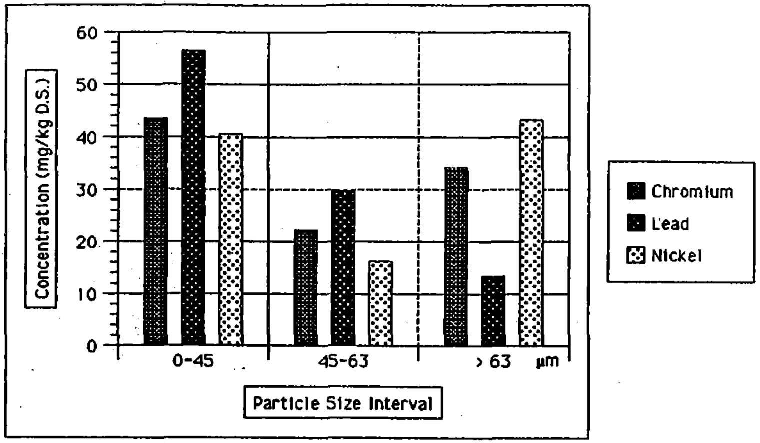

Fig. 6: Canal Ghent-Terneuzen. Granular Differentiation.

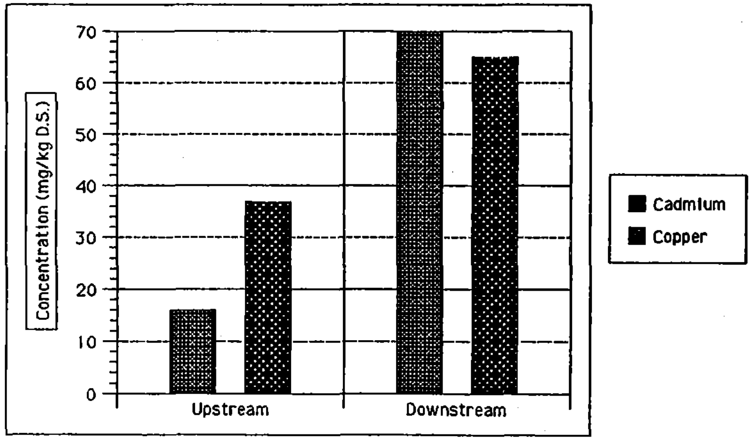

Fig. 7: The river LAAK. Natural granular differentiation.

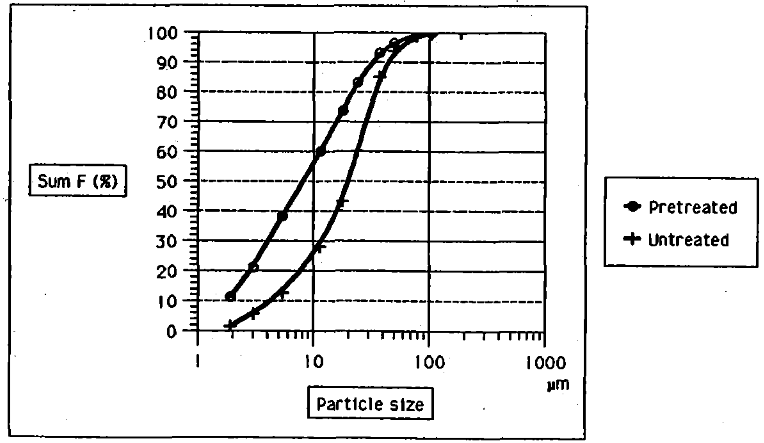

Fig. 8: Particle size distribution. Pre- and non pretreated sample.

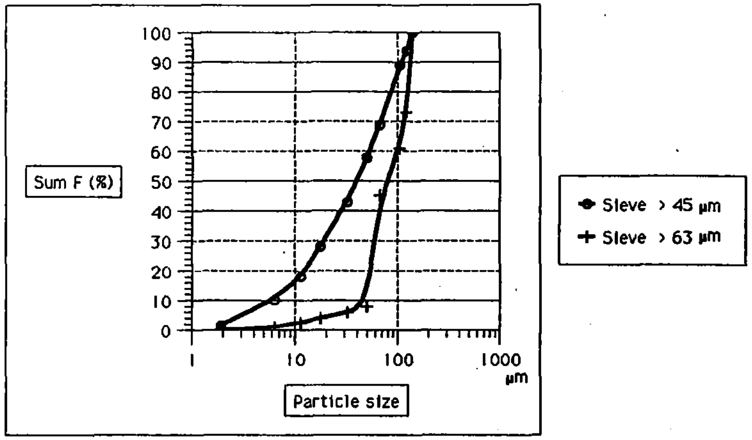

Fig. 9: Sieving efficiency. Particle size distribution of sieve rest.

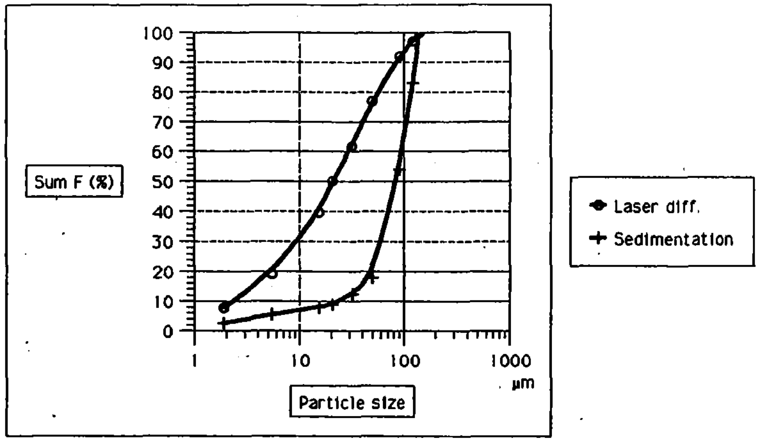

Fig. 10: Comparison of two different granulometric techniques (river LAAK sediment).

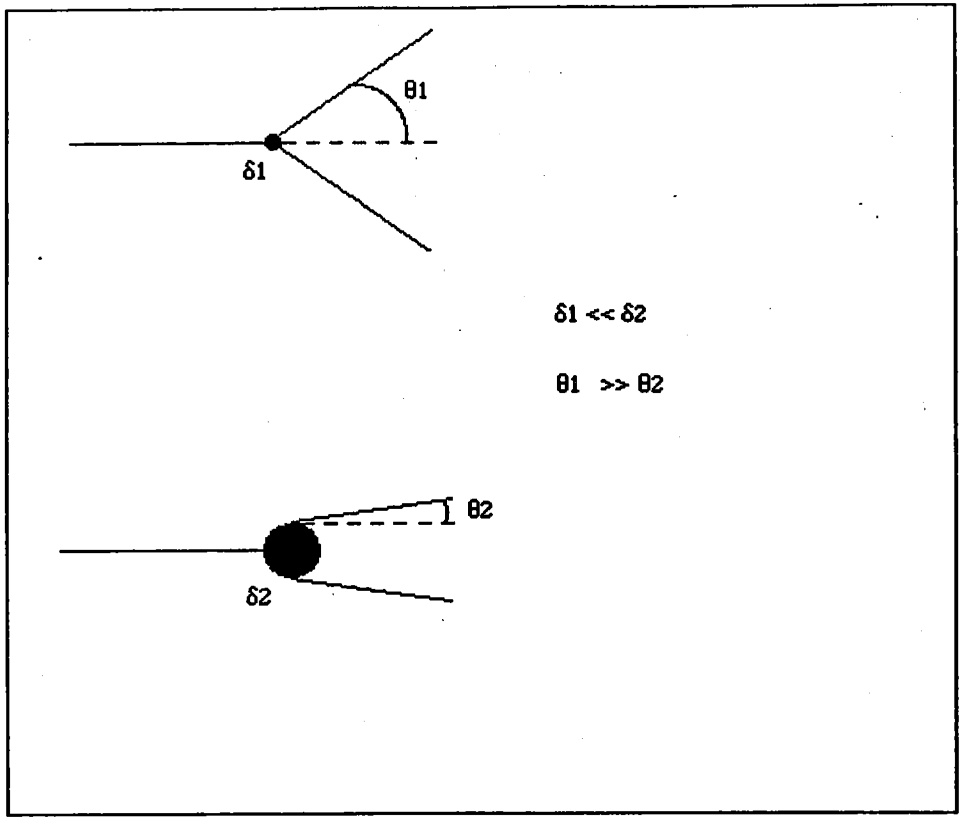

fig 11. principles of laser diffraction

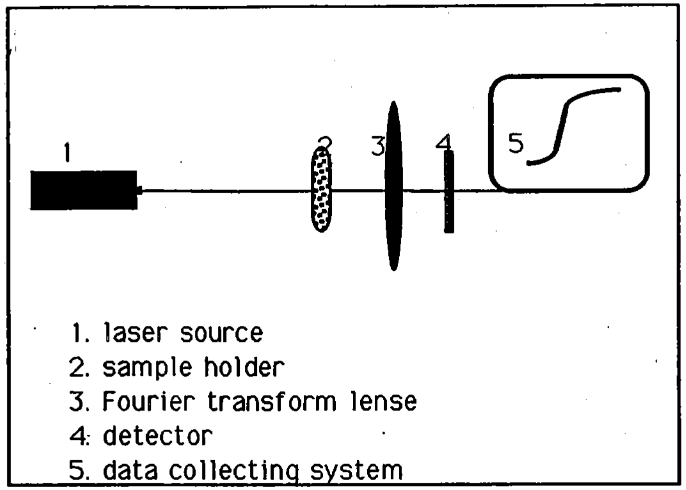

fig 12. Laser diffraction
(schematics)

CORRECTING PROBLEMS OF ESTUARINE AND COASTAL WATERS HEAVY METALS SEDIMENTS POLLUTION

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ABSTRACT

Environmental impact of pollution by heavy metals in estuarine and coastal sedimentary complexes involves waters, the immediate bottom surface sediments and deposits. Developments in analysis techniques here examined go back some ten years. Decomposition of sample proceedings are compared to other methods. Grain size effects, norms and analytical methods are assessed.

INTRODUCTION

The vertical composition of geological layers and ice enables to trace variations in the composition of the Earth's atmosphere and oceans. Sediment analysis steadily gains in importance because pollutants, such as heavy metals, organochlorine pesticides, chlorinated hydrocarbons and dioxines are enriched in bottom deposits by a factor of 1000 or more and act as reservoirs of potentially remobilizable materials, hence its importance to trace man-caused pollution of water [1]. The role of sediments was recognized in lake eutrophication studies and in water acidification. Stream sediment analysis is used for the detection of mineral deposits and sediments in geochemical prospection and environmental monitoring. Sediment pollution studies are mainly devoted to that of heavy metals (a problem since 1920), fuel derived hydrocarbons (e.g.P.A.H), industrial pollutants: e.g. chlorinated hydrocarbons (after 1920), PCB's (after 1930) and phtalates (after 1950), and finally, pesticides (after 1940)and radionuclides (after 1945) [2].

SAMPLING

A representative image of the actual composition of the sediment layers requires a minimum number of samples. Moreover, analysis must have maximal reproductibility. Sampling intruments have not changed much over the last two decades: they can be divided in three classes: grabs, gravity-corers, and dredgers [3]. Systematic and random sampling methods still form the basis of sampling theory. A recently published classification of dredged material from Belgian waterways provided a standardized "stratified random sampling" procedure [4]. Mixed subsamples whose number depends upon the possible change of environmental conditions within the dredged zone are analyzed.

DECOMPOSITION OF THE SEDIMENT SAMPLE

The decomposition method depends upon the nature of the sample, and of the subsequent analytical work, determined by the compound(s) to be analyzed: heavy metals require mostly a spectrometric and/or electroanalytical method each with specific requirements about the purity of the analytical agent.

Generally, decomposition methods must be limited in time and effective (not necessarily complete), not contaminate the sample, avoid the use of large volumes of chemicals, be the least polluting possible, not interfere with the decomposition vessel, either by attacking the vessel or by retaining sample components in its walls, and not result in the loss of constituents (volatilization, change of the original constitution).

OVERVIEW OF THE DECOMPOSITION METHODS

Originally decomposition methods used in rock and mineral analysis were applied. They include decomposition by oxidizing and non-oxidizing acids, decomposition by fusion with acid or alkaline products, decomposition by other means (in bombs and sealed tubes) or products (chlorination) [5].

With acid decomposition no impurities are introduced into the sample, and the concentration of an acid can be varied by dilution, allowing a selective dissolution of heavy metals. With fusion, mostly restricted to the determination of a total metal content, large amounts of salts are introduced into the sample solution with high background signals as a result.

Depending upon the decomposition technique, different amounts of heavy metals are extracted from sediments [6]. A total metal content of sediments cannot be used as a criterion to assess the potential effects of a contamination: the molecular form of a component determines largely its properties. The partitiong of trace metals over different geochimecal fractions furnishes information about the origin and the physicochemical (i.e. mobilization and transport), and the biological availability.

A selective dissolution of different geochemical phases has been used for the separation of detrital and non-detrital fractions in carbonate rocks (Hirst), of Fe-oxide fractions of polymetallic (ferro-manganese) nodules (Arrhenius), and of ferro-manganese and carbonate minerals (Chester) [7].

In multi-step sequential extraction Gibbs distinguished between "readily available" heavy metals (in solution or adsorbed), "less available" metals (bound by complexation in organic material or by coprecipitation in metallic hydroxides thus only released by chemical attack) and "nearly unavailable" heavy metals which are bound in crystal structures. Later Engler introduced the "easily" and"moderalety" reducible phases. The sequential extraction sheme of Tessier was improved by Salomons and later by Kersten who made a distinction between exchangeable cations, a carbonate fraction, easily reducible phases (Mn-oxide and partly amorphous Fe-oxyhydrates), moderately reducible phases (amorphous and poorly crystallyzed Fe-oxyhydroxides), a fraction bound to organic matter and sulfides and a residual fraction (detrital silicates and crystalline Fe-oxides) [8]. Welté separated the moderately reducible fraction just before the final lithogenic phase and attacked the residual phase with concentrated nitric acid [9]. Roger compared two different sequential extraction procedures and found that readsorption phenomena minimized the first steps and overemphasized the last ones. Kheboian found a redistribution of metals during the selective extraction and their conclusions were commented by Tessier [10]. While multi-step sequential extraction techniques are more useful than single-step extractions for predicting long-term adverse effects on the environment from contaminated sediments, considerable problems remain or are generated. Indeed several extraction solutions have insufficient selectivity, the ratio solid matter/volume extracting solution is sometimes critical, especially when the sample has a high buffer capacity, each treatment must be checked whether it forms water-soluble or -insoluble products, and whether readsorption and precipitation take place.

Quite important for evaluating the environmental impact of contaminated sediments is the fact that the portion of the sequential fractions changes according to the sample treatment [11].

A routine analytical procedure must give information on the association of metals with different geochemical components. A three step extraction can be regarded as a minimum and should consist of extraction of exchangeable cations, carbonate fraction and easily reducible phase with 0.1 M hydroxylamine/0.01 M nitric acid at pH 2, extraction of metals bound to organic matter and sulfides with 30 % hydrogenperoxide/nitric acid at pH 2 followed by an extraction with ammonium acetate to remove readsorbed metals and finally an attack of the remaining residue with strong acids, e.g. hydrofluoric/perchloric acid.

Microwave-oven based procedures which have already replaced some conventional digestion techniques with hot plates, muffle furnaces and low-temperature radio-frequency ashing. Complete dissolution of the sample is obtained in about three minutes. The sample may not go dry during heating, since this would result in losses of silicon, as gaseous silicontetrafluoride, and possibly other volatile elements. Up to 100 samples per person and per day can be prepared for analyses [12].

OTHER SAMPLE TREATMENT METHODS

Methods described above are time-consuming. Substantial time-saving can be obtained with microwave drying and digestion techniques. Shorter sample treatment methods have been investigated. The most direct approachis to analyze samples which dit not undergo a chemical treatment. An atomic absorption spectrophotometer equipped with a graphite furnace allows such a direct technique but it remains uncertain whether environmental important metals, such as cadmium, can be analyzed with this method [13].

The solid sample can also be brought into suspension and injecting it into a plasma spectrophotometer.

Particle size of the slurry proved to be important as it passes through a nebulizer prior to the injection in the plasma: a diameter of 2 um couldn't be exceeded, larger particles gave unstable signals. The direct slurry-injection technique showed measurable fluctuations of the nebulization process, even when the particle diameter condition was fullfilled [14].

GRAIN-SIZE EFFECTS

Variation in heavy metal concentration of sediments is related to the granular composition. The coarse-grained quartz fraction (63-500 µm) contains less heavy metals than gravel (>1 mm), especially the fine-grained silt fraction (<63 µm) and clay minerals (<2 µm).

Grain-size correction aims to reduce the chemically inert sediment fraction: coarse-grained quartz, feldspar and carbonate minerals. Several corrective methods are possible [15]. A relevant grain size fraction using a settling tube for <2 µm particles (the "Atterberg" technique) or a sieve for fractions >16 µm can be isolated. The isolation of the <63 µm fraction (63 µm is the break between sand and silt on Wentworth's Ø-scale) has been advocated. An important argument in favor of the <63 µm fraction is that trace metals are present mainly in clay and silt particles and that this fraction is nearly equivalent to material in suspension which is by far the most important way of sediment transport. As the difference sand/silt is, also put at 40 µm, some authors prefer the use of 60 µm sieves. Yet, separations are time-consuming, especially the Atterberg technique, and sieves sometimes contaminate sediments: the welds of a stainless steel sieve produce a contamination by tin, zinc, cadmium and especially lead; nylon sieves may loose zinc [16].

ANALYTICAL METHODS

Fine-grained particles (<63 µm), with the same characteritics as suspended matter act as vectors for transport of heavy metals. Analyses of sediments must give information either on the particles themselves, and on their surface structure or on the nature, amount and properties of the heavy metals pollutants adsorbed on the particles. It can be performed by microbeam techniques [17]. Multi-element analysis is a trend observed in the last years. Atomic emmision spectroscopy (AES) using plasma excitation (inductively coupled ICP and direct current plasma techniques DCP) gained ground in the last decade because of its low limit of detection and wide dynamic range [18]. The multi-element capability is made possible by selection of a wavelength free from interferences. The strongest possibility of AES is ICP-mass spectrometry (ICP/MS) which utilizes an ICP as ion source and a quadrupole mass spectrometer as detector. It is mor sensitive and has fewer spectral interferences than in conventional ICP. In nuclear activation, reactor neutrons and accelerator-produced charged particles, e.g. protons, and high-energy photons induce the emmission of gamma-rays. Due to charged particles' limited penetration range (<0.5 mm) this allows only near-surface analysis [19]. X-ray fluorescence spectrometry (XRF) offers a large dynamic range and a relative speed [20]. Energy and wavelenght dispersive XRF techniques are generally adopted in geochemical analysis. Mass spectrometry is mainly used for a precise determination of the isotope ratio in geochronology.

The bulk of sediment analysis is still done with more conventional single-element methods such as atomic absorption spectrometry (AAS). Flame-AAS remains less sensitive than graphite-furnace AAS. Preconcentration, e.g. chelate extraction into organic solvents, helps to overcome partly this inconvenience [21]. In hydride-generation AAS, elements such as As, Sb and Se are volatalized using e.g. sodium-borohydride. Primary interferences are caused by the presence of other hydride forming elements for instance from the platinum group. The cold vapour technique for determination of mercury is still in use in sediment analysis [22]. Electroanalytical methods, e.g. anodic stripping voltammetry are more suited for analysis of heavy metals in water [23].

EVALUATION OF HEAVY METALS CONTAMINATION OF DREDGED MATERIAL (table 1)

The environmental impact of (polluted) sediments must be evaluated from both chemical and biological point of view. Chemical criteria must encompass all possible contaminants, each with at least three levels: a "no-pollution" (=background), a "possibly" and a"strongly" contaminant level, a decision making procedure with quidelines on how to manage contaminated sediments, and precise methods for analysis of the samples (the same methods as used for the draft of the contamination levels). In The Netherlands the Waterways Administration (Rijkswaterstaat) elaboarated criteria which were also used in the Soil Quality Note. The concentration of a metal is compared with reference values.

TABLE 1 OVERVIEW OF SEDIMENT QUALITY CRITERIA

Metal	The Netherlands[a] GEL	ASL	ALL	USA/ EPA[b]	Canada/ OME[c]
Cadmium	2	7.5	30	6	1
Mercury	0.5	1.6	15	1	0.3
Arsenic	85	85	150	3-8	8
Chromium	480	480	1.000	25-75	25
Copper	35	90	400	25-50	25
Nickel	35	45	200	20-50	25
Lead	530	530	1.000	40-60	50
Zinc	480	1.000	2.500	90-200	100

[a] Soil Quality Note. See also Report of the House of Representatives. The Hague, No.21250 (1-2), 1988-89
GEL: general environmental quality; ASL: assessment level; ALL: alarm level.
[b] EPA Guidelines (1982)
[c] Ontario Ministry of the Environment (OME).
All concentrations expressed in mg/kg dry matter.

In the USA, EPA guidelines help to judge dredged materials: each metal has two values, the lowest one corresponds with a "no-pollution" level, and the highest with strongly contaminated sediment. Only upper values are published for cadmium and mercury (table 1).
Figures comparable with those from EPA are found in the Guidelines from the Ontario Ministry of the Environment which foresee, for dredged material with metal content exceeding the upper limit, land disposal under strictly controlled conditions;an "environmental impact procedure" must be used to manage the disposal area (table 1).
Other authorities published criteria regarding the quality of soils and of liquid and solid drainage products, e.g. the London Dumping Convention and the USA Army Corps of Engineers-Waterways Experiment Station.

Biological tests or bioassays evaluate the possible transfer of heavy metals to the bio-environment. Chemical analysis, e.g. sequential extraction,give only a limited view on biotransfer. Four questions have to be answered by bioassays[24]:

(1) which heavy metal fraction is bio-available? The bio-availability of heavy metals in sediments is related to the solubility and the mobility of the metal which is affected by salinity, synthetic chelators, pH, redox potential and biomethylation.
(2) How much of the heavy metal is taken up ? Sequential extractions can give a partial answer to that question.
(3) How does the uptake works ?
(4) What is the level of (ecological) toxicity of pollutants ? Zoo- and phytotoxicity depends upon factors such as concentration and specific toxicity of the pollutant, intrinsic sensitivity of the organism and the exposure time. Conventional toxicological parameters, e.g. the no-effect level (NEL), concentration-factor (CF = tissue concentration/sediment concentration) and the lethal concentration 50 % (LC 50) can describe the ecological

toxicity.

CONCLUSION

Environmental conditions have been altered, even seriously deteriorated, particularly during the period 1930-1970.

Industrial expansion, population concentrations, lower mortality and a throw-away philsophy, all contributed to the rapid intensive pollution of sediments.

Two topics, to be studied, developed from this situation to which few paid any attention until lately: how could the intensity of such pollution be scaled, and, how can we foster abatement [25]?

Though a new sampling procedure has been devised, very little change, let be improvements, have been reported in methodology over the last years. Only limited satisfaction has evolved from time-consuming decomposition methods. Equally virtually unchanged has been the study of grain size effects. Analytical methods have been marked by an evolution toward multi-element techniques.

What evalution can we make ? Candidly put, the current situation remains rather muddled, perhaps due to the lack of data pertaining to the analysis of sediments, thoyghit must be stressed that bioassays are a most important tool to evaluate the environmental impact of dredged materials.

Disposal of tainted sediments remains a priority problem. More dumping will not do any longer, hence the development of "environmental impact assessment procedures", absolutely necessary for proper management of disposal areas. Construction of artificial islands as dumping- and/or -processing sites for wastes has been suggested and, in some cases, implemented. Evidently, highly contaminated sediments need to be treated prior to "disposal"[26].

The use of dredged sediments has been suggested in agriculture: however, such practice carries inherent dangers, and it should be restricted to sediments containing no pollutants and sufficient rich in nutrients, viz. essential elements needed by plants.

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CONSOL : A COMPUTER SIMULATION MODEL FOR THE CONSOLIDATION OF DREDGED MATERIAL

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ABSTRACT

The consolidation of silt is a very complex process. CONSOL is one of the first attemps to translate the dispersed empirical knowledge about sediment consolidation into a global mathematical approach. A module on the prediction of evaporation and shrinkage characteristics has been included.
The model has been calibrated based on a series of laboratory experiments (consolidation colums) and has been applied to predict the consolidation of different types of silt in the Antwerp region.
The model is developed based upon the finite difference technique and can be used in a PC and workstation version.

INTRODUCTION

The consolidation rate of fine grained material becomes one of the most critical parameters to find an acceptable solution for the treatment and storage of maintenance dredged materials because the available reclamation area becomes deficient.
An adequate prediction of this consolidation rate under different boundering conditions concerning drainage, layer thickness, initial density, a.s.o. will contribute to an efficient utilisation of the remaining areas.
Laboratory experiments are one of the possibilities but they have some disadvantages such as :

- long duration of the experiment (timescale = 1/1)
- problems with oxidation and algue growth in the columns
- difficulties to simulate underdrainage and evaporation effects

To avoid these shortcomings and technical problems a well calibrated mathematical model is a most promising tool. CONSOL opens new perspectives for an in depth evaluation of a large number of different alternative solutions in an economical way. Only a few laboratory and/or prototype tests are required for the calibration of the model.

MODEL DESCRIPTION

Scope of the model

Before the start of the theoretical modelling activities the following targets were formulated :

- The model has to simulate settling and consolidation phenomenae in one dimension.
- Evaporation and shrinkage effects should be included.
- Different boundary conditions concerning drainage and waterlevels should be possible.
- The model should accomodate different kinds of silt regardless grainsize distribution and mineralogic characteristics.

In order to respond to the above mentioned requirements, each type of silt is characterised in the model by the following calibration functions :

- Conductivity function : relation between hydraulic permeability, void ratio and water content.
- Consolidation function : relation between void ratio and effective stress.
- Retention function : relation between pore water pressure and water content.

Basic theory

A detailed description of the model and its basic functions can be found in ref 1. In this paper only the most important features are described. For the **conductivity function** in saturated soils three alternative approaches are possible :

- The first one is based on the theoretical approach of Kozeny-Carman (1972) (ref 2).
- The second one supposes a logaritmic function between void ratio and permeability (applied by Been and Sills, Van Tol, Blümel and Taminga (ref 3, 4 and 5).
- Any empirical curve (to fit measured data).

Unsaturated states of the consolidating silt layers are modeled as a function of the water content and the conductivity in saturated state

$$K = K_S\, w^c \qquad (1)$$

with :

K : permeability in unsaturated conditions
K_S: permeability in saturated conditions
w : water content
c : empirical constant

For the **retention function** in unsaturated soil conditions three alternatives are possible:

- The approach of Corey (ref 6)
- The relation of Van Genuchten (ref 7)
- Any empirical curve

The **consolidation function** is the most important one and expresses the internal stress due to the self-weight of the silt layers and due to external forces. The total internal stress can be subdivided into pore water pressure and effective stress.

Consolidation results in a compaction of the silt. Theoretical and laboratory experiments have shown a relation between the effective stress and the void ratio.

An exponential relation is proposed :

$$e = e_\infty + (e_0 - e_\infty)\,(1 + \sigma/\sigma_0)^{-\beta} \qquad (2)$$

with :

e : actual void ratio
e_∞: minimal void ratio at an infinite effective stress
e_0: maximal void ratio at zero stress
σ_0 , ß : empirical constants

For unsaturated soil an additional phenomenon exists : the shrinkage. Raedschelders (ref 8) and Bronswijk (ref 9) have shown a relation between water content and void ratio (see fig.1). Shrinkage occurs till a limit water content (w_∞). At that moment the shrinkage limit has been reached at a void ratio e_∞.

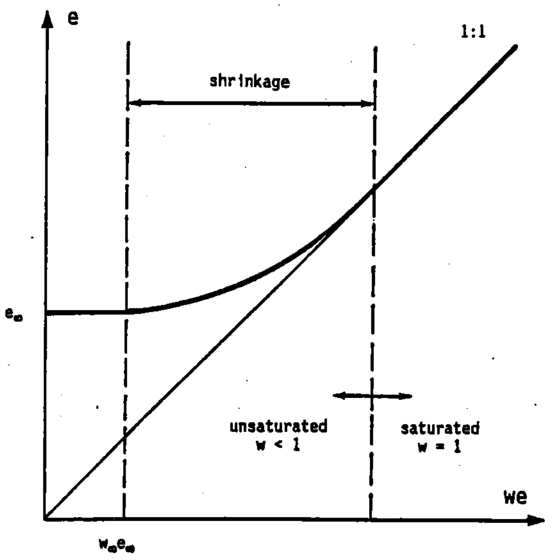

FIG. 1 : SHRINKAGE CHARACTERISTICS

The model

The pore water transport is caused by two phenomenae :

- a flow due to different hydraulic potentials, described by the well-known Darcy formula;
- a (slow) global movement of grains and pore water due to settling and consolidation.

The overal equation for the pore water is (ref 2) :

$$\frac{\delta q}{\delta z} = \left[\frac{\delta we}{\delta e}\right] \left[\frac{d\epsilon}{dt}\right] \qquad (3)$$

with :

q : flow
w : water content
e : void ratio
ϵ : settlement
t : time

From this equation we see that a flow of pore water results in an increased settlement depending on the relation between w and e. The solution depends on the boundary condition above and beneath the silt layer which can vary from one simulation to the other.

The top boundary conditions are determined by :

- the existence of a water layer on top of the silt (surface drainage conditions)
- rainfall charcteristics
- evaporation charcteristics
- infiltration conditions

The bottom conditions can vary as indicated in fig. 2 :

- an impermeable bottom (1)
- a drainage layer with a fixed potential (2)
- a natural bottom (3a and 3b)
- drainage ditches with horizontal transport of the pore water (4)

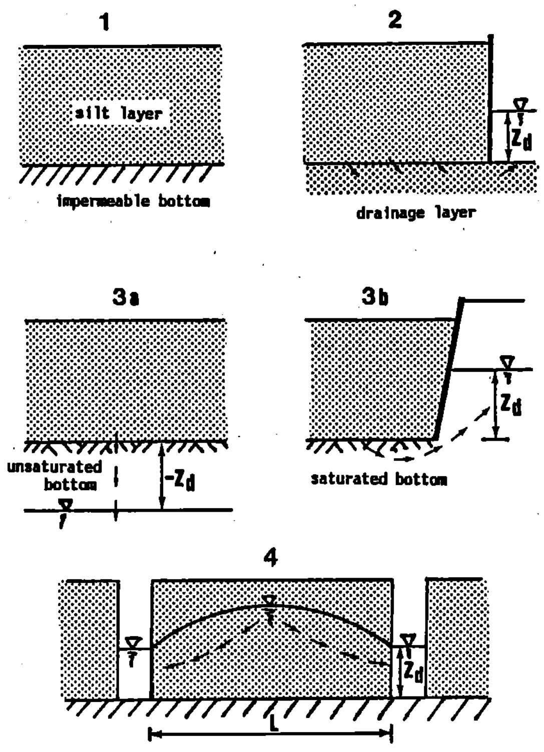

FIG. 2 : BOTTOM CONDITIONS

Mathematical solution

The partial differential equation (3) is solved using the finite difference technique. The silt layer is divided into a series of sublayers with constant characteristics. From an initial density or void ratio the other parameters are calculated as well as the pore water fluxes based on the Darcy equation and the imposed boundary conditions. The consolidation is calculated from equation 3 at different time steps Δt. For each sublayer the volumetric settlement is calculated as well as the resulting void ratio, shrinkage and water content. Finally the resulting density is calculated as a basic data for the next time interval. A flow chart of the program is given in fig.3.

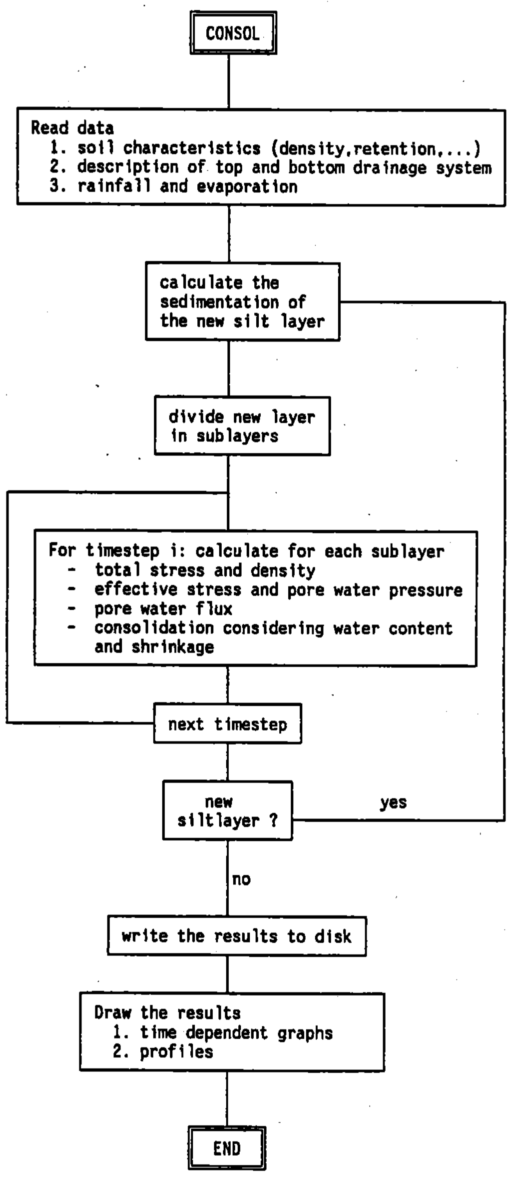

FIG. 3 : FLOW CHART OF CONSOL

Model results

During each run all characteristics are simulated as a function of time and depth. Each of the following figures can be generated automatically by the program:
- mud layer thickness vs. time
- water heigth vs. time
- total heigth vs. time
- efflux volume vs. time

as well as the following profiles :
- silt density vs. heigth (fig.4)
- porosity vs. heigth
- water content vs. heigth (fig.5)
- hydraulic potential vs. heigth
- shrinkage vs. heigth
- effective stress vs. heigth
- total stress vs. heigth
- pore water pressure vs. heigth
- hydraulic conductivity vs. heigth (fig.6)
- pore water flux vs. heigth

A few of the above mentioned graphics are selected in fig. 4 to 6 resulting from the consolidation of a 2 meter silt layer (initial density 1.10 kg/m^3) with surface and under-drainage and an evaporation potential of 1 mm/day.

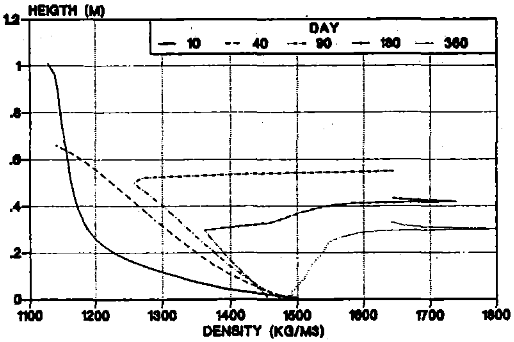

FIG. 4 : EXAMPLE 1

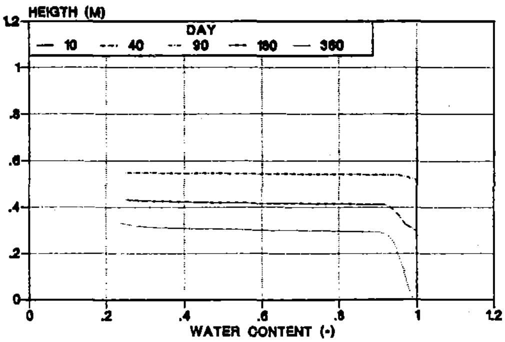

FIG. 5 : EXAMPLE 2

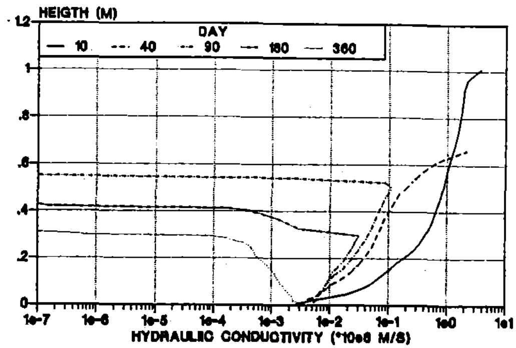

FIG. 6 : EXAMPLE 3

Model test

The model has been tested based on a laboratory experiment by Been and Sills (ref 3) in which a consolidation column of 0.64 m height and an initial density of 1142 kg/m^3 with undrained conditions has been monitored during 35 days (including regular density profiles). Fig. 7 and 8 show the high similarity between the laboratory results and the model calculations if enough calibration data are collected from careful laboratory tests.

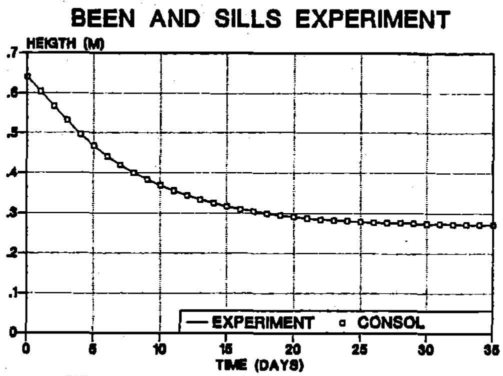

FIG. 7 : EVOLUTION OF THE LAYER TICKNESS

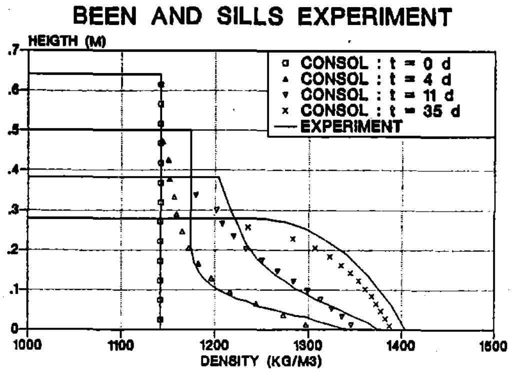

FIG. 8 : DENSITY PROFILES

APPLICATIONS OF THE MODEL

General remarks

Since its development the CONSOL model has been used for different projects mainly for the evaluation of different boundary conditions at the planning stage of projects (ref 10, 11) such as the influence of initial density and layer thickness, of high evaporation values, of an underdrainage system, a.s.o.
Some of these results are discussed further. For these tests a typical silt has been chosen with a low sand content of 10 to 20 %. The different calibration curves are chosen based on available geotechnical data and on a litterature survey.

Layer thickness with constant initial density

A series of four runs have been calculated under identical conditions (initial density of 1.10 t/m^3 surface and underdrainage , normal evaporation of 1mm/day) in which only the layer thickness has been varied between 0.5 and 2 m. From fig. 9 it can be seen that the average density of the whole layer increases faster when the initial layer thickness is smaller especially during the first months.

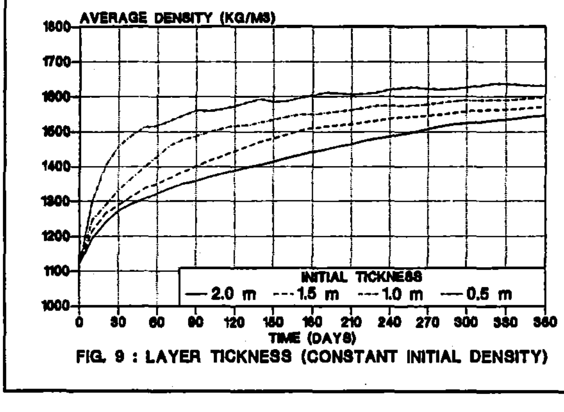

FIG. 9 : LAYER TICKNESS (CONSTANT INITIAL DENSITY)

Initial density with constant silt load

A second series of four runs has been simulated with a varying initial density and layer thickness, so that the total sediment load (kg of dry material per m^2) remains constant.
From fig. 10 it can be seen that the evolution of the average thickness is very similar for all four simulations. This shows the importance of the total sediment load (tons dry material/m^2). For an efficient dewatering process in a dewatering field this will be the main parameter to influence the required consolidation time.

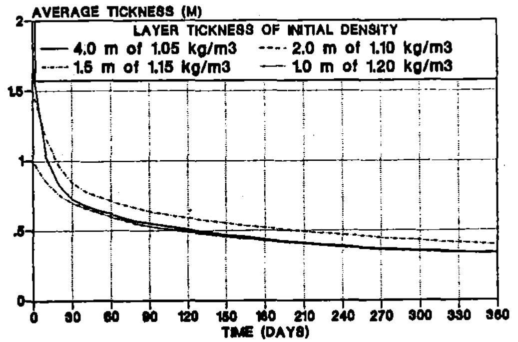

FIG. 10 : INITIAL DENSITY WITH CONSTANT SILT LOAD

Evaporation influence

A third series of runs has been calculated with a variable evaporation rate between 0 and 8 mm/day (rainy winterday vs. a very hot summerday). The calculations have been done for an initial layer thickness of 2 meter and an initial density of 1.10 t/m^3.
The influence of the evaporation is limited due to the creation of a hard crust which "protects" the underlying layer from further drying (fig.11). When the initial sediment load is reduced the relative importance of evaporation will increase.

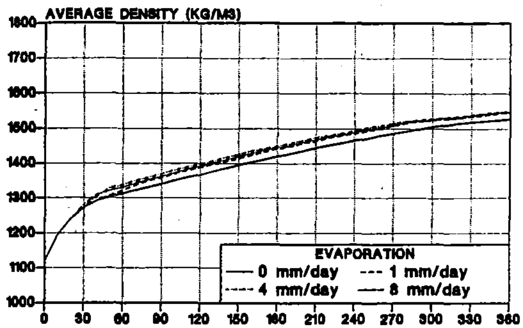

FIG. 11 : EVAPORATION INFLUENCE

Other parameters

A final series of runs aims to evaluate the relative importance of the different techniques (fig.12). Each of the runs differs from the former only by one parameter :

- run 4.1: no underdrainage, no surface drainage, no evaporation
- run 4.2: underdrainage, no surface drainage, no evaporation
- run 4.3 : under- and surface drainage, no evaporation
- run 4.4 : under- and surface drainage, 1 mm evaporation

From fig. 12 it can be seen that drainage is by far the most important parameter for a quick dewatering of a silt layer. An efficient drainage consists of both a good surface drainage system and an underdrainage system.

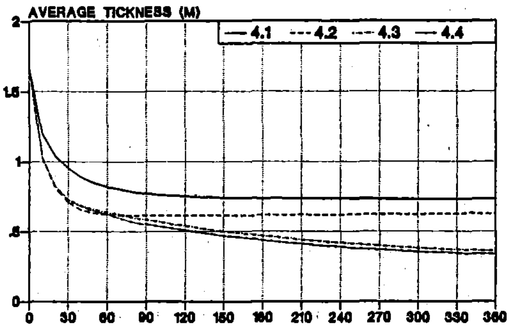

FIG. 12 : INFLUENCE OF BASIC PARAMETERS

CONCLUSIONS

- From the different applications realised with the CONSOL model it can be concluded that the model is an efficient tool to evaluate and select the best boundary conditions for a given silt which has to be dewatered.
- Drainage conditions, both surface and underdrainage systems, are very important for an efficient consolidation process.
- The sediment load is the main parameter to influence the consolidation time of a certain silt.
- The initial density of the hydraulic fill of a dewatering field is of secondary importance of a good drainage system is provided.
- The evaporation phenomenae influence only a thin layer at the surface of the fill.
- Some efforts are required to gather enough data on the different silts in order to select realistic calibration parameters and curves which are necessary to take full advantage of the potentialities of the CONSOL model.

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SEQUENTIAL ANALYSIS AS A TOOL FOR THE ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF CONTAMINATED DREDGED SLUDGE

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ABSTRACT

Sequential analysis is a technique aiming at the successive destruction of specific sedimentary phases; simultaneously, pollutants linked to these phases are liberated.

Our method includes five different steps :

1. in the first step, a buffer of pH = 5 liberates the adsorbed ions and the carbonate phase
2. in the second step, hydroxylammine at pH = 5 reduces the iron and manganese oxyhydroxides
3. in the third step, the acid sensible fraction which is left after the previous steps (the reducible, exchangeable and carbonate fractions are also acid sensible) is destroyed at pH = 2
4. in step 4, the oxidizable fractions (particulate organic matter and medium stable sulphides) are eliminated
5. step 5 involves the total destruction of the remaining sedimentary fraction and represents the residual crystalline phases

Severe testing of the method indicated that the various chemical reagents are applied in an order of increasing aggressiveness. Inversing some of the steps leads to a strong reduction of the amounts liberated by former previous step(s).

INTRODUCTION

The distribution of trace metals between the dissolved and solid (sediment) phases in aquatic systems, is governed by a series of parameters, one of them being the composition of the solid matter (e.g. Duinker et al., 1982; Balls, 1989; Baeyens et al., 1987). This means that a specific metal will preferentially bind to a specific sediment fraction and as a consequence will only be mobilized when that sediment fraction is degraded or modified. In a sediment, spatial and temporal pH and redox variations are currently observed. In fact, redox conditions can vary from oxic over suboxic (this corresponds to the zone of Fe (III) and Mn (IV) reduction) to anoxic (this corresponds to the zone of sulphate reduction). Corresponding to these Eh-pH changes, some specific sediment fractions are altered.

In order to be able to predict mobilization of trace metals from sediments, we have developed a sequential extraction scheme, that simulates the natural Eh-pH changes. According to successive extractions, the different lithogenic phases of the sediment are destroyed, and at the same time the associated metals liberated.

The mobility of the metals associated to the sediment decreases after each extraction step. The scheme we use is a modification of the schemes reported by Robbins et al. (1984) and Förstner and Patchineelam (1981). It distinguishes five different sediment fractions :

1. the exchangeable and carbonate fraction;
2. the reducible fraction;
3. the acid sensitive fraction (this is the fraction remaining after steps 1 and 2 and dissolving at pH 2);
4. the oxidizable fraction (organic matter and sulphides);
5. the residual fraction.

METHOD

DESCRIPTION

The sediment is immediately after sampling stored in an inert atmosphere, in order to avoid oxidation of reduced sediment fractions and a redistribution of the metals over the various sediment fractions. The extraction steps are also carried out soon after sampling to avoid aging of the sediment (bacterial processes modify the sediment composition on a longer time scale).

The first two extraction steps occur in a glove box under an inert atmosphere.
After homogenization of the sample, several subsamples are taken : they are used for determinations of porosity, major elements including organic carbon, trace elements and also for the sequential extraction procedure. The extractions are carried out on 2 gram sediment (two replicates) in the following way :

Exchangeable and carbonate fraction

The sample is two times extracted with 40 mL of 0.516 M acetic acid, buffered with 1 M sodium acetate to pH 5, during 2 hrs.
Afterwards, the extractans and the sediment are separated by centrifugation.

Reducible fraction

The residue of extraction step 1 is two times extracted with 40 mL of 1 M hydroxylamine buffered with 0.175 M sodium citrate to pH 5, during 2 hrs.
Afterwards, the extractans and the sediment are separated by centrifugation.

Acid degradable fraction

The residue of extraction step 2 is three times extracted with 33 mL of 0.01 M nitric acid. Afterwards, the extractans and the sediment are separated by centrifugation.

Oxidizable fraction

The residue of extraction step 3 is two times oxidized with 100 mL of 30 % hydrogen peroxide (at pH 2), until dryness.
Then the residue is extracted (overnight) with a 1 M ammonium acetate solution in 6 % nitric acid.

Afterwards, the extractans and the sediment are separated by centrifugation.

Residual fraction

The residue of extraction step 4 is lyophilized. To 0.25 g of this dry sediment, 6 mL hydrochloric acid, 2 mL nitric acid and 2 mL hydrogen fluoride is added. The teflon container is then heated to 60 °C during 12 hrs.
Afterwards, the solution is evaporated and the residue redissolved in 4 % nitric acid.

After the extraction, the solutions are acidified with ultrapure nitric acid to pH 1 and stored for analysis in pretreated polyethylene containers.

TESTING THE AGGRESSIVENESS OF THE EXTRACTION STEPS

The extraction scheme we use, has been chosen on the basis of the aggressiveness of the various extraction solutions. Indeed, steps 1 and 2 are carried out at a pH of 5, but the extraction solution in step 1 contains only buffer, while in step 2 it also contains a reductor. Step 3 is carried out at pH 2, a much more acidic medium as for the previous steps. The extraction solution in step 4 is also at pH 2 but contains in addition an oxidant; moreover, the extraction occurs at 60 °C and not at room temperature as it is the case in the previous steps. Finally, step 5 is a total destruction method involving hydrogen fluoride.

In order to verify the assumed aggressiveness of the various extraction solutions, we changed the extraction scheme. Instead of using the normal sequence (1 to 5), we applied the extraction solutions in a random order. Therefore, we prepared a large, dried and homogenized sample, collected in the Scheldt estuary. To avoid stability problems with the sample, all experiments were carried out in a relatively short period (about 14 days).

Fe and Mn were the selected metals in these experiments, because their total concentrations were relatively high, and their distribution over the five sediment fractions quite different.

From the results shown in figures 1a to 1j the conclusions summarized in the next paragraph can be drawn.

The fifth extraction step deals with the determination of the residual metal concentration in the sediment by using a total destruction method. When this step is performed earlier than the last one, it is logic that no more metal will be extracted afterwards.

In all our experiments, the fifth extraction step has been maintained at the last position. When the fourth or acid-oxidation step is placed in first position, then the sum of this fraction and the residual fraction always exceed 95 % of the total metal content.

Hence, extraction steps 1 to 3 should always be performed before steps 4 and 5. If for example step 4 is performed in second position, the two steps afterwards, independently which of 1, 2 or 3, do not yield any additional extracted metal.

Steps 1 to 3 are far less aggressive than the last two ones, and for them it is much more difficult to assess to what extent they also extract metals belonging to the next step; in other words to what extent do the first three steps overlap ?

From the obtained results, it appears that each of the first three steps maintain in anyway a certain specificity. The step placed in an earlier position will become more important compared with the two other ones (the metal extraction yield will be higher), but never eliminate them.

In a first approximation, it seems that extraction step 2 is somewhat more aggressive than steps 1 and 3 (step 2 yields somewhat higher Fe and Mn concentrations than steps 1 or 3), but this may also be due to the nature, the specificity of the sampled sediment.

The reducible Fe and Mn compounds seem not or difficultly mobilized by extraction steps 1 and 3.

We also carried out experiments where we added in step 2 (which consists of two subextractions) a spike of oxidized Fe or Mn to the sediment.

Four different situations were simulated :

1. no addition, thus the standard procedure
2. an amount x of metal oxide is added at the start of the extraction procedure
3. an amount x of metal oxide is added between the first and second subextraction
4. an amount x/2 of metal oxide is added before each of the two subextractions.

These experiments indicated that within the variability of the method (about 10 % for each step), the spike of oxidized metal was recovered.

Finally, it was remarkable to notice that, independent of the order of application of the first three steps, the sum of the extracted metals (Fe and Mn) for these three steps remained fairly constant : between 23.7 and 26.9 % for Fe, between 74 and 82.9 % for Mn despite the large difference in distribution of both metals over the lithogenic sediment phases.

APPLICATION OF THE SEQUENTIAL EXTRACTION METHOD

Since sequential analysis results can give us information about the impact of a contaminated sludge on the environment, it is a useful tool to select the best destination for such material.

For the Hooge Maey including the "Zandwinningsput" at Antwerp, a restructuration and sanitation plan must be developed. The "Zandwinningsput" contains dredged sludge, contaminated by several inorganic and organic pollutants (Mondt et al. 1991), so to select the best treatment procedure or to decide for an alternative destination, sequential analysis results are very useful.

According to total sediment analysis (Mondt et al. 1991), the "Zandwinningsput" can be subdevided into three zones.

In each of these zones sequential analysis have been carried out for manganese, cadmium and lead.

MANGANESE

More than 1/3 of the total amount of Mn present, is found in the first and most mobile fraction of the sludge and more than 60 % is found in the fractions 1 and 2 (for zone 1 only 50 %).

This means that an increase in the ionic strength (a higher salinity) of the interstitial water of the "Zandwinningsput" or a lowering of the redox potential, can potentially mobilize 60 % of the manganese content in zones 2 and 3, and 50 % in zone 1 (these values are maximum prognoses).

The mobilization rates related to the first two fractions of the sequential extraction method are very fast. Desorption of manganese adsorbed onto the surface of sediment particles or dissolution of manganese carbonates (at pH 5 and high ionic strength) and manganese (IV) reduction reactions are chemical reactions and are much faster than for example bacterial degradation rates of organic matter.

If thus the ionic strength of the interstitial water would increase and the pH reaches a value of 5, or if the sediment would become anaerobic, then all or part of the manganese belonging to fractions 1 and 2 can rapidly enter the interstitial water and eventually the percolate water.

About 13 to 15 % of the manganese content belongs to extraction step 3. This fraction can only be mobilized when the pH decreases strongly (the pH has a value of 2 in the extraction solution). Such low pH values were never observed in the "Zandwinningsput"; when 10 g mud was diluted with demineralized water to 100 g, all pH values exceeded 7.

In extraction step 4 we cannot distinguish between organic bound manganese and manganese sulphide. Organic bound manganese will be slowly liberated through the action of bacteria.

The sulphides found in this fraction have a medium stability (not enough soluble to be dissolved at pH 2, and not stable enough to belong to the residual fraction), or they are covered by an organic layer so that they only dissolve after the organic coating has been removed.

Only 10 % of the manganese content belongs to this fraction.

The last fraction is the residual one. This fraction represents manganese that only can be dissolved through a very strong acid treatment (a total destruction), and is harmless for the environment. Between 13 % (zone 3) and 26 % (zone 1) of the manganese is found in this fraction.

CADMIUM

More than 1/3 of the total amount of cadmium in the sludge (even more than 50 % in zone 1) belongs to fraction 4. Cd is thus essentially bound to a fraction which can only be removed by oxidation.

This fraction includes the organic compounds as well as the sulphides of medium stability (see also the discussion of fraction 4 above for manganese). The organic bound cadmium will only slowly be liberated in the interstitial water by bacterial activity. Oxidation of sulphides can occur faster.

Still 1/3 of the camium in the sludge is present in fractions 1 and 2. These fractions are degradable when the ionic strength increases in the interstitial water or when the sludge becomes anaerobic. Moreover, these fractions are very mobile and their dregradation rate is high.

In the residual and for the environment non-dangerous fraction 5, practically no cadmium is present (1.5 % to 2.3 %).

LEAD

More than 60 % of the total amount of lead in the sludge (more than 50 % in zone 1), is present in fractions 1 and 2.

These values are comparable to those for manganese, and mean that a large part of lead is very mobile. An increase in the ionic strength of the interstitial water or a lowering of the redox potential leads to lead liberation.

This relatively large mobile lead fraction may be an explanation for the higher heterogeneity observed for lead concentrations in the bulk as well as the fine grain size sediment fractions in the "Zandwinningsput" (Mondt et al. 1991).

The oxidizable fraction (organic and sulphide bound lead) contains between 15 % (zones 2 and 3) and 30 % (zone 1) of the total lead amount. The slow bacterial liberation or the faster chemically based oxidation, is thus for lead less pronounced than for cadmium.

In the fifth, residual fraction, we find about 15 % of the total lead content. This is much lower than in Scheldt bottom sediments, where this fraction is the most important (Panutrakul and Baeyens, 1991).

CONCLUSION

While analysis of bulk sediment can only give a black or white answer, namely :

1. the sludge is poorly or not at all contaminated and then any destination can be given to it without danger for the environment
2. the sludge is heavily contaminated (more than the accepted level), which implies either a specific treatment or a selected destination

sequential analysis results can inform us about the consequences a contaminated sludge can have on the environment according to the selected treatment or destination.

For the "Zandwinningsput", two scenarios for treatment were examined :

1. removing the sludge and exposing it to the air
2. capping the sludge

These treatments will only have an influence on the sequential extraction fractions 1, 2 and 4. Indeed, the fifth or residual extraction fraction is very inert and will not be mobilized.

Manganese and lead show relatively large amounts in this inert form (13 to 26 % for Mn and 14 to 18 % for Pb), but not cadmium (only 2 %). Concerning extraction fraction 3, it is noticed that mobilization of this fraction only occurs at low pH (lower than 2). Such low values are normally not reached in sludge.

This means that for cadmium 15 to 25 %, for manganese 14 % and for lead 2 % will be neither mobilized. The effects of the sludge treatment on the remaining extraction fractions is summarized below.

Removing the sludge and exposing it to the air

The first extraction fraction is very mobile and sensible to an increase of the ionic strength (salinity) of the pore water. The sludge should thus be isolated from saline surface water, since large fractions of lead (40 to 50 %) as well as manganese (34 to 43 %), cadmium only for 7 to 24 %, can be mobilized in this way.

The exposure of the sludge to the air, results in a relative fast oxidation of organic compounds and sulphides and the liberation of pollutants included in extraction fraction 4.
This fraction contains 32 to 55 % of the cadmiun content, 15 to 30 % of the lead content and 8 to 12 % of the manganese content.

Capping the sludge in the dumping ground

This treatment will in principle not influence the first and very mobile extraction fraction. By placing the sludge, however, in a closed system, it will start fermentating (this means an anaerobic degradation of the organic compounds and the production of gases such as methane).

At the same time, metals bound to the organic fraction (extraction fraction 4 minus the metal sulphides), will be liberated into the pore water.

The situation becomes more complex (but better for the environment from the viewpoint of mobility) as soon as sulphides are being produced. The metals liberated from the organic compounds, reprecipitate then as metal sulphides.

The extraction fraction 2, the reducible fraction, will also be degraded in anaerobic conditions, but again sulphides present in the interstitial water will reprecipitate the liberated metals immediately.

Summarizing this treatment, we can say that in the absence of sulphides, maximum 54 to 65 % cadmium, 29 to 43 % lead and 17 to 38 % manganese can be mobilized into the pore waters, but as soon as sulphides are present, the metals will reprecipitate as sulphide complexes.

Despite the fact that we have made several validation experiments, the sequential extraction method should still be considered as an indicative, and not an absolute, method. In the literature, still conflicting data about trace element readsorption during sequential extraction is reported (e.g. Nirel and Morel 1990; Belzile et al., 1989).

However, together with other approches, microbial techniques, particle analysis, etc... sequential extraction results can yield valuable information about the potential danger of a contaminated sludge.

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Fig. 1.a: sequence 4-3-1-2-5

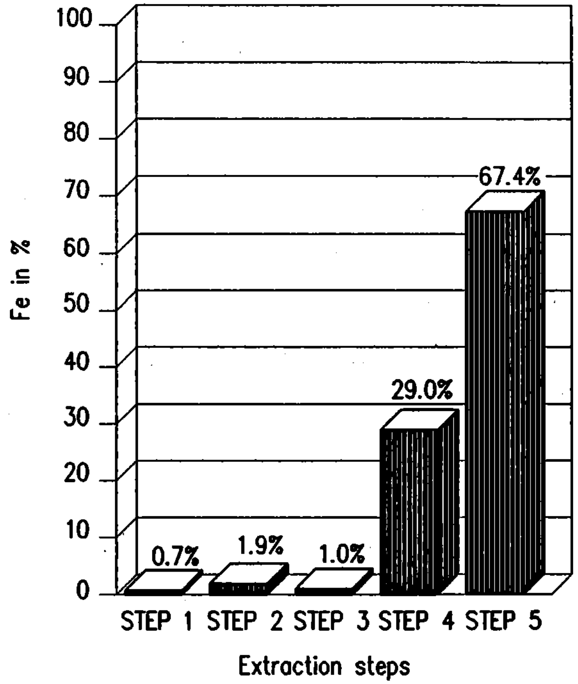
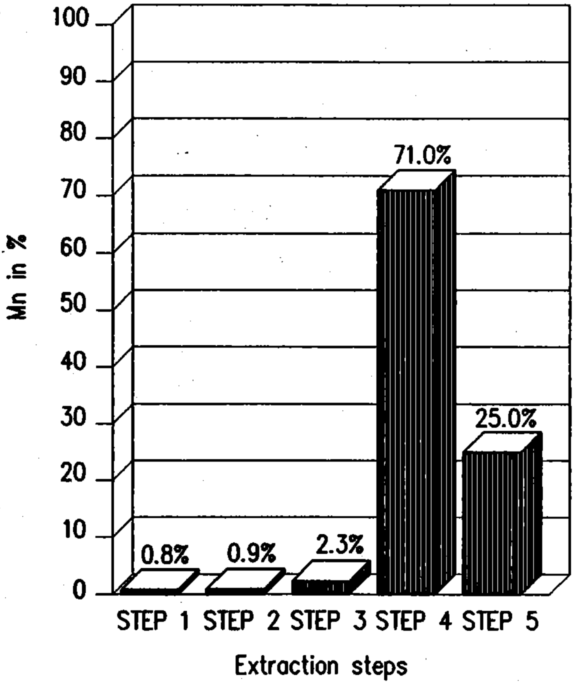


Fig. 1.b: sequence 4-3-1-2-5



Extraction steps:
_ STEP 1: exchangeable and carbonate fraction
_ STEP 2: reducible fraction
_ STEP 3: acid degradable fraction
_ STEP 4: oxidizable fraction
_ STEP 5: residual fraction

Fig. 1.c: sequence 2-4-3-1-5

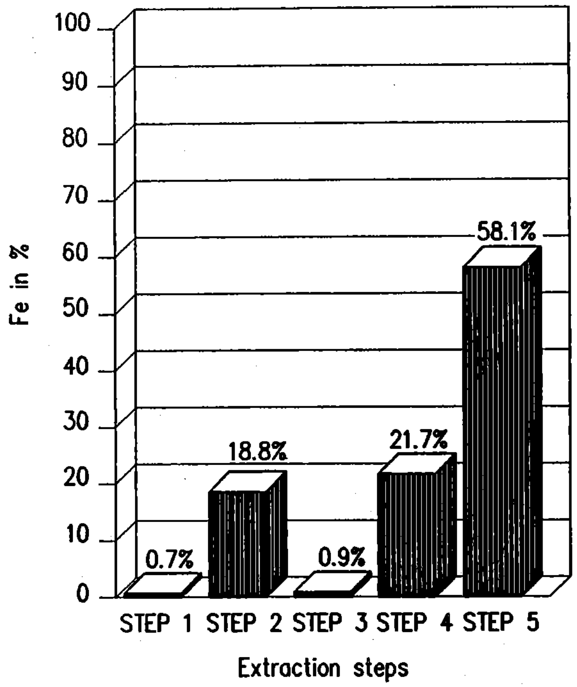
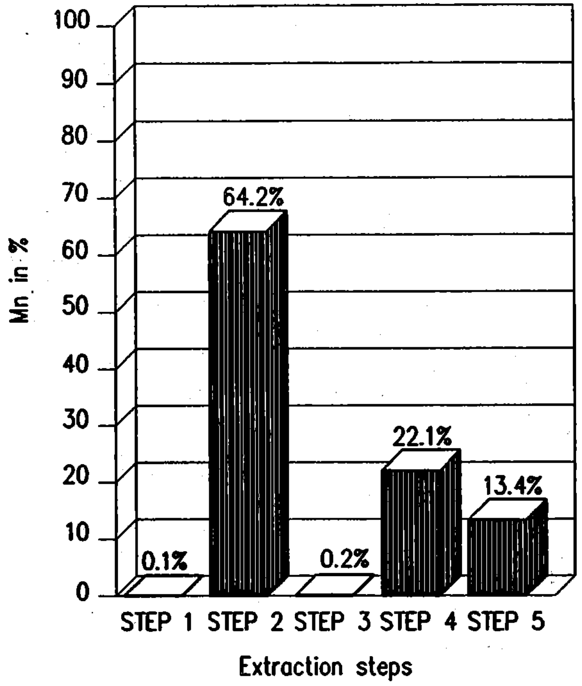


Fig. 1.d: sequence 2-4-3-1-5



Extraction steps:
- STEP 1: exchangeable and carbonate fraction
- STEP 2: reducible fraction
- STEP 3: acid degradable fraction
- STEP 4: oxidizable fraction
- STEP 5: residual fraction

Fig. 1.e: sequence 1-2-3-4-5

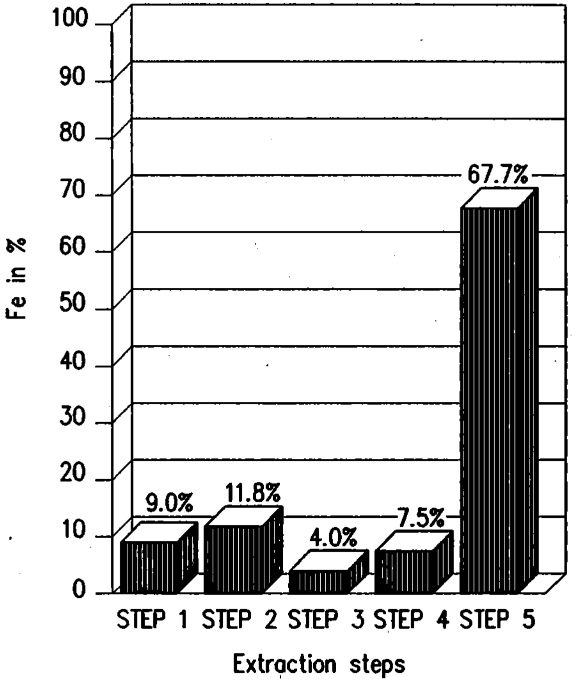
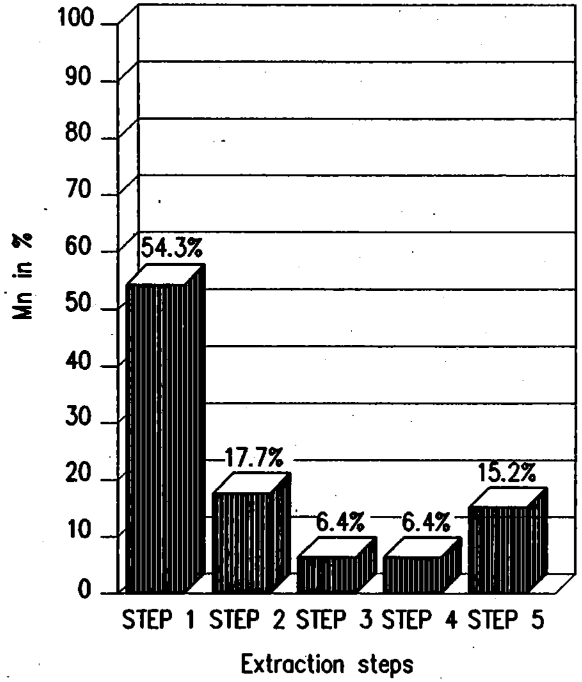


Fig. 1.f: sequence 1-2-3-4-5



Extraction steps:
_ STEP 1: exchangeable and carbonate fraction
_ STEP 2: reducible fraction
_ STEP 3: acid degradable fraction
_ STEP 4: oxidizable fraction
_ STEP 5: residual fraction

Fig. 1.g: sequence 2-1-3-4-5

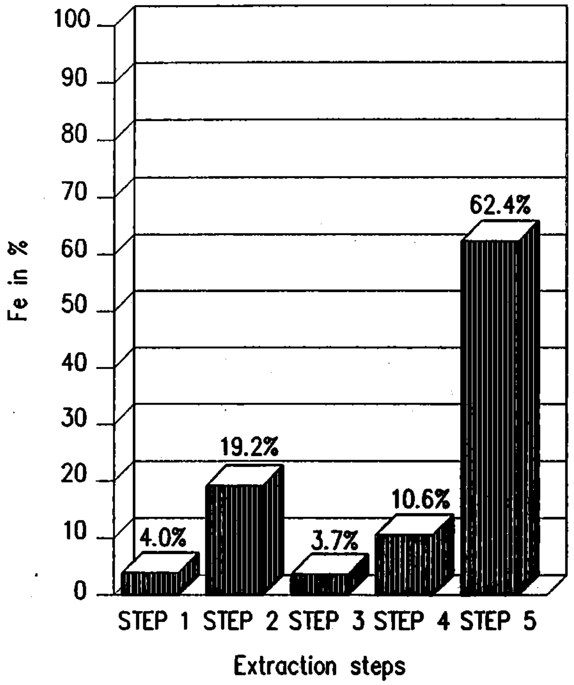
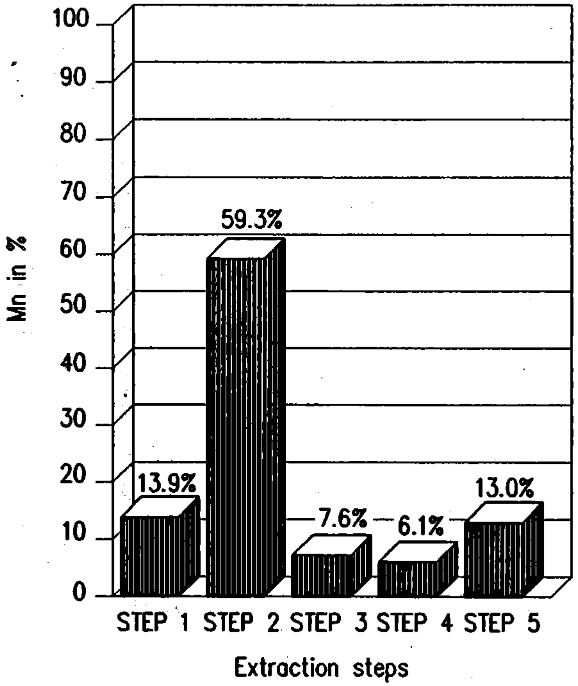


Fig. 1.h: sequence 2-1-3-4-5



Extraction steps:
_ STEP 1: exchangeable and carbonate fraction
_ STEP 2: reducible fraction
_ STEP 3: acid degradable fraction
_ STEP 4: oxidizable fraction
_ STEP 5: residual fraction

Fig. 1.i: sequence 3–1–2–4–5

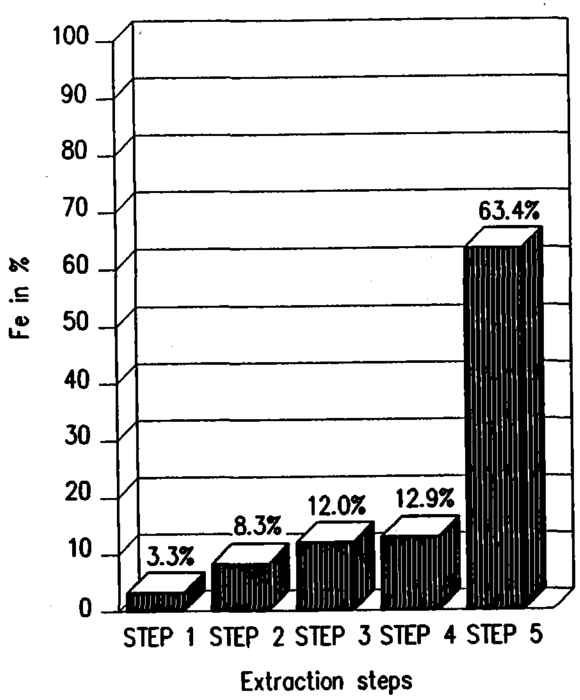
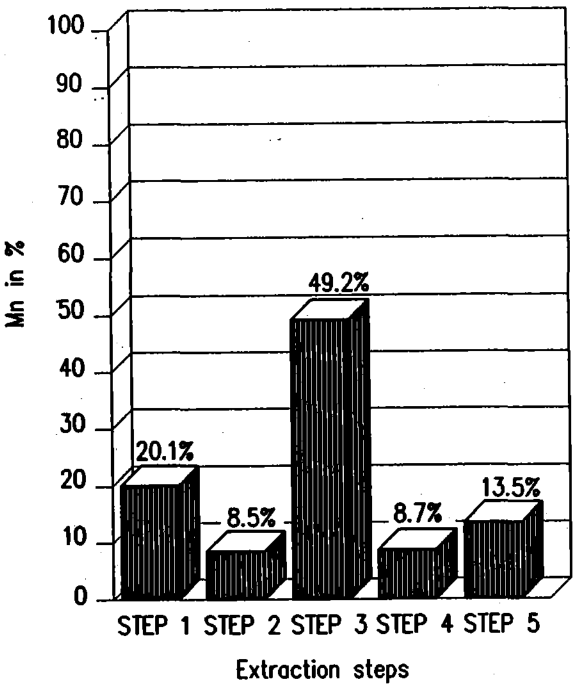


Fig. 1.j: sequence 3–1–2–4–5



Extraction steps:
- STEP 1: exchangeable and carbonate fraction
- STEP 2: reducible fraction
- STEP 3: acid degradable fraction
- STEP 4: oxidizable fraction
- STEP 5: residual fraction

MINERALOGICAL ASSOCIATIONS OF HEAVY METALS IN THE SEDIMENTS OF A CONTAMINATED HARBOUR SITE IN THE NETHERLANDS : A CASE STUDY

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ABSTRACT

In this paper the results are presented of an investigation into the distribution of heavy metals present in the sediments of the harbour of Stein in the Netherlands, as a prelude to the design of a treatment process. To obtain information upon the distribution of contaminants in the original sediment, several hydrocyclone products were produced, analyzed for their heavy metal contents and studied for the mineralogical associations of the heavy metals. For identification of the heavy metal associated mineralogical phases, Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) techniques were used. For these sediments it was shown that the heavy metals lead, zinc, cadmium and copper were predominantly present in the form of sulphide minerals.

INTRODUCTION

A characterization of contaminated sediments with respect to the distribution and mineralogical associations of the contaminants is often a prerequisite for the development of a physical or chemical treatment process. However, such a characterization should not be some academic exercise but should be aimed to identify physical separation properties and/or chemical extraction properties of the contaminants, which can be exploited in a full-scale treatment process.

For the development of any physical separation process for cleanup of heavy metal contaminated dredged materials it is important to establish whether the heavy metals occur in the form of individual particles, coatings or adsorbed to clay minerals or organic matter. Also, for the development of chemical treatment technology, information about the chemical and mineralogical composition of the heavy metal associated phases is essential.

To obtain information on the mineralogical associations of the heavy metals, selective chemical extraction techniques are often used [1]. However, the interpretation of the results is not unambiguous since no selective chemical extraction is completely selective and in the case the heavy metals are present in other mineralogical forms than those considered in the selective extraction procedure, the interpretation of the results can be completely erratic. Furthermore, no direct information is obtained on the physical occurrence of the heavy metals.

In contrast with a selective chemical extraction analysis, a physical analysis of the heavy metal associated phases by means of Scanning Electron Microscopy can provide direct qualitative information on the physical occurrence of the heavy metal associated phases (particles or coatings, size of particles), their elemental composition and sometimes even their mineralogical composition.

For harbour of Stein sediments the distribution and mineralogical associations of heavy metals were studied. Several hydrocyclone underflow and overflow products were analyzed for their heavy metal contents and studied for the distribution of the heavy metals. Scanning Electron Microscopy (SEM) was used for analysis and identification of the heavy metal associated phases.

LOCATION AND HISTORICAL BACKGROUND ON CONTAMINATED SITE

The contaminated harbour of Stein is situated on the bank of the river Maas (Meuse) in the provence of Limburg in the Netherlands. A schematic plan of the harbour is given in fig.1.

In the past the harbour of Stein has been used mainly for transloading of bulk materials such as coal and ore concentrates and more recently also sand and gravel.

When dredging activities were planned it was discovered that the sediments of the harbour centre and the harbour mouth were severely contaminated with the heavy metals lead, zinc, cadmium and copper.

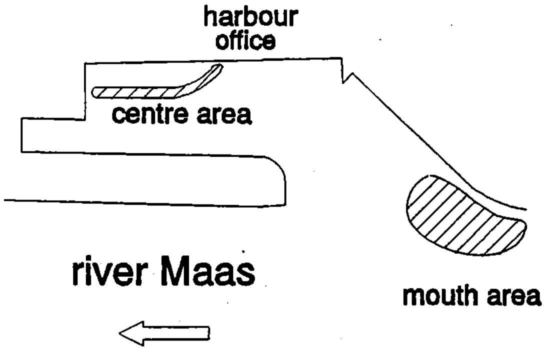

Fig. 1: Schematic plan of the harbour of Stein

HYDROCYCLONE SEPARATION OF HARBOUR SEDIMENTS

A composite sample of harbour sediments was collected from the harbour centre area indicated in fig. 1. After collection the sample was thoroughly homogenized and used as the feed for a hydrocyclone separation program (feed 0).

A schematic representation of the hydrocyclone separation program is given in fig. 2. From hydrocyclone separation step one to five, the d_{50} cut points of separation varied from approximately 250 microns for the first step to several microns for the fifth step. Each hydrocyclone step consisted of two hydrocyclone separations. All underflow products of the primary hydrocyclones were treated once again with a second series of hydrocyclones to remove an extra portion of ultra fine material from the primary underflow products. The final products were numbered 1 to 6 as indicated in fig. 2. Detailed information on the hydrocyclone separation program is given in reference [2].

RESULTS

All hydrocyclone underflow and overflow products were analyzed for their particle size distributions. The cumulative size distribution curves for the hydrocyclone underflow products 1 to 5 and the final overflow product 6 are presented in fig. 3. The particle size distribution of the original hydrocyclone feed 0 is given in table 1.

Table 1: Size distribution of hydrocyclone feed 0

Size (μm)	distribution (wt %)
+ 1000	34.28
+ 500	13.21
+ 300	9.78
+ 150	7.39
+ 75	5.56
+ 38	4.49
- 38	25.29
	100.00

All hydrocyclone products were analyzed for their lead, zinc and cadmium contents. The results of these analyses are presented in table 2. The lead and zinc contents of the original feed 0 are also included in this table.

Table 2: Quantitative analyses of hydrocyclone underflow and overflow products

product number	Pb (ppm)	Zn (ppm)	Cd (ppm)
0 (feed)	8100	1)	19.0
1	870	590	0.8
2	3700	880	3.0
3	12000	2600	10.5
4	13500	3100	30
5	12500	3500	22
6	12000	4600	50

1): not determined

All hydrocyclone underflow products 1 to 5 were contaminated with lead, zinc and cadmium. However, for the three metals (lead, zinc and cadmium) analyzed, a clear trend was observed of higher levels of contamination in the finer sized underflow products. Since hydrocyclone separation is not an absolute separation, the question remained open whether the coarse products 1 and 2 were contaminated by a small portion of (misplaced) highly contaminated fines or by coarser sized heavy metal associated particles in the hydrocyclone products.

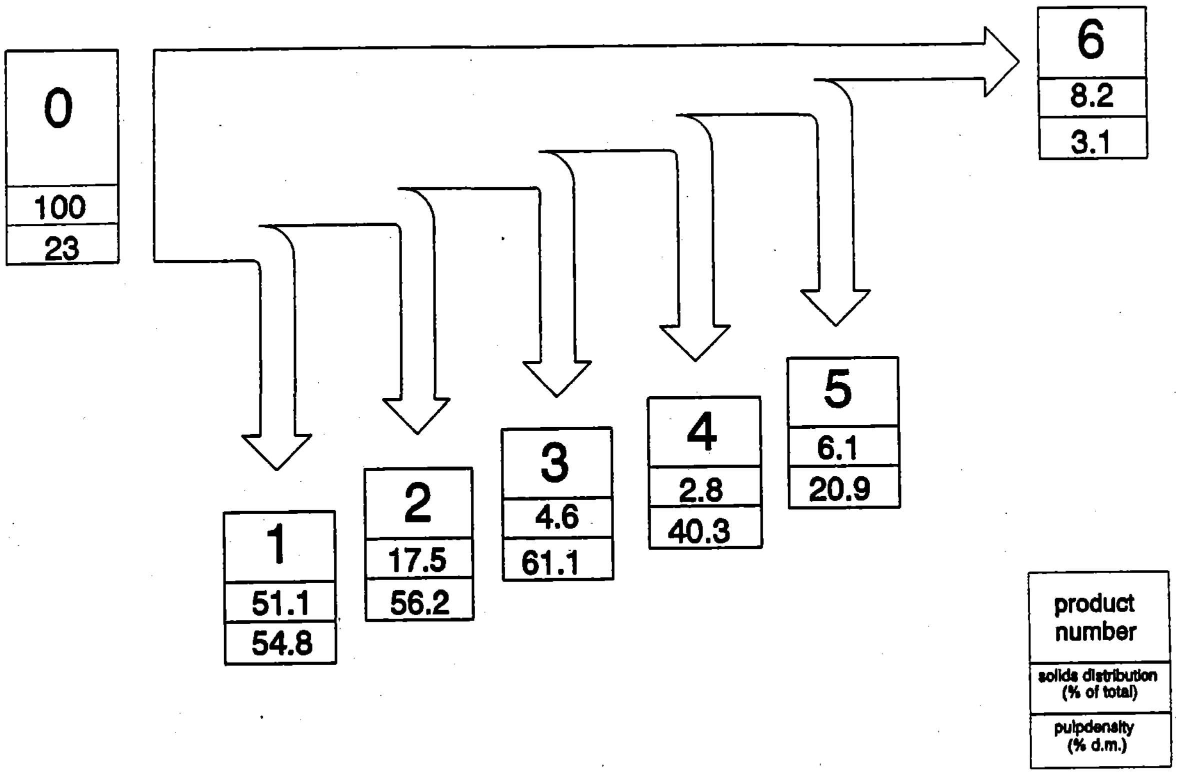

Fig. 2: Schematic representation of the hydrocyclone separation program

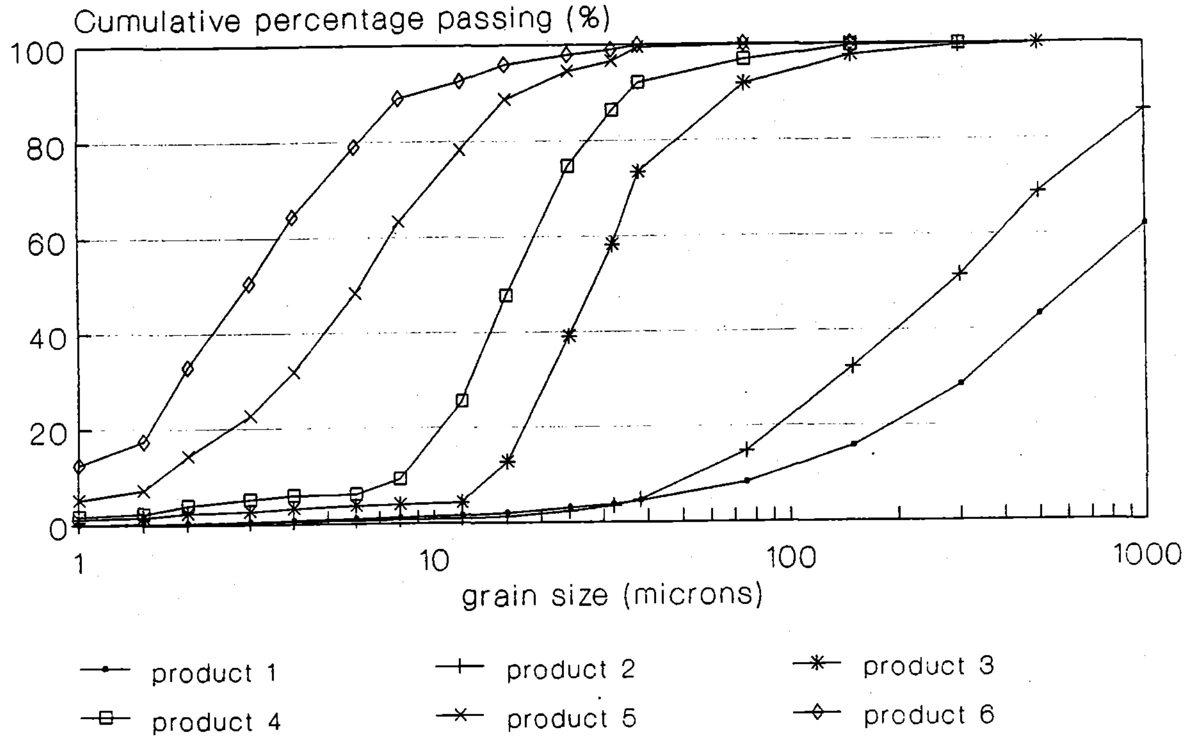

Fig. 3: Cumulative size distribution curves for hydrocyclone products

To answer this question, product 1 was analyzed for its particle size distribution and the distribution of heavy metals over the different size fractions. The results of these analyses are presented in table 3.

Table 3: Size distribution and heavy metal analyses of different size fractions (hydrocyclone product 1).

size (μm)	distribution (wt %)	Pb (ppm)	Zn (ppm)	Pb load (ppm)
+ 500	56.8	310	460	176
+ 300	14.7	320	1)	47
+ 150	12.6	480	1)	60
+ 75	7.6	730	520	55
+ 38	3.7	1300	1)	48
- 38	4.6	9500	1)	437
	100.0			823

1): not determined

These results indicate that lead, and possible also zinc, are essentially present in all size fractions but in extremely high concentrations in the finer size fractions.

When calculating the contribution of all size fractions to the total lead contamination of hydrocyclone product 1 (table 3) it appears that a portion of 4.6 % of (misplaced) minus 38 micron fines contributes a major part, i.e. 53 % (437 ppm), to the total lead contamination in hydrocyclone product 1.

IDENTIFICATION OF HEAVY METAL ASSOCIATED PHASES (HARBOUR SEDIMENTS)

Because the heavy metals were present in all size fractions, it was expected that the heavy metals were present as discrete particles or associated with particulate matter. For determination and analysis of the heavy metal associated particles Scanning Electron Microscopy (SEM) was chosen. With this technique a sample of sediment can be scanned for a presence of heavy metals and individual particles can be analyzed for their elemental composition.

SEM ANALYSIS OF HYDROCYCLONE PRODUCT 1

Particles of abnormal density as compared to the density of the bulk material were pre-concentrated from hydrocyclone product 1 by means of a mechanical gravity concentration technique. A dark coloured heavy particle concentrate was obtained in this fashion of which a sample of approximately 20 mg was taken for Scanning Electron Microscopical (SEM) analysis. This sample was carefully spread on double adhesive tape in such a way that all particles were placed in a single layer, free from each other. The complete sample was then coated with a thin electrically conducting layer of graphite.

In fig. 5 a series of SEM images (magnification 1000x) are shown of the heavy particle concentrate. The particles shown in fig. 5a have been scanned for lead, zinc and cadmium. The white dotted areas in fig. 5b, c en d indicate the presence of respectively lead (fig. 5b), zinc (fig. 5c) and cadmium (fig. 5d). All heavy metal containing particles were identified as heavy metal sulphide minerals. In table 4 the complete results of the identification of heavy metal associated particles are presented.

Table 4: Mineralogical composition of the heavy particle concentrate as determined by SEM

mineral	chemical composition
galena	PbS
pyrite	FeS_2
chalcopyrite	$CuFeS_2$
sphalerite	ZnS
greenockite	CdS
iron oxide	Fe-oxide or hydroxide

In fig. 5a the cubic crystal structure of the mineral galena (PbS) can be clearly recognized. Figs. 5b and 5c show that the mineral sphalerite (ZnS) is intergrown with galena (PbS) and pyrite (FeS_2). Figs. 5b and 5d show that the mineral greenockite (CdS) is intergrown with galena (PbS). These results indicate that lead, zinc, cadmium and copper occur not only in the form of individual sulphide minerals but also in the form of complex intergrown minerals.

SEM ANALYSIS OF HYDROCYCLONE PRODUCTS 5 AND 6

From both hydrocyclone products 5 and 6 a small amount of approximately 10 to 20 mg material was taken and analyzed by Scanning Electron Microscopy (SEM).

Because no significant differences in composition were observed between both hydrocyclone products 5 and 6, the results of the SEM analysis of the two samples are presented together in table 5.

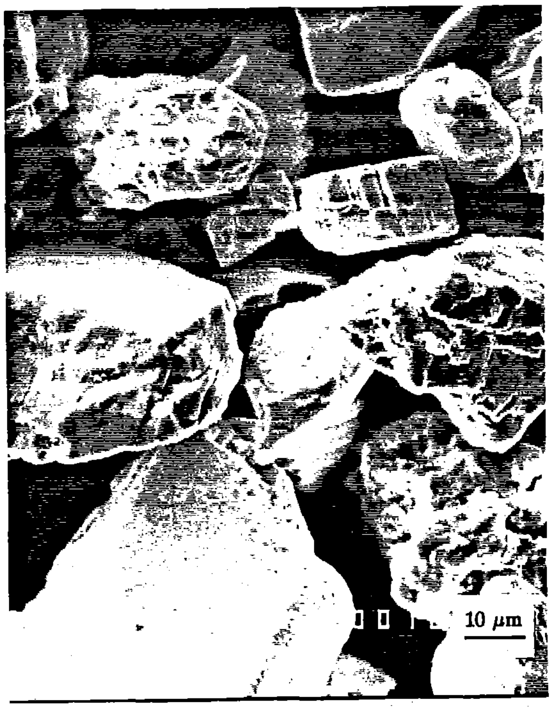

Fig. 5a: SEM photograph of heavy particle concentrate (magn. 1000x)

Fig. 5b: X-ray image lead distribution ($Pb\text{-}L_{\alpha}$)

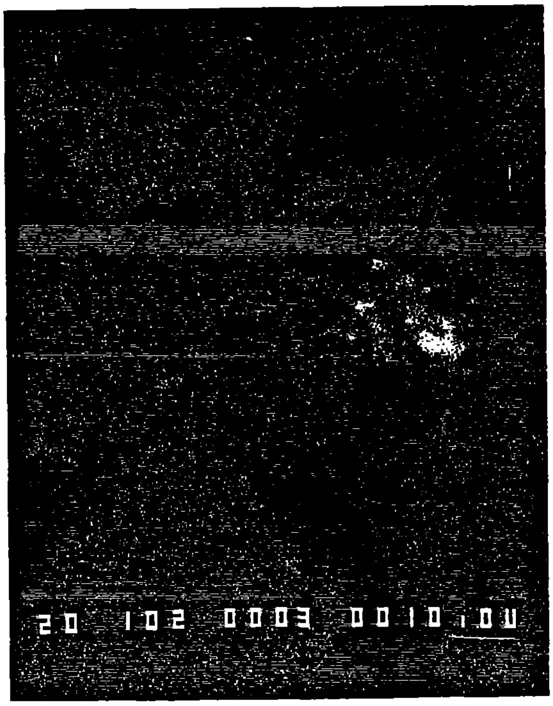

Fig. 5c: X-ray image zinc distribution ($Zn\text{-}K_{\alpha}$)

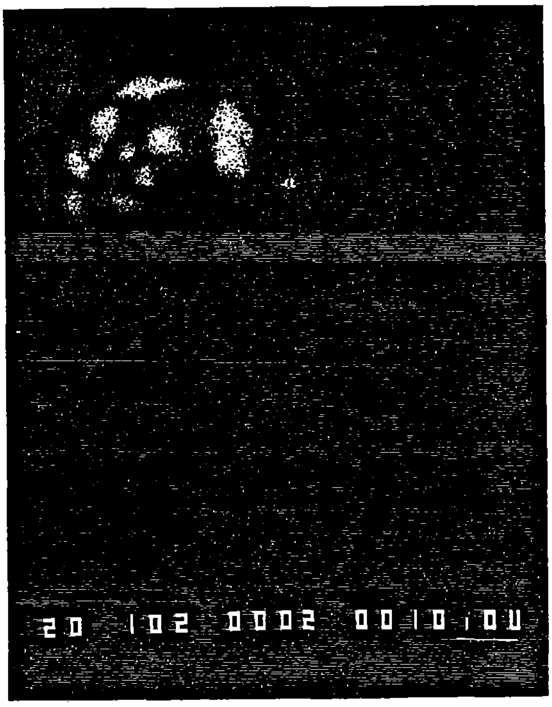

Fig. 5d: X-ray image cadmium distribution ($Cd\text{-}L_{\alpha}$)

Table 5: Mineralogical composition of heavy minerals present in hydrocyclone products 5 and 6 as determined by SEM

mineral		chemical composition
galena	(**)	PbS
pyrite	(**)	FeS_2
chalcopyrite	(*)	$CuFeS_2$
sphalerite	(*)	ZnS
unidentified		Zn, Fe compounds
iron oxide		Fe-oxide or hydroxide
chromite		$FeCr_2O_3$
barite		$BaSO_4$
monazite		Ce-phosphate

(*) or (**) indicate relative abundance

In both samples, small fragments of heavy minerals (most 1 to 2 micron in size but some 3 to 5 micron in size) were present. From the heavy metal associated particles analyzed, the minerals galena and pyrite were predominant, but the minerals chalcopyrite ($CuFeS_2$) and sphalerite were also present in appreciable concentrations. Barite, chromite, monazite and iron oxides were also detected but these minerals were present in relatively low concentrations.

The metal cadmium was not detected in these samples. However, from the chemical analysis (table 2) it is clear that cadmium levels were relatively low, so that the actual probability for detecting any cadmium containing particles was also low. But since the mineral greenockite had been detected in the heavy particle concentrate of hydrocyclone product 1, it seems likely that cadmium will also be present in these samples as the mineral greenockite.

IDENTIFICATION OF HEAVY METAL ASSOCIATED PHASES (HARBOUR MOUTH SEDIMENTS)

A sample of harbour mouth sediments was collected from the harbour mouth area indicated in fig. 1. These mouth sediments were of a very fine (muddy) texture. The grain size distribution of this sediment and distribution of heavy metals over the different size fractions was determined by TNO-MT research Apeldoorn. The results of these analyses are presented in table 6.

Again it was shown that all size fractions were severely contaminated with the heavy metals lead, zinc, cadmium and copper.

Table 6: Size distribution and heavy metal analyses of different size fractions (harbour mouth sediments)

size (μm)	distr. (wt %)	Pb	Zn	Cd	Cu
			(ppm)		
+ 500	0.1	710	2400	27.0	140
+ 250	0.1	408	3500	16.5	106
+ 125	0.6	345	3100	25.0	144
+ 63	2.6	270	1900	17.2	119
+ 20	26.8	512	540	4.8	47
- 20	69.8	495	2200	40.0	172
	100.1				
overall		407	2000	29.8	127

For determination of the main mineralogical constituents of these fine sediments a X-ray diffraction (XRD) analysis was performed and for identification of the heavy metal associated phases Scanning Electron Microscopy (SEM) was used.

XRD ANALYSIS (HARBOUR MOUTH SEDIMENTS)

Prior to XRD analysis it was necessary to remove possible coatings of organic matter from the mineral grains since such coatings might disturb the X-ray diffraction pattern. Therefore the sample was given a special pretreatment with hydrogen peroxide to remove any organic coatings [3]. The results of the subsequent XRD analysis are shown in table 7.

Table 7: Bulk mineralogical composition of harbour mouth sediments as determined by XRD

mineral	chemical composition
α-quartz	SiO_2
albite	$NaAlSi_3O_8$
microcline	$KAlSi_3O_8$
Illite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$
kaolinite *	$Al_2Si_2O_5(OH)_4$

* weak indication for presence of this mineral

The main mineralogical constituents were identified as α-quartz, albite, microcline, illite and kaolinite. For the mineral kaolinite only weak indications existed for its presence. No heavy metal containing mineralogical phases could be detected from the X-ray diffraction pattern.

SEM ANALYSIS (HARBOUR MOUTH SEDIMENTS)

A small amount of 10 to 20 mg sample was taken and analyzed by Scanning Electron Microscopy (SEM).

The results of the SEM analysis of the harbour mouth sediments showed that the heavy metal sulphide minerals were also present in these sediments despite their absence in the XRD results. The analytical results were comparable to the results obtained in the earlier analysis of hydrocyclone products 5 and 6 but the concentrations of heavy metal associated particles were lower and the mineral chalcopyrite was not detected.

The fact that copper and cadmium associated particles could not be detected is probably due to the low probability of detecting these metals since they are present in relatively low concentrations. However, it seems likely that all heavy metal sulphides have been transported in the same way from the centre of the harbour to the harbour mouth, so copper and cadmium sulphide minerals can also be expected to be present in the harbour mouth sediments.

DISCUSSION

The heavy metal associated particles identified in the sediments of the Harbour of Stein were all identified as (complex) heavy metal (Pb, Zn, Cd and Cu) sulphides. On the basis of the present work it is not possible to say whether some of the heavy metals also occur adsorbed to organic matter or clay minerals. However, it was clearly shown that heavy metal sulphide minerals are the predominant heavy metal bearing species present in these sediments.

On the basis of the heavy metal analysis of several hydrocyclone fractions and the presence of heavy metal containing particles in all size fractions it is evident that hydrocyclone treatment cannot be applied for cleanup of these sediments. Additional physical separation techniques such as gravity concentration or flotation have to be used for removal of the heavy metal sulphide particles.

Scanning Electron Microscopy (SEM) proved to be a simple, quick and low-cost method for identification of particle associated heavy metals. SEM analysis is therefore strongly recommended for determination and identification of heavy metal associated particles whenever such particles can be expected. But also when heavy metal associated particles are not directly anticipated, the technique can be useful to obtain a first impression on the occurrence of the heavy metals. It is our experience when dealing with heavily contaminated sediments, that heavy metals frequently tend to occur in the form discrete mineral particles.

Acknowledgement

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CHARACTERIZATION OF METALS (Cd, Cu, Pb, Zn, Mn and Fe) IN FIVE FLEMISH DREDGED MATERIAL SAMPLES

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ABSTRACT

The behaviour and speciation of Cd, Cu, Pb, Zn, Mn and Fe in five dredged material samples, originating from marine, estuarial and fresh water environments, were studied in laboratory experiments.

All original samples were in a very reduced state. Although pH of all sediments ranged between 7 and 8, striking differences were observed in buffering capacity. Total metal contents also varied considerably and were correlated with the fine granulometric fractions.

Leaching of the metals under varying conditions of pH, buffering capacity of the solvent and redox potential was studied. The mobility in distilled water remained very low. When extracting agents at pH 5 and with a more considerable buffering capacity were used, leaching increased substantially. Clear differences could be observed in function of the redox conditions of the sediments. The greatest solubility was found at intermediate oxidation states, releasing up to 20 % of the total contents of Cd and Zn, 2% for Cu and 10 % for Pb. Adding a chelating agent released even more metals, 30 % for Cd and Zn, 10 % for Cu and up to 60 % for Pb. For Fe and Mn however, leaching decreased continuously with higher oxidation state.

Sequential extraction schemes were tested in an attempt to relate the leaching behaviour to the composition of the solid fraction. Two sequential extraction schemes yielded very different results, which emphasized the necessity for further research in this area. Fractionation according to Tessier et al. 1) revealed that, except for organic matter bound copper, there was not a systematic shift of the solid element fractions with increasing oxidation states. Therefore it is suggested that the leaching behaviour as influenced by oxidation mainly is affected by bounding energy changes within the solid fractions.

INTRODUCTION

The mobility and hence the availability of sediment bound heavy metals to the surrounding environment is strongly determined by the way these metals are incorporated in the solid phase - as oxides, carbonates or sulfides, adsorbed or exchangeable, organically bound or free in solution either as a hydrated ion or as an organic or inorganic complex 2), 3). Five sediment samples, originating from marine, estuarial and fresh water environments in the Flemish region were selected for the study of

Table 1 General characteristics of the samples

Sample	Granulometry 0-2 µm	2-50 µm	> 50 µm	pH (1:5)	Eh mV vs SHE	Buffering capacity (pH = 4.3) mmoles HCl/kg DM
A	34.5	56.9	8.6	7.1	2.4	2357
B	4.8	3.9	91.3	7.8	22.4	185
C	24.0	36.2	39.8	7.5	20.4	1000
D	10.0	39.6	50.4	7.5	27.4	529
E	43.3	46.6	10.1	8.0	59.4	6900

			Total contents					
Sample	OM (%)	CaCO3 (%)	Cd mg/kg DM	Cu mg/kg DM	Pb mg/kg DM	Zn mg/kg DM	Fe mg/kg DM	Mn mg/kg DM
A	9.6	11.2	13.2	139.7	178	1200	68399	997
B	2.7	3.4	1.7	19.4	29	153	9812	122
C	6.6	6.6	6.1	73.6	117	579	25426	294
D	4.4	4.6	5.6	76.7	134	859	25526	357
E	10.9	28.4	2.6	37.3	80	313	30713	573

the behaviour and speciation of their Cd, Cu, Pb, Zn, Mn and Fe contents.

CHARACTERIZATION OF THE SAMPLES

The samples were analyzed for total metal contents, pH and redox potential, buffering capacity and particle size distribution to assess their general characteristics (Table 1). The texture varied from sand (sample B) to silty clay (sludge E). Although pH was neutral for all samples, big differences appeared with respect to buffering capacity. As metals tend to be more leachable at lower pH values [4], a stronger buffering capacity will lower the chances of mobilisation as acidification is more unlikely.

Since the redox state also is an important factor in the behaviour of metals [5), 6)], it has to be considered in laboratory experiments. All samples were in a very reduced state as shown by the Eh values. Upon dredging and disposal, sediments get into oxidizing states.

Total metal contents show a great variation, but were positively correlated with the presence of the fine fraction < 100 µm.

LEACHING OF METALS UNDER DIFFERENT CONDITIONS

Leaching in distilled water

For assessing the leachability in water, the DIN 38414 test [7] was used. Three consecutive extractions were carried out at liquid/solid ratios of 10 for 24 hours. Levels of copper, cadmium and zinc were determined using furnace atomic absorption spectrometry.

The concentrations in the liquid remain very low, even at high liquid to solid ratios (Table 2). Also, total quantities released are very low and amount to no more than 1 % after the three extractions. The adsorption of metals by sediments and the very sparingly release afterwards constitutes indeed a natural buffering and purifying mechanism in surface waters.

Leaching in NH_4OAc-EDTA

For comparative studies, further tests were carried out with NH_4OAc and NH_4OAc-EDTA. The latter is used in testing the nutrient status

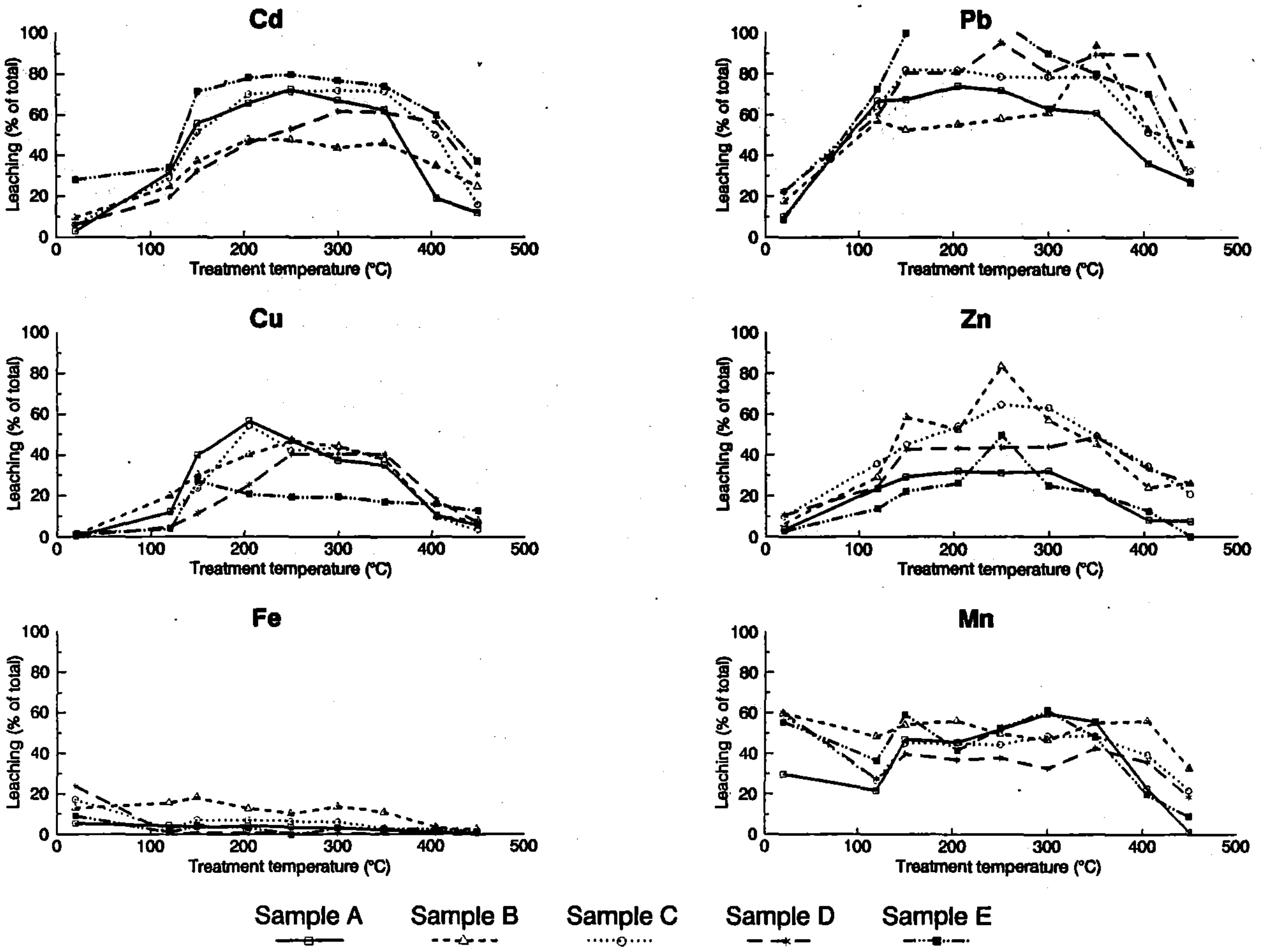

Fig. 1 Leaching of Cd, Cu, Pb, Zn, Fe and Mn in 0.5 M NH_4OAc + 0.02 M EDTA as a function of sample treatment temperature

of soils, as it is assumed to release soluble, adsorbed and complexed forms of metals in soils 8), 9).

To investigate the influence of oxidation state on the leaching behaviour, subsamples were subjected to different thermal treatments:

1. No treatment, i.e. native sludge in its reduced state. During shaking, ascorbic acid was added to prevent oxidation 10).

2. Drying at 120 °C during 12 hrs.

3. Drying at 120 °C and subsequently heating during 4 hours at increasing temperatures up to 450 °C, so that at the highest temperatures, the samples are totally ashed and thus extremely oxidized.

The thus treated samples were extracted with 0.5 M NH_4OAc + 0.02 M EDTA 9) at a liquid/solid ratio of 5. To asses the influence of EDTA in this extraction proces some extractions were effected with a pure 0.5 M NH_4OAc solution.

Concentrations in the extracts were determined with flame atomic absorption, using standard solutions, prepared in the extracting matrix.

Leachability of heavy metals was always lowest for the untreated sample (Fig. 1). The quantities leached increased strongly up to a temperature of about 250 °C. The more important leaching of freshly oxidized sludge has also been reported by Skogerboe et al. 11) in a real scale experiment. After treatment at the highest temperatures, the leachability decreased to values below those of the 120 °C dried sample, but remained still higher than those of the native samples.

It appeared that organic matter (OM) played an important role in this particular leaching behaviour. The following relationship could be used to describe the leaching pattern:

$$\text{Leaching\%} = a + b.\text{OM\%} + c.\text{OM\%}.T$$

with: OM%: Organic matter content (% of dry mass)
T: Treatment temperature (°C)
a, b, c: regression constants
Leaching%: percentage of total contents leached

This relation was significant to the 0.1 % level for Cd, Cu, Pb and Mn and to the 1 % level for Zn.

The solubility of Fe and Mn on the other hand decreased as the sediments were more oxidized. Also in soil systems, both elements can exist in reduced as well as in oxidized forms 5), 6), the latter being less soluble.

Leaching of Cu and Pb was remarkably enhanced when EDTA was present. Its influence on the leaching of Cd, Cu, Fe and Mn was less pronounced.

FRACTIONATION OF THE METALS IN THE SOLID PHASE

For the fractionation of the solid phase, two sequential extraction schemes, the method according to Emmerich et al. 12) and the Tessier et al. 1) procedure have been tested. Table 3 outlines the procedures. From Fig. 2, it appears that the results are quite different, as fractions that are assigned to the same solid phase (f.i. organically bound) differ significantly. Clearly, there are still difficulties concerning the specificity of the reagents and the interpretation of the phases extracted.

For sample A, a sequential extraction following Tessier et al. 1) was carried out on all

Table 2 Concentrations in the leachate of the three fractions (1 2 3) following the DIN 38414 test 7) and cumulative percentages of total contents leached (%)

	Cd (µg/l)				Cu (µg/l)				Pb (µg/l)			
Sample	1	2	3	%	1	2	3	%	1	2	3	%
A	0.1	1.9	0.3	0.19%	12	6	6	0.19%	3	2	3	0.04%
B	0.7	0.3	0.7	0.93%	17	1	1	1.31%	8	0	0	0.29%
C	0.6	0.1	0.3	0.15%	14	6	6	0.31%	10	2	3	0.11%
D	0.4	0.3	0.3	0.16%	10	3	3	0.19%	5	9	4	0.11%
E	-	0.2	0.1	0.12%	10	5	5	1.69%	0	1	0	0.02%

	Zn (mg/l)				Fe (mg/l)				Mn (mg/l)			
Sample	1	2	3	%	1	2	3	%	1	2	3	%
A	0.00	0.00	0.00	0.00%	0.2	0.1	0.1	0.00%	0.3	0.0	0.0	0.00%
B	0.10	0.00	0.00	0.00%	0.8	0.0	0.0	0.00%	0.0	0.1	0.3	0.00%
C	0.10	0.00	0.00	0.00%	0.5	0.0	0.1	0.00%	0.1	0.1	0.1	0.00%
D	0.10	0.00	0.00	0.00%	0.1	0.1	0.1	0.00%	0.4	0.1	0.1	0.00%
E	0.00	0.00	0.01	0.00%	0.1	0.0	0.0	0.00%	0.4	0.7	0.0	0.00%

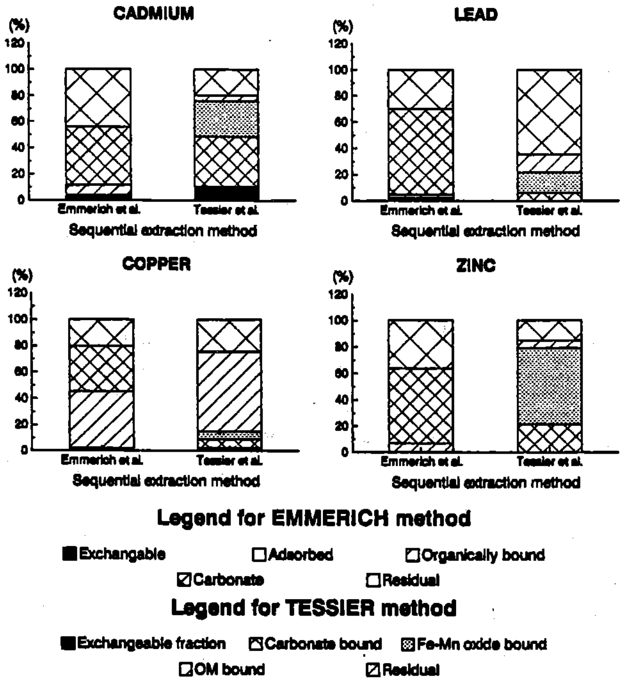

Fig. 2 Results of two different sequential extractions (Emmerich et al. [11]) and Tessier et al. [1]) on the same sample

thermally treated subsamples (Fig. 3). The distribution of the metals over the different fractions differs clearly between the elements. Copper seems to be mainly associated with the OM bound fraction. Cadmium and Zn are found for an important part in the carbonate fraction, while Pb exists mainly in the residual fraction. Iron also is mostly associated with the residual form, while Mn mostly seems to be present in the carbonate and in the Fe-Mn oxide bound fraction to an equal extend.

Table 3 Order of sequential extraction sequence and designated chemical form extracted in the methods following Tessier et al. [1] and following Emmerich et al. [11].

Tessier et al.	Emmerich et al.
1 *Exchangeable* 1 M $MgCl_2$	*Exchangeable* 0.5 M KNO_3
2 *Carbonate bound* 1 M NaOAc/HOAc pH = 5	*Adsorbed* H_2O (3x)
3 *Fe-Mn oxide bound* 0.04 M $NH_2OH.HCl$ in 25% (v/v) HOAc	*Organically bound* 0.5 M NaOH
4 *Organic matter bound* H_2O_2/HNO_3	*Carbonate* 0.05 M Na_2-EDTA
5 *Residual* $HF-HClO_4$ digestion	*Residual* 4 M HNO_3

As treatment temperatures are higher, organic matter contents decrease and become zero above 400 °C. Thus, a decrease and even disappearance of the organically bound fraction is to be expected. This is clearly the case for Cu. For Pb also, a decreasing tendency in that fraction is observed, but not for Zn and Cd. The correlation between OM content after thermal treatment and OM-bound metal is indeed very significant for Cu ($r = 0.9644$, significance at 0.1 % level), somehow significant for Pb ($r = 0.748$, 5 % level) but not significant at all for Zn ($r = 0.6324$) and Cd ($r = -0.5206$). This illustrates the decreasing association with organic matter in the order Cu > Pb > Zn > Cd, a sequence that has also been observed by Stevenson [13]), Saar & Weber [14]) and Baham [15]).

Although at the highest treatment temperatures, organic matter is no more present, significant "organically bound" fractions still seem to exist for Cd, Pb and Zn. Hence it must be concluded that with this fraction, also metals, associated with other solid phases are extracted. Thus the sulfide bound fraction that is (partially) being oxidized may be released.

Shifts in the Tessier fractions do not allow to explain the increasing leachability at higher temperature treatments. Copper mainly shifts from the organically bound to the residual fraction, a fraction that is considered to be more strongly bound. Hence, it may be concluded that leaching of heavy metals from thermally treated sediments is mostly controlled by changes in bounding energies within specific fractions, rather than through shifts between fractions.

SUMMARY AND CONCLUSIONS

Although the total metal contents and the chemical and physical properties of the samples differed strongly, leaching of heavy metals in water was very low for all samples. Upon dredging and land disposal, however, the sediments get into an oxidizing environment, which may cause important changes in leaching behaviour. Thermal treatments were used to oxidize samples in a quick and reproducible way. The leaching behaviour in function of treatment temperature was followed by NH_4OAc-EDTA extractions. Intermediate oxidized samples showed a maximum in leachability. Thus for assessing maximum leachability of sediments, it may be recommended to do leaching tests after heating the sample up to 250 °C.

Two sequential extraction schemes yielded very different results. Further research is needed with respect to the speciation of metals in the solid phase of sediments. The sequential extraction according to Tessier et al. [1] did not reveal a systematic shift in the solid element fractions upon oxidation of the samples. Therefore, it may be suggested that the leaching behaviour as influenced by oxidation mainly is affected by bounding energy changes within the solid fractions.

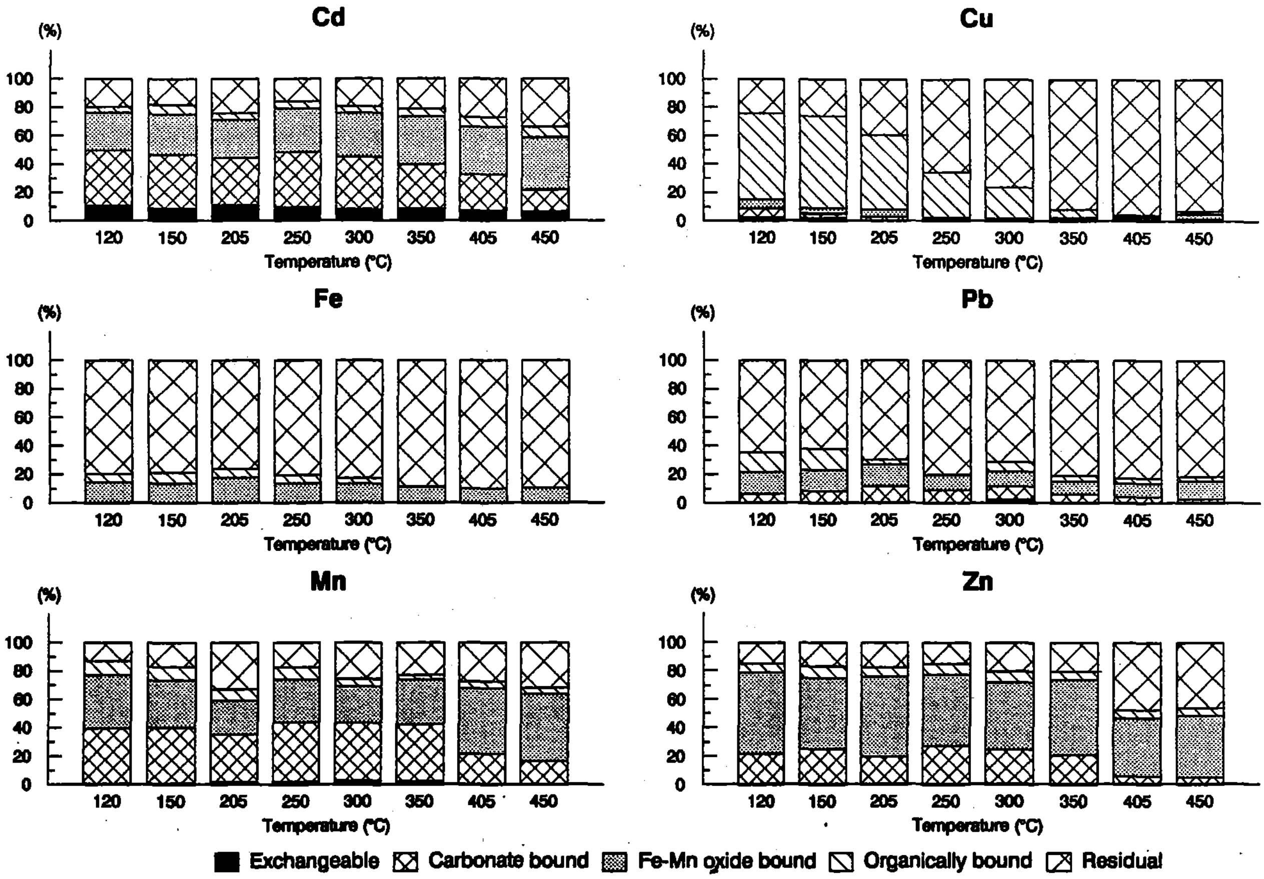

Fig. 3 Sequential extraction following Tessier et al. [1] for different sample treatment temperatures of Sample A

ACKNOWLEDGEMENT

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STUDY IN BEHAVIOUR AND MICROSTRUCTURE OF A DREDGED SLUDGE

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ABSTRACT

The drying rate (at 30ºC and 45ºC), the water sorption (at p/p_o = 0.5 and 0.95), the consolidation in oedometer test and in triaxial test as well as the coefficient of hydraulic conductivity in function of water content were measured on a dredged sludge from the Rhine river estuary. Some study in mineral composition and in microstructure was done. A tendency to aggregation (aging) was discovered both macro- and microscopically, which increased with storing time and decreased with temperature of storing. Aggregation is indicated also by (1) a lowered water sorption with storing time, i.e. a higher particle thickness, (2) lowering of drying rate with storing time and formation of macroand micropores visible in the dried specimen. Weight loss on heating indicated the presence of amorphous materials which trapped water and increased the energy needed for its evaporation. This effect was smaller when the sample was stored for a longer time. Presence of amorphous material may cause the low permeability of the sludge under study.

Coefficient of hydraulic conductivity (log) decreased linearly with log consolidation stress and with the degree of consolidation, i.e. time elapsed from the stress application. The shape of consolidation curves of stored sludge indicated also the possible aggregation.

INTRODUCTION

It was found in some previous study on (1) bentonite suspensions and pastes and on (2) marine clays, that their properties vary with the time of storage both at a high water content (a) and air dry conditions (b). Evidently these changes went in opposite directions in case (a) and (b).[1),2),3)]

A thorough study of a dredged sludge was performed to understand better its behaviour and thus to be able to make a prognosis, e.g. of its settlement with time and with drying. This was a pilot study, thus a broad range of experimental methods was used.

Only selected results will be presented here.

MATERIAL, METHODS AND RESULTS

Dredged sludge from Rhine river estuary was supplied by Geomechanica, Delft, in November 1989. Its properties were as follows:

- water content	W_n = 220% to 280%
- clay fraction content	$f_{<2\mu m}$ = 15%
- silt fraction content	$f_{(2-20\mu m)}$ = 75%
- liquid limit	W_1 = 120%
- plastic limit	W_p = 41%

External specific surface as measured by water sorption was:

- at p/p_o= 0.5	S = 29 - 37 m^2/g
- at p/p_o= 0.95	S = 158 - 177 m^2/g

The mineral composition of the sludge is as follows:

XRD of the unfractionated material indicated the presence of low quartz, calcite, illite, kaolinite and the possibility of a 14 Å mineral (chlorite, smectite) most probably in mixed layers.

SEM indicated in the matrix of clay particles of the morphology of illite numerous fragments of Diatomeae and some pieces of flora of organic and silica composition. Grains of amorphous silica were to be seen in the clay matrix of stored sludge samples. Quartz and feldspar grains were to be found and some small calcite grains were detected. Chemical composition as measured by KEVEX was characteristic for mica: (illite); i.e Si, and Al with some Ca, K and Fe. Chloride from the soluble NaCl was detected and a crystal of anathase (tytanium oxide) was found.

Stored samples were very unhomogeneous and their microstructure was strongly dependent on preparation and pretreatment which manifested also in sample behaviour.

Drying rate:

The dredged sludge after a thorough stirring was put into 6 greased glass beakers of the internal diameter 5 cm, surface area A = 20 cm^2, heights h = 5 cm, at the initial

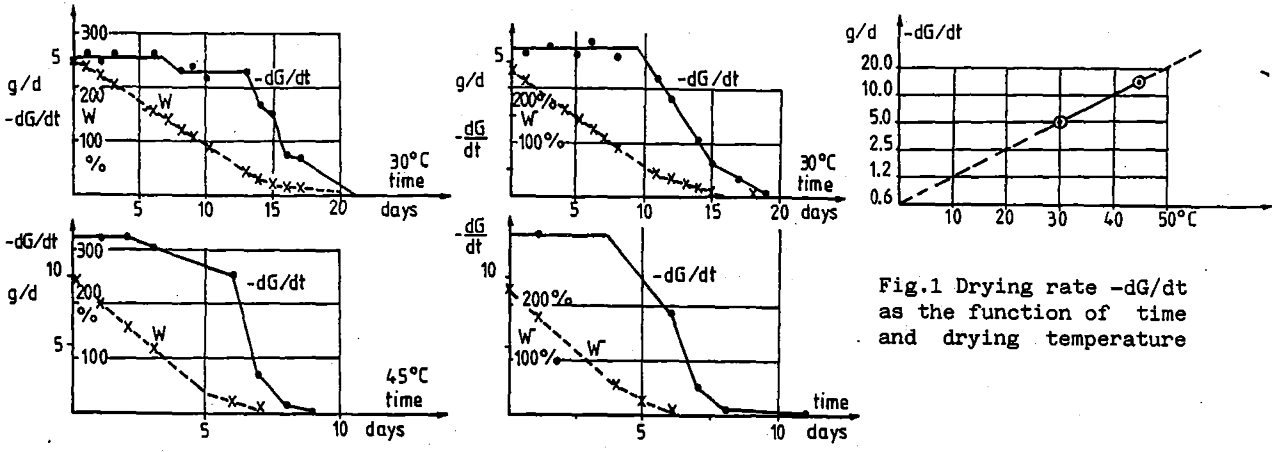

Fig.1 Drying rate -dG/dt as the function of time and drying temperature

weight, G_o = 101 to 110 G. It was dried to the constant weight in two constant temperature cupboards:

- at 30ºC
- at 45ºC

recording the weight change with time (series I). After one day drying at 110ºC the water sorption was measured (see below).

The measurement of drying rate (and water sorption) was repeated after the sample was stored for one month in the laboratory (series II). Results are presented in Fig. 1 and in Table 1.

The weight loss per unit time and unit surface - area was estimated and dividing it by the specific weight of water (1 G/cm^3) the value of k.i in cm s^{-1} was obtained (Table 2).
Dried specimen were inverstigated by SEM: size of aggregates increased with storing time and with the drying temperature. Number of macropores increased with drying temperature and the regularity of their distribution increased with storing time (Fig. 2).

Water sorption:

About 5 g of the dredged sludge or about 2 g of the air dry residual were either predried at 110ºC or put directly in an aluminium dish 2x3 cm, and placed in a desiccator, containing a solution which created a suitable relative water vapour pressure atmosphere:

- p/p_o = 0.5 - over the saturated $Mg(NO_3)_2$ solution (10-14 days)
- p/p_o = 0.95 - over the 10 % H_2SO_4 solution (14 to 26 days); this corresponds to higroscopic water content measurement.

Thus the following determinations were performed:

(a) WS test of the sample as suplied (3x)
(b) WS test of sample predied at 110ºC (3x).

Next all the samples were dried for 1 day at 110ºC, 8h at 220ºC and heated 4h at 400ºC and 1h at 800ºC. This heat treatment was applied also to samples which were not subject to WS test (TG).

The measurements were repeated four times in definite time intervals:

WST-1: sludge was stored for 1 month at ambient automn temperature,
WST-2: sludge was stored for 2 months more at ambient winter temperature,
WST-3: sludge was stored for 1 month more in the laboratory at 20°C - 24°C,
WST-4: samples after the drying rate measurement were stored for 1-2 months in air dry state and their water sorption was measured.

Table 1. Change in drying rate - dG/dt with time. (Series I and Series II).

Time	I	II 30ºC	Time	I	II 45ºC
	g/h			g/h	
2-4h	0.2	0.2	2-4h	0.45	0.5
	g/day			g/day	
1-7 days	5	5.5	1-2 days	13	13.3
13 days	linear decrease in drying rate		>6 days	linear decrease in drying rate	

Table 2. Initial drying rate as the function of time (Series I)

Value	Time	30ºC	45ºC
		mg h^{-1}	cm^{-2}
$\frac{-dG/dt}{A}$	2-4 h	10.0	22.5
	1-2 days	10.4	27.1
		cm	s^{-1}
$K.i = \frac{-dG/dt}{A}$	2-4 h	2.78 x 10^{-6}	6.25 x 10^{-6}
	1-2 days	2.89 x 10^{-6}	7.52 x 10^{-6}

Table 3. Water sorption of the sample as supplied (undried, mean of 3 tests) and weight loss on heating.

Sample	W %°	Retention $W_a(p/p_o = 0.5)$ % 14 days	Sorption $W_a(p/p_o=0.95)$% 26 days	Weight loss to 220°C 8 h	−ΔG % from 110°C (G) to 400°C 4 h	 to 800°C° 1 h
WST-1 start 22.11.89	252	6.33 ± 0.03	45.3 ± 2.4	4.89 ± 0.30	12.2 ± 1.1	18.5 ± 0.9
WST-2 start 8.01.90	234	5.69 ± 0.02	36.4,± 0.84	4.89 ± 0.16	10.4 ± 0.36	17.97± 0.09
prestored at ambient temp.			TG	4.57 ± 0.11	7.70± 0.54	17.06± 0.17
WSt-3 start 8.02.90	230	5.62 ± 0.08	39.4 ± 3.0	4.58 ± 0.14	9.9 ± 0.6	17.7± 0.2
~~prestored~~ at ambient temp.			TG	4.95 ± 0.22	7.64± 0.05	17.09± 0.09

Results are presented in Table 3 and 4, as related to the sample weight at 100°C before the water sorption test (b, Table 4), or after the water sorption test (a, Table 3). Results of direct heat treatment are also indicated (TG). In Table 4 there are compared the values of water sorption of

(A) sludge dried at at 110°C

(B) sludge dried at 30°C (see drying test)followed by oven drying at 110°C.

(C) sludge dried at 45°C (see drying test)followed by oven drying at 110°C.

Table 4. Water sorption of oven dried samples after various treatments (mean of threetests) and weight loss on heating.

Test	W_o %	W_a $(p/p_o = 0.5)$= 14 days	Water sorption $W_a(p/p_o = 0.95)$ % 14 days	Weigt loss −Δ G from 110°C (%) to 220°C	 to 400°C	 to 800°C
A: Wst-2 110°C	234± 1	4.06± 0.08	36.9± 0.7	5.03± 0.21	11.9± 0.7	19.0± 0.2
B: WST-4 30°C;110°C	3.96± 0.26	4.98± 0.35	34.1± 7.3	4.08± 0.34	9.6± 2.0	18.2± 0.5
C: WST-4 45°C;110°C	2.74± 0.39	3.84± 0.54	35.8± 13.2	4.38± 0.49	10.6± 0.8	17.7± 0.9
A: WST-3 110°C	230.0± 0.2	4.16± 0.03	38.5± 2.1	4.63± 0.12	11.1± 0.2	18.1± 0.1
B: WST-4 30°C;110°C	2.24 ± 0.02	3.42± 0.05	24.2± 4.8	4.93± 0.88	8.63± 0.90	16.8± 0.6
C: WST-4 45°C;110°C	2.64± 0.15	3.76± 0.25	38.3± 14.3	4.8± 1.1	9.5± 0.7	17.6± 0.4

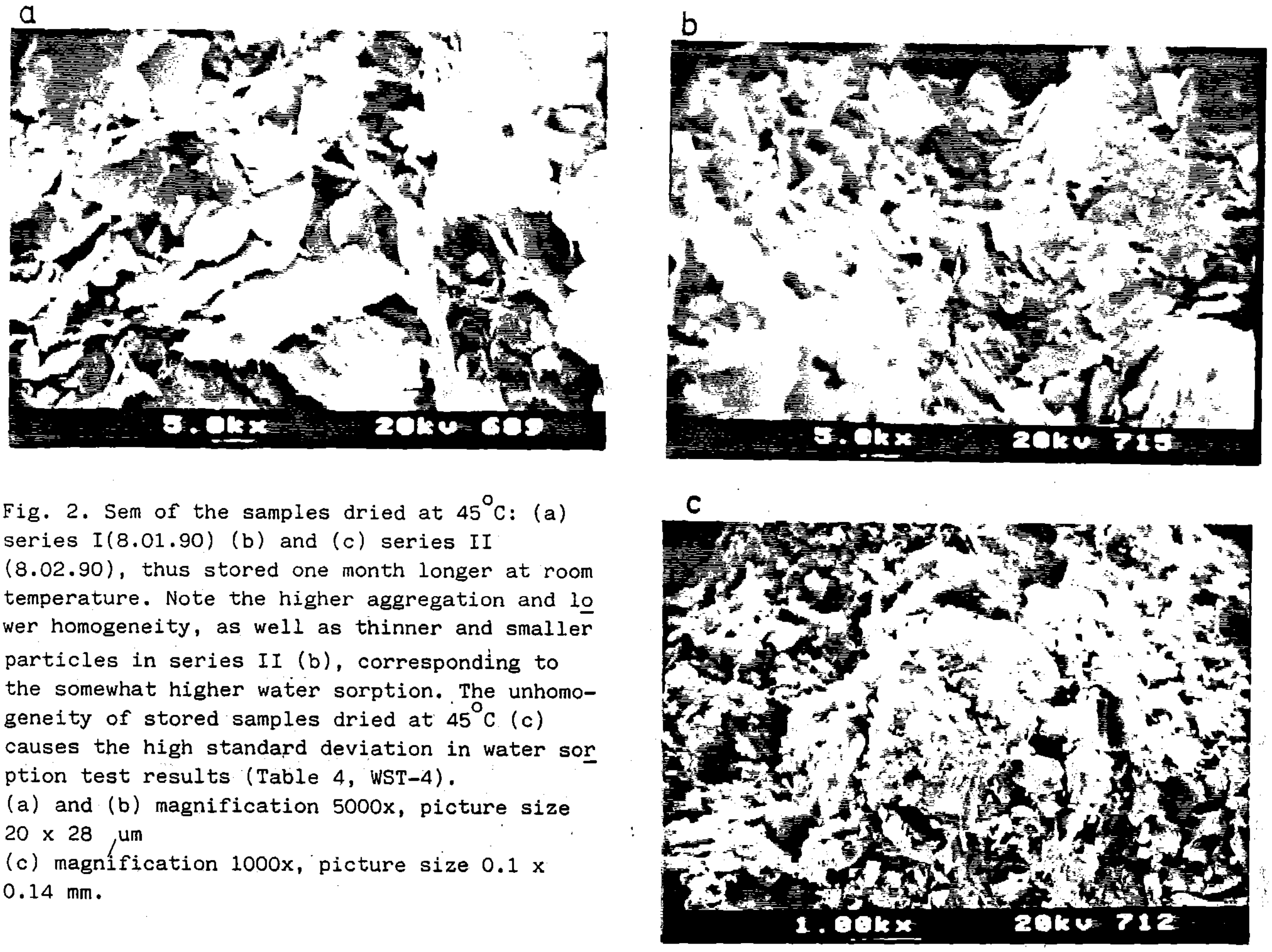

Fig. 2. Sem of the samples dried at 45^{o}C: (a) series I(8.01.90) (b) and (c) series II (8.02.90), thus stored one month longer at room temperature. Note the higher aggregation and lower homogeneity, as well as thinner and smaller particles in series II (b), corresponding to the somewhat higher water sorption. The unhomogeneity of stored samples dried at 45^{o}C (c) causes the high standard deviation in water sorption test results (Table 4, WST-4).
(a) and (b) magnification 5000x, picture size 20 x 28 µm
(c) magnification 1000x, picture size 0.1 x 0.14 mm.

The standard deviation presented in Table 3 and of samples (A), Table 4, seldomly exceeds 1% whereas that of samples (B) and (C) was much higher, (5 to 14% Table 4). This indicates the sample inhomogeneity, which was indeed observed in SEM, Fig. 2.

Oedometer test:

A Know amount of the sludge was placed in a cylindrical oedometer on a porous plate covered with a filter paper (A=33cm^2, h_o=2cm). The sample bottom was connected via a flexible tube and a T-valve with a displaceable calibrated burette, which water meniscus was levelled with the sample bottom. The whole system was filled with water. The burette was lowered to get a 25 cm difference in elevation heads, i.e. this suction at the sample bottom, and the water escape was measured as the function of log time. The end of primary consolidation was estimated as 24 h, which was kept in sample II at all loading steps. A longer consolidation could cause a change in microstructure, which would be difficult to interpret.

The following loading steps were applied:

u/γ_w= -25cm, -50cm, -100cm.

This last step created troubles. For simplicity reasons γ_w will be omitted in further discussion.

Keeping the pore water pressure at the value of -100cm, the sample was covered with a porous plate and the following values of consolidation stress werw applied:

σ_c= 12.5kPa, 25kPa, 50kPa, 100Kpa, 200kPa and 400kPa.

measuring both the water outflow and the change in sample heights.

After the end of consolidation at σ_c= 400kPa the sample II was unloaded stepwise by the step mentioned above to u= -100cm and the water inflow was measured. It was very small, thus it is not indicated here. The final sample weigth and dimensions were determined and the water contents at the given consolidation pressure were calculated. Thus the relation between the log σ_c and the water content was obtained, Fig.3, which was similar for both samples.

Coefficient of hydraulic conductivity was calculated from:

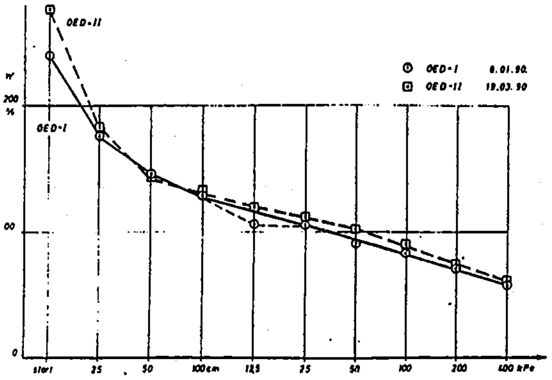

Fig. 3 Relation betwen consolidation pressure (log) and water content in oedometer test.

(1) Darcy´s law:

$$k = \frac{Q}{A\ i\ t} = \frac{V_2 - V_1}{A\ i\ (t_2 - t_1)}$$

Where V_1 and V_2 are the volumes of water which escaped in times t_1 and t_2 respectively and the hydraulic gradient is

$$i = \frac{H}{1}$$

Where Δh is the increase in total stress (expressed in cm H_2O) in the given consolidation step and 1 is the length on which the gradient is acting. It was assumed that

$$1 = h(t) \text{ at } \sigma = -u \quad \text{and}$$

$$1 = \frac{1}{2}h(t) \text{ at } \sigma > -u$$

Where h(t) is the sample heights at the given time t. This is correct for initial time of consolidation when the degree of consolidation is small. Otherwise due corrections should be introduced.

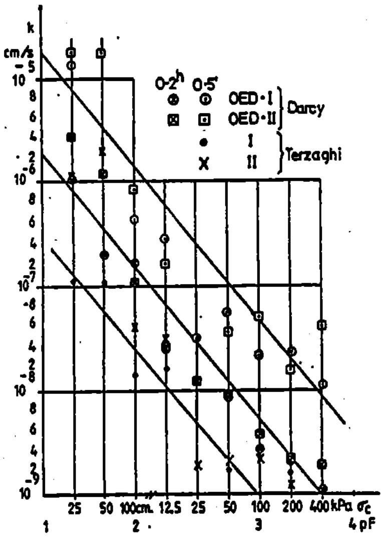

Fig.4 Relation between the coefficient of hydraulic conductivity (log) and consolidation pressure (log) in oedometer test.

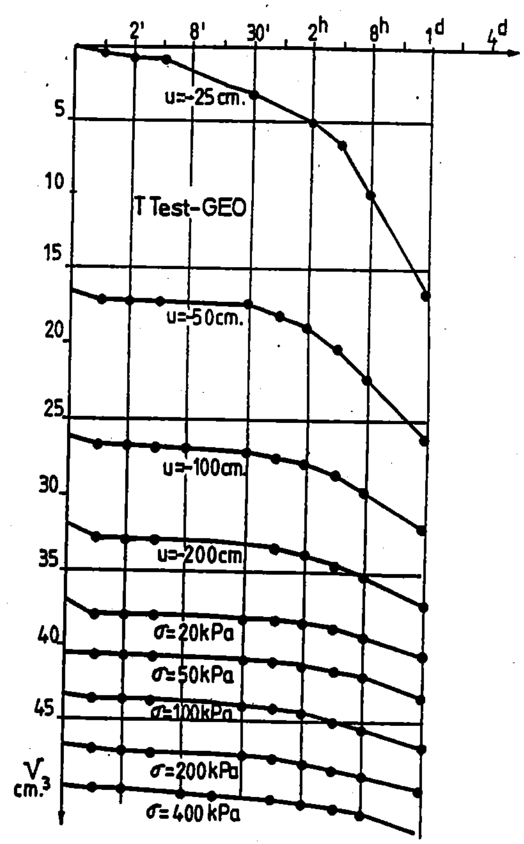

Fig.5. Consolidation curves in triaxial test

(2) Terzaghi´ s consolidation theory

$$k(-u) = T_{50}\ m_v\ \gamma_w\ \frac{h^2(t)}{t_{50}}$$

$$k(\sigma) = T_{50}\ m_v\ \gamma_w\ \frac{/\ 1/2\ h(t)/^2}{t_{50}}$$

Here k(-u) and k(σ) are the coefficients of hydraulic conductivity measured by water suction and consolidation pressure respectively, T_{50} = 0.2 is the time factor and t_{50} is the time both at 50% consolidation, γ_w = 1 G/cm^3 is the specific weight of water.

The coefficient of volume change is

$$m_v = \frac{-\Delta h(t_o \text{ to } t_f)/h_o}{\Delta \sigma} = \frac{-\Delta \varepsilon}{\Delta \sigma}$$

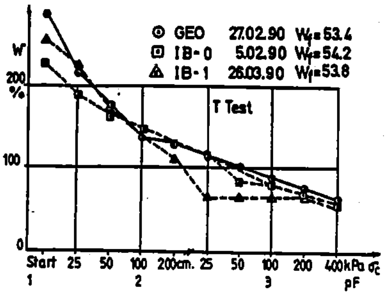

Fig. 6. Relation between the consolidation pressure (long) and water content in triaxial test.

and it is the ratio of the relative change in heights during the given consolidation step (strain) to the increase in consolidation pressure, which is expressed in cm of water colum and multiplied by $_w$. Relation between and the consolidation pressure is presented in Fig. 4.

Triaxial test

Tubes in the cylindrical sample pedestal were filled with deaired water, the pedestal was covered with a porous stone and a filter paper and it was connected by a flexible tube and T-valve with a movable calibrated burette, its water meniscus being levelled with the sample basis. A cylindrical rubber menbrane was fastened to the pedestal by several O-rings and stretched on a cylindrical sample holder, the space between these two elements being evacuated. The rubber menbrane was filled with a known amount of ludge to the heights of ca.8cm (G_o = ca.90G, Ø=3.6cm, A=ca.10cm^2)and protected from evaporation.

Water suction was applied lowering the burette by 25 cm and thus achieving this difference in elevation heads. The volume of escaping water was registered as the function of log time until the end of primary consolidation which was assumed as one day. The following consolidation pressures were aplied:

u = -25cm, -50cm, -100cm, -200cm,
o_3 = 25kPa, 50kPa, 100kPa, 200kPa, 400kPa.

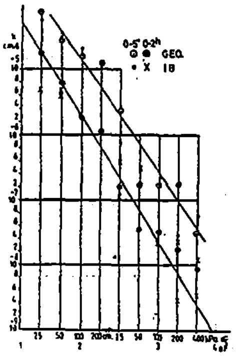

Fig. 7. Relation between the coefficient of hydraulic conductivity (log) and the consolidation pressure (log) in triaxial test.

Test	cm^{kg}/s	n	r_{xy}
OED, 0-5'	4.69 x 10^{-4}	1.307	-0.90
OED, 0-2h	9.29 x 10^{-5}	1.393	-0.95
OED, Terzagli	2.74 x 10^{-4}	1.954	-0.90
Ttest 0-4'	1.55 x 10^{-2}	1.593	-0.94
Ttest 0-2h	2.20 x 10^{-3}	1.508	-0.96

Table 5. Parameters of regression lines.

The sample weight was measured at the end of the consolidation procedure and it was dried for one day at 110 ^{o}C to determine the water content. Consolidation curves are indicated in Fig. 5 snd relation between the water content and the consolidation pressure is presented in Fig. 6, compare Fig. 3. In both cases 24h were assumed as the end of consolidation. A straight linear relation between the log coefficient of hydraulic conductivity (which was estimated in a similar way as in consolidation test) and the log consolidation pressure was obtained and it is presented in Fig. 7.

DISCUSSION

An instabiliti of the dredged sludge is indicated by the high difference in specific surface at various relative humidity, p/p_o conditions, as well as by the difference between the plastic and liquid limit. the reason may be eighter

- a variability in particle thickness, which was indeed observed (see below), or
- a high amount of amorphous material,

This material looses the internally sorbed water at temperatures exceeding 110^o C. Indeed the weight loss G(110^o C to 220^{o}C of the dredged sludge under study was exceptionally high, reaching up to 5% and the G(220^o C to 400^o C) amounts to 3%.

This value increases after the water sorption test(see below), thus at least partly it is not due to the presence of organic matter, but to microstructure and composition. Organic matter was present here mainly in form of small fragments of plants(SEM).

In analogy to bentonite suspensions of thoroughly studied microstructure, this dredged sludge indicated a tendency to aggregate (aging): if freshly stirred it forms an elastic, viscous gelly mass with internal repulsion pressure prevailing (turgor). After a certain storing time i.e. hours or days, the solid phase(containing dissolved salts) and form aggregates, which manifest itself in change of its properties (see below the drying rate, water sorption, etc.) The older the aggregated systems was, the more difficult it was to regain the homogeneity by mixing. All the tests were performed using the freshly and thoroughly mixed sludge, except the triaxial test sample TT-IB1. The material under study indicated variation in properties depending on treatment, on time and temperature of storage..

(1) Drying rate decreased with time of storage of the sludge in a closed container, which is caused by aggregation processed (compare bentonite,5),1) and by increase in attraction energy between neighbouring elements. Initial drying rate changed with storing time (one month) from 5 to 5.5 G/day, both at 30°C. Macropores were visible after drying at 45°C in the lower part of the sample, the drying-rate being 13.0 and 13.3 G/day respectively. The top part of these samples (ca. 0.5cm) was macroscopically homogeneous.

(2) Aggregation with time was observed macroscopically in this sludge (see its description) and it was also observed in SEM (Fig.2). The size of macroaggregates increased with the storing time and the regularity increased as well.

(3) Water sorption decreases with time of storage, depending on storage temperature and on the relative humidity of its measurement (Table 3). Higroscopic water content as measured at p/p_o = 0.95 decreased after two months storage at low temperature from 45.3% to 36.4%, and to 39.4% if stored at 20º C, whereas the water sorption as measured st p/p = 0.5 decreased in the first case from 6.3% to 5.7%. In SEM also a small increase in particle thickness is observable, Fig.2.

(4) High inhomogeneity in water sorption at p/p_o = 0.95 was detected, if the sample was stored and dried slowly either at 30ºC or at 45ºC after a certain time of storage (Table 4).

Standard deviation was 5 to 14%. This indicated the separation of the sludge into various microstructural phases during storing and/or drying. Indeed high inhomogeneities were observed by SEM (Fig. 2) and they may influence clay properties. Such a separation was observed during the study of bentonite suspensions (compare[1]).

(5) The dredged sludge may contain a high amount of amorphous material, which retains some water at 110ºC and thus its weight loss on static heating, ΔG (110ºC to 220ºC) is high. At more elevated temperatures ΔG(220ºC to 400ºC) the organic matter may decompose, but also internal (interlayer) water proceeds to escape. Thus the weight loss was in the sludge exceptionally high and amounted to (Table 3, TG).

(1) ΔG (110ºC to 220ºC) = ca. 5 %
(2) ΔG (220ºC to 400ºC) = ca. 3 %
(3) ΔG (400ºC to 800ºC) = ca. 9 %

The highest change was observed in the second case (2): after water sorption it increased to 7.3% in unstored sample and to 5.3-5.5%, in the stored one. This value depends also on the drying temperature (Table 4): in samples dried at 30ºC it was 3.7% to 5.5%, whereas in samples dried at 45ºC it was 4.7 to 6.3%. All these indicate some changes in microstructure, some "trapping" of internal water, which needs now a higher energy to escape. Indeed in SEM grains of amorphous silica were visible, which could be the reasons of these phenomena. Also the aggregated structure may trap water and impede its escape. In the third case (3) the ΔG values decreased withy storing time.

(6) Sudden escape of water was observed at low suction in the oedometer test; in some cases it amounted to over 10 cm^3 . This may be due to water exclusion in the aggregation process.

(7) The sludge for one of the triaxial test samples (TTIB1) was stored for several months and it was no thoroughly stirred to disrupt the aggregates before the sample formation. The aggregated state of this sample might have caused its unusual behaviour(Fig. 6), i.e. expulsion of water both at u = - 200 cm and at σ'_c = 25kPa, which content remained afterwards constant up to σ'_c = 200 kPa. This expulsion could have been caused by (1) a high interaggreate attraction, when the diffuse layer repulsion was neutralizad by the external load, (b) expulsion of interaggreate water from micropores, connected with the collapse or the microstructure.

Knowledge of the drying rate and its temperature dependence allows to estimate its value at an arbitrary temperature by inter- or extrapolation. Even one measurement may be enough if the LeChatelier-Braun rule is applicable, which states that the rate of endothermal reaction is approximately doubled, if the temperature is increased by 10° C. This was indeed observed for the drying rate (Fig.1).

If the drying rate is devided by the drying surface area (here 20 cm^2) and by the specific weight of water (1 G/cm^3) a value of coefficient of hydraulic conductivity, as multiplied by the hydraulic gradient is obtained, i.e. k i (see Table 2). The hydraulic gradient is unknow, but here it should be a function of the difference between the water vapour pressure inside the sample and in the ambient atmosphere. If it is assumed as i = 1, then the values in Table 2 are close to coefficient of hydraulic conductivity as measured in triaxial test ($u = -100$cm) or in oedometer test ($u = -25$cm), time 0 - 2h (Fig. 4 and 7). The values of k and of dG/dt should be function of water potencial: the higher the water potencial, the slower would be the escape of water whether in drying or in permeation. Indeed the coeffient of hydraulic conductivity (its logarith) decreases linearly with the increase in log consolidation pressure, which lowers the water content. Between the consolidation pressure and pF should exist the following relation:

$pF = \log / (\sigma_c \times 10)/\sigma_o /$ where $\sigma_o = 1$kPa

$pF = \log (-u/u_o)$ where $u_o = 1$ cm H_2O

Thus the Fig.4 and Fig.7 represent also the straight linear relation between pF and log k. If the consolidation pressure in these Figures were presented as "consolidation pressure head" h_c, then an equation discribing the lines in Fig. 4 and Fig. 7

$\lg k = \lg k_o - n \lg h_c$

would have a form similar to Gardner equation

$$k = a / (h^n + b)$$

with $b = 0$, where a, b and n are soil dependent parameters and h is the pressure head, k_o is the coefficient of hydraulic conductivity at $\log h_c = 0$

Knowledge of water sorption allows the estimation of the average specific surface, S, multiplying its value (at the given relative humidity indicated in paranteses) by the suitable coefficient, thus here:

$S = W_a (p/p_o = 0.5) \times 585$ m^2/g H_2O

$S = W_a (p/p_o = 0.95) \times 390$ m^2/g. H_2O

The values of k, n and of the correlation coefficients are shown in Table 5 and the regression lines are presented on Fig. 4 and 7, Table 5.

The higher the water sorption, the tinner (smaller) are the clay particles and thus the hydraulic conductivity would be the lower, whereas the water content at the given consolidation pressure would increase.

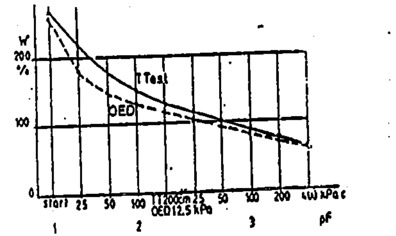

Fig. 8. Comparison of consolidation inodoemeter test and in triaxial test.

The knowledge of the weight loss on heating gives some information on the mineral composition and on microstructure which is outside the scope of this paper.

The study of consolidation of the slurry perforned on two different apparatus in two different laboratories gave reproducible results, provided the sample microstructure did not change in storage (see sample TT-IB1). The differences in behaviour in triaxial test and in oedometer test (Fig.8) may be attributed to different microstructures (particle preferred orientation), produced by the strees applied: vertical stress in oedometer test producing particle arrangement perpendicular to it; an all around pressure in triaxial test producing random particle orientation, which may hold more water. There are some data indicating that in drying the particles may arrange parallel to the drying surface as this is the result of suction. This may influence also the hidraulic conductivity of the surface layer. Thus any parameter pertainig to the geotechnical behaviour of the dredged sludged may depend on the history of this sludge which influences particle arrangement and aggregation state.

ACKNOWLEDGEMENTS

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ON THE ESTIMATION AND INTERPRETATION OF MARINE SEDIMENT PROPERTIES USING AN ACOUSTIC MEASUREMENT APPROACH

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ABSTRACT

In order to derive the geological properties of a marine system from acoustical measurements, models which describe the physical phenomena taking place are required as well as modern digital signal processing methods to assure a fast mode of operation. Therefore, a model is proposed which takes into account absorption and dispersion effects. In order to model the behaviour of mud deposits, a density gradient is simulated. Furthermore, a parametric approach is presented to estimate the PSD (Power Spectral Density) of the colored noise sources. Finally, the synthetic reflectograms generated with this model are compared with the measured reflectograms.

1 INTRODUCTION

Traditionally, subbottom profiling and seabed study involve three distinct steps : data gathering, data processing and interpretation. Data gathering is either done by physically sampling the bottom or may resort to indirect techniques based on seismic explorations. The direct sampling method is a cost-effective and inaccurate tool since the environment is disturbed. Therefore remote sensing using acoustic reflectometry in particular is a complementary and accurate technique. The proposed method is used to determine some specific geological characteristics of mud deposits and other sediment types in estuaries and seas. The modelling of the acoustic propagation phenomena in multi-layered structures has attained a high degree of perfection, resulting in a great similarity between measured echograms and synthetically computed echograms [1,2,3]. The a priori knowledge gained through modelling is important in the inverse procedure which will allow the mapping of subsurface sediments using parameter estimation methods and system identification [3,4]. Due to the speed and accuracy of the proposed measurement method, it will be possible to gain information in real time.

This paper is organized as follows: in section 2 the measurement procedures and set-up are described, while in section 3 the modelling approach for the synthetic echograms is discussed briefly. The validation of the models is carried out in section 4. Finally, the geological interpretation problem is envisaged.

2 THE MEASUREMENT TECHNIQUE

Acoustic reflectometry is used to study the sediment layers and the near subbottom in a marine environment. In this case information up to a few meters of depth via a non-disturbing technique is aimed; i.e. without having the composition and location of the sediment layers altered while measuring. This implies that the use of probes towed along the seabottom is excluded. The acoustic echosounding method is for this remote sensing task a far better candidate then the techniques based on seismics. This is due to the fact that it is possible to generate emitted pulses with a high power content electronically (up to a few kW) and to the short duration of an experiment. Because of the low penetration aim, it becomes possible to scan the bottom with a high repetition frequency (e.g. 5 records/second).

Although from metrological point of view, the acoustic reflectometry seems to be a good measurement method, it follows from practice that the interpretation of the echograms is not a simple task, due to the poor definition of 'mud' (but also of other sediments), to the influences of the used instrumentation and the physical environment where the experiments have to be carried out. The definition of mud is certainly one of the most difficult tasks because it is a very heterogeneous, cohesive sediment composed of a small fraction of sand and an important fraction of clay and organic material. The authors of this paper were also involved in the organization of a workshop dedicated towards a definition of mud, held in Brussels [5]. Furthermore, the modeling of the present correlated noise sources corrupting the measured echograms is required in order to validate the model used for the acoustic wave propagation proposed in [1] and [2]. It is also necessary to integrate in this model the effect of the instrumentation used to gain the physical measurements [1]. Once the synthetic reflectograms, and hence the models are validated, an estimator for the acoustic parameters is constructed [3].

The currently used measurement set-up for subbottom profiling echosounders is shown in figure 1.

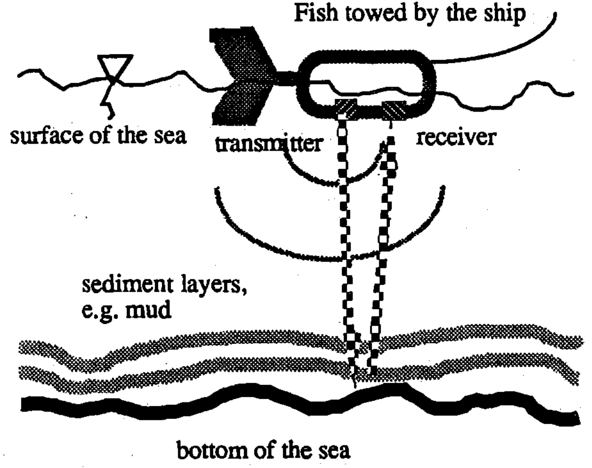

Figure 1: A typical subbottom profiling echosounder measurement set-up: the transceiver part.

A measurement probe is towed aside the ship. The probe contains a set of transmitter/receiver transducers (several piezo-electric or ceramic sensors to receive and/or more ceramic transducers to transceive), which is located in a dynamic acceptable housing, called a fish. The transmitter converts an electrical impulse into an acoustic wave. The required power of the emitted signals is determined by the attenuation and the thickness of the media and has a value ranging up to several kW. The emitted power can be seismic, sonic or ultrasonic (from a few mHz up to several hundreds of kHz). The actual transducers usually produce an amplitude modulated impulse signal with a fixed carrier, e.g. 3.5 kHz or 12 kHz in the audioband or 300 kHz in the ultrasonic band. The spectrum is therefore determined by the spectrum of the applied time window convolved with a Dirac-distribution located at the carrier frequency, which is mostly yielding narrowband signals [6]. It has been shown, however, that such signals are not optimal [1], although they remain still very popular.

In addition to the classical echosounder equipment described above, a Dynamic Signal Analyzer (DSA710-SPINNOV) is incorporated in the measurement set-up in order to digitize the measured echograms with a bitrate of 16 without aliasing problems (anti-alias filtering: 11th order Cauer elliptic filter, pass band ripple of ± 0.3 dB, stop band attenuation 96 dB with digital filtered passband equalization (0.01dB) [7]).

The DSA-equipment offers furthermore the advantage that estimators, which will be discussed further on, can be implemented in a VME-environment in order to assure a fast mode of operation (FFT algorithms implemented in DSP-firmware library).

The noise measurements are carried out in silent conditions, which means that the transceiver part of the measurement equipment is only working in receiver mode. Doing so, not only the noise due to the marine environment is picked up, but also the periodic noise due to the machinery on board of the vessel (engines, generators,...). In this measurement procedure, the transfer characteristic of the transceiver part is included in the measured noise also. The modelling approach for the acoustic wave propagation phenomena as well as the colored noise sources is treated and discussed in section 3. A typical echogram, recorded in the Kalo lock, is shown in figure 2.

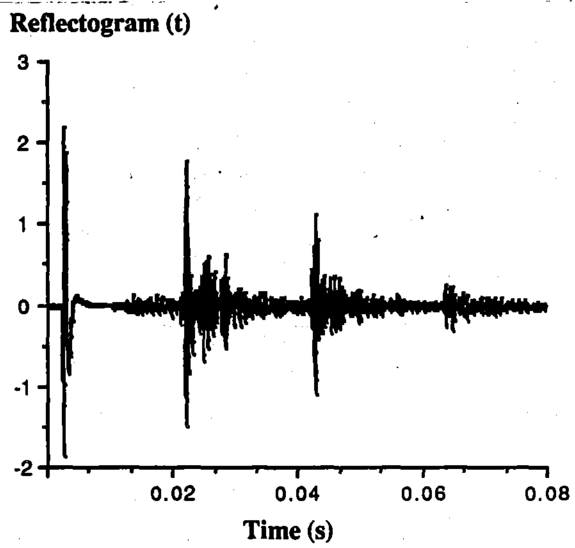

Figure 2: A reflectogram recorded in the Kalo lock

One recognizes the emitted pulse, interwoven reflections on a mud layer containing a gradient of the density and the primary as well as secondary reflections on the sea-floor.

3 MODELLING

The real world complications of non-ideal sources, noises and inhomogeneous propagation paths necessitate a more sophisticated approach in order to obtain usable geological data. Therefore, the modelling of the acoustic wave propagation as well as the colored noise sources corrupting the measured echograms will be discussed briefly. Assuming that the acoustic wave propagation is linear, a convolution model for the noisy reflectogram in time domain is given by:

$$r(t) = \mathfrak{F}^{-1}\left[H_m(\omega) . H(\omega) . S_m(\omega) \right] + n(t) \qquad (1)$$

with: $H_m(\omega)$ the transfer characteristic of the measurement equipment
$H(\omega)$ the transfer function of the marine system
$S_m(\omega)$: the spectrum of the acoustic input signal
$n(t)$ the colored noise sources

Modelling of the acoustic wave propagation

The proposed model is based upon a layered structure representation of the seabed [1]. Furthermore, the effects of absorption and dispersion are taken into account using the Futterman theory [1]. The inhomogeneous propagation paths are caused by various factors: the definition of the mud deposit itself, the stratification of the layers, scattering and the presence of a density gradient in the layers, especially the mud layer. Therefore a noiseless simulation is carried out for the measured reflectogram shown in figure 2, without taken into account the influence of the measurement equipment. The geological parameters involved in the model are determined from samples taken on the same location where the acoustic reflectograms were recorded (density profile, sediment type). The acoustic parameters (quality factor and velocity of sound) are obtained from the work of Hamilton [8]. An accurate estimate for the thickness of the water layer is calculated from the cepstrum of the measured reflectogram. With this set of parameters (table 1) the marine system is described with a 4-layer model (seawater - mud - clayey sand - sand). For the mud layer as well as for the clayey sand layer a density gradient is incorporated in the model. The simulated reflectogram is shown in figure 3.

layer	thickness (m)	density (kg/m³)	velocity (m/s)	Q
1	15	1030	1500	1000
2	2.7	1200 1300	1550	50
3	2.7	1500 1550	1600	40
4	∞	1800	1700	20

Table 1: Set of parameters used in the simulation.

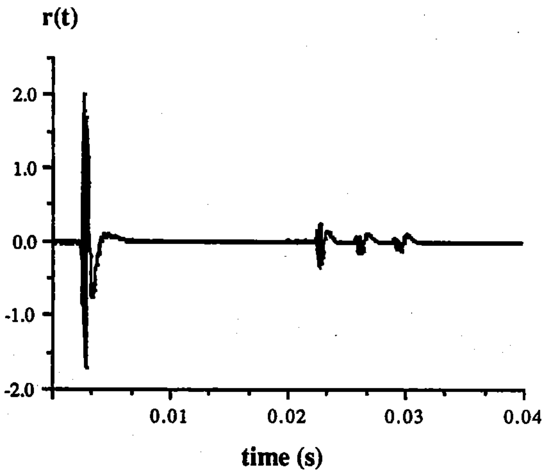

Figure 3: Simulated reflectogram with parameter values given in table 1.

Modelling of the colored noise sources

A study has already been made on the noise sources corrupting the measured echograms [9]. The PSD of the correlated noise sources, generated by propellers, engines, stabilizers, the fish incorporating the transducers, the water waves and the marine background noise, is estimated using a non-parametric as well as parametric approach [9],[10]. The estimated PSD obtained with the autocorrelation method and with an ARMA modellisation are compared with the periodogram (fig. 4 and 5).

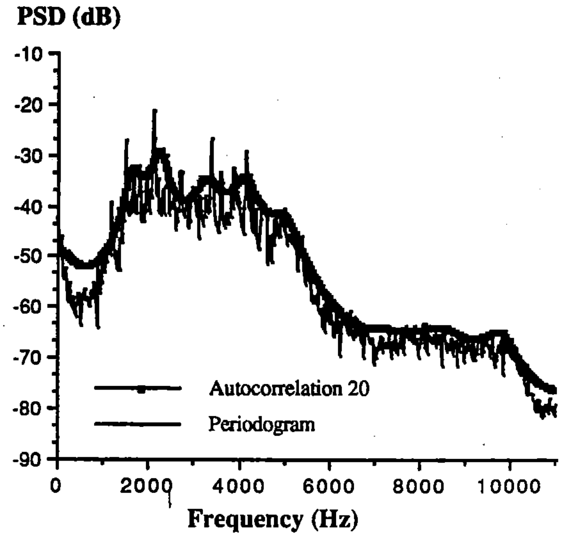

Figure 4 : Estimated PSD with autocorrelation method and with the periodogram

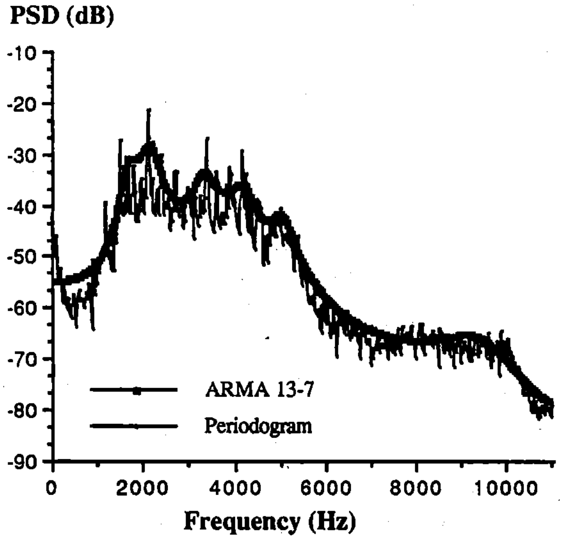

Figure 5 : Estimated PSD with ARMA modellisation and with the periodogram

This study demonstrates that the shape as well as the fundamental components appearing in the estimated PSD correspond with the periodogram. Furthermore, this parametric approach makes it possible to incorporate the influence of the colored noise sources into the model which describes the acoustic propagation phenomena.

4. MODEL VALIDATION

The measured echograms are compared with synthetic echograms which are calculated taking into account the used measurement set-up. Calculating the time signal n(t) in (1) from the estimated PSD with ARMA-model and taking into account the transfer characteristics of the measurement equipment (receiver filter, Time Varying Gain amplifier) the synthetic reflectogram can be validated.

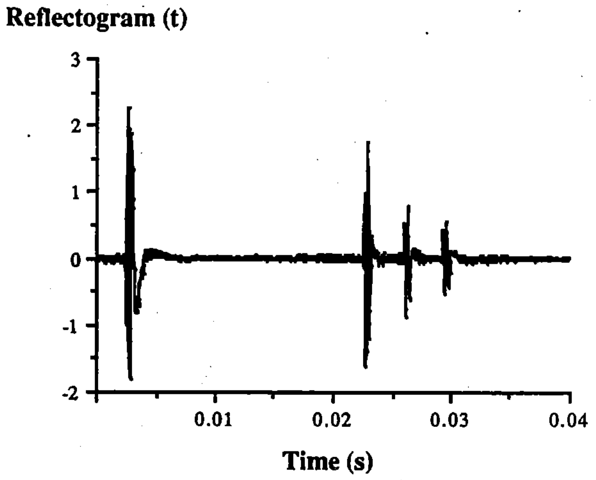

Figure 6 : Synthetic reflectogram including the effect of the receiver network, TVG amplifier and the colored noise sources.

5. GEOLOGICAL INTERPRETATION

The goal of the acoustic reflectometry is to produce a 3-dimensional image of the subsurface that accurately portrays the geology. However, the physical parameters, such as the linear absorption coefficient and the velocity of sound, used in the model are purely acoustic. An estimation procedure was introduced, starting from a measured and noisy reflectogram, in order to extract the geophysical parameters involved in the model for the acoustic wave propagation [3]. Therefore, an estimator based on the classical Maximum Likelihood Estimator (MLE) for linear systems was constructed by introducing the transfer function H(ω) of the marine sytem. It was shown that with this estimation procedure not only the thickness of the deposits and the acoustic impedance but also the linear absorption coefficient can be estimated [3]. To portray the geology, marine geological and environmental data is desired and therefore some sediment properties must be derived from the acoustic parameters. At present, some ambiguity exists in this problem. To solve it, a knowledge based system is proposed to yield precise sedimentological data. The requirement of expertise in complementary domains leads to an intense collaboration of various partners. Acoustic knowledge and expertise, marine geology and sedimentology and knowledge engineering itself must make the link between the acoustic parameters and the mapping of the subsurface in terms of geological information.

6. CONCLUSION

In this paper, the acoustic reflectometry is discussed as a measurement technique for the remote sensing of stratified marine systems. A modelling approach is introduced, which takes into account the acoustic wave propagation phenomena as well as the correlated noise sources present in the marine environment and the transfer characteristic of the measurement set-up. The complete model is validated using a set of parameters obtained from geological sampling. Furthermore an estimation and interpretation approach was proposed.

7. ACKNOWLEDGEMENTS

The authors would like to express their gratitude towards the University of Brussels and the Belgian government for supporting the research and want to thank the members of the crew of the Belgian Oceanographic Ship the "BELGICA" for their outstanding help during the campaigns along the Belgian coast and the Scheldt.

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MECHANICAL STRENGTH DETERMINATION OF COHESIVE SLUDGES

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ABSTRACT

The consistency of waste sludge is one of the characteristics that determine its suitability for disposal at sanitary landfills. Because of the complexity and the long time needed for the performance of a triaxial test, faster methods for the routine determination of sludge consistency are needed. A good alternative is found in the vane shear test. In this article a description of the vane shear test and of a fall cone penetration test is given.

INTRODUCTION

Many waste materials occur as water-rich sludges. Among them are the sludges emerging from sewage treatment and from the purification of various industrial waste waters. Also the production of drinking water from ground or surface waters generates a waste sludge stream. Many of these waste sludges are disposed of at controlled landfills.

Because of their initially high water content (typically about 95%) the sludges are de-watered prior to their disposal. There are two reasons for this. The volume of the waste stream can be highly decreased by dewatering, which lowers transportation and dumping costs. Secondly, waste materials dumped at controlled landfills must be "enough consistent" in order to not interfere with the normal landfill exploitation.

When the solid fraction of the sludge consists of very fine, colloidal particulates, dewatering may be quite difficult and expensive. It then becomes important to know just how far dewatering must proceed in order to have a "consistent enough" product.

The consistency of the sludge must be brought in accord with the possibilities of the landfill exploitation. In special cases the landfill exploitation will have to take into account the consistency of the dumped waste materials. In any case a knowledge of the consistency will be required. Direct methods for measuring the consistency or mechanical strength are then needed.

The characterisation of the consistency of dewatered sludge is the subject of this article. The research mentioned herein is part of a research project started in october 1989 by SVW. The attention in this research project is focused on the consistency of sewage and drinking-water sludges, destined to be disposed of at sanitary landfills. The project could lean on the results of a preceding study of literature on determination methods for geomechanical properties of sludges (Geuzens, 1989).

MECHANICAL STRENGTH PARAMETERS

The consistency of sludge may be described by soil mechanical terms. The mechanical behaviour of dewatered colloidal sludges is mainly plastic and best compared with the mechanical behaviour of soft clays.

The mechanical strength of clay or sludge is characterised by its shear strength. The shear strength is the maximum internal reaction shear stress which can be generated in the sludge mass. It is a physical property of the sludge, determined by the nature of the solid particles, the water content and the degree of compactation of the sludge.

In general the shear strength is also a function of the normal stress on the (potential) yield surface. Using the Mohr-Coulomb criterion, we have :

$$\tau = c + \sigma . \mathrm{tg}\ \varphi$$

with : τ = shear strength in kPa ($1\ \mathrm{kPa} = 1000\ \mathrm{N/m^2}$)
c = cohesion in kPa
σ = normal stress on the yield surface, in kPa
φ = internal friction angle

The parameters c and φ completely define the consistency of the sludge (consistency as resistance to failure or plastic yielding). As with saturated clay, the shear strength of water-rich colloidal sludges is mainly due to cohesive forces and less to internal friction ($\varphi \approx 0°$). This leaves only cohesion (c) as the relevant parameter for such materials.

Many different methods are used to measure the shear strength of a soil or of any other particulate system. The principle of each of these methods is simple : one will determine the differential loading needed to bring a sample to failure or plastic yielding. However, the different ways of loading, the dynamic course and the velocity with which the loading is supplied, and uncertainties about the nature and extension of the yield surface, introduce difficulties in the interpretation and validity of the test results.

For evaluating the mechanical stability of sludge on landfills and the mechanical stability of landfills as a whole, the triaxial test undoubtedly is the most appropriate method. This test however is difficult and time-consuming and therefore not fit for routine practice. More fast and more easy measurement methods are needed. An overview of such test methods, which have already been used in the study of the suitability of dewatered sludges for landfilling, is given by Neuschäfer and Döhler (1988).

THE LABORATORY VANE SHEAR TEST

The vane shear test is well known to soil mechanical engineers. It is most often used in the study of the stability of clay soils. The laboratory vane shear test has been repetitively used in research concerning the suitability of sewage sludge for landfilling (Gay a.o., 1981, Möller a.o., 1985, Otte-Witte, 1989). The test apparatus is commercially available and highly standardised.

Recently also the sample pre-treatment was standardised (Loll a.o., 1989). A sludge sample is divided and refined until it can pass a sieve of mesh width 10 mm. It then is build in in a container of height 12 cm and diameter 10 cm. This is done in three layers and each layer is compacted in a prescribed manner. For this the so-called little Proctor rammer is used, known from the soil mechanical Proctor test. This rammer has a weight of 2,5 kg and is dropped from a height of 30 cm. 10 blows are given per layer. A detachable collar on the sample holder allows to equalise the upper surface of the sludge sample. It is common usage to measure the density of the sample thus compacted. This standardised way of sludge pretreatment and compactation may also be used for other mechanical tests.

The vane test apparatus is shown in Fig. 1. The performance of the test is as follows. The vane is put vertically in the sludge sample to a depth of 4 cm. The vane itself has a height and a diameter of 12,5 mm. This vane is connected to the under side of a torsion spring. The upper side of the spring can be twisted by means of an electric drive with constant and low velocity (10° per minute). In this way an ever growing moment is imposed on the vane. When this moment is great enough, the vane will no longer be kept still by the sludge but will begin to turn. The maximally generated deflection angle of the spring is recorded.

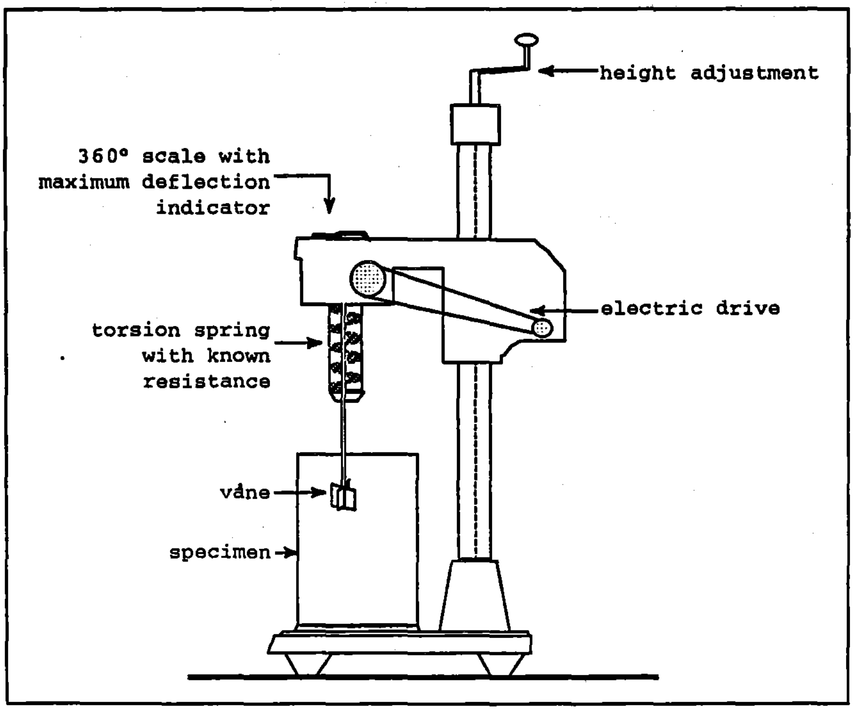

Fig. 1 : Vane test apparatus

When the resistance of the spring is known, the maximally generated moment on the vane can be calculated from the maximally generated deflection angle. Assuming a uniform distribution of shear resistance on the cylindrical yield surface around the vane, the shear strength of the sludge can be deduced from the maximally generated moment. On each sample, pretreated as described above, three measurements are performed. The average of the three results is given as the measurement result.

The vane shear strength (symbol: C_v) theoretically is equal to the shear strength as determined in a so-called UU (unconsolidated, undrained) triaxial test. Möller (1985) however found systematically higher values for C_v as compared to C_{uu} (factor 2 à 3). The fact that the yield surface in the vane test is imposed on the sludge, whereas in the triaxial test it may develop freely, could be a reason for these differences. For this reason the use of C_v in stability calculations can only be done with the necessary precautions.

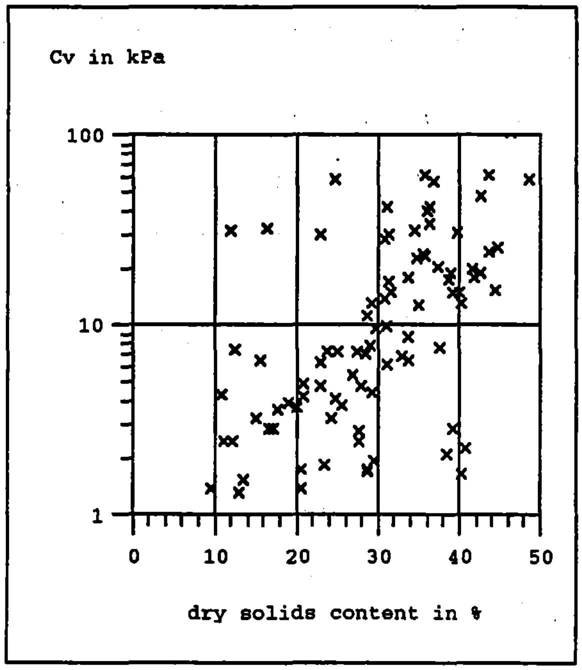

Fig. 2 : Vane shear strength C_v versus dry solids content.

Of different sewage and drinking water sludges the dry solids content and the vane shear strength were determined (Fig. 2). Values are between 10 and 50% dry solids and 1 and 60 kPa shear strength, respectively. The results clearly show that the dry solids content can not be a sufficient parameter to judge on the consistency of a sludge. This is exactly the reason why more direct consistency measurement methods are needed.

THE FALL CONE PENETRATION TEST

The fall cone penetration test is another fast measuring method for the consistency of particulate systems. It is known from ground mechanical engineering, but also from other technical fields, as for example food industry. The test is generally not as highly standardised as the vane test. Especially the dimensions of the fall cone are somewhat arbitrary chosen according to the application.

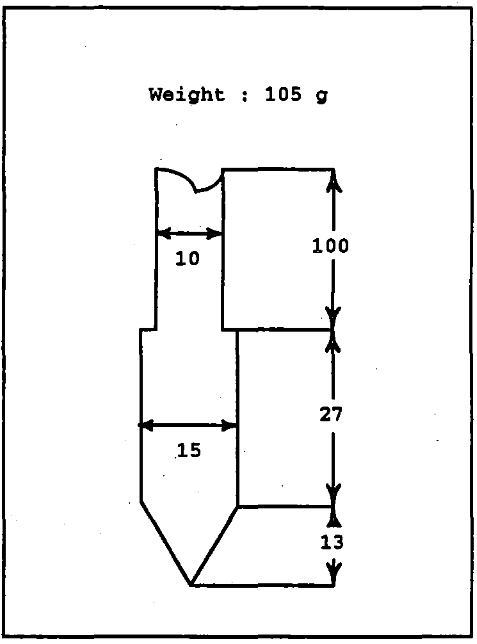

Fig. 3 : Dimensions of the fall cone in mm.

The test as it was performed in our research was based on the use of a high precision penetrometer in conjunction with a specifically designed fall cone. A container of height ±5 cm and diameter ±5 cm is filled with the sludge which is gently pressed by hand. The calibrated fall cone is placed on top of the equalised surface and allowed to fall for 10 seconds. The penetration depth is then accurately measured (±0,01 mm for penetration depths smaller than 10 mm, ±0,1 mm for penetration depths greater than 10 mm). As with the vane test an average of three trials is taken as the result. The dimensions of the fall cone used are given in Fig. 3.

The measurement result of a fall cone test is a penetration depth. Simultaneous measurements with the vane test enable to translate this penetration depth to vane shear strength. It is common usage in soil mechanics to calibrate penetration tests to more direct shear strength measurement methods. Fig. 4 shows the results of both tests, performed simultaneously on some 50 samples of sewage and drinking-water sludge.

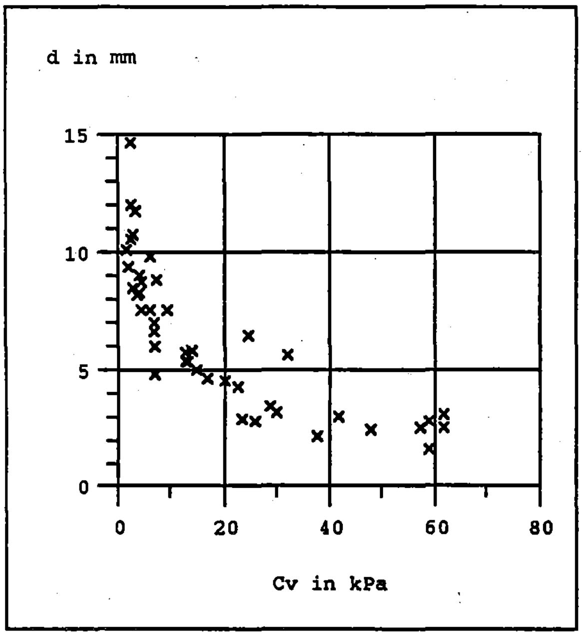

Fig. 4 : Fall cone penetration depth d versus vane shear strength C_v.

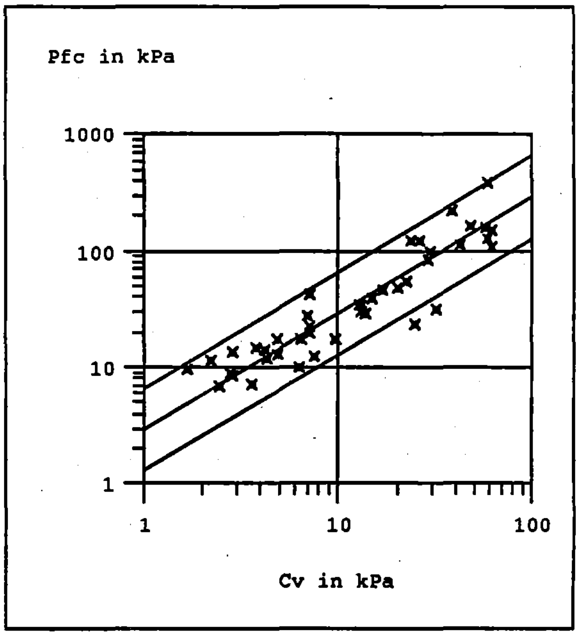

Fig. 5 : Relation between P_{fc} and C_v.

The penetration depth of the fall cone can be transformed into a fall cone bearing capacity according to :

$$P_{fc} = G / \pi.(d.tg\alpha)^2 \qquad (1)$$

with P_{fc} = the fall cone bearing capacity (in units of stress)

G = the weight of the cone

α = the half angle of the cone tip

For the fall cone used equation (1) reduces to : :

$$P_{fc} = 985 / d^2 \qquad (2)$$

(P_{fc} in kPa if d in mm)

As the measured consistency values were concentrated in the lower value region, the logaritmic values of P_{fc} and C_v were used in a regression analysis. It was found that :

$$\log P_{fc} = 0.47 + \log C_v \qquad (3)$$

$$\text{or : } \log C_v = -0.47 + \log P_{fc} \qquad (4)$$

(3) and (4) give after recalculation : :

$$P_{fc} = 2.95\ C_v \qquad (5)$$

$$\text{or : } C_v = 0.34\ P_{fc} \qquad (6)$$

Fig. 5 gives P_{fc} and C_v in logaritmic coördinates with the regression line and the 95 % confidence interval for a prediction of C_v from a knowledge of P_{fc} (or vice versa). The correlation coëfficient of log(P_{fc}) versus log(C_v) was 0.92. This proves a statistically significant relation between the results of both tests.

CONCLUSIVE REMARKS

For the routine determination of the consistency of sludges for landfilling, relatively fast and easy measurement methods are at hand. Two such measurement methods are described in this article.

A direct measurement of the shear strength of cohesive sludges may be performed with the highly standardised vane shear test. The use of the vane test guarantees an harmonisation with research in this area in other EC countries.

Other measurement methods may be compared to the vane test by simultaneous measurements. This was illustrated in this article for a penetration test with a specifically designed fall cone. The fall cone test was less reproducible than the vane test. Its performance however is a little faster.

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THE SPATIAL DISTRIBUTION OF POLLUTANTS (INORGANIC AND ORGANIC) IN A DREDGED SLUDGE PUMPING GROUND

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ABSTRACT

The "Zandwinningsput at the Hooge Maey" is a pit with a surface of approximately 30 ha and a maximum depth of 16 m.
Suspended dredged sludge is pumped into the put via a fixed injection pipe. The coarser and denser sediment fraction accumulated close to the inlet pipe, while the finer material is transported by the fluid to the overflow at the opposite side of the pit.

The spatial gradient of the small sediment particle sizes induces a gradient of the pollutant concentrations. Most trace metal concentrations are related to the percentage of the small size fraction (less than 63 micrometer) in the sediment.

A correlation table between 23 parameters (organic pollutants are not included) measured in 9 samples, spatially representative for the whole pit, show that :

1. all trace metals are correlated
2. all trace metals are very good correlated (r is at least 0,95) with N, % less than 63 micrometer, Al and ignition loss at 550 °C and disregarding a few exceptions, good correlated (r is at least 0.9) with Na, Mg, the ignition loss at 1100 °C and the % less than 2 micrometer
3. negative correlations are observed between the trace metals and pH as well as the ignition loss between 1100 and 550 °C.

The organic solvents and the micro-organic pollutants show spatial patterns which are different from those of the trace metals. The explanation is that trace metals and organic pollutants are not linked to the same sedimentary fraction.

PAH's (Polycyclic Aromatic Hydrocarbons) and phtalateesters show the same but relatively at random spatial distributions.
Oils and grease are essentially concentrated at the sludge inlet.

INTRODUCTION

The sludge disposal which has been studied, can be considered as an incorporated area of the general waste disposal site called "Hooge Maey".

This disposal site is situated in the harbour area of the city of Antwerp (fig. 1).

The site has been used as a municipal and industrial uncontrolled waste disposal site since 1967.

As a result of preliminary environmental investigations in this area ordered by OVAM (Public Company for Waste in Flanders, 1985), from which is was concluded that groundwater contamination occurs, the city of Antwerp ordered to establish a global study about the sanitation of the area with respect to groundwater pollution including remedial actions.

The principal goals of the investigation can be summarized as follows :

1. global characterisation of the dumped waste materials :
   - municipal waste
   - industrial waste
   - maintenance dredging sludge

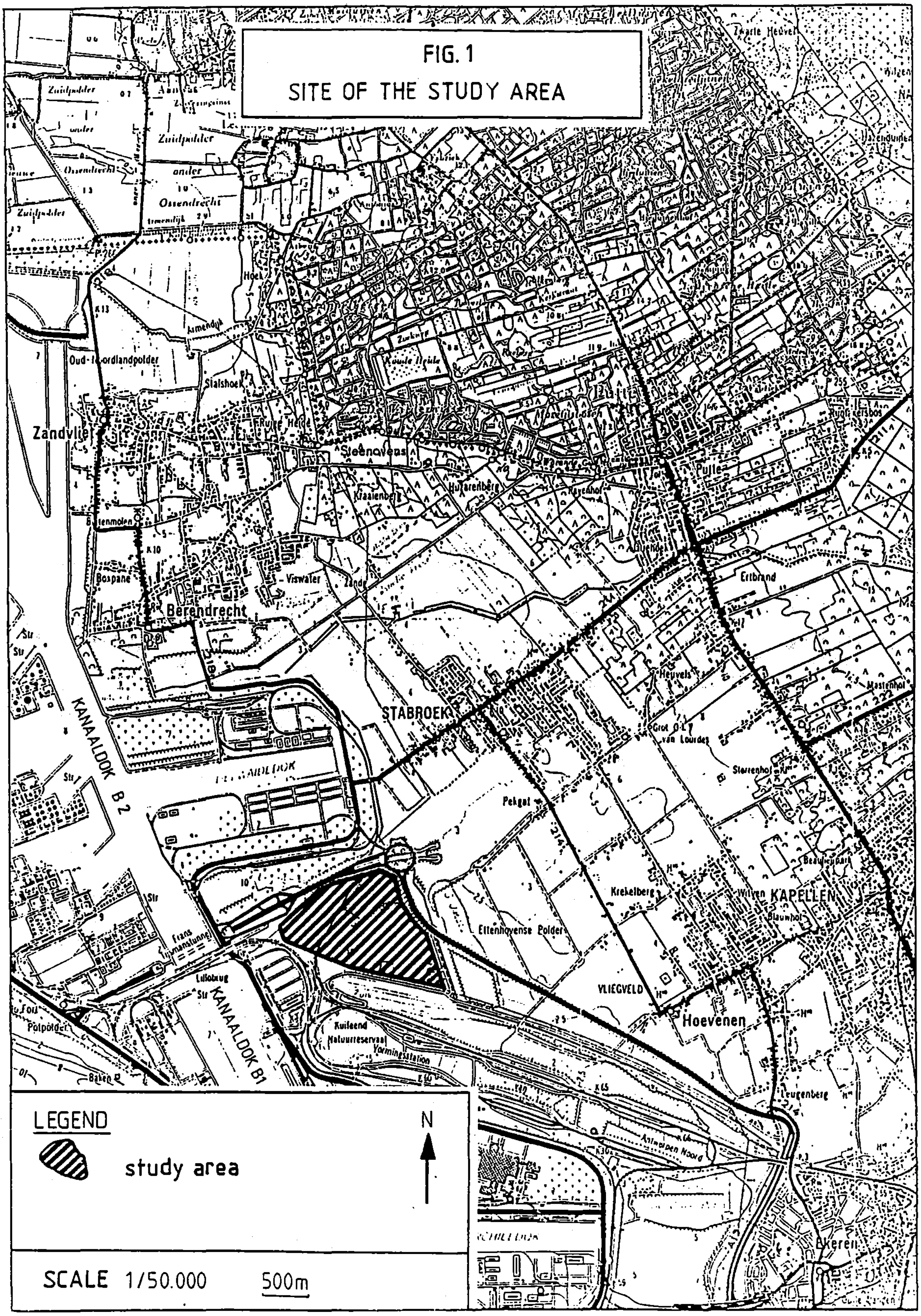


FIG. 1

SITE OF THE STUDY AREA

LEGEND

▨ study area

N

SCALE 1/50.000 500m

2. determination of the environmental impact :
   - surface water
   - groundwater
   - subsurface layers
3. detailed description of the feasible remedial actions :
   - technical aspects
   - budget evaluation
   - planning of activities

About 25 % of the "Hooge Maey" area, which is about 150 ha, has been used as an unconfined disposal of polluted maintenance dredged material (fig. 2).

This area, called "Zandwinningsput", used to be an excavation area for construction purposes.

The polder clay, at an initial depth of ± 5 m below surface level, was removed and sand was excavated until a depth of 12 to 15 m.

After this running period, dredging sludge was dumped from 1980 until now.
The total amount of disposed dredging sludge in this lake, can be estimated up to ± 3,000,000 m3.

Surface water of this lake is drained by means of a weir and ditch to the Schijn river (fig. 2).

Suspended dredged sludge has been pumped into the pit via a fixed injection pipe during the last 10 years.

So, a granulometric gradient and stratification could develop during this running periode.

The coarser and denser sediment fraction accumulates close to the inlet pipe, while the finer material is transported by the fluid to the overflow at the opposite side of the pit.

Starting this study, we assumed that also the chemical and physical gradient and stratigraphy will occur in the same directions as mentioned above.

METHODS AND MATERIALS

OBTAINING REPRESENTATIF SLUDGE SAMPLES

A sampling pattern has been established as follows (fig. 2 and fig. 3).

In this way, 9 representative mixed samples have been composed, each of three different subsamples of the same depth and in the same coring group.

The sludge samples have been taken by use of a bailer boring auger set at the indicated depths of 0,5 m, 2.0 m and 4.0 m.

As it concerns a non-cohesive soil, the drilling was equiped with a casing tube to line the bore hole. The diameter of this casing was 4".

By use of this sampling pattern, we tried to establish some knowledge about the spatial distribution of pollutants in a sludge disposal in the vertical as well as in the horizontal direction.

In this paper, we will further describe the presence of inorganic and organic trace contaminants in this maintenance sludge disposal site.

INORGANIC POLLUTANTS

The analysis procedures for the metals in above mentioned mixed sediment samples can be described as follows.

All metals except Hg and As

Prior to analysis, the sediment is mineralized. To 0.25 g sediment, 2 mL nitric acid, 6 mL hydrochloric acid and 2 mL of hydrofluoric acid are added.

The teflon container is closed and heated to 60 °C during 12 hrs. The solution is then evaporated and the residue redissolved in 25 mL nitric acid (4 % v/v).

The analysis methods used are Flame and Graphite Furnace Atomic Absorption Spectrometry and Inductively Coupled Plasmaemission Spectrometry (e.g. Panutrakul and Baeyens, 1991; Baeyens and Dedeurwaerder, 1990).

BETECH n.v.

Fig. 2: Position of sludge samples

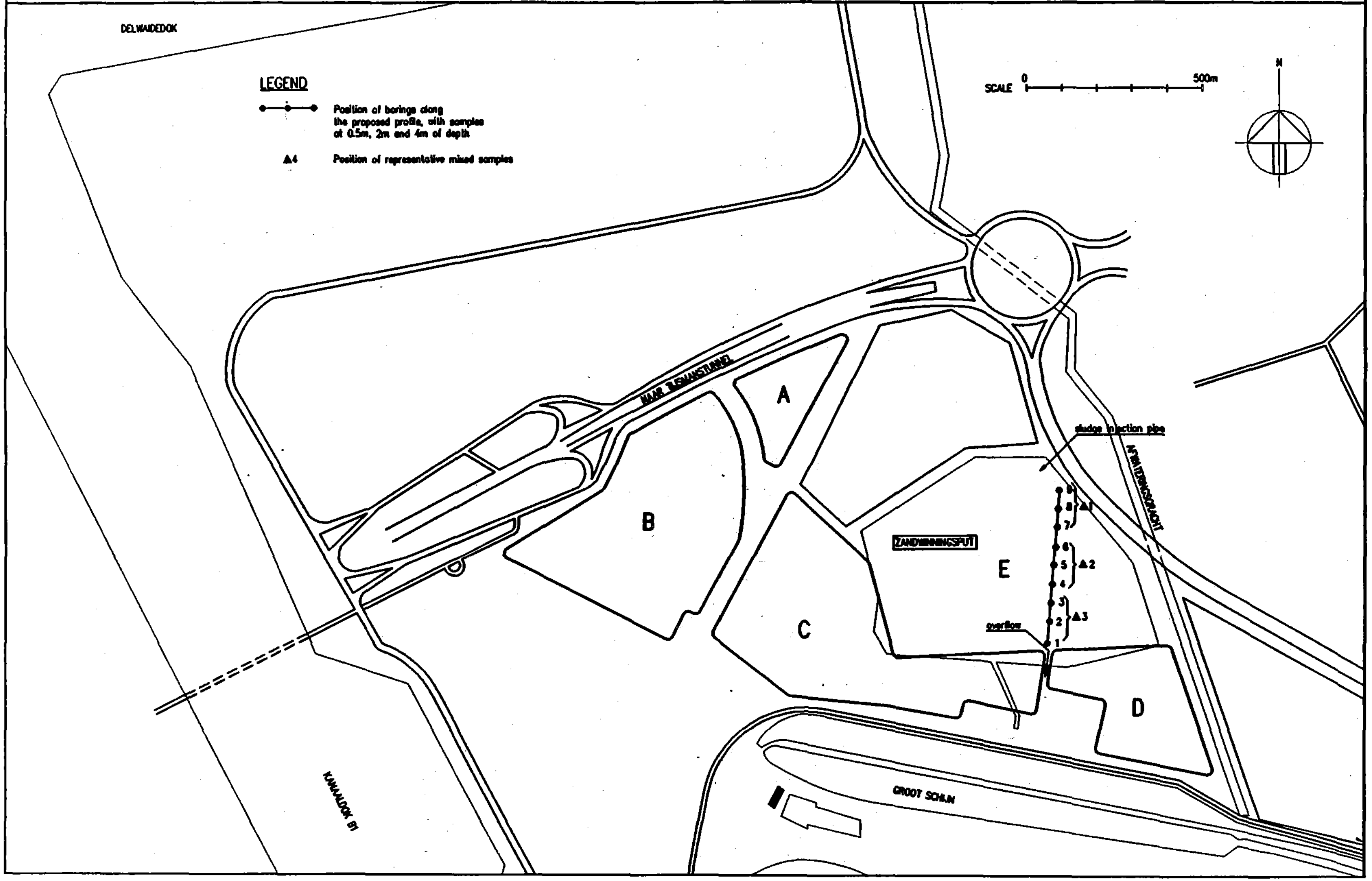
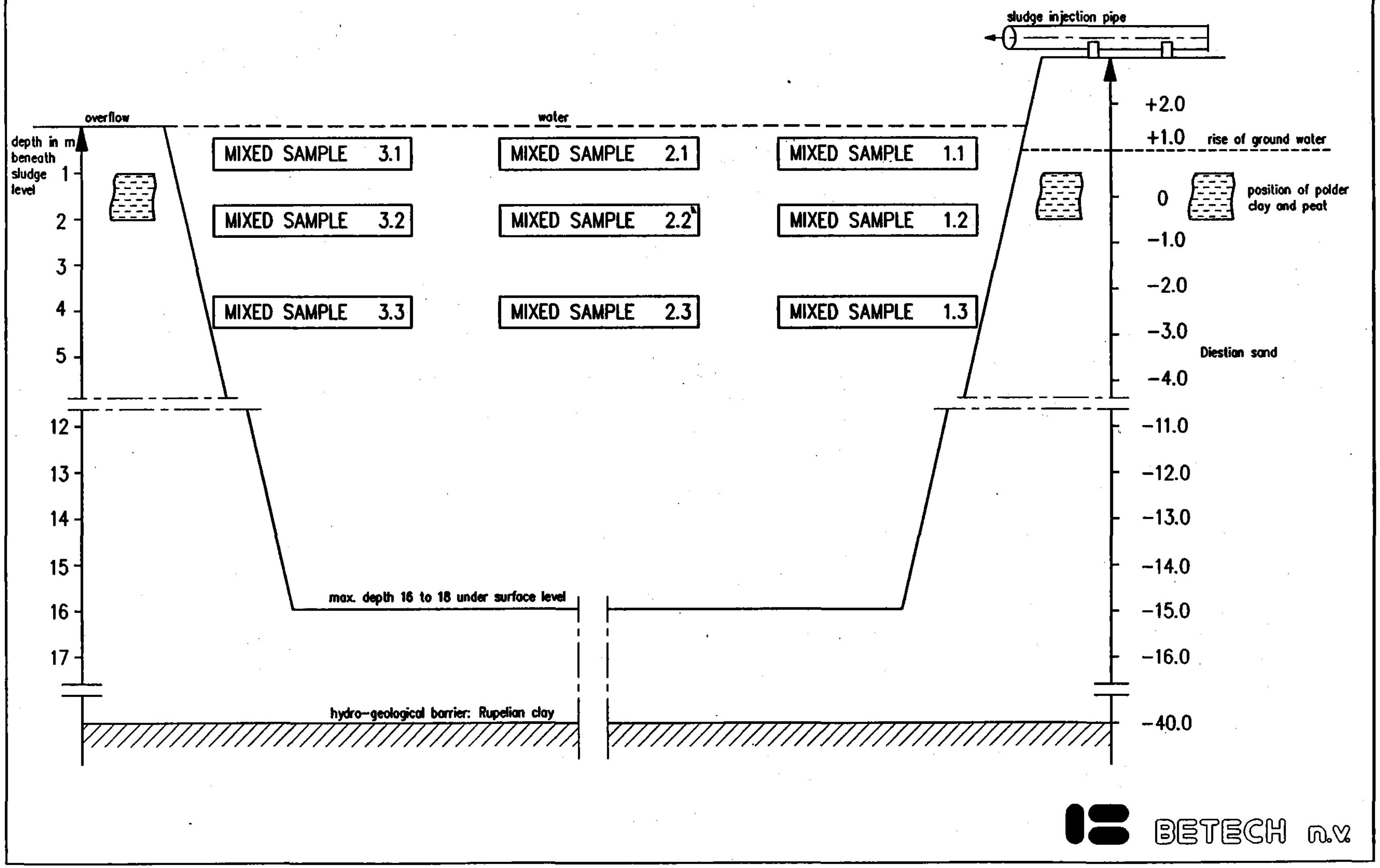


Fig. 3: POSITION OF SAMPLES
ZANDWINNINGSPUT – HOOGE MAEY



Hg and As

The mineralization of the sediment is different from the previous method. To 0.25 g sediment, 4 mL of a nitric acid/hydrochloric acid (9:1 v/v) mixture are added. The teflon container is closed and heated to 60 °C during 12 hrs. The solution is then diluted to 50 mL. The analysis of Hg is carried out with Flameless Atomic Absorption Spectrometry after reduction of all mercury present in the sample to Hg (0) (e.g. Baeyens et al. 1989, Leermakers et al. 1990). As is measured with Graphite Furnace Atomic Absorption Spectrometry.

Organic carbon, nitrogen and ignition loss (PF)

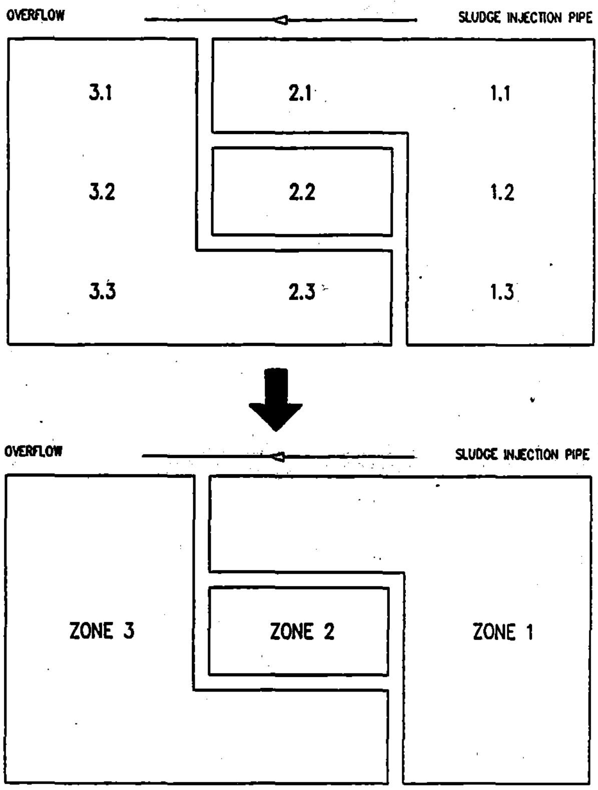
The determination of organic carbon and nitrogen is carried out with a Carbo-Erba C/N analyzer after elimination of the carbonates from the sediment. The ignition loss (PF 550 °C respectively PF 1100 °C), is the difference in weight of the sediment at 105 °C (3 hrs) and at 550 °C (3 hrs) respectively at 1100 °C (3 hrs).

RESULTS AND DISCUSSION

INORGANIC POLLUTANTS

Spatial results

The 9 mixed-samples of the "Zandwinningsput" can be classified in three groups, which we will call zones, on the bases of their nature (the structure, texture, grain size distribution, major elements) and their degree of contamination. These zones are :



Zone 1 is closest to the mouth of the sludge injection pipe (mixed samples 1.1, 1.2, 1.3 and 2.1) and consists of sandy, low contaminated sediment. Zone 2 represents only one mixed sample (sample 2.2) of which the structure and contamination degree is intermediate between zones 1 and 3. Zone 3, which is most distant from the injection pipe, consists of muddy, highly contaminated sediments (mixed samples 2.3, 3.1, 3.2 and 3.3). Zones 1 and 3 can be considered as fairly homogeneous, although some of the elements may show anomolous concentrations in particular samples.

The concentrations of metals (As, Hg, Cd, Pb, Cr, Be, Al, Fe, Mn, Ca, Mg, K, Na), as well as a number of physico-chemical parameters (granulometry, organic C and N, PF 550 °C and 1100 °C) have been analysed in these 9 mixed-samples, in the bulk sediment and in the fraction < 63 µm. The spatial distribution of the concentrations of some of these metals and physico-chemical parameters are shown in figures 4.1 to 4.3. The most important results can be summarized as follows.

- A granulometric gradient is observed in horizontal direction, from the injection pipe towards the outlet. In vertical direction this gradient is much weaker.

- In contrast, some pollutants show strong vertical concentration gradients. This may be explained by the leaching process taking place during several years, inducing an enrichment or accumulation of pollutants with depth.

- The more the fine grain size fraction (< 63 µm) increases, the higher the total pollutant concentrations in the sample are.

  In addition, we noticed that in samples with a high amount of coarse material (sandy sediments), the pollutant concentrations in the fine fraction are much higher than in the fine fraction of muddy samples. This seems not unusual : in samples with only a small percentage of fine grains, these grains adsorb the pollutants much stronger. The pollution is as a matter of fact concentrated in the small amount of fine grains, while in samples with a high amount of fine grains, it is dispersed over this large fraction.

- Considering specific pollutant concentrations, it is observed that the dredged sludge is characterized by high As concentrations. In most cases the C-norm is exceeded, when comparing with the reference frame VROM of the Netherlands. The total concentrations of Cd in the mud are close to the C level, while the total concentrations of Pb and Hg in the mud are more limited and are situated at their respectively B levels.

Correlations of detected pollutants

Correlations between total concentrations (fig. 5.1)

The correlation coefficients between the trace metal concentrations of Hg, Be, Cd, Pb, Mn, As and Fe (the latter element is a major one) in the mixed-samples of the "Zandwinningsput", are all higher than 0.9, except one (the correlation between Be and Pb).
If only very strong correlations are considered (correlation coefficients above 0.99), than two groups of two elements remain : Hg and Cd on the one hand, Fe and Mn on the other hand.

Considering the correlations between the trace metal concentrations mentioned above and the classic parameters for the fine grain size fraction of the sediment (organic carbon, N, PF 550 °C and 1100 °C, % < 63 µm, % < 2 µm and Al), we find good correlations (correlation coefficients above 0.95) between the metals and N, PF 550 °C, % < 63 µm and Al except for Pb, where alle correlations are around 0.9.

The latter result is a consequence of the larger heterogeneity of the Pb concentrations in the "Zandwinningsput", compared to other metals. A very large fraction of Pb is present in the exchangeable and carbonate phase (see our related paper Baeyens et al., 1991), and is thus very mobile.

The correlation coefficients between the trace metal concentrations and the PF 1100 °C and % < 2 µm (parameters of the fine grain size fraction) range between 0.9 and 0.95, besides a few exceptions, while those between the metals and the organic carbon content are often below 0.9.

The reason that a good correlation between the trace metals and organic N is observed, and a much weaker between the trace metals and organic C, is due to the analysis method. Organic C and N are measured simultaneously with the same device, but inorganic C interferes with the determination of organic C.

An incomplete elimination of the inorganic carbon (the carbonate fraction) leads to too high organic C values.

Fig. 4.1

SLUDGE DISPOSAL - ZANDWINNINGSPUT (HOOGE MAEY)

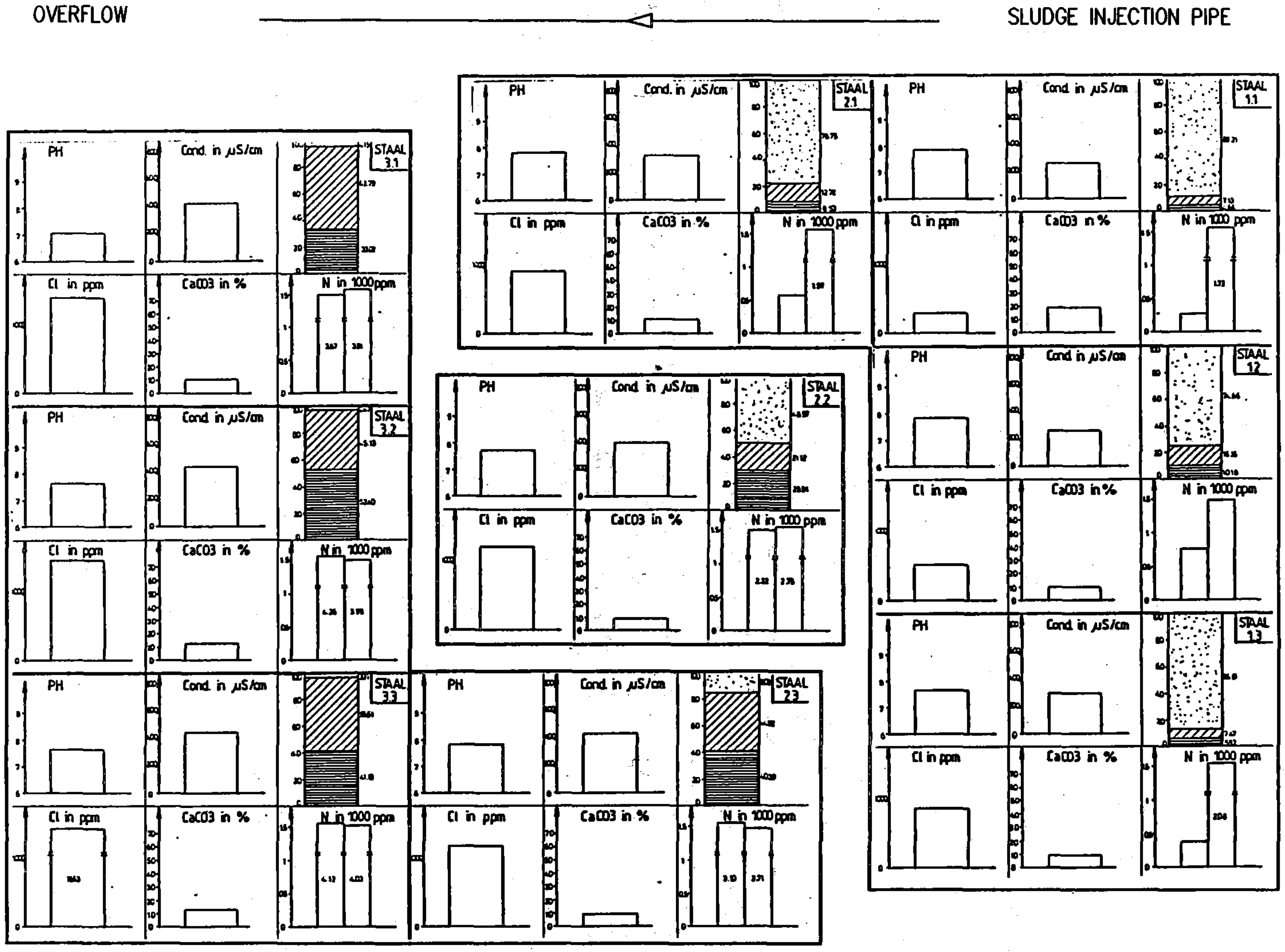


Fig. 4.2

SLUDGE DISPOSAL – ZANDWINNINGSPUT (HOOGE MAEY)

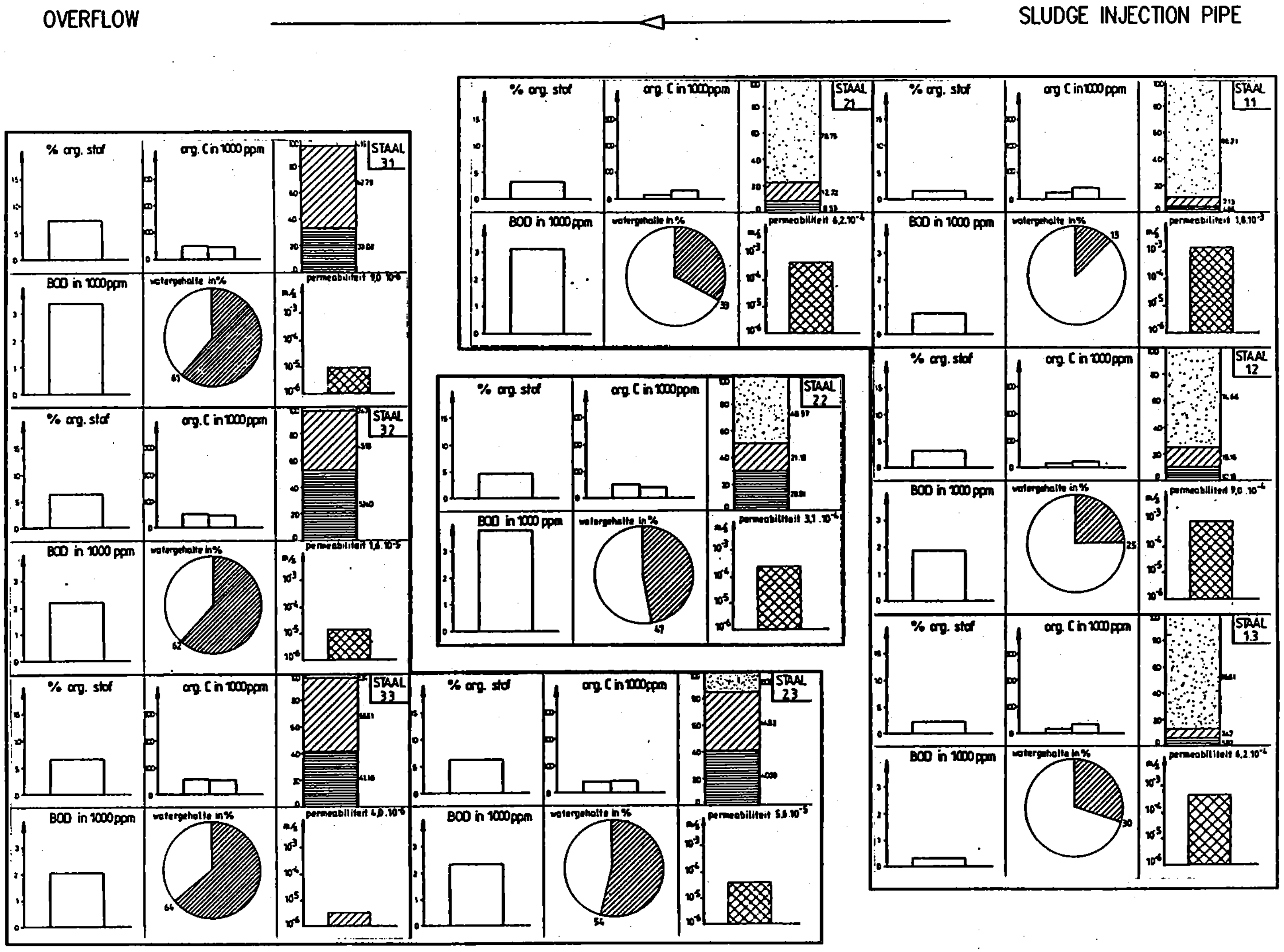


Fig. 4.3

SLUDGE DISPOSAL – ZANDWINNINGSPUT (HOOGE MAEY)

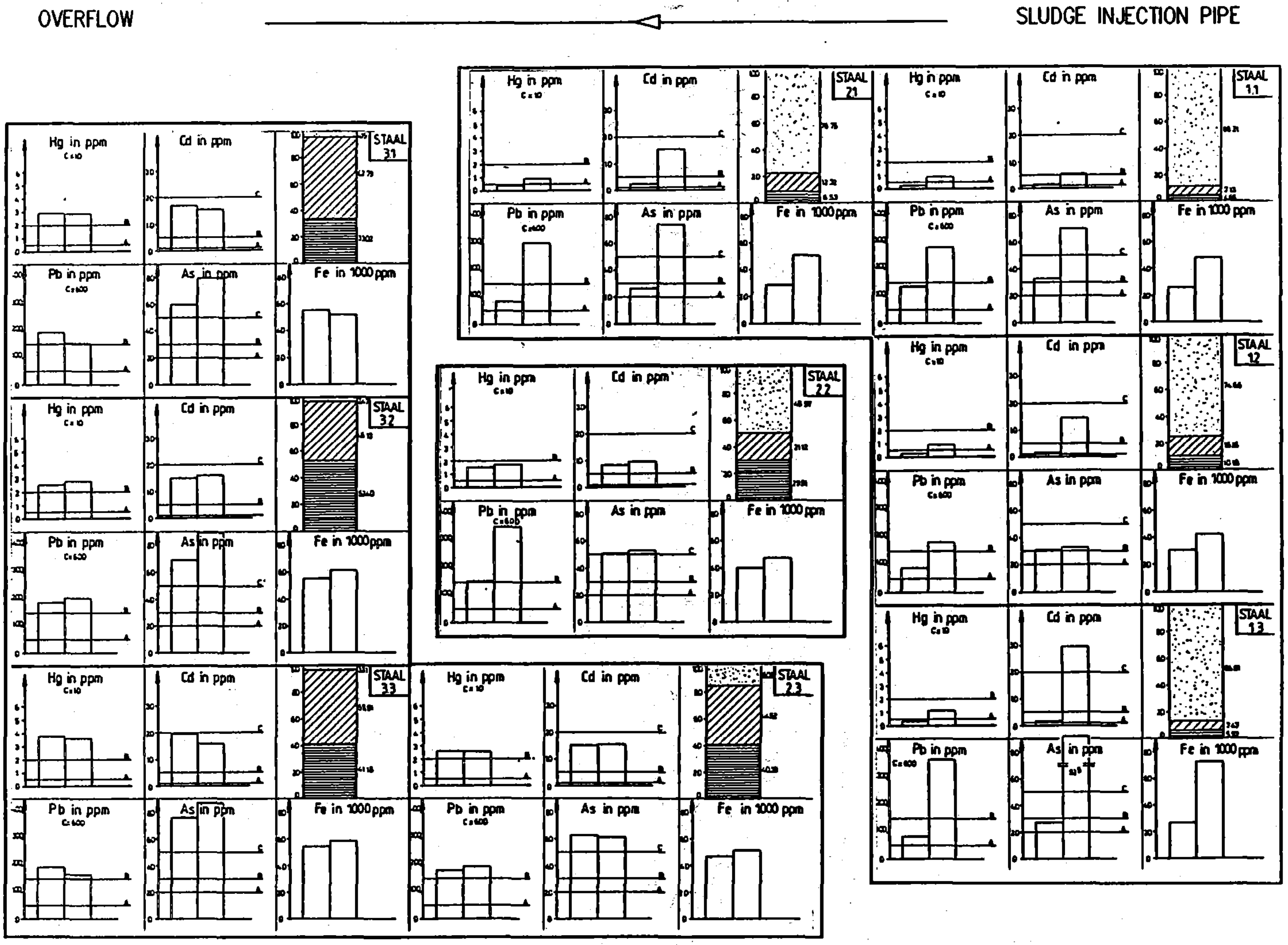


Fig. 5.1 CORRELATION MATRIX : Bulk analyses

	Hg	Be	Cd	Pb	Fe	Mn	As	Org C	N	PF 550°C	PF 1100°C	PF 1100 −550°C	< 63µ	< 2 µ	pH	Cond	Cl⁻	BOD	Mg	Ca	Al	K	Na
Hg	1	+	+	+	+	+	+		+	+	+	−	+	+	−	+			+		+		+
Be	+	1	+		+	+	+		+	+		−	+	+	−				+		+		+
Cd	+	+	1	+	+	+	+		+	+	+	−	+	+	−	+			+				
Pb	+		+	1	+	+	+	+	+	+	+		+		−				+				
Fe	+	+	+	+	1	+	+		+	+	+	−	+	+	−	+			+		+		+
Mn	+	+	+	+	+	1	+		+	+	+	−	+	+	−				+		+		+
As	+	+	+	+	+	+	1	+	+	+	+	−	+	+	−	+			+		+		+
Org C				+			+	1				−			−				+		−		
N	+	+	+	+	+	+	+		1	+		−	+	+	−	+	+		+		+		+
PF 550°C	+	+	+	+	+	+	+		+	1		−	+	+	−	+	+		+		+		+
PF 1100°C	+		+	+	+	+	+		+	+	1		+		−				+		+		+
PF 1100 −550°C	−	−	−		−	−	−	−	−	−		1	−	−		−	−	−	−		−	−	−
< 63µ	+	+	+	+	+	+	+		+	+	+	−	1	+	−	+			+		+		+
< 2 µ	+	+	+		+	+	+		+	+		−	+	1		+			+		+		+
pH	−	−	−	−	−	−	−	−	−	−	−		−	−	1	−	−	−	−		−	−	−
Cond	+		+		+		+		+	+		−	+	+	−	1	+		+		+		+
Cl⁻									+	+		−			−	+	1		+				
BOD												−			−			1					
Mg	+	+	+	+	+	+	+	+	+	+	+	−	+	+	−	+	+		1		+		+
Ca																				1			
Al	+	+			+	+	+		+	+	+	−	+	+	−	+			+		1		+
K												−			−							1	
Na	+	+			+	+	+		+	+	+	−	+	+	−	+			+		+		1

BETECH n.v.

The trace metal concentrations correlate well with the major elements Na and Mg, weakly with K (correlation coefficient between 0.65 and 0.75), and very weakly with Ca. Negative correlations were observed between the trace metal concentrations and the pH, as well as the ignition loss difference between 550 °C and 1100 °C (PF 550 °C and PF 1100 °C).

Both results confirm each other : the trace metal concentrations decrease with increasing pH (the higher the pH means also the more carbonate in the sediment) and with an increasing ignition loss difference between 550 °C and 1100 °C (this difference is also a measure for the carbonate content).

These observations also explain the weak correlation between trace metals and Ca, which is mostly bound to carbonates.

Correlations in the sediment fraction smaller than 63 µm (fig. 5.2)

After isolation and analysis of the fine grain size fraction, we observed no longer a clear correlation between the trace metals. In the fine sediment fraction some metals belong to the organic fraction, other metals to the carbonate or clay fraction etc...

A high organic matter content does not necessarily imply a high content of each trace metal (when a specific metal is predominantly bound to the clay fraction and when this clay fraction is for example low, then the concentration of that specific metal will be low too).

In the fine grain size fraction, the following parameters are found to be correlated :

1. Hg, Mn, organic C, N, PF 550 °C and 1100 °C, Mg and Al (this group is the group of the organic matter - probably Hg is bound to these organics - and the clays - probably Mn is bound to this mineral -.
2. Be, Cd, Fe and K (As is also correlated with Fe and to a lesser extent with the other ones).

   This group may represent the group of the oxy-hydroxides and the medium stable sulphides, according to the sequential analysis results (Baeyens, et al., 1991).
3. Pb shows no strong positive correlation, only a weak correlation with Ca (the carbonate fraction ?) and a strong anticorrelation with the elements of group 1.

ORGANIC POLLUTANTS

Oils and greases

The results for oils and greases are summarized in table 1.

Table 1 : "Zandwinningsput" (1,2,3) in mg/kg

Overflow--------◄---------Inlet pipe

Sample / Depth	3	2	1
1 (0.5 m)	20	11	514
2 (2 m)	74	46	62
3 (4 m)	20	24	38.5

The results demonstrate an important pollution for the mouth of the sludge injection pipe (1.1) of the "Zandwinningsput".

The higher values for the sample at 2 m depth in the "Zandwinningsput" indicates an oozing through to level 2.

PAH's

No important pollution was observed for PAH's.

The distribution pattern for the individual PAH's is very irregular.

The most often occurring molecules are phenanthrene and pyrene (table 2). In general, the highest values are found at level 2 (2 m) and 3 (4 m) and at the mouth of the sludge injection pipe (1.1)

Fig. 5.2 CORRELATION MATRIX : Analyses fraction < 63 μm

	Hg	Be	Cd	Pb	Fe	Mn	As	Org C	N	PF 550°C	PF 1100°C	PF 1100 −550°C	Mg	Ca	Al	K	Na
Hg	1					+			+	+	+	+					–
Be		1	+		+							–		–			–
Cd		+	1	–				–			–	–					
Pb	–			1		–		–	–	–	–		–		–		
Fe		+			1							–					–
Mn	+			–		1			+	+			+		+		–
As							1										–
Org C			–	–				1		+	+						–
N	+			–		+			1	+	+						–
PF 550°C	+			–		+		+	+	1	+						–
PF 1100°C	+		+	+	+	+	+	+	+	+	1						–
PF 1100 −550°C	+	–	–		–							1				–	–
Mg						+						–	1		+		–
Ca														1		–	–
Al						+						–	+		1		–
K												–		–		1	–
Na	–	–			–	–	–	–	–	–	–	–	–	–	–	–	1

BETECH n.v.

Table 2 : PAH's (phenanthrene (a) and pyrene (b) in mg/kg) for the "Zandwinningsput" (1,2,3)

Overflow--------◂---------Inlet pipe

Sample / Depth	3	2	1
1 (0.5 m)	0.020	0.050	0.800(a)
	0.410	0.390	0.590(b)
2 (2 m)	0.160	0.085	- (a)
	0.410	0.640	0.110(b)
3 (4 m)	0.290	0.085	0.090(a)
	1.200	0.890	0.550(b)

Phtalate esters

The following phtalate esters were detected : dimethyl, diethyl, di-n-butyl, butylbenzyl and bis(2-ethylhexyl) phtalate.

The same characteristics as for the PAH's were observed : increasing amounts of components from level 1 to level 3, with the exception of the mouth of the sludge injection pipe.

The most important derivative (bis(2-ethylhexyl)phatlate) is represented in table 3.

Table 3 : bis(2-ethylhexyl)phtalate in mg/kg)

Overflow--------◂---------Inlet pipe

Sample / Depth	3	2	1
1 (0.5 m)	1.2	0.7	6.6
2 (2 m)	3.4	2.8	0.3
3 (4 m)	4.2	1.7	1.0

Solvents

The determinations were done on the acetonitrile extract of the samples. The accurace in this method was ± 1 mg/kg.
For samples 1, 2 and 3 only traces of benzene, toluene and C-2 aromatics are detected.

The amount of samples for investigating the fraction < 63 µm was insufficient to quantify exactly individual components.

The study of the samples of granules < 63 µm indicates that the results are mostly consistent with the bulk samples.

CONCLUSION

When a disposal site has been runned in a one way direction from inlet pipe to overflow, some characteristics of the spatial distribution of pollutants can be described als follows.

- A granulometric gradient is stronger in the horizontal direction as in the vertical direction.
- in contrast, most of the inorganic pollutants show strong vertical concentration gradients.
- the total pollutant concentrations increase with increasing fine grain size fraction, although the pollutant concentration in the fine fraction of coarse material is much higher than in the fine fraction of muddy samples.
- A positive correlation between inorganic pollutants has been observed, especially concerning heavy metals, in bulk samples.
  On the contrary, in the fine size fraction, a clear correlation between trace metals has no longer been observed.
- at the mouth of the sludge injection pipe, i.e. coarse grain size material, an important concentration of oils and greases has been indicated, as the dredged spoil can be considered as a sieve for oils and greases.
- No important pollution has further been observed for PAH's, phtalate esters and solvents.

Maintenance dredged spoil disposals, characterised by a one way injection technique have some particular advantages :

- most pollutants are concentrated related to the observed grain size gradient

- inorganic pollutants and heavy metals are concentrated near the bottom of the disposal site or towards the existing overflow

- the coarse grain size, found near the sludge injection pipe, can be considered as a preliminary filter for organic pollutants as oils and greases.

In general, by use of this running method, a clear stratification of contamination occurs, which can be very useful towards proposed specific treatment or other selected destinations for this dredged material.

Nevertheless, hydrogeological and soilmechanical consequences can be more complex.

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TREATMENT OF POLLUTED DREDGED MATERIAL : TURNING THEORETICAL EVIDENCES INTO OPERATIONAL PRACTICE

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ABSTRACT

The retention mechanisms of inorganic pollutants in sediments and particularly in dredged material have been studied thoroughly. The elucidation and quantification of the general findings form the basis of the physico-chemical treatment techniques, which were developed. It was found that in the speciation of metal pollutants, particularly the organic matter and the metal oxide fraction play a key role. Furthermore a strong phase equilibrium exists between the solid and liquid phase. This paper presents the theoretical background, from which the fraction separation and extraction plant were constructed. It also refers to some of the promising results.

I. INTRODUCTION

The knowledge about the behaviour of contaminated dredged material has improved tremendously during the last few years. Also the number of techniques particularly developed for separation, sanitation and isolation have increased simultaneously. However, due to lack of scientific back up, such techniques often have proven to be rather unsuccessful. Contamination to the environment is always caused by some kind of chemical anomaly, which has to be removed, degraded or isolated. The full range of pollutants, recovered in dredged material in fact has to be divided into different categories:

- INORGANIC pollutants: e.g. heavy metals (including the man-made), anionic species, etc... Inorganic species, including heavy metals cannot be destroyed in the environment. They may only be transformed into various forms of compounds, some of which may be more or less toxic.
- ORGANIC pollutants: In this group it is mandatory to make a distinction between synthetic organic pollutants and bio-organic pollutants (e.g. sewage-water, bio-industries).

One should be worried more about the first group than about the second one. In contrast to the inorganic species, the organic species may be characterized as destroyable, although the complete destruction of some of them may require quite some time. Pollutants of the first group remain present. They have the intrinsic possibility to become critical at all time. Therefore there is a need to immobilize or to remove them from the ecosystem if possible in order to minimize future effects.

Although SILT offers a full range of treatment techniques, which are applicable over a wide variety of contamination problems, this paper will be restricted to the inorganic pollutants, and in particular the behaviour of heavy metals. It will demonstrate how theoretical studies, and fundamental scientific research actually served as an input to the development of the SILT physico-chemical treatment procedures. A thorough understanding of the chemical interaction mechanisms is only possible by combining several distinct scientific specialities, leading to the development of one fully integrated treatment plant. A further implication is that each particular problem with contamination at each particular site often requires the design of a tailor made solution. This will be illustrated with some operational evidence.

II. RETENTION MECHANISMS OF INORGANIC POLLUTANTS

A. Introduction

In general, the complexity of retention and interaction mechanisms of a pollutant with the soil and the aqueous fractions of the ecosystem (e.g. dredged material) is governed by a wide variety of reactions: hydrogen-bounding, ion-exchange, formation of inner- and outer sphere complexes (including chelation), adsorption, etc... (Marinsky e.a., 1975; Gamble, 1972) Natural dredged material has to be regarded at as a multi-component system, which means that a tremendous number of different equilibria are involved in the overall resulting retention reaction. By disadvantaging one equilibrium, another may be advantaged and vice versa.

B. Inorganic pollutants: the heavy metals

When the term "heavy metals" is mentioned, quite often one refers to its toxic properties, rather than to what is covered in reality by this denotation. In fact there are two questions to be answered: 1. what are heavy metals? and 2. what makes them to be toxic? Heavy metals are metallic species with a density greater than 5 g/cm^3, which is an easy definition. In Mendeljev's table, starting from Vanadium all metals are heavy metals. Nevertheless other metal elements like Beryllium with a density of 1.85 are also toxic, without being a "heavy metal", whereas other heavy metals on the contrary are not toxic at all. Toxicity is the property to interfere with natural biochemical reactions (Mewis, 1983). Toxic products therefore react either chemically or physico-chemically with certain receptors, causing unfavourable effects for the biospecies. The toxicity of heavy metals is however not a result of its density. Their are two ways heavy metals may interact in biochemical processes. Directly by inhibiting or catalysing those reactions, and indirectly by replacing metal ions in bio-metalphore molecules. Particularly in that position, these metal ions are able to catalyse harmful reactions through the interaction of outer-shell electrons. In addition the interaction constants of heavy metal ions with (bio)-organic molecules are in general quite large, causing the ion bond to be very strong. From the fact that heavy metals are atomically "bigger", which means that their atomic radius is larger, due to the higher number of electron-shells, they are also better candidates to interfere with biochemical reactions. Due to their possible toxicological effects following metals are to be checked for their presence in dredged material, and this regardless whether they are present in toxic or non-toxic concentrations to men: **Be**, **Cd**, Cr, Co, Cu, **Hg**, **Pb**, **Mn**, **Ni**, Se, Zn. The elements in bold are toxic and those, which are underscored, are essential for human-beings. It is clear that only very small trace concentrations of those elements are required. Above this concentrations they often become toxic. Chromium is a special element. It is toxic under the +6 oxidation state and essential under the +3 oxidation state. All of above mentioned metal ions present toxicological effects to living organisms by interfering with certain biochemical reactions.

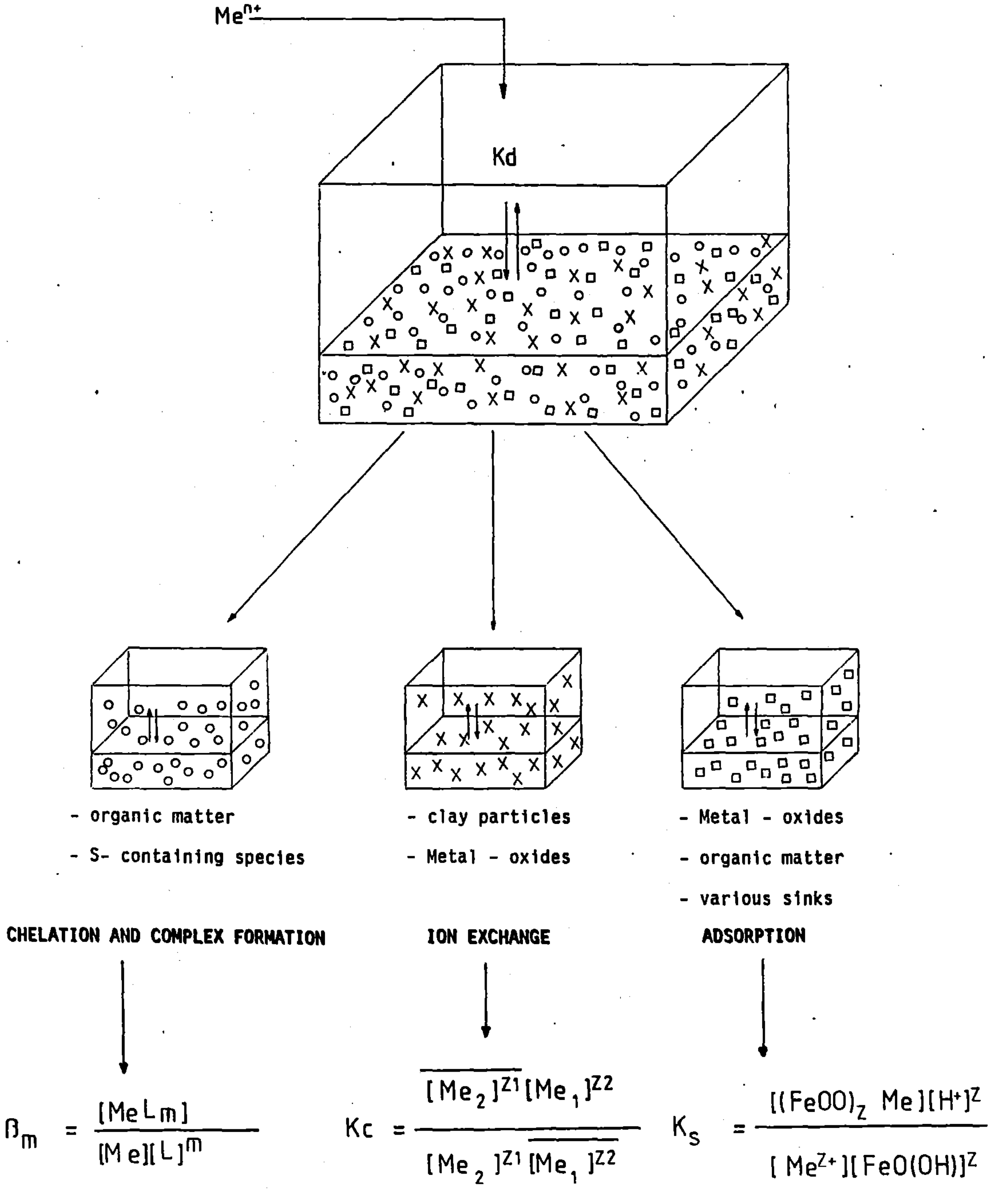
C. The behaviour of heavy metals in sediments

C.1 A general retention model

The knowledge of the retention mechanisms of heavy metals in a sediment is the first important step in the development of treatment techniques. Although numerous scientific publications (Oakley e.a., 1981; Davies-Colley, 1984; Lion e.a., 1982; Verloo, 1988; etc.) already have been dedicated to this subject, still a lot remains unknown. The interaction mechanism of metals with the sediment is very complex, and a huge number of reactions and combinations are being involved. The various single components, it consists of are not all elucidated at present time. The overall resulting retention reaction for one single metal can be described by combining the interactions of this metal with the different fractions of the sediment. This is called a single component system. Describing the same retention mechanism for a complete sediment, involves the combination of various single cell retentions of a metal with a fraction of a sediment, and the cross interaction, resulting from the competition of two or more metals. The study of single component systems usually results in applying an extraction procedure to the sediment e.g. Tessier (Tessier e.a., 1979). Although some controversy about the validity of such study methods exists, it often results in the general approved evidence, that particularly in the immobilization of many metal species, only 1 or 2 fractions play a key role, i.e. the organic material and the hydrous metal-oxides. (Sposito, 1986)

Figure 1

General model for the retention of metal cations in an environmental system, with a solid and liquid phase.



$$\beta_m = \frac{[MeL_m]}{[Me][L]^m}$$

$$Kc = \frac{\overline{[Me_2]}^{Z1}[Me_1]^{Z2}}{[Me_2]^{Z1}\overline{[Me_1]}^{Z2}}$$

$$K_s = \frac{[(FeOO)_Z\ Me][H^+]^Z}{[Me^{Z+}][FeO(OH)]^Z}$$

A general model for the interaction of heavy metals with a sediment is shown in figure 1. A metal enters the complex environmental system through the aqueous phase. The chemical form in which it is present will quite rapidly become governed by the pH and oxido-reduction state of the system, together with the chemical composition of this phase. This is by the interaction with anions, hydroxides, carbonates and in particular with the solubilized organic matter. In the sediment the metal ions will also interact with the various fractions (organic matter, oxides, clay, sand...). The sediment however will compete with the aqueous phase, which results in an equilibrium state between both phases. This equilibrium is expressed with the so-called K_d value.

$$K_D = \frac{[Me]_{Adsorbed}}{[Me^{z+}]\left\{1 + \sum_{1}^{n\ OH} \beta_n[OH]^n + \sum_{1}^{n\ CO_3} \beta_n[CO_3]^n \ldots + \ldots \sum_{1}^{n\ L_1L_2} \beta_{nm}[L_1]^n[L_2]^m\right\}} \qquad (A)$$

In which:

- the nominator expresses the concentration of a particular metal in the solid phase.
- the denominator expresses the concentration of the same metal in the liquid phase. This is the sommation of all chemical forms, under which the metal is present in solution.

In the case of a metal ion distribution, this constant expresses in a numerical way how strong the ion is scavenged from the aqueous towards the sediment phase. In general and under natural occurring conditions and including those, which we most often are confronted with these K_d values are typically in the order of magnitude from 10 to 10^5 for all metal ions, meaning that from 90 to 99.999 % is recovered in the sediment.

As was mentioned above a large number of equilibria are involved in the overall retention reaction in the sediment. However the most important ones are:

1. the chelation with the organic matter fraction and the sulphide complexation
2. the ionexchange in clay minerals and oxides.
3. the adsorption to organic matter, oxides and other sinks.

C.2 Complexation and chelation

Humic substances and related compounds recovered in sediments, comprise a large segment of the world's organic reservoir. The name "humic" is often referred to as a generic name for the total organic matter pool in soils. Humic acids are generated by biological and chemical degradation of plant and animal detritus. The so formed products tend to associate into more complex, and at the same time more stable chemical structures (Schnitzer and Khan, 1978). Due to their polyelectrolytic properties (Thurman, e.a., 1983), and their large quantities of functional groups (De Brabandere, 1989), they are able to form very strong complexes with metal ions. Considering the organic matter as a monomeric ligand L, this interaction may be written in the following stepwise equilibrium reactions.

$$\begin{array}{cccc} Me^{z+} & + \ L & \rightarrow & MeL \\ \vdots & \vdots & & \vdots \\ Me^{z+} & + \ mL & \rightarrow & MeL_m \end{array}$$

$$\text{with } \beta_m = \frac{[MeL_m]}{[Me]\,[L]^m} \text{ and } \beta_m = K_1.K_2......K_m$$

Not only the complexation with natural organic matter, but also the complexation with sulphide bearing species forms an important sink for most metal ions. Particularly Cd, one of the most important problem causers, is mainly present under a sulphide complex under reducing conditions (Van Elewijck, 1990). From extraction experiments Davies-Colley e.a. (1984) also showed that almost all Cadmium can be found in the sulphide and organic fraction. They assumed that all Cadmium is present as solid sulphides.

C.3 The ionexchange with clay minerals and oxides

When the concentration of the metals in solution is increasing, the mechanism of ionexchange becomes more important. Clay minerals for instance have reversible adsorption properties towards different cations. This is due to their specific structure and surface, which is covered with a residual usually negative net charge. The ionexchange reaction on clays is generated by the fact that cations with a different charge density compete with each other and with the hydrating ions on the surface of the clay minerals. It is generally assumed that clay minerals cannot compete with oxides and organic matter for the retention of heavy metals (Gigg, 1985). Nevertheless, these particles show a strong affinity for oxides and organic matter which in turn may adsorb or complex heavy metals. In this way clay minerals thus indirectly contribute to the immobilization of heavy metals.

For a cation Me_2 with a charge z_2 replacing a cation Me_1 with a charge z_1, being adsorbed on the surface of a particle, the reaction can be written as follows:

$$z_1Me_2^{z2+} + \underline{z_2Me_1^{z1+}} \rightarrow \underline{z_1Me_2^{z2+}} + z_2Me_1^{z1+}$$

$$\text{with} \qquad {}^{Me2}_{Me1}K_c = \frac{\underline{[Me_2]^{z1}}[Me_1]^{z2}}{[Me_2]^{z1}\underline{[Me_1]^{z2}}}$$

(the underscored species are present on the surface)

From the equilibrium equation it can be seen that the relative concentration of both competing metals in solution is an important factor ruling this retention mechanism. At relatively high concentrations, these interactions are reversible for most of the cations. At very low concentrations i.e. at trace levels, the metal cations are retained on very high selective sites, characterized by high K_c values. In some cases up to 4 levels of interactions have been detected (Cremers, e.a., 1978). Nevertheless at less lower concentrations most cations can be exchanged.

C.4 Adsorption on oxides, organic material, and other sinks

Adsorption takes place when metal cations are being scavenged from the liquid phase and exchanged for protons present on the surface of metal oxides, particularly Mn, Fe and Al. In the case of iron oxide the reaction is written as:

$$z\ FeO(OH) + Me^{z+} \rightarrow z\ H^+ + (FeOO)_zMe$$

These interactions are in general much weaker than ionexchange and complexation, although some metals are preferably associated with oxide fractions, e.g. Ni on MnO_2. At high metal pollutant concentration this type of interaction will take place also on the surface of humic substances, although again the retaining strength will be smaller.

C.5 The influence of the oxido-reduction conditions.

The ultimate fate of heavy metals will be influenced by the salinity, the pH, the phase composition (in particular the presence of soluble metal complexing agents). However, far the most important factor ruling the speciation is the redox-potential. A shift in the oxido-reduction state of the system always causes drastic changes in chemical associations. Under natural conditions particularly microbiological activity is the promotor for all kinds of transformations. The consumption of oxygen in underwater soils causes the sediments to be reduced. This results in the creation of different zones, which are characterized by gradually increasing reductive capacities: A) the nitrate reduction zone; B) the sulphate reduction zone and C) the methane formation zone. The last two zones best meet the prevailing conditions, for the treatment of dredged material. The sediment is usually black coloured, caused by the formation of metal sulphides and organic matter complexes. Metals are being immobilized as long as no oxidation of sulphides or organic material takes place.

Upon oxidation the speciation becomes regulated by the formation of oxides, although the complexation with organic matter remains important. In general only some functional sites are being oxidized, the most important being sulphur-bearing and phenolic sites. The largest part of functional sites consists however of carboxyl groups, which are not attained by air oxidation. The retaining forces however become weaker, upon oxidation. This results in a possible leaching out of the metal ions.

III. EXPERIENCE OF SILT IN THE FIELD OF PHYSICO-CHEMICAL TREATMENT OF DREDGED MATERIAL

A. Physical separation

In the isolation of metal pollutants from a sediment system, three types of interaction play a key-role. This was shown above. Therefore they form the basis of possible treatment techniques. In a system in which dredged material is mechanically separated, sand is being extracted from the remaining part of the sludge. This sand fraction consists majorly of oxide and oxide-like particles. It was shown in the previous chapter that the retaining forces between metal cations and oxides in general are weaker. Therefore this operation results in an enrichment of the relative concentration in the remaining fine grained material.

B. Extraction

By the application of an extraction, the purpose is particularly to change the existing phase equilibrium between the solid and liquid phase, i.e. the K_d.

From formula (A) in chapter II, it can be seen that this equilibrium may be influenced either by:

1. increasing the importance of the liquid scavenging effect.

   or by:
2. weakening the complexing forces in the solid phase

The first option means that the concentration of OH^-, CO_3 or any other ligand in solution must increase. This can be achieved by increasing the pH, or by the addition of strong complexing agents, which can compete with the sediment. Increasing the pH also causes the increase of precipitation of some metal-OH and metal-CO_3 species. On the contrary, humic material will be solubilized. The net result with respect to the solubilization of the metals however will be rather doubtful.

For this reason the development of an extraction technique by SILT was based on this delicate equilibrium between the solid and liquid phase. The final process acts on both sides. The extraction procedure is basically a three step technique, in which the contaminated sediment is first submitted to a strong washing and extraction procedure, followed by a phase separation, whereas finally it is conditioned again to a reusable material.

C. The physico-chemical separation plant

C.1 The fraction separation unit

The installation is particularly developed for the reduction of the volume of the spoil, requiring treatment or disposal. Furthermore the clean sand can be recycled. SILT operates two separation installations for this type of treatment.

The Krankeloon is a pilot installation with a capacity of 30 m^3 an hour. It is equipped with 1 cyclone with a cut-off size of 63 µ, and a small filter belt press. A sand pump draws the spoil from the well. It is then passed over a screen in order to remove the larger particles. It is stored in a buffer tank from which a constant flow is supplied to the hydroclycione. The sand is stored. This installation can be used in a preparatory stage to define the optimum parameter settings in large scale sanitation operations.

These parameters are:

- dimensions of required cyclones
- efficiency of the cyclone, i.e. in and outflow
- required pressure ratio upper and underflow
- density characteristics during the thickening of the sludge
- dry matter concentration at the belt filter press
- variation of all parameters by changing sludgefeed.

Particular results for the Krankeloon plant are shown in table 1.

Table 1
Relative enrichment of heavy metals in under and upper flow by hydrocyconage.

Element	Feed	Underflow	Upperflow
Cd	1	0.17	0.88
Co	1	0.19	1.37
Cu	1	0.10	1.49
Hg	1	0.22	1.87
Pb	1	0.13	1.36
Zn	1	0.19	1.57

The second installation is a mobile 1000 m^3 unit. It can be installed both on shore or on a pontoon. It is equipped with 38 hydrocyclones and 6 filter belt presses. The incoming dredged material is supplied to a two-stage separating device and subjected to physical cleansing. The material is separated into a sand and a silt fraction in a first stage with 6 hydrocyclones with a particle cut-off size of 63 µ. The sand fraction is washed and subsequently dewatered.

Compared to other standard separation techniques, the Silt plant goes even further. Through an additional separation between 20 and 63 µ the fractional sequestration of the metals is optimized. This is done by a second battery of 32 hydrocyclones with a particle cut-of size of 20 µ. Both fractions are then dewatered. Most of the pollutants are concentrated in the fraction below 20 µ. Good environmental returns and cleansing rates can be achieved with this installation. Depending on the incoming material the residual fraction contains up to 80 % of the pollutants. This fraction is to be treated further or to be disposed of.

C.2 The extraction unit

It was shown already that particularly organic material is the main factor ruling the retention equilibria in the sediment. By deactivating this fraction a large part of most of the metals can be extracted. Most of the organic matter ligands are carboxylic and phenolic functional sites, which either act solely or in combination with each other. Under the deprotonated form they are negatively charged, and easily solubilized. In a solution of pure organic matter at a pH of 10 the organic matter starts to precipitate at a pH value between 4 and 2. If a metal is associated with this fraction, it will be driven out of its complex once all functional sites are protonated. This is shown in figure 2. In various batches a solution containing a metal ion is mixed with a soil organic matter extract. It is equilibrated at different decreasing pH-levels. The metal remains associated with the organic material until this latter is completely protonated. At this point the organic material coagulates within a very narrow pH range of 0.2 pH units, and the metal is released from its complex. This experiment was carried out under reducing conditions, which equally prevail in the case of under water soils and dredging operations.

The extraction process of Silt consists of several steps. The first step is to characterize the buffer capacity of the system. Therefore an accurate acid-base titration is mandatory. From this item the amount of reagent needed, is calculated. Just beyond the point of "break through" is the critical point, at which metals are being removed from the sediment. In order to avoid the metals to adsorb on other sinks once they are in the liquid phase, a chelating agent is added. This latter has to remain active beyond the working pH level for the extraction operation step.

In the extraction at first a desorption phase is induced. The sediment is thoroughly being mixed with a combination of extractants. This is carried out in two or three batches, depending on the composition of polluting metals in the sediment and on the end result, which is required. The next step is the elimination of the metals from the liquid phase. Finally both the solid and the liquid fractions are conditioned appropriately. They are either dumped or prepared for further reuse.

Figure 2
Heavy metal complexation characteristics of purified soil organic matter as function of pH.

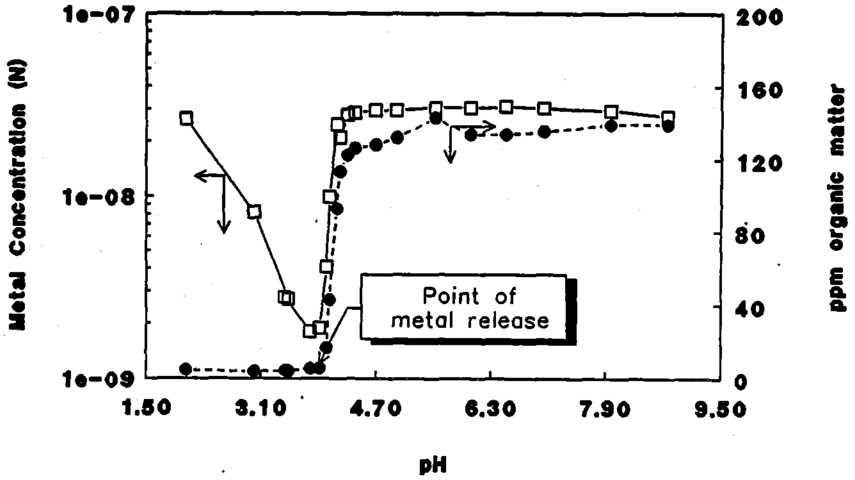


Table 3

Extraction yields for specific metal ions from dredged sludge with the SILT physico-chemical extraction plant.

% Removed from the dredged material using:				
Element	an Extraction with water	a Weak extractant in one step	a Medium extractant	a Full scale extraction in two steps
Cd	1.34	24.16	57.85	100.0
Cr	0.20	6.58	10.06	56.56
Co	1.96	23.65	44.61	95.73
Cu	0.24	4.29	4.37	56.90
Mn	0.34	22.08	75.80	100.0
Ni	1.44	22.43	30.90	80.0
Pb	0.26	31.54	65.67	100.0
Zn	0.46	42.38	58.35	100.0

The precise design of the necessary adaptations on the installation is based on a model which has been developed in collaboration with the State University of Gent (Tack e.a., 1990) Each sanitation is caused by particular pollutants, which necessitate A) different reagents, and B) other reactor specifications. This enables a true tailor made solution for each problem. Particular extraction results for most heavy metals are shown in table 3. In this case the dredged material under consideration comprised only of a small quantity of heavy metals. This means between the A and B standards of the Dutch VROM regulations. This means that all elements are present at relatively low concentrations, at which they are firmly being retained by the sediment. The table shows several removal results for various metal ions, with respect to different applications of the SILT process. Also the release of heavy metals by applying a blank extraction with water is shown. Total concentrations were measured upon a total HCl-HNO_3 digestion of the sample, followed by AAS-ICP detection.

From the results in table 3 it is clear that the most human toxic heavy metals are removed up to a level of 100 %. This is the case for Cadmium, Manganese, Lead and Zinc. Other elements are also being removed to an significant degree. Although complete removal thus is perfectly feasible from a technical point of view, such drastic procedures are rather seldom required. A medium extraction will most often meet the desired final result. Sometimes a gentle extraction may also fulfil the needs. Particularly in the case of mono-pollutants, i.e. where the pollution is caused by only one or two metal ions mild extraction routines are can be chosen. In that case the extraction may take place in a continuous process, which can be integrated in the dredging process. The extraction then takes place while the dredged material is being transferred from the dredger to the final deposit, because of the fact that the dredged material only needs a minor conditioning after the treatment.

The full scale extraction process is a discontinuous batch process, followed by an appropriate conditioning. It may however be conducted on-line, requiring large buffer capacities for intermittent storage of the dredged material. An important factor in choosing the final extraction procedure is the combination of extractants. SILT guarantees that its procedure is not harmful to the environment. This means that full biological recovery after the treatment is perfectly feasible. No toxic agents are being used, and extractants from organic origin are totally bio-degradable. However, it is clear that one should always be very careful with such definitions. Therefore SILT always determines conscientiously the amounts of reagents needed in order that not less but also not more products than strictly necessary are being used.

IV. CONCLUSION

A good understanding of the immobilization mechanism is in fact the only tool, which is available to the technician to proceed to the development of treatment techniques. In spite of all technical complications related with the execution, this paper has demonstrated that one of the few tools for the sanitation of polluted dredged material is the physico-chemical separation, in which a mechanical treatment is combined with a chemical extraction. It also showed that the SILT process has very promising results. Although in the scope of this paper the cost analysis has not been shown, the technique also is very price-competitive with regard to other treatment techniques.

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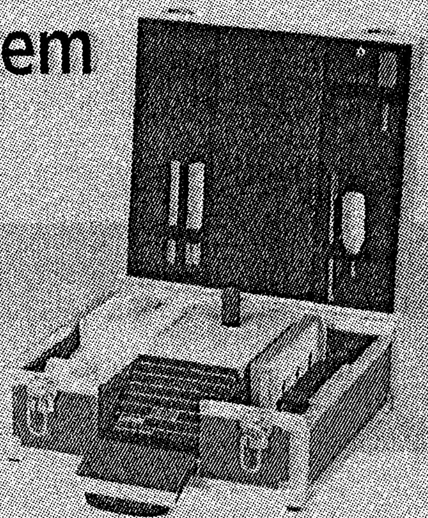

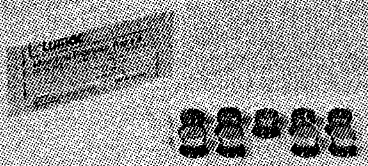

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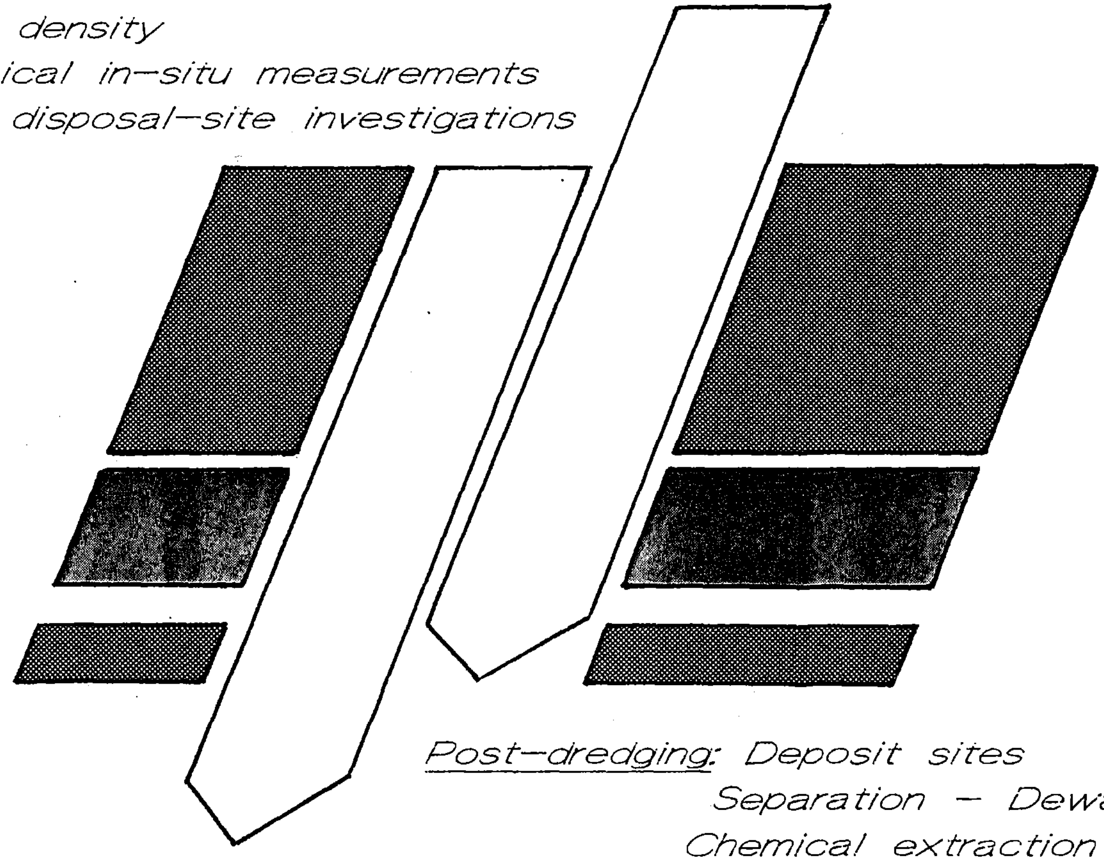

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DREDGED MATERIALS AND ENVIRONMENTAL IMPACT

USE OF MODELS TO CALCULATE ENVIRONMENTAL IMPACT OF DUMPING OF DREDGED MATERIALS IN DUTCH COASTAL WATERS

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0 ABSTRACT

In the Netherlands models are developed to calculate the transport of contaminants through the North Sea water-system and to calculate the risk of effects on the ecosystem on a defined place as a result of a dumping elsewhere. In this paper a combination of models is chosen to build a model-framework, in order to assess the effects of the dumping of dredged materials into the sea.
The effects of the dumping of dredged materials as calculated with the model-framework on the ecological functioning of the North Sea can be visualized by AMOEBA.
A description is given of the model-parts contributing to the framework and the way in which these are linked.
The effects of the dumping of dredged materials in sea are now being assessed using this model-framework. The integration of the model-parts themselves however is still subject for ongoing studies.
The model-framework will also be used for calculating the implications of the Dutch policy for reduction of loads of contaminants in dumped dredged material.

1 INTRODUCTION

Dredged materials form an important source of pollution in the Netherlands, since much of the load of contaminants of the rivers Rhine, Meuse and Scheldt is accumulated in the estuaries of these rivers. Dredging throughout the year is necessary to maintain navigation routes at a sufficient depth. An important way of disposal of dredged materials is dumping at sea. It is not possible to measure the effects of these dumpings in the field seperately from effects of other sources of pollution. Field measurement have to be evaluated with the aid of models.

The aim of this paper is to demonstrate that a choice of models placed within a model-framework can be used to assess the effects of the dumping of dredged materials into the sea.

Fig. 1 shows that the input of contaminants in dredged materials is part of the total input of pollutants into the North Sea ecosystem. Toxic substances originate both from land and sea based activities. On land the main sources are related to traffic, industry, agriculture and domestic activities. Pollutants from these sources mostly find their way to the sea through river discharges and atmospheric deposition.
At sea direct inputs of pollutants result from offshore- and shipping-activities, while also the dumping and incineration of waste materials contribute to the total load of pollutants into the sea. An indirect input from land based activities is the dumping of dredged materials into the North Sea.

In The Netherlands various models are developed to calculate the transport and effects of contaminants in the North Sea.
The project MANS (Management Analysis North Sea) has been initiated to build management tools to support the development of an integral vision on the sustainable functioning and utilization of the North Sea water-system. In the MANS-study, models have been developed in order to study the transport of toxic waste inputs and dredged materials into the North Sea, with their effects on the water-quality, the sediment quality and their exposure to the ecosystem (ref. 1).

Also an ecological oriented model has been developed. This model, called REFEREE, evaluates the risk to the North Sea ecosystem posed by a variety of activities or calamities.
The REFEREE-project (Risk Evaluation Framework for Estimating the Risk of Ecological Effects) was initiated to establish the effects of industrial dumpings in the North Sea, at a large distance from the dumpsite, e.g. in accumulation areas like the Wadden Sea (ref. 2).

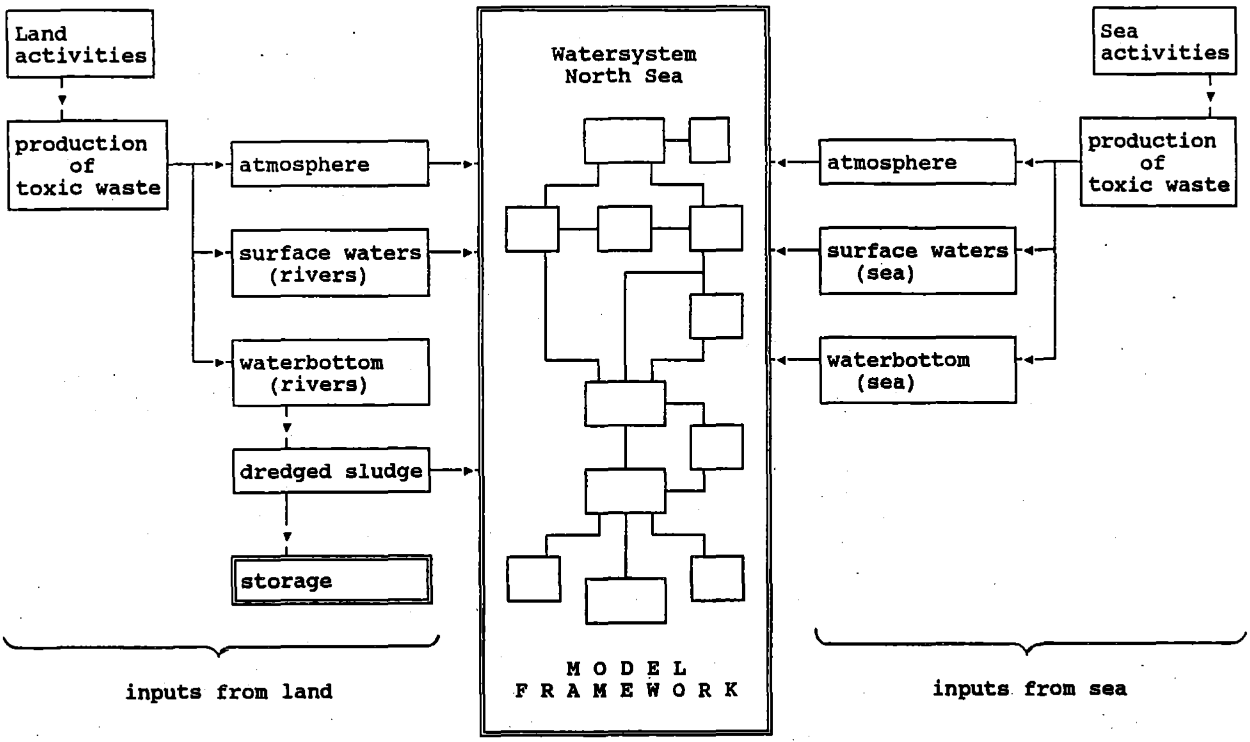


Figure 1. Dredged materials as part of the total input of pollutants into the North Sea water-system.

The impact of the dumping of dredged materials on the North Sea ecosystem can be quantified by using parts of the models described above. In this paper a choice of these 'model-parts' is being integrated into a framework, which finally should create a tool for evaluating the impact of the dumping of dredged materials on the ecosystem. In that way also different alternatives for the dumping of dredged materials can be investigated on their effects for the North Sea ecosystem.

There is a need to formalize the relation between activities - such as dumping of dredged materials - and the effects of regulations on the one hand, and the ecological functioning of the North Sea, on the other (ref. 3). This relation can be visualized by AMOEBA, which stands for A general Method Of Ecological and Biological Assessment.
AMOEBA is an ecological index, which has been formulated as a tool in water-quality management and policy-making. This AMOEBA-index describes the status of selected organisms in comparison to a reference situation in the 1930's (ref. 4). The index is used here to compare results of model-calculations to the situation in the 1930's.

2 MODEL-FRAMEWORK

A model-framework as shown in fig. 2 is used to quantify the impact of the inputs of dredged materials on the North Sea ecosystem.
In this framework, a selection of models of three research activities are integrated, i.e. models from the MANS-, REFEREE- and AMOEBA-studies. In fact these studies overlap and a choice has been made how to link the models to one framework. Here the general outline of the chosen integrated model framework will be given. In the next paragraphs the three constitutive components of the framework are discussed in more detail.

The components of the first part of the model framework originate from the MANS-project.
In the MANS-models the input of pollutants is distributed over a dissolved and a particulated fraction. This distribution is calculated with the aid of partitioning coefficients depending on local physical and chemical conditions.
It gives the input for the long-term mass transport simulations for both dissolved and suspended substances. Flow patterns from hydrodynamic models form the base for the long-term transport simulations. From the simulated settling of particles and

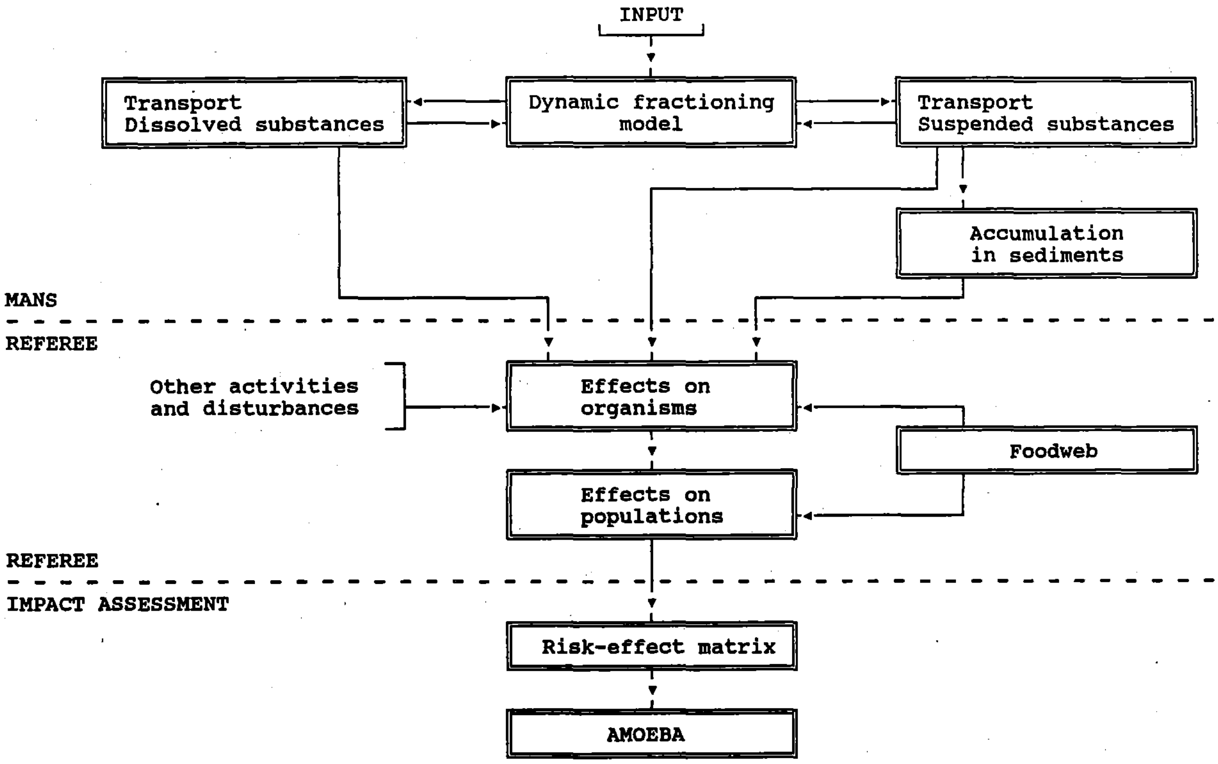


Figure 2. Model-framework for assessment of impacts of dumping dredged materials on the North Sea ecosystem.

their adsorbed pollutants, the accumulation of pollutants in the bottom sediments is calculated.
The results of these models are the spatial distribution of pollutant-concentrations in the dissolved phase and in the suspended and bottom sediments. In fact these are the external concentrations of pollutants to which the marine ecosystem will be exposed.

These external concentrations are input for REFEREE to quantify the ecological effect on a single species level (autecological effects). The effects are translated in reproduction- and mortality-factors, which finally determine the population size of the species under consideration.
The results of the quantification of effects on a population level can be used for the quantification of effects on other populations by use of the knowledge of the marine foodweb. For this purpose a selection of relevant species (representative for the North Sea ecosystem and/or for the type of disturbance under consideration) has been made. For each species a so called ecoprofile is made, which describes the main ways along which the species is influenced in the ecosystem, e.g. its preys, predators, pollution-related physiological factors, etc.

The results of the REFEREE calculations are the species density or the population size.

The effects on the population of a selection of species due to different (human) disturbances can be presented in several ways. One way is the so called AMOEBA presentation. In this presentation the computed population size of a number of species is compared to a relatively undisturbed situation in the 1930's. The presentation has the advantage of a quick impression of the divergency of the present disturbed state of the ecosystem from a reference situation.

3 MANS

3.1 Introduction

In the MANS-study management tools have been built to support the development of an integral vision on the sustainable functioning and utilization of the North Sea water-system. Models have been developed for impact assessment of policy options. The models cover different relevant fields

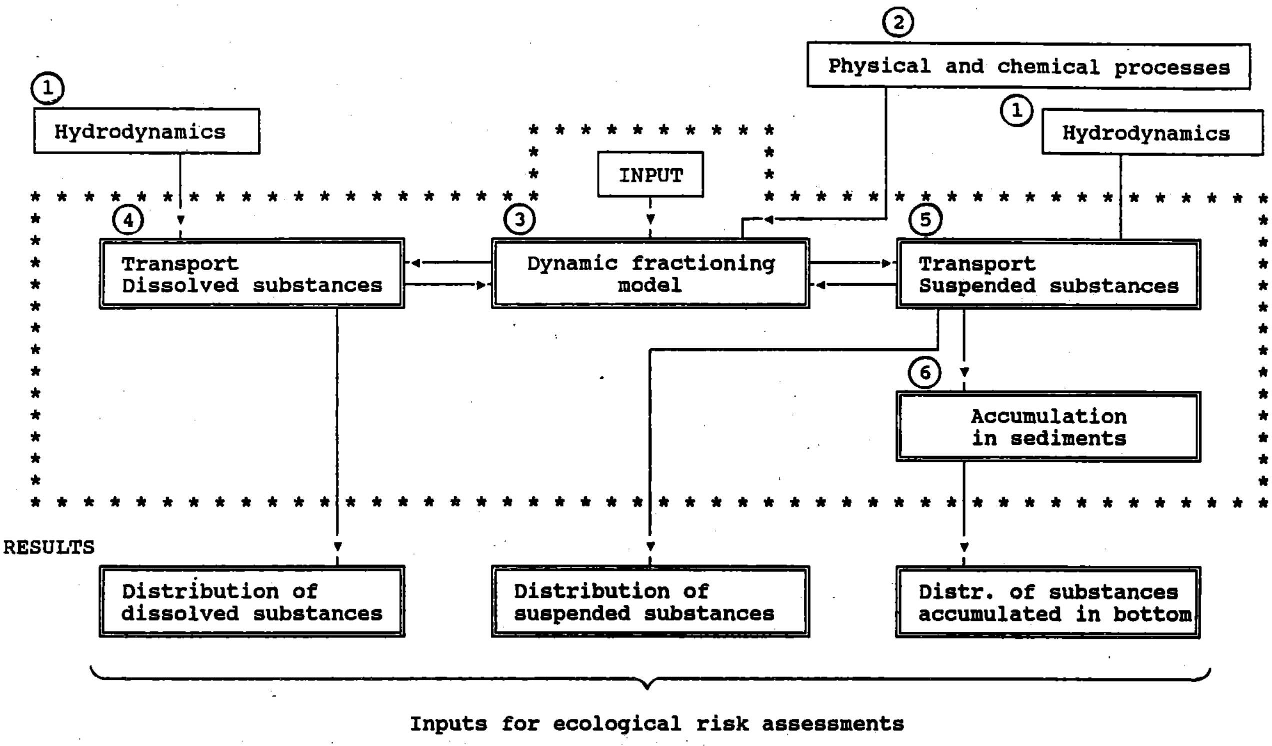


Figure 3. MANS-models as used in the framework.

for policy analyses:

- risk assessment of the occurrence of calamitous spills and related environmental damage;
- input and accumulation of toxic substances;
- eutrophication due to input and accumulation of nutrients;
- physical planning of the sea-use in relation to impacts on the water-system and the use of the sea.

The models are being linked together in an integrated MANS model-framework. In the context of this paper only a part of the models from the field "input and accumulation of toxic substances" will be discussed.

3.2 Description of the models

The MANS-models as indicated in fig. 2 are outlined in more detail in fig. 3. The model components have numbers (1) to (6) to refer to in the description.

Investigations can be carried out for two areas, the Southern North Sea (ZUNOWAK model-area) and a larger part of the North Sea (GENO model-area), see fig. 4. Two-dimensional depth-averaged hydrodynamic models (1) of these areas are used to simulate wind and tide-induced currents. Averaging of the computed tidal flow over the diurnal tidal period provide residual transport patterns as base for long-term water transport simulations. A somewhat different averaging proces is used to compute residual transport patterns for long-term suspended sediment transport simulations. The difference in the averaging proces has to do with the fact that the sediment is not transported if the current velocities are below a certain level. Simulations of salinity and suspended solids were used to calibrate the dispersion coefficients and the rates of sedimentation and erosion of particles in the models.

Inputs of pollutants from rivers, dumpings and atmospheric deposition are transported as dissolved substances and as substances adsorbed to suspended sediments. The inputs are partitioned into dissolved and particulated fractions by the dynamic fractioning model (3). The partitioning depends on the distribution coefficient K_d, which is a function of local physical and chemical conditions (2). Fig. 5 shows the exchange of the substances between the compartments water, suspended sediments (anorganic and organic) and bottom. K_d, which determines the local distribution between the dissolved and particulated fraction, is a function of salinity,

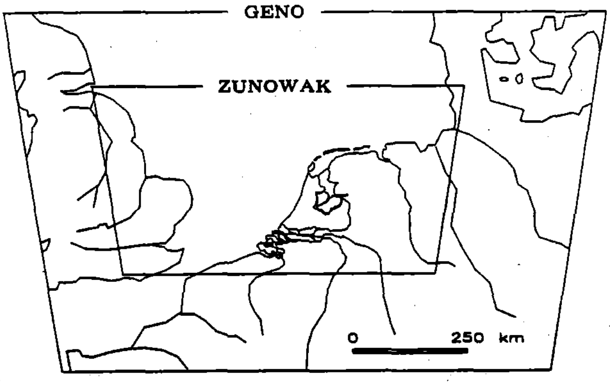


Figure 4. Two areas for model-investigations.

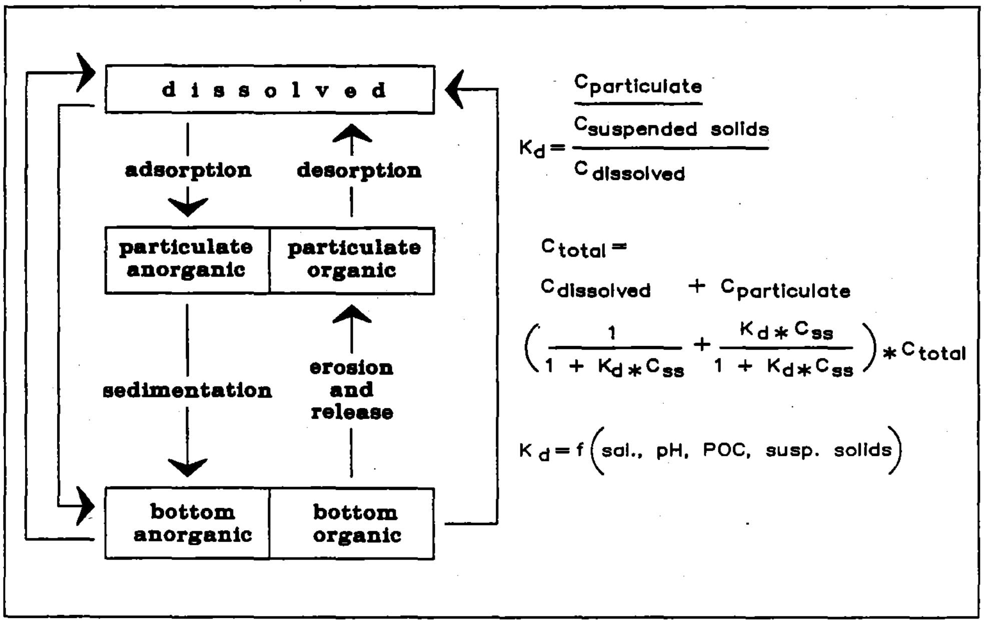
pH, particulated organic carbon concentration (POC) and the concentration of suspended solids.

As a result of the dependence on the particulated organic carbon concentration, the distribution between the dissolved and suspended fraction is influenced by the eutrophication condition of the sea.
The dynamic fractioning model not only determines the partition of the inputs over the dissolved and suspended fractions, it also determines the distribution in the whole model area, depending on the local conditions.

The transport of the dissolved fraction is simulated by a model (4) which produces spatial distributions of concentrations of the dissolved substances.
The transport of the substances adsorbed to the suspended sediment is simulated by a model (5) which produces spatial distributions of concentrations of substances adsorbed to suspended sediments. In this model also sedimentation and erosion is simulated. From the simulated settling of particles and their adsorbed pollutants, the accumulation of substances in the bottom is quantified by the bottom accumulation model (6). By means of long-term simulations local bottom quality profiles can be computed. Also spatial distributions of concentrations in the top layer of the sediment can be produced by the model.

3.3 Illustration

As an illustration some results of the models for the 1985 situation for cadmium will be shown. Cadmium inputs from rivers, dumpings and atmospheric deposition for 1985 are used as model input.
Fig. 6a shows the spatial equilibrium distribution of the concentration of dissolved cadmium, as computed by model (4).
Fig. 6b shows the spatial equilibrium distribution of the concentration of particulated cadmium, as computed by model (5).
Long-term simulations with inputs from 1900 up to 1985 (and further to 2000 as a scenario) are made



$$K_d = \frac{\;\frac{C_{particulate}}{C_{suspended\ solids}}\;}{C_{dissolved}}$$

$$C_{total} =$$

$$C_{dissolved} + C_{particulate}$$

$$\left(\frac{1}{1 + K_d * C_{ss}} + \frac{K_d * C_{ss}}{1 + K_d * C_{ss}}\right) * C_{total}$$

$$K_d = f\left(\text{sal., pH, POC, susp. solids}\right)$$

Figure 5. Exchange of substances between the compartments water, suspended sediments and bottom. C = concentration and C_{ss} = concentration of suspended solids.

for the accumulation model (6). From the simulated settling of particles and the adsorbed cadmium, the accumulation of cadmium in the bottom is computed. The toplayer of the sea-bed is continious disturbed by flow and wave induced turbulences, bioturbation and trawl fishing. Therefore a mixed sediment toplayer of 10 cm is assumed.

A result of the accumulation model is shown in fig. 7 for a location in the Dutch Western Wadden Sea for 1985. Fig. 7a shows the concentration of cadmium in the suspended sediments and in the mixed top layer of the bottom sediment. Note the phase difference, due to the mixing in the sediment-layer. Fig. 7b shows a profile of the cadmium concentration in the bottom.

Fig. 8 shows another result of the accumulation model, i.e. the spatial distribution of the cadmium concentration in the mixed top layer of the sediment for 1985.

Results as shown in fig. 6a, 6b and 8 are used as inputs for the ecological risk assessment.

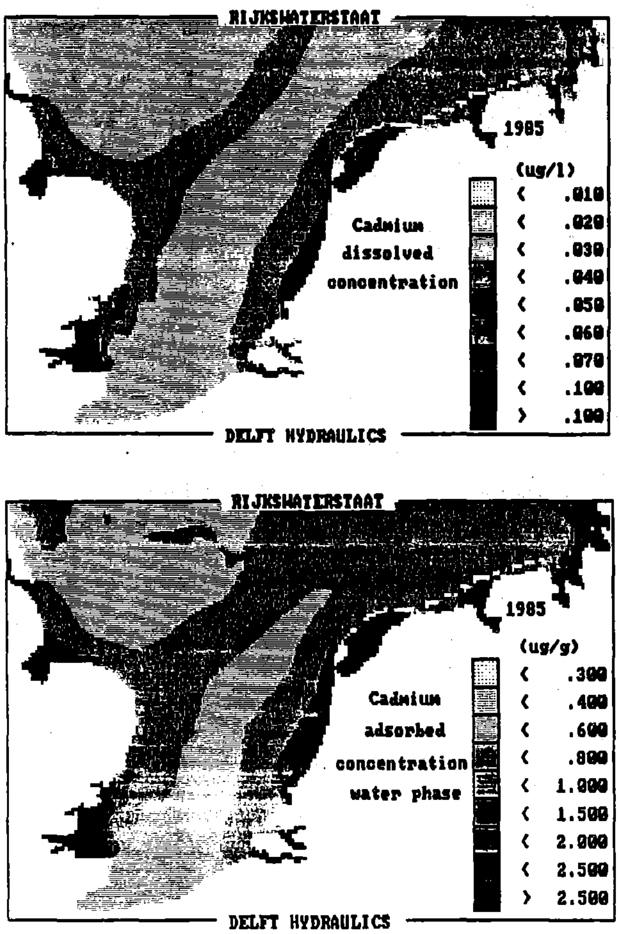


Figure 6. Concentration of cadmium dissolved (a) and adsorbed to suspended sediments (b).

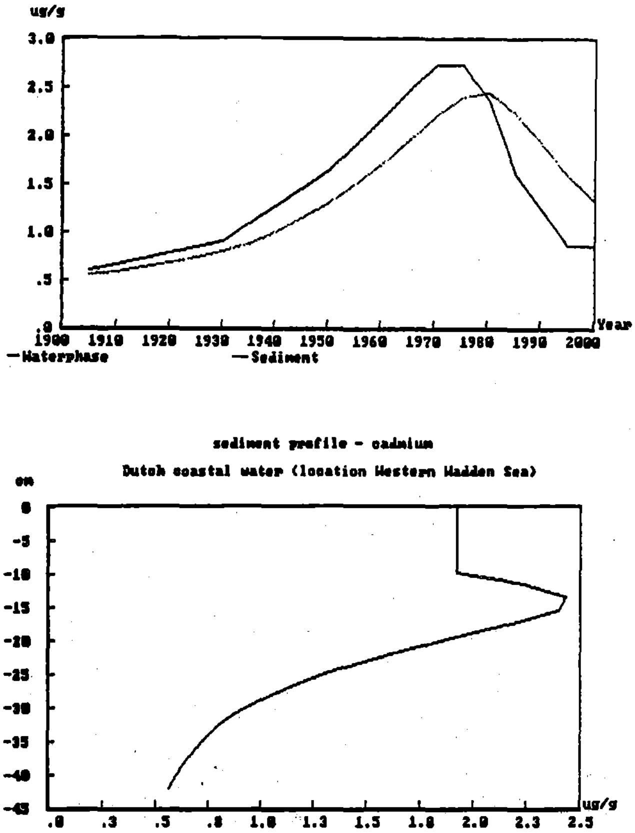


Figure 7. Calculated concentration of cadmium in suspended sediments (solid line) and in the mixed bottom top-layer (interupted line) (a) and in a bottom profile (b) (Dutch Wadden Sea, 1985).

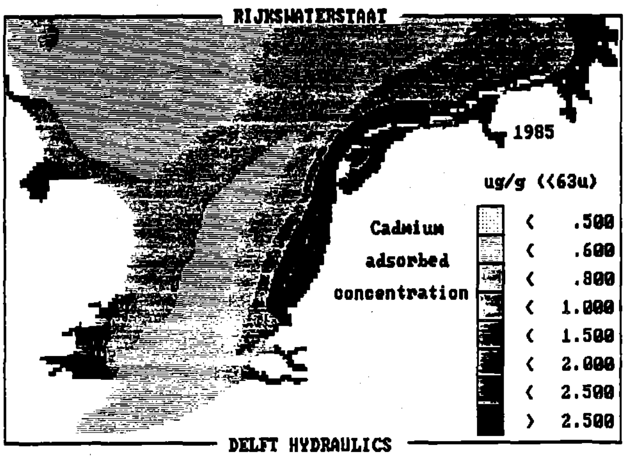


Figure 8. Calculated concentration of cadmium in the mixed top-layer of the North Sea bottom-sediment for 1985.

4 REFEREE

4.1 Introduction

The REFEREE-concept is being developed in order to estimate the ecological risks to the North Sea environment in a logical and systematic way, based upon available data and generally accepted insights.
The objective is to find and test explanations for already occuring effects, as well as forecast potential effects in the short-medium term. In REFEREE quantification of chances is combined with the modelling of (ecological) effects. Ecological *risk* is expressed in terms of the *chance* (probability, expectation) that an activity has or will result in a defined ecological *effect* of a certain size. The effects are expressed as long-term changes in population size of selected indicator species.

Sections of the prototype of this instrument, called REFEREE, have been used to demonstrate an ecological risk assessment of industrial waste dumpings (ref. 2), fisheries (ref. 5,6) and oil-discharges from production platforms (ref. 7).

4.2 Description of the models

The direct impact of contaminants on specific organisms are modelled with REFECT.
The translation of direct impacts at individual species level into final overall ecological effects is calculated with REFOOD.

The inputs for REFECT are the concentrations of pollutants to which the organisms are exposed, as calculated with the MANS-models (see section 3).
In REFECT autecological effects (effects on a single species) are quantified by using a diagnostic program which integrates the expert opinions on both the sensitivity of individual species and the toxicity of substances (pollutants).
In that context the impact of dosis-effect relations depends on the circumstances which have an influence on this relationship, e.g. external concentrations of a pollutant, the rate at which a physiological proces occurs etc.
In REFECT, the sensitivity of a species for a pollutant is based on, on the one side the toxicological profile of that pollutant and on the other side the ecological profile of the species involved. In addition to these, several preconditions both for the existence of the organism and the exposure of the substance are valid.
In fig. 9 an example of an ecological profile is

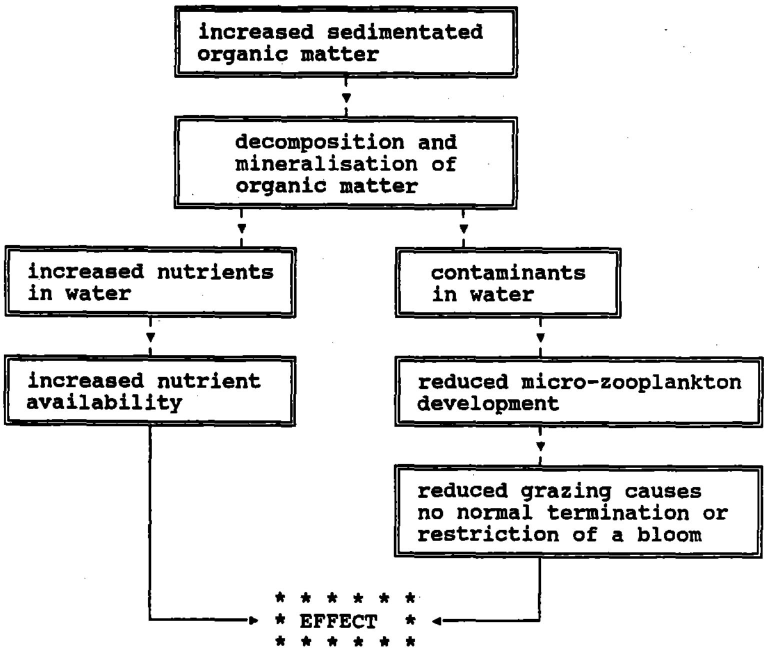


Figure 9. An example of an ecoprofile flowdiagramme as used for REFEREE and simular to the ecoprofile-diagramme used for AMOEBA (from ref. 15). The effect of increased length and intensity of the spring bloom of Phaeocystis pouchetii.

given. An ecological profile describes the main characteristics of a species and its living conditions.

The characteristics of the ecoprofile combined with the relevant toxic proces and the chance of exposure of an individual organism to the pollutant give the sensitivity of the species involved. In REFECT this is being translated in a distribution of chances for reproduction and mortality of the species affected by the exposure to the pollutant. The competition between species however also has an important influence on the reproduction- and mortality-rates. This influence is for a part quantified in the ecoprofile used for REFECT, but is also subject to the quantifications made in the next step of REFEREE, a module called REFOOD.

REFOOD is an ecosystem model containing information on the food relations between selected species or groups of species. It formalizes empirically determined relations between the magnitude or changes of selected species or groups of species. REFOOD is split up into four modules, schematically presented in fig. 10.

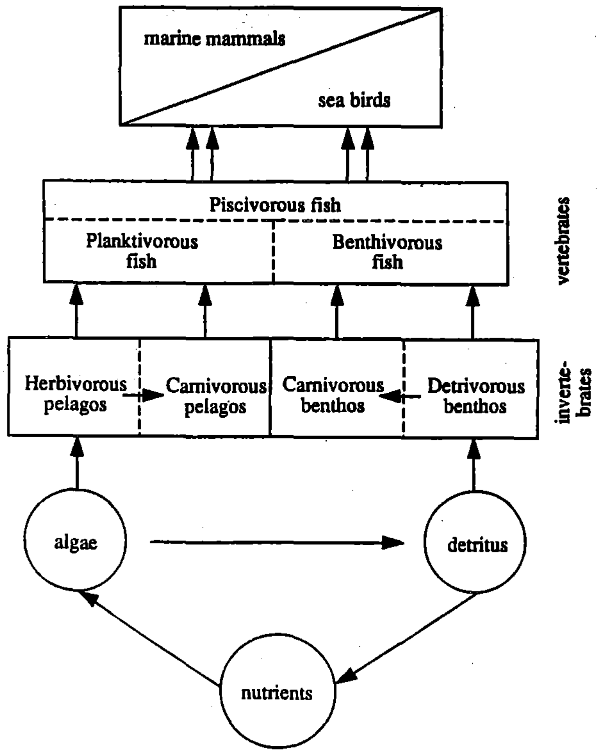


Figure 10. REFOOD

For each module a series of indicator species or species-groups are selected, based on ecological and economical criteria, i.e.:

- PRED	:	3 mammals and 4 birds
- FISH	:	15 fish species
- CONS	:	11 invertebrates species or groups of species
- PROD	:	phytoplankton, detritus and nutrients

The sets of potential food sources and potential predators are listed for all species. Both opportunistic and selective feeding strategies are incorporated for each species/group.
Changes in densities of selected species/groups are the resultants of gains (production, birth, etc.) and losses (predation, mortality, catches, etc.).
General model formula for all organisms is:

$$dB_i/dt = \Sigma\ (c_i * F_i) * B_i - \Sigma\ (m_j * P_j) * B_i$$

where in:

B_i = species density
$\Sigma\ (c_i * F_i)$ = species (re)production rate
$\Sigma\ (m_j * P_j)$ = species mortality rate

With respect to the species (re)production rate:

c_i = relative food conversion, concerning prey i,
F_i = density of prey i.

With respect to the species mortality rate:

m_j = relative mortality constant for species j,
P_j = density of organisms causing mortality.

Calibration of parameters is based on empirical data gleaned from a vast body of literature. A more comprehensive description of the model formula, parameter selection and calibration can be found in a seperate report (ref. 8).

4.3 Illustration

REFOOD 1.0 is used to simulate the development of the density of species over a period of 15 year for two conditions:

- resembling the impact of the level of contamination in the 1980's,
- resembling the situation during the 1930's.

The potential disturbance of contamination can be categorized in 3 main classes:

1. Food-chain contamination, resulting in chronic exposures of vertebrate toppredators, like marine birds, mammals and fish.
2. Sediment contamination, resulting in chronic exposure of benthic invertebrates (and demersal fish).
3. Water-contamination, resulting in chronic exposure of zoöplankton (and fish).

Although there is a lot of ecotoxicological information on acute (and semi long-term) effects of particular chemicals to selected marine species, it is not easy to quantify the environmental effects of a real chronic exposure to a cocktail of contaminants by a broad range of relevant marine species, as appearing in the field situation.
Appropriate experimentation, in which organisms can be exposed to chronic contamination under controlled (semi-)natural conditions, is needed to provide these data. The available data from these studies are however too scarce to get a reliable quantitative assessment of ecotoxicological effects. However, the impact of contamination is (as good as possible) quantified in REFEREE, with the following assumptions.

Foodchain-contamination: From diet-experiments with seals (ref. 9) and diving ducks (ref. 10,11), it is assumed that in coastal areas the reproduction of mammals and birds might be reduced by 50-60 respectively 40-60 %. Most mammals and birds feed in coastal areas.

Sediment-contamination: From mesocosm-experiments it is observed that polluted coastal sediments result in a 36% lower production of macrozoobenthic invertebrates compared to an non-polluted reference sediment. The coastal area is assumed to be 15000 km^2 (the coastline of UK, B, NL, D and DK is about 1500 km long, the contaminated area is about 10 km along the shore), or 1.7% of the North Sea area. The production of macrozoobenthos in the 1980's is therefore assumed to be 0,983 of the production in the 1930's.

Additionally, discharges of oil-based muds result in an extra mortality of macrozoobenthic species around drilling locations. From a separate study (ref. 7) on the ecological risks of this discharges on the Dutch continental shelf, the general mortality of macrozoobenthos can be extrapolated (see table 1).

Table 1.Mortality rate (per year) of zoobenthic organisms in North Sea sediments polluted due to oil-based mud inputs.

Echinoderms	0.039
Molluscs	0.085
Polychaetes	0.031
Coelenterates	0.085
Crustaceans	0.021
Meiofauna	0.031

Water-contamination: From enclosure experiments (ref. 12) it can be shown that water-pollution can result in reduced reproduction rates of zooplankton. However, in general this will occur only very locally, resulting in local environmental problems. These effects are beyond the scale of the general North Sea REFEREE-instrumentum. An exception is made for PCB's. PCB concentrations in coastal water (0.1 $\mu g.l^{-1}$; ref. 13) reduce the zooplankton reproduction by 25% (ref. 14). Extrapolated to a coastal area of 1.7% of the North Sea, it is assumed that the zooplankton production in 1980's is 0.995 of that in 1930's.
Discharges of production-water only have local impact (ref. 7).

Although all three classes of contamination pose a potential risk to fishes, effects on fish are ingnored due to lack of ecotoxicological information. Moreover it can be argued that mortality due to fisheries will outshine an increased mortality risk by contamination, whereas reproduction problems due to pollution will not easily result in reduced recruitments, as only a very small fraction of larvae become juvenile fish due to (density dependent) predation.

The ecological risks from contamination have been calculated for all three classes together. The reliability is limited due to the rough estimations of the magnitude of sediment and water-pollution impacts. The results are shown in fig. 11.

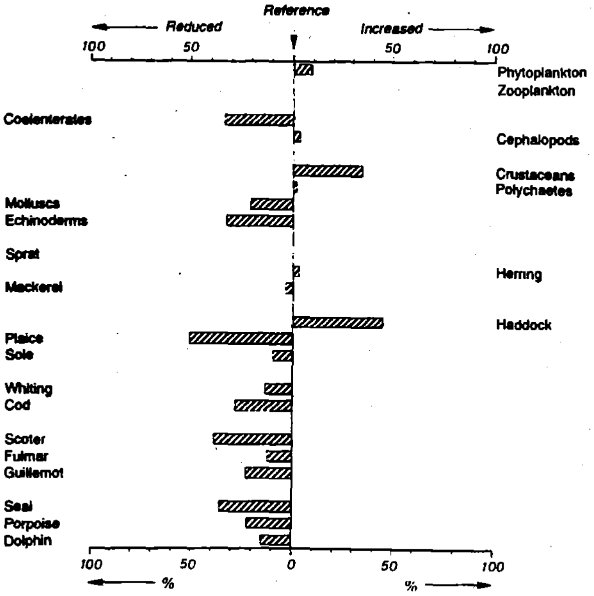


Figure 11 Risk for indicator-organisms to reduce or increase due to increased contamination between the 1930's and the 1980's.

5 AMOEBA

Several effects on the marine ecosystem due to human activities have been discovered in the past years. These effects are generally effects on specific species, varying from increased algal blooms to decreased populations of the common seal. Up till now, however, there is no complete picture of the ecological functioning of the North Sea.

This makes it difficult to decide within water-quality management on the issue of what is acceptable and what is not, especially regarding the preservation of ecological values. As an answer to this problem and in order to make abstract ecological objectives more quantitative and verifiable, the AMOEBA-approach was developed (ref. 4).

There are many species of plants and animals in the sea. Only for a limited part of these organisms a substantial amount of knowledge on their behaviour and functioning is available. Over thirty of these species, which form a reasonable cross-section of the whole system, have been selected.

For each species a so called ecoprofile has been made (see fig. 9), which on basis of our present knowledge describes the functioning and food-relationships of that species (ecoprofiles also have been used for the model REFEREE). The numbers in which these species occur give a picture of the ecological condition and an indication of the health of the North Sea.

It has been ascertained what these figures were in the 1930's, when the pollution was not so serious and the use was less intensive. This unaffected - or almost unaffected - situation is used as reference. This is a pragmatic compromise between available knowledge on the one hand and a situation in which man had relatively little influence on the other.

By comparing the present with the earlier figures it can be seen how the 'health' of the sea has developed. The present affected situation and the reference situation are visualized in the AMOEBA-figure (fig. 12).

In the AMOEBA-figure for each species the circle represents the reference numbers, e.g. 9000 seals, or 16000 hectares of sea-grass. The current numbers are superimposed on this, e.g. 450 seals and 3000 hectares of sea-grass. The points are joined together by a line which has an amoeba-like shape. The line does not indicate a direct relationship between the species.

This overview clearly shows how unintentionally drastic human use of the North Sea has been for the state of ecology in the last sixty years. In summary, there is a shift from long-living to short-living species. The water-system is incomplete and unbalanced in composition.

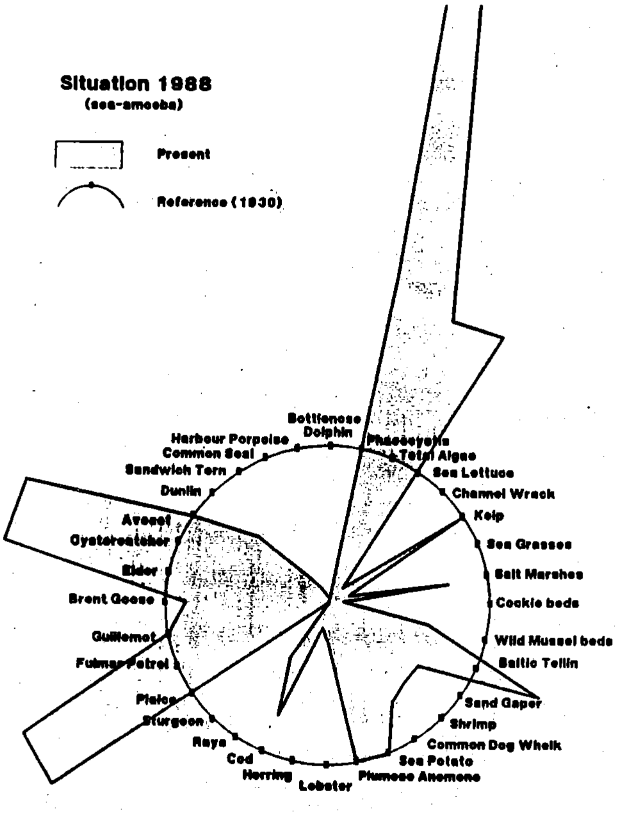


Figure 12AMOEBA (from ref. 4).

It is also possible to visualize the effect of activities as such and of regulations on the ecological functioning of the North Sea or parts of it, like the coastal area and the Wadden Sea.

Results of the illustration of REFEREE mentioned above can be expressed as an AMOEBA (fig. 13). At this moment, the 34 (groups of) organisms used in REFEREE are not the same as the organisms used in the AMOEBA as shown in fig. 12. The principle however is the same.

In this way the use of the AMOEBA-technique for the presentation of the results of the model-framework, can help to give a quick view of the effect of the dumping of dredged materials on the North Sea ecosystem.

6 DISCUSSION

A framework of models has been presented which can be used to assess the effects of dumping of

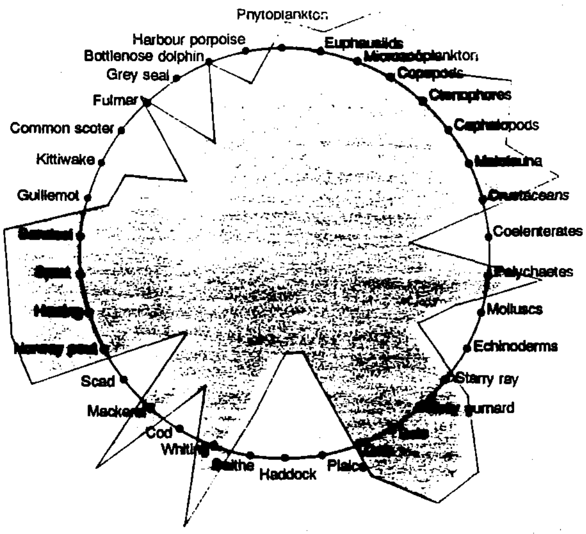


Figure 13 An AMOEBA as calculated with REFEREE.

dredged materials at sea.
The models have been chosen from three recent research-activities which are still in progress.

The selection of MANS-models as used in the framework in this paper are partly in the developing stage, others are more or less operational. The illustration is given for cadmium for 1985. It can also be produced for other substances and for different options of dumping of dredged materials. Further calibration of the models is necessary. The models are linked together into a MANS model-framework to be used for integral policy analysis purposes.

The REFEREE-instrument is still under development, and the results presented in this paper should be seen as a demonstration. Model formulation, calibration and definition of the impact of contamination have to be further improved. At this moment toxicological data of PCB's, cadmium and oil are present in the model.
It will be necessary to specify the model for various regions, because of regional differences in ecosystem-structure and perturbation-intensities. The present version, REFOOD 1.0, is calibrated on a general North Sea situation. This basic version can be specified for given regions (e.g. coastal areas or coastal seas).
It is interesting to mention that not only effects of pollution can be calculated and compared at this level, but also effects of non-chemical types of disturbances as e.g. the withdrawl of organisms by fisheries or mechanical disturbances caused by sand and gravel excavation.

AMOEBA can be used as an illustration, to visualize effects of one or more perturbating factors, or as a target in water-management policy. In both cases the involved organisms can be different. Of course, each regional AMOEBA has its own organisms. The general AMOEBA (fig. 12) contains organisms of all trophic levels and should be representative for the ecosystem of the Dutch coastal zone. The AMOEBA calculated with REFEREE contains organisms representative for the whole North Sea area. As concerned the aspect of the trophic levels, AMOEBA will be further evaluated and developed.

The framework of models as presented here, has been used for assessing effects of oil-pollution in the offshore industry. The effects of the dumping of dredged materials in sea are now being assessed using the framework of models. The integration of the computer-models themselves however is still subject for ongoing studies. The same counts for the comparison of the effects of the main user-functions on the North Sea, a study called Integral Risk Analysis.

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ECOLOGICAL IMPACT OF DREDGED MATERIAL DISPOSAL IN BELGIAN COASTAL WATERS

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ABSTRACT

Important dredging works are executed under the responsibility of the Coastal Service to maintain depth in the Belgian coastal harbours and the shipping channels to these harbours and the Westerscheldt (Antwerp).

Approximately 25 million m³ is now dredged annually from these area's; the dredged spoil is disposed off on different sites in Belgian Territorial Waters.

Additional capital dredging is planned to deepen the access channels to Ostend, Zeebrugge and the Westerscheldt.

In the framework of the application of the Guidelines of the Oslo Commission for the disposal of dredged material at sea (the Oslo Commission was established to supervise the implementation of the Oslo Convention which is signed and ratified by Belgium), a comprehensive study was made on the ecological impact of the dredging activities of the Coastal Service. The study was jointly executed by the regional and national authorities.

This study was particularly important since the guidelines will be revised in 1991.

The study gives a complete review of the dredging activities : dredging sites, dredging techniques, disposal sites and an evaluation of the possible ecological impact. During this study a large number of samples were taken from the dredging sites and from other locations on the Belgian Continental Shelf for chemical analysis.

The present paper gives the results of this study and the Belgian position on the revision of the Oslo Commission Guidelines.

INTRODUCTION

The juridical and administrative framework of the dredging works

When dumping dredged spoil in the North Sea, special attention must be drawn to the possible environmental effects. The Oslo Convention, signed in 1972 and ratified by Belgium in 1978, is the international framework in which the environmental aspects have to be addressed.

The specific Guidelines of the Oslo Commission concerning the dumping of dredged spoil must be applied by Belgium and further elaborated for the Belgian situation.

The situation in other Contracting Parties of the Oslo Convention

It is apparent that most Contracting Parties have difficulties in applying the abovementionned Guidelines.

The problems are mainly situated on the following topics :
- the lack of comparable data on background concentrations in the North Sea;
- the lack of information on possible input of pollutants in marine waters by dredging operations;
- the difficulty to define uniform and precise standards due to the great diversity of geological and geographical boundary conditions.

This situation was confirmed several times during different sessions of the important international symposium on "Environmental aspects of dredging activities", which took place in Nantes, France in 1989.

In these circumstances the majority of all Contracting Parties is in favor of an effect oriented approach.

The Third North Sea Conference

During the third International Ministers Conference on the protection of the North Sea (The Hague, 1990), the problem of dredging activities was also discussed in depth.

In the final declaration of the Conference, the Oslo Commission was instructed to complete, in 1991, the revision of their Guidelines for dredged material disposal, and to take into account the most recent scientific information. In this context the Oslo Commission was also asked to examine further-going measures to control the imput of pollutants resulting from the dumping of dredged spoil contaminated by human activity. The Commission was also asked to consider the establishment of an environmental evaluation procedure, which must take into account alternative dumping on land, regionally defined environmental quality criteria and dispersion characteristics.

The aim of the study reported in this paper was precisely to gather information for the revision of the Guidelines and thus to be able to elaborate them in accordance with the Belgian situation.

DREDGING ACTIVITIES

Dredging sites

Under the responsibility of the Coastal Service, dredging is executed in the four Belgian Coastal harbours and the access channels to these harbours and to the Westerscheldt-river.

The following table gives a global view of the quantities dredged between 1975 and 1989.

work year (from 01/04 .. to 31/01 ..)	coastal harbours (Nieuwpoort-Oostende Blankenberge-Zeebrugge) (m^3)	access channels to the coastal harbours and to the Westerscheldt (m^3)
1975 - 1976	4.600.000	19.800.000
1976 - 1977	5.100.000	21.900.000
1977 - 1978	5.000.000	20.800.000
1978 - 1979	5.900.000	21.400.000
1979 - 1980	4.700.000	25.800.000
1980 - 1981	5.100.000	38.400.000
1981 - 1982	4.800.000	47.700.000
1982 - 1983	5.100.000	42.700.000
1983 - 1984	5.300.000	30.000.000
1984 - 1985	7.500.000	18.000.000
1985 - 1986	7.800.000	20.500.000
1986 - 1987	4.800.000	52.200.000
1987 - 1988	6.900.000	26.100.000
1988 - 1989	5.800.000	19.200.000

In the table no distinction is made between maintenance dredging and capital dredging.
It can however be stated that in the harbours of Nieuwpoort, Blankenberge and Oostende only maintenance dredging was executed in that period and that the higher quantities listed in the table (especially in the third column) must be attributed to the extension of the harbour of Zeebrugge and the deepening of the shipping channels.
It appears that in the last decade, the total amount of dredged sediment has diminished from about 50 million m^3 annually in the period 1980-1985 (extension of the harbour ofZeebrugge) to 35 million m^3 annually in 1985-1988 (deepening of the shipping channels); it is now of the order of 25 million m^3 annually (maintenance of the realised depths).
Most of the dredging work is actually situated in and around Zeebrugge and in the maritime access channels to the Scheldt Estuary (22 million m^3 annually). Only about 3 million m^3 is annually being dredged from the smaller ports of Oostende, Nieuwpoort and Blankenberge.

The amounts dredged from the smaller harbours (including the access channels) remain relatively constant, but decrease for Zeebrugge harbour; one of the reasons for this is the application of the results of an extensive study to optimize dredging activities which was executed by the Coastal Service.

Disposal sites in the Belgian coastal waters

The dredged spoil is disposed off on the dumping grounds shown in fig. 1.
A part of the dredged sand however is also used for beach and forshore restoration.
These dumping sites were in the past selected on the basis of the following criteria :
- economical sailing distance for the type of dredger used in that area ;
- sufficient distance from the dredging site to limit recirculation of dumping losses to a minimum.

For the small harbours, the disposal sites were not changed in the last decade, and they receive annually an amount of dredged spoil which remains more or less the same.
For Zeebrugge harbour and the access channels however, the situation has much changed since 1980 :
- up to 1984, 90 % of the spoil dredged from those areas, went to the dumping site S1;
- from 1984 till 1986 the amount of spoil which went to this site diminished to around 60 % because other dumping grounds (S2, R4 and Zeebrugge Oost) were also being used;
- from 1986 onwards, a more intensive use of the latter allowed a further reduction in the amount allocated to S1 to ca. 47 %.

Expectations for the future

A distinction must again be made between maintenance dredging and capital dreding; furthermore, the quantities mentioned hereafter are only given as an indication.
In the near future the expected amounts are estimated as follows :
- Nieuwpoort and its access channel : in the harbour a yearly amount of maintenance dredging, varying between 440.000 m^3 and 650.000 m^3 (in situ) depending on whether or not the dock and the yacht harbour are dredged; in the access channel maintenance dredging of approximately 65.000 m^3 to 80.000 m^3 (in the hopper) annually;
- Oostende and its access channel : maintenance dredging of about 1.950.000 m^3 (in the hopper) annually; in the framework of a renovation plan for Oostende harbour capital dredging of about 2.800.000 m^3 (in situ) is being considered;
- Blankenberge : maintenance dredging between

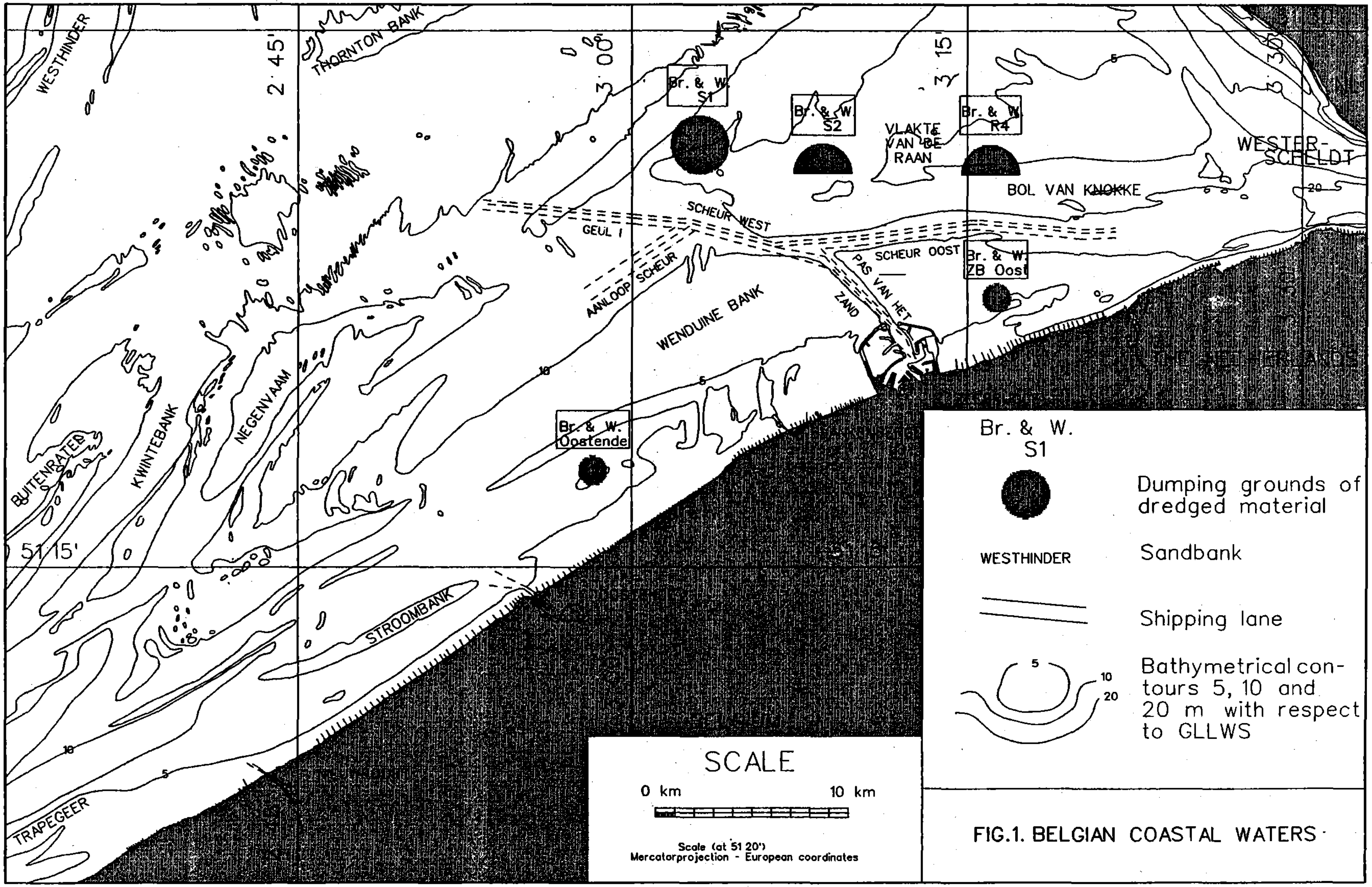


FIG.1. BELGIAN COASTAL WATERS

65.000 m^3 and 110.000 m^3 (in situ) annually, depending on whether or not the yachting harbours were dredged;

- The navigational channels to the Westerscheldt and to Zeebrugge (and Zeebrugge harbour itself) : as a result of the forementioned optimization study the total annual amount of maintenance dredging has diminished since 1986 : it is expected that this amount will stabilize at approximately 21 million m^3 (density 1,6 t/m^3); in the future, capital dredging is foreseen in the navigational channels and Zeebrugge harbour whereby an amount of about 44.450.000 m^3 (density 1,6 t/m^3) would have to be dredged.

DREDGING AND DUMPING TECHNIQUES

Description of the dredging vessels used in the Belgian coastal area.

At this moment, four types of dredgers are in use, giving a different turbidity on the dredging site :

- trailing hopper suction dredgers : dependent on the suction heads used and the overflow;
- stationary hopper suction dredgers : dependent on the overflow and the use of waterjets on the suction pipe;
- bucket dredgers : dependent on the losses during pick-up and the transport of the buckets;
- cutter dredgers : dependent on the type of cutterhead.

Research to reduce turbidity

The sources of turbidity are different depending on the type of dredger. In the past research has already led to important improvements concerning the dredging operations executed under supervision of theC oastal Service. During this research emphasis was put on optimizing the dredging process and also the monitoring of dredging activities, increasing the density of the spoil, the utilisation of very precise positioning systems, and increasing the primary production of every dredging unit.
Furthermore, pump regulation systems and anti-turbidity-overflow-shafts were installed.
Other improvements, which also demand important investment, are under consideration.
It is clear that all improvements which were introduced to diminish turbidity, are also beneficial to the environment.

Selection criteria of the dredging vessels

The choice of a particular type of dredger depends on the site, the hydrodynamic and meteorological circumstances, and the nature of the sediment to be dredged. There are, however, no absolute selection criteria. The evaluation is made on the basis of economic, technical and environmental criteria.
The trends for the future are :

- working with "big" trailing suction dredgers (type 10.000 m^3) in the major shipping channels;
- the use of trailing suction dredgers of the 2.000 m^3 type in the minor shipping channels and the inner harbour of Zeebrugge;
- the use of medium sized trailing suction dredgers (5.000 m^3) in the outer harbour of Zeebrugge, which are best suited for this;
- in the smaller coastal harbours, work is continued with bucket dregers and cutter dredgers.

SEDIMENTOLOGY

Regional hydrodynamic conditions and sedimentology

The Belgian continental shelf is characterized by fairly strong tidal currents, the prevailing south-westerly and westerly winds, short bottom-stirring waves and a small waterdepth (0 to 15 meters).
The bottom composition varies from fine to medium sized sand off-shore, to muddy sediments in the coastal zone.
The morphology of the area is characterized by the delta of the Westerscheldt-estuary, sand and mud flats, tidal gullies and sandbanks.
The area is further characterized by the presence of a marine turbidity maximum that also explains the presence of mud fields along the Beligan coast. One notes not only fairly high sediment transports, but also a limited exchange of sediment with the rest of the North Sea and the Scheldt Estuary. The present dredging and dumping activities are causing displacement of sediment which is important compared to natural processes.

Sedimentology on the dredging sites and disposal sites

The bottom sediments on the site of the dumping grounds consists mostly of fine to medium sized sand. The fairly high proportion of sandy sediments is remarkable, notwithstanding the fact that at most of these dumping grounds, spoil is dumped with a fairly high mud content.
The morphology of the dumping grounds is regularly surveyed hydrographically; the morphological evolution of the bottom of the dumping grounds is monitored by drawing up charts, showing the variation in depth, and cross-profiles. The dumping grounds show bottom-changes which are especially important at the S1 disposal site and which have to be linked to the dumping of spoil.

Physico-chemical characteristics of the sediments in the dredging area's

§ Sampling procedure

In order to evaluate the quality of the dredged sediments along the Belgian coast, 77

samples of bottom sediment from the dredging zones, and 3 samples of dredged spoil from the hopper of a trailing suction dredger were taken.
Furthermore for comparative reasons, 10 bottom samples were also taken from the Belgian Continental Shelf outside the shipping channels, together with 3 special reference samples : namely, two samples of undisturbed tertiary clay and one historical mud sample, sampled in 1905 and belonging to the collections of the Belgian Royal Institute for Natural Sciences.
The size of the area, the amount dredged and the expected variability in horizontal distribution of contaminants were taken into account to determine the number of samples and their location, in order to have results which are representative for a well-defined area.
The chapters of the Guidelines of the Oslo Commission concerning the chemical characterization of dredged material were also strictly adhered to.

§ Methodology

The samples were examined on their general fysico-chemical characteristics and their organic and inorganic contaminant content.
Therefore, use was made (amongst others) of the list of components that ask for priority attention in the framework of the Oslo Convention (Annex I, "black list" and Annex II, "grey list") and the Guidelines.
As much as possible analysis procedures were used in agreement with the prescriptions for the analysis of sediments in the context of the joint monitoring program of the Oslo and Paris Convention (Joint Monitoring Program - JMP).

§ Results and discussion

* All samples from the dredging sites have strong negative redox-potentials.
* The samples taken from the harbours differ from those of the marine shipping channels off-shore, by :
  - a higher content of fines;
  - twice the content of organic matter;
  - 50 % more inorganic nitrogen (nutrients).

The samples taken on the Belgian Continental Shelf are almost pure sand. Notwithstanding the fact that the highest content of fecal coliforms were found in the harbour samples, these contents are of the same order of magnitude of those found in the marine shipping channels. Between the harbours, no significant differences were found for these parameters.

* The content of heavy metals is higher in the harbour samples than in the marine shipping channels; the samples from the Belgian Continental Shelf have "low" to "very low" contents. The concentrations in the reference samples are mostly of the same order of magnitude as those in the bottom samples of the marine shipping channels. This is understandable, since heavy metals are bound to the finer fraction (mud).
* By normalisation to aluminium, an estimate can be made of the enrichment in the harbours compared to the shipping channels. Mercury is on an average 70 % enriched, cadmium 30 %. These two metals were not found in the samples taken from the Belgian Continental Shelf. In the reference samples, the content of cadmium is approximately half of that in the samples from the marine shipping channels. Mercury however is present in the tertiary clay in approximately the same concentration as in the samples from the shipping channels.
As an example of a list II-substance : for lead, the guidelines define "significant quantities" as 0,05 % (or 500 ppm). On average, the lead-content found in the dredged spoil is 10 to 100 times lower.
* Five groups of organic compounds were analyzed : tributyltin, polyaromatic hydrocarbons, polychlorinated bifenyls, organochlorine pesticides and purgeable organic compounds.
Organochlorine pesticides were found in a limited number of samples, and only in small concentrations.
On the other hand, important differences were found between the different harbours for the other organic compounds; even within one particular harbour, big differences were noticed. For this reason geometric mean values were calculated for tributyltin and polyaromatic hydrocarbons, to give a more realistic picture of the situation :

- Tributyltin (TBT) : is, with the exception of one sample, only found in the harbours, and then mainly in the yachting and fishing harbours. Geometric mean values of 8 to 35 ppb were found. Since tributyltin is very toxic for the marine ecosystem (mainly for shellfish) there is a real risc of accute effects on biota.
- Polyaromatic hydrocarbons (PAH's) : are found in all samples, also in those from the Belgian Continental Shelf. The geometric mean concentration in the four coastal harbours is 2 to 9 times higher than in the shipping channels off-shore. The highest concentration was measured in a sample taken close to the "old" sea-lock at Zeebrugge (approximately 460.000 ppb); also in the immediate neighbourhood, including the fishing harbour, important increases were measured : i.e. approximately 30.000 ppb, compared to ca. 2.000 ppb for the rest of the harbour of Zeebrugge.
  In the other 3 harbours, geometric mean values of 750 to 1400 ppb were found, which is 2 to 4 times higher than in the shipping channels.
  Polyaromatic hydrocarbons correlate with the organic fraction, and were therefore also "normalized" to the content of organic matter. These normalized values indicate an enrichment of 50 % in those three harbours. Further research is necessary here.
- Polychlorineated bifenyls (PCB's) : PCB's are lipophilic as PAH's and can be correlated with the organic fraction.

Normalized to organic carbon no enrichment in the harbours compared to the marine environment could be noticed (not normalized : on average 5 to 25 ppb).

- Purgeable organic compounds : the mean contents of those substances vary widely from one harbour to the other (from 20 to 9000 ppb), and sometimes in one particular harbour big differences occur. The mean value in the shipping channels is approximately 75 ppb. At the same location where unusual high polyaromatic hydrocarbons were found (in the harbour of Zeebrugge), very high concentrations of purgeable organic substances were also found.
  Both groups probably originated from the same source(s); a comprehensive investigation on polyaromatic hydrocarbons distribution at this location will be linked to a further investigation concerning purgeable substances.

* On the basis of the results of the analysis of the samples taken in the hopper, it can be concluded that during the dredging process, part of the fine fraction is washed out. Together with this fraction, a part of the organic material also disappears.
In consequence of this, the spoil in the hopper is less charged with contaminants.
A more comprehensive research is necessary to make an accurate evaluation of this "wash-out".

ECOLOGY

Description of the eco-system of the Belgian Continental Shelf

The eco-system, in a well-defined geographical area, is constituted of the biotic factors (or the total of organisms living together) in their abiotic environment.
The cycle of matter (e.g. C and N) lies on the basis of the functioning of the complex eco-system.
For the plankton biomass and production (phytoplankton as well as zooplankton) decreasing gradients are mainly observed from the coast to the open sea, and parallel with the coast, also decreasing gradients, from east to west. This tendency is directly connected with the increased concentrations of nutrients close to the coast by the input from rivers and canals, and at the east coast by the input from the Scheldt river.
For the benthos populations (meiobenthos, macrobenthos and epibenthos) and for the demersal fish populations (in other words, the secondary species), one can state in general that the biomass gradient are decreasing from the coast to the open sea, in the same way as for the plankton. Parallel with the coast however, they are decreasing from west to east in contrast with the plankton gradients.
In general terms, a coastal zone and an "open" marine area can be identified, separated by a transition zone, whereby in the coastal and the transition zone a further distinction can be made between the eastern and the western part :

1. Coastal zone (5 à 10 km wide) :
   * W-coastal zones populated by "typical coastal populations" characterized by :
     - mean abundancies;
     - small diversity;
     - dominant species (shrimp, breading area for juvenile fish).
   * E-coastal zone : "poor contaminated area" where only some species survive which can be sporadically present in high abundancies.

2. Transition zone (up to 30 km out of the coastline) :
   * W-transition zone (= area of the "Flemish Banks") : is a "mean area" characterized by :
     - mean abundancies;
     - mean diversity;
     - sometimes dominant species (often seasonal dominancies).
   * E-transition zone, "liveable polluted area", corresponds to the mud field before the Belgian coast, and characterized by :
     - high abundancies;
     - small diversity;
     - dominant species.

3. Open marine area (30 km out of the coastline and more) : can be catalogued as "diversified zone", characteristic for a non polluted, untouched environment :
   - low abundances;
   - great diversity;
   - absence of dominant species.

ENVIRONMENTAL EFFECTS OF DREDGED MATERIAL DISPOSAL

The disposal of dredged material in the North Sea has physical, chemical and biological environmental effects. In general, the effects can be summarized as follows.

Physical environmental effects

Physical environmental effects of "dumping" dredged spoil consist of :
- dispersal of mainly the fine grained spoil;
- increase of turbidity;
- covering of the bottom with new sediment at the site of the dumping grounds;
- change of the bottom composition.

During each dumping operation a mechanism of separation occurs whereby the lesser mobile sand fraction remains on the dumping ground. The fine grained mud is washed out and can be dispersed over a much wider area. Experiments on the dumping ground S1 have shown that mud forms the major part of these dumping losses, and that these losses are finally assimilated in the loosely packed mud deposits close to the coast.

Immediately after each dumping operation, the dumped spoil forms a vertical density current directed towards the bottom.

The increase of suspension load in the upper parts of the water column (due to the dumping operation) is significant, but brief : this increase disappears by the turn of the next tide. The bottom covering depends strongly on the type of spoil and the dumping ground. In most cases a small rise of the bottom of the dumping ground, due to the dumping operations, is observed; however, at the dumping ground S1 this bottom rise is much more important. These bottom rises are caused by the accumulated sand fraction of the dumped spoil.

In the area under consideration, significant changes in bottom composition can occur naturally in relatively short periods. However, this concerns here only a redistribution of the stock of sediment under the influence of hydrodynamic circumstances, and in accord with the most recent morphological evolutions (e.g., the extension of the harbour of Zeebrugge). One can thus state that over a longer period, the global bottom composition, in the coastal zone has remained more or less constant.

As a result of the dredging works, and more specifically, of the dispersal and overflow losses, the total amount of loosely packed mud deposits, spread-out over the sea bottom, can be influenced. This last physical effect results in the long term, in an enrichment of the coastal area with loosely packed fine grained mud spoil. The importance and the location of these loosely packed mud deposits is a function of the dynamic equilibrium which, amongst others, is determined by seasonal phenomena.

With the help of tracer experiments it is possible to evaluate the dispersion of the fine grained dumping losses which leads to an optimization in the use of the dumping grounds, limiting the effect of dispersion as much as possible.

Chemical environmental effects

The chemical effects of dredging operations occur when contaminants are mobilized out of the dredged spoil into the environment. Distinction has to be made between the pollutant behaviour in suspension and the behaviour in the sediment.

Contaminants in the water column interact with the available particulate matter (organic and inorganic) and are also distributed between the suspended matter and the sediment by sorption processes. Pollutants are however not fixed in the sediment in a permanent way, but can be recycled eg. by desorption processes induced by chemical and biological agents. In a suspension system, an equilibrium is established between the pollutant concentration in the water phase and in the particulate phase. For each modification in the physico-chemical environment, an new equilibrium is installed.

Pollutants can be mobilized by desorption by changes in the salinity, the redox potential, the pH or the situation of the organic matter. Also in the upper layer of the deposited sediment, similar mobilization processes can occur whereby pollutants are divided through sorption and desorption between the upper layer of the sediment and the water column.

Apart from the potential mobilization of pollutants present in the sediment, one can consider the balance of the pollutant transfer resulting annually from the dredging operations.

It is therefore necessary to know the amounts of material dumped and the concentrations of pollutants. With such a "load" calculation the importance of the dredging operations can be compared to the natural geochemical background and to other pollutant fluxes (eg. the input from the Scheldt Estuary) in the same area.

Biological environmental effects

The physical as well as the chemical effects of dredged material disposal have their influence on one or another biological compartment of the system, for example by interfering with the primary production, by disturbing the organisms or through ecotoxicological effects.

An increase in turbidity, causing a decrease of light penetration in the water column, can have negative effects on the primary production. However, also nutrients can be released, whereby primary production could be increased with eventual eutrophication effects as a result.

Increased turbidity, bottom covering and modification of the bottom composition can disturb marine life in one way or another. The excess of mud and the high concentrations of suspended matter cause clogging of the gills, high mortality of fish larvae and benthic invertebrates.

After sedimentation of dumped spoil, the sedentary invertebrates are buried under a sediment layer at the disposal site. The mobile species are forced to migrate, while the immobile species will die.

Beside the effect on the benthic fauna, bottom covering can render the area unsuitable as spawning and nursary grounds. Frequent disposal operations can lead to a permanent alteration of the bottom composition. Since most of the organisms are closely linked to the type of sediment substrate wherein they live, any modification in the bottom composition will have its direct effects on the living communities concerned. The chemical effects of the dredging activities, and more particularly the impact of the mobilization of contaminants out of the spoil into the environment by the displacement of material, have biological effects on the level of the ecotoxicology and the pathology.

POSSIBLE CRITERIA FOR EVALUATION AND CLASSIFICATION OF DREDGED SPOIL

General

To determine wether or not spoil has a detrimental effect on the environment when dumped into the sea, a range of assessment methods can be used, from chemical "total" analysis to bioassays on a real scale in the field. Both of these extreme approaches have substantial disadvantages.

Chemical criteria

Classification systems which are exclusively based on the relatively cheap determination of the chemical pollution content of the spoil, are necessarily artificial, since it is impossible to determine the real effects from it. They can form one of the elements which can be used indicatively for the evaluation.

Biological criteria

Preliminary biological tests in the field are not to be recommended either because of their long duration and of the extreme costs. Uniform and internationally recognized tests on laboratory scale have to be determined as quickly as possible and used for the evaluation of the possible influence on the marine organisms.

Mixed criteria

It is not evident that a compromise, situated between those two extremes, will show any relevance as long as the relationship between chemical analysis and biological effect is not clearly established.
For this complex problem, there is (with the actual state of affairs) only an adequate way of approach, namely the pragmatic, effect-oriented one. Such a solution could consist of :

- basing the evaluation of the spoil on chemical lixiviation tests instead of on total analyses, and thus approximate the biological availability;
- the execution of bio-essays of limited scope, whereby a number of reference organisms are exposed to concentrations of pollutants as formed in the lixiviating tests, however augmented by a safety factor;
- in addition to the results of laboratory tests, also take into account the results of biological monitoring of the former and the actual disposal sites and compare them to those of a carefully chosen reference area.

BELGIAN APPROACH CONCERNING ECOLOGICAL EFFECTS OF DREDGED SPOIL DISPOSAL IN THE SOUTHERN BIGHT OF THE NORTH SEA

Interim impact evaluation

The actual state of the research, allows only to assess in a provisional way the possible environmental impact of dumping dredged spoil off the Belgian Coast.
On the basis of findings, formulated in the chapter about the possible environmental effects, it can be presumed that the influence will be felt mainly in the following area's :

* PHYSICAL :
- on the dumping ground, by bottom covering by the sand fraction;
- on wider areas, permanent change in the bottom composition by dispersion of the fine mud fraction;
- an increase in turbidity of the water column, which occurs only in the case of dumpings executed in short intervals.

* CHEMICAL :
- through the mobilisation of pollutants out of the spoil, when the dredging operation brings the spoil in an environment with different physico-chemical conditions (oxygen, salinity, ...);
- by a global pollutant transfer when the displaced spoil is considered as the carrier of a certain "pollution load".

* BIOLOGICAL :
- direct impact on the bottom life, especially on the sedentary benthic fauna and on the breeding- and spawning sites;
- an eco-toxicological impact which is at present difficult to evaluate.

  On the basis of the existing Guidelines of the Oslo Commission, it was however decided that only the spoil from the area's in Zeebrugge harbour which was heavily contaminated by tributyltin and polyaromatic hydrocarbons could no longer be disposed off in the North Sea.

Future Research and Monitoring Strategy

It appears from the interim impact evaluation that big gaps still exist in the knowledge about the possible physical, chemical and biological environmental effects resulting from the dumping of dredged material.
A more intensive research in these area's will therefore be necessary. Parallel with this research program, a monitoring program will be established in which amongst others the results of the research shall be assessed.

Future research

* PHYSICAL
- further optimization of the dredging techniques (density in hopper, overflow system control, dumping systems, etc.) : some technical aspects of this topic are discussed more in detail further on;

- physical research for the selection of dumping grounds with minimal dispersion and maximal primary dumping efficiency. It is expected that existing mathematical models can be adapted to study the sediment movements on the Belgian Continental Shelf. Tracer tests (which are planned by the Coastal Service in the near future) must be used for calibrating these models.

* CHEMICAL
- research to determine the most important mechanisms of pollutant dynamics with a view to evaluate the quality of dredged spoil on the basis of lixiviation tests (still to be nearer defined) instead of on the basis of total analyses;
- further investigation on the dredging sites with high concentration of pollutants, whereby attention must be paid to the horizontal and vertical distribution of these pollutants with a view to identify the sources and to enable an assessment of possible prevention measures (e.g. TBT);
- research into solutions to separate the relatively small amounts of problematic dredged spoil from the rest of the spoil and to dispose of it in an alternative way;
- the possible release of pollutants after deposition of dredged material should be compared to other fluxes in the marine environment, such as the input from the Scheldt river.

* BIOLOGICAL
- research with a view to determine criteria, taking the form of bio-assays on a small scale and of bioaccumulation tests in which a number of reference organisms are exposed to pollutant concentrations as established in the above mentioned lixiviation tests, with the application of a safety factor;
- comprehensive biological survey of dumping sites, newly selected on the basis of physical investigation : study of the infauna, determination of the sediment type and of the physicochemical living conditions.

Monitoring program

A monitoring program for dredged spoil dumping sites, can be focused on the characteristics of the sea bottom, and should aim at evaluating the physical as well as the chemical effects on the organisms at sea bottom level. It should include measurements of :

* PHYSICAL
  - location of the dumped spoil;
  - sea bottom topography and structure of the sediment;
  - turbidity.

* CHEMICAL
  - distribution of metals and other substances in the sediment;
  - pollutant mobilization;
  - chemical quality for marine life and for feeding.

* BIOLOGICAL
  - recording of the benthos, fish populations and larvae (before and during dredging activities and possible recolonization after stopping a particular dumping activity;
  - physiological effects on biota;
  - bioaccumulation of pollutants from the sediments in the marine organisms.

Possibilities to reduce the impact of the dumping of dredged spoil

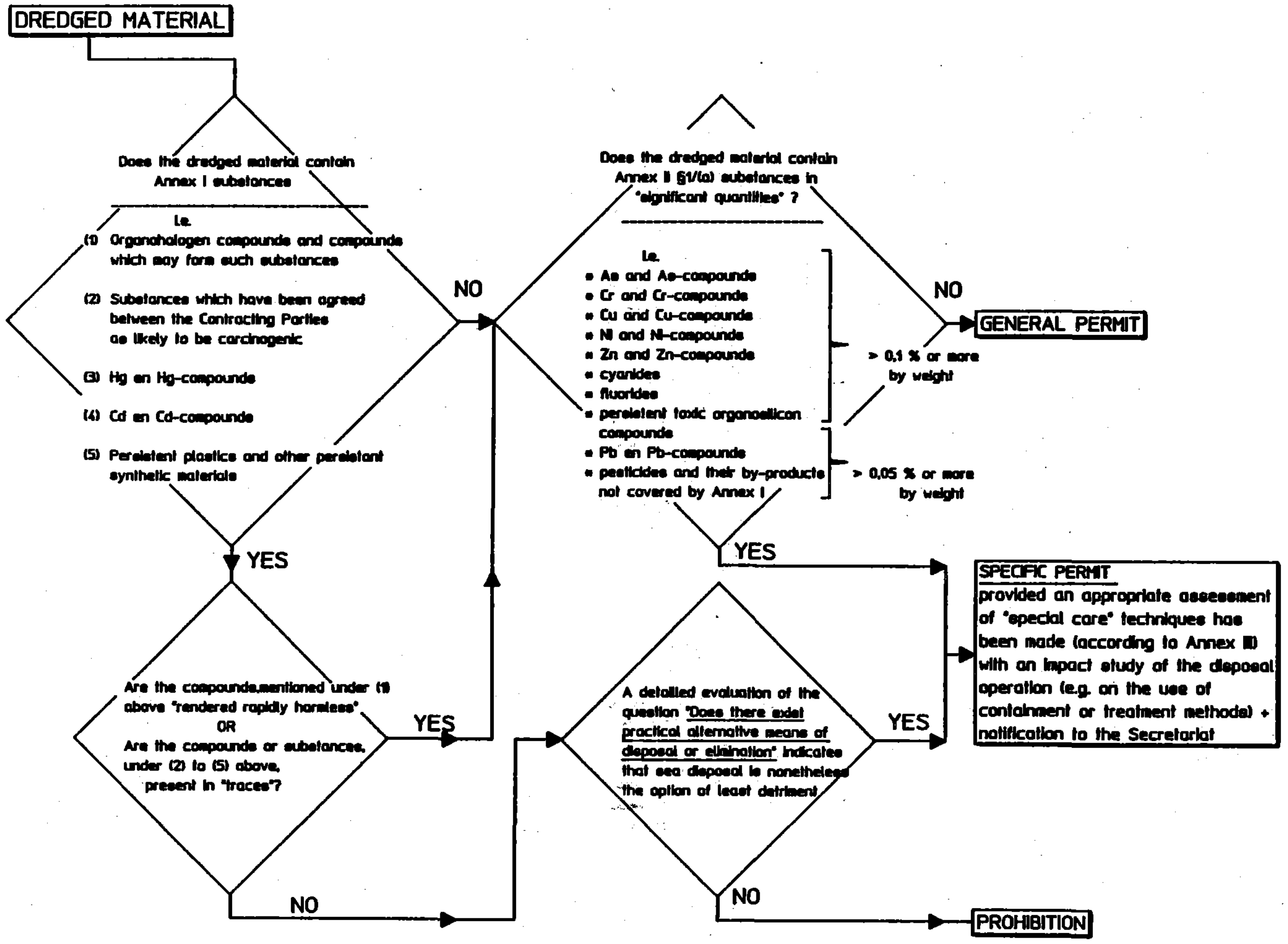
* possibilities linked to the technical aspects of dredging :
  - keeping the volumes to be dredged to a strict minimum;
  - taking measures to increase the efficiency of the dredging cycle, and more particularly to increase the concentrations of the spoil in the hopper : this will diminish the overflow and the turbidity and will increase the efficiency of the disposal site through a smaller dispersion of fine dredged spoil;
  - taking measures to improve the dumping techniques, e.g. by dumping mud through a pipe to the sea-bottom to diminish turbidity and dispersion, by using mud screens, diffusers etc. .....;
  - selective dredging, i.e. : dredging the sites with heavily contaminated sediments separately from the other sites, so that the contaminated spoil can be reserved for eventual further treatment;

* alternative possibilities linked to the use of the disposal sites :
  - choosing dumping sites where dispersions or the effects of dispersion are minimal; here, one can also consider to arrange the dumping sites in a special way, e.g. with underwater dams;
  - dumping problematic spoil in overdepths eventually combined with "capping" of the spoil with a protective layer;
  - treating the contaminated spoil in situ or in the hopper so that a less contaminated spoil can be dumped;
  - store the contaminated spoil on land.

* more in general, the possibility of "beneficial uses" should be examined, such as replenishment of beaches, or restoring of dunes.

BELGIAN EXPERIENCE AND VIEWPOINT CONCERNING THE APPLICATION OF THE GUIDELINES OF THE OSLO COMMISSION

The Belgian study, which closely followed the Guidelines, led to the following conclusions :
1. The chemical characterization of the spoil from the Belgian harbour and navigation channels has shown that the criteria for the interpretation of the "significant quantities" indicated in Annex II of the Guidelines (fig. 2) cannot create any problems; they are fairly "broad" and do not take into account the total pollutant transfer resulting from the amount



SCHEME FOR A CHEMICAL EVALUATION
OF DREDGED MATERIAL, BASED ON THE
OSLO COMMISSION GUIDELINES

FIGURE 2

of dredged spoil.

2. "Trace contaminants" and "rapidly converted into substances which are biologically harmless" arekeynotions for the interpretation of annex I-substances of the Guidelines. It can however be remarked that, according the Guidelines, thesenotionsdo not seem applicable in the following cases :

- in the case of dredged material consisting predominantly of sand, gravel or rock, found in area's of high currents or wave energy and in the absence of appreciable pollution sources (probably "appreciable point sources" are meant here, and not the mouth of estuaria);
- in the case of material to be dumped which is substantially similar in chemical and physical properties to the sediments at the proposed disposal site. The Guidelines should clarify these exceptions.

3. In addition to the necessity of better defining these exceptions, it is felt by the Belgian authorities that it would be useful to have criteria which can be used by policy making bodies to establish the conditions under which licences can be granted for dumping dredged material (permit, specific permet, prohibition).

4. In this context the Guidelines state that decisions should be made on the basis of a toxicological evaluation. A clear description of a commonly accepted, effective standard methodology is however not available. The methods as well as the criteria for a toxicological evaluation should be included in the Guidelines. It is however clear that time will be needed to fix these toxicological criteria in a scientifically acceptable way.

5. Belgium accepts that interim criteria must be applied, in which the chemical composition can be used indicatively. These criteria must take into account the background concentrations in the area's concerned, together with the biological availability of the chemical pollutants and the total pollutant transfer. When more accurate toxicological standards are available, the interim criteria must be replaced. It is also clear that these criteria can not be applicable for the whole region covered by the Oslo Convention; regional specifications will have to be considered.

6. Since it is desirable to limit the physical effects of the dumping of dredged spoil, the Guidelines should also contain indications about the possible physical criteria, which can consider the possibilities to optimize the dredging and dumping techniques and the use of alternatives to limit the dispersion of the spoil.

RECENT STEPS TAKEN BY THE BELGIAN AUTHORITIES WITH RESPECT TO THE APPLICATION OF THE OSLO CONVENTION GUIDELINES

The signing of an "Agreement of co-operation" between the national and the regional authorities.

The environmental policy concerning the North Sea and in particular concerning the application of the Oslo Convention, is a national competence. The execution of dredging works in the harbours and shipping channels is however a regional competence. On the 12th of June 1990 an "Agreement of co-operation" was therefore signed between the national and Flemish regional authorities to do everything possible, concerning the dumpings of dredged material at sea, to arrive at an efficient and far-reaching cooperation with the aim of protecting the Belgian Convention waters.

Dispositions taken concerning the dumping of dredged material in Belgian coastal waters

On the basis of the results of the study concerning the ecological impact of dredged spoil disposal in Belgian waters, and in accordance with the Guidelines of the Oslo Commission it was decided in common accord between the national and regional authorities that the dredged material from the area's in Zeebrugge harbour, which where found to be heavily contaminated by tributyltin and polyaromatic hydrocarbons, could no longer be disposed off directly in the North Sea. Therefore a project to purify these contaminated sediments by a micro-biological treatment in situ, has started up. In a first phase the proposed method will be tested in a small protected area of Zeebrugge harbour. The test was started in the summer of 1990; results are expected by the end of the same year. If the test proves to be successful, the microbiological trearment will be extended to the other heavily contaminated area's of Zeebrugge harbour.

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DISTRIBUTION OF HEAVY METALS AT A DISPOSAL SITE FOR CONTAMINATED ESTUARINE DREDGED MATERIAL

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ABSTRACT

The objective of the study was to monitor the concentration of metals in the bed sediments of the River Tees dredged channel and the associated disposal site and surrounding area, and to draw conclusions on whether or not the metals become dispersed after disposal in the coastal environment.

The River Tees is located in the North East of England on the North Sea coast. The estuary is of the partially mixed type, hence the estuarine sediments are likely to be a mix of fluviatile and marine origin. Dredging is carried out from 500m downstream of Newport bridge to the turning circle at the seaward end of the approach channel. The dredged material from maintenance dredging is disposed of at the inner disposal site and the dredged material from capital dredging is disposed of at the outer disposal site.

On recommendations from the earlier work, sampling on a grid of 10 by 10 at 1km intervals orientated north-east/south-west with an inner grid of 10 by 10 at 0.5 km intervals was carried out. Samples from this grid were split into four size fractions <20µm, 20-63µm, 63-90µm and >90µm. Heavy metal analysis for the six metals studied previously, cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), lead (Pb) and zinc (Zn), was conducted on all except the greater than 90µm fraction.

Two subsequent surveys of the disposal area were undertaken, together with a comprehensive set of river samples. The <90µm fraction was analysed for ten metals, the six investigated previously Co, Cu, Fe, Mn, Pb and Zn, plus cadmium (Cd), chromium (Cr), nickel (Ni), and mercury (Hg).

A sequential extraction analysis was also carried out on a number of samples on the final survey to determine the amount of metal associated with each chemical phase of the sediment.

INTRODUCTION

The annual quantity of dredged material released into the coastal waters of the UK is in the order of 50 million tonnes per year. This quantity of material has the potential for considerable effect on the environment. Firstly the sediment itself is likely to have an adverse effect on the coastal environment by burying turbidite dwelling organisms and by changing substantially the sediment regime of the area. The pollutants associated with the sediment, in particular heavy metals, could also have considerable effect on the coastal environment.

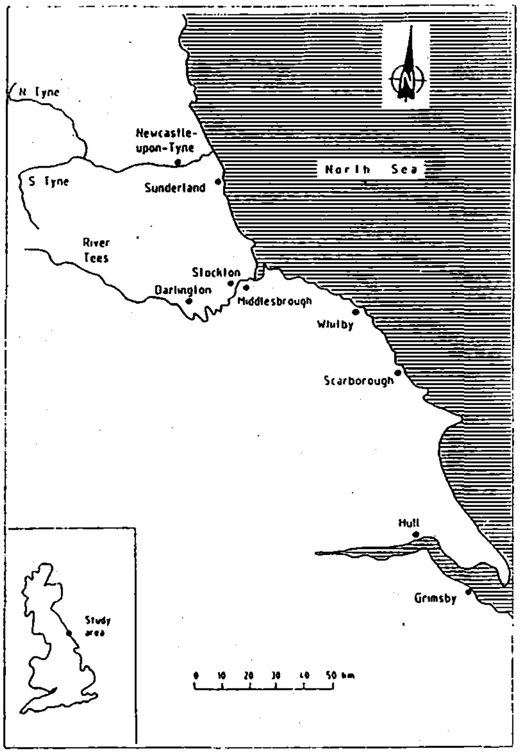


Fig. 1 Location map of River Tees

There is current concern over possible effects on the flora and fauna in the area of disposal activities. One area of particular concern is whether the metals adsorbed onto sediment dissolve in a fully saline environment. The United Kingdom has obligations, under international agreements to limit marine pollution resulting from disposal at sea of dredged material. The Food and Environment Protection Act (Part II) 1985 and through it, the Oslo and London Dumping Conventions will continue to have an increasing impact on the dredging contractors in the UK.

Metal pollutants enter an estuary in dissolved and particulate form, as a consequence of both natural processes and anthropogenic activities. The principal sources are river input at the tidal limits, freshwater run off and outfalls discharging from the banks and also from coastal waters on incoming tides (Ref 1). Sediments from areas of intense shipping and industrial activity tend to have higher metal concentrations of metals than those from less active areas. The increased concentration of metals can have adverse effects on the flora and fauna of the disposal site if it is 'bioavailable' (attached to ion exchange sites or incorporated into the organic or poorly crystalline phases of the sediment). The proportion of the metal which dissolves after disposal has been shown by previous workers to be insignificant (Ref 2). The bioavailable fraction however is of particular importance since anthropogenic metal input is often in a bioavailable form.

The Department of the Environment (DoE) commissioned Hydraulics Research (HR) to study the estuarine transmission of heavy metal pollutants in an attempt to determine the extent to which they are accumulated within an estuary or are passed out to sea and the factors affecting their transmission (Ref 3).

The River Tees is located in the North East of England on the North Sea coast (Fig 1). The estuary is of the partially mixed type, hence the estuarine sediments are likely to be a mix of fluviatile and marine origin.

Dredging is carried out from 500m downstream of Newport bridge to the turning circle at the seaward end of the approach channel (Fig 2). The channel is dredged by Tees and Hartlepool Port Authority using two trailing suction hopper dredgers and a grab dredger. The dredged material from maintenance dredging is disposed of at the inner disposal site and the dredged material from capital dredging is disposed of at the outer disposal site (Fig 2). The ten year (1979 to 1988) average dredged quantity for the channel was 1.8 million in-situ cubic metres per year most of which is from maintenance dredging.

The objective of the study was to monitor the concentration of metals in the bed sediments of the River Tees dredged channel and the associated disposal site and surrounding area (Fig 2), and to draw conclusions on whether or not the metals become dispersed after disposal in the coastal environment.

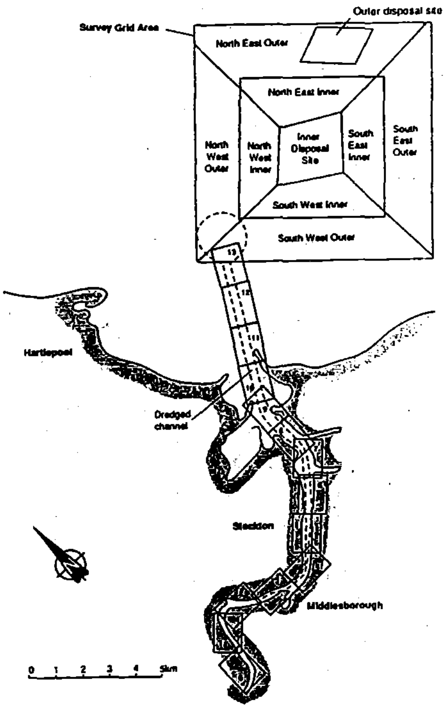
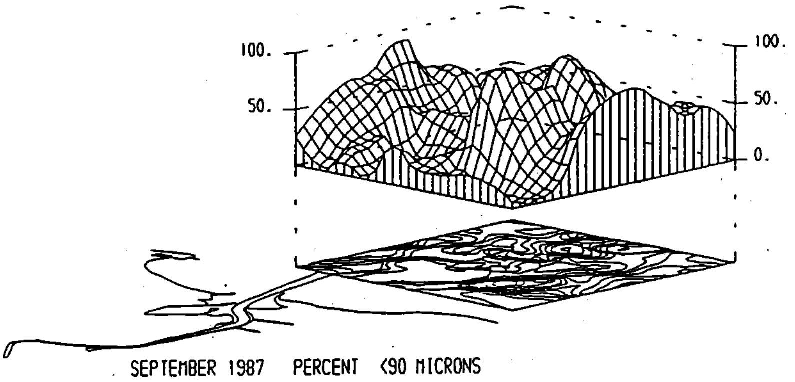


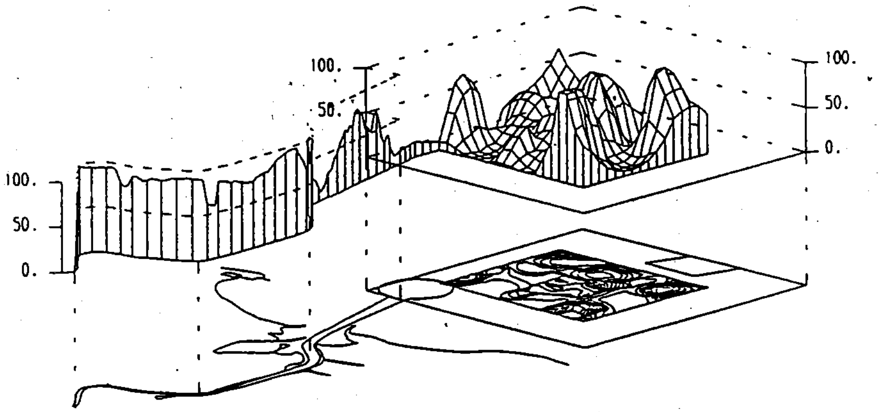
Fig.2 Map of study area

Metals are not evenly distributed throughout the particle size range of the sediment, the metal concentration being found mainly in the clay and silt fraction. It was decided that separation of grain size by sieving at 90μm would be the most cost effective method of compensating for grain size differences. 90μm was chosen since this is the break point used by MAFF (Ministry of Agriculture Fisheries and Food) in its sediment analysis and would enable comparison of results.

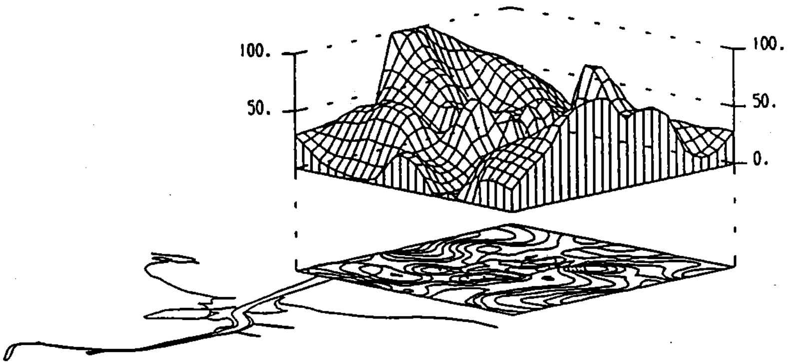
Sampling on a grid of 10 by 10km at 1km intervals orientated north-east/south-west with an inner grid of 10 by 10 at 0.5 km intervals was carried out. Samples from this grid were split into four size fractions <20μm, 20-63μm, 63-90μm and >90μm. Heavy metal analysis for the six metals studied previously, cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), lead (Pb) and zinc (Zn), was conducted on all except the greater than 90μm fraction.



SEPTEMBER 1987 PERCENT <90 MICRONS

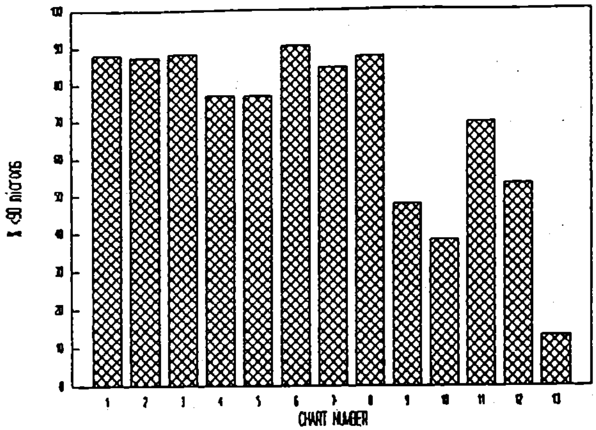


JUNE 1988 PERCENT <90 MICRONS

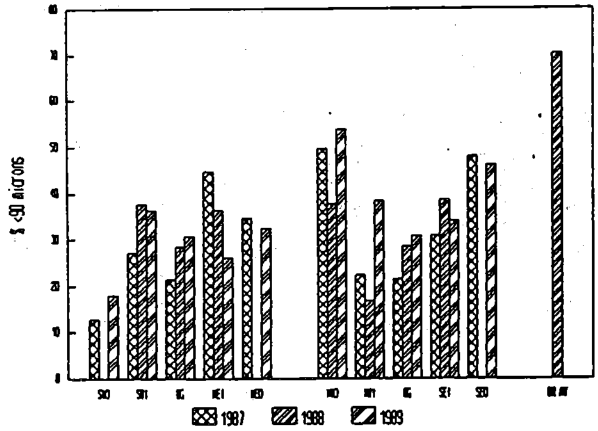


MARCH 1989 PERCENT <90 MICRONS

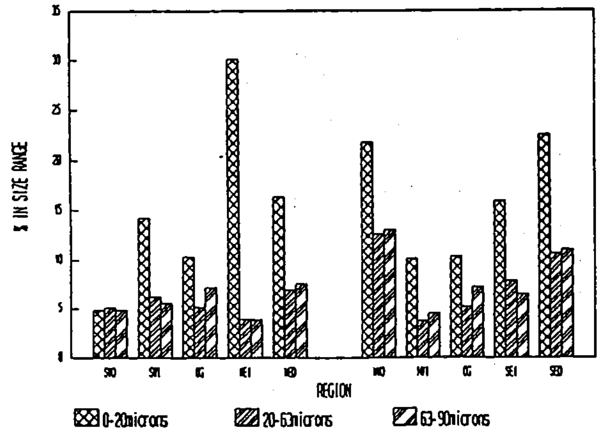
Fig. 3 Isometric projections of % <90 microns



Distribution in dredged river 1988



Distribution in disposal ground and surrounding areas



Distribution of metal on each size fraction

Fig. 4 Averaged area histograms of particle size

Two subsequent surveys of the disposal area were undertaken, together with a comprehensive set of river samples. The <90μm fraction was analysed for ten metals, the six investigated previously Co, Cu, Fe, Mn, Pb and Zn, plus cadmium (Cd), chromium (Cr), nickel (Ni), and mercury (Hg).

A sequential extraction analysis was also carried out on a number of samples on the final survey to determine the amount of metal associated with each chemical phase of the sediment.

DETAILS OF SURVEYS

All samples in the study were taken using a 0.5L Van Veen Grab. Since the disposed sediment is likely to spread out on the sea bed as a thin layer a sub sample of the surface 20mm of the 100mm deep grab sample was taken for analysis. The samples were stored in plastic bags prior to analysis. Samples taken for speciation analysis were sealed in plastic bags and frozen to inhibit chemical processes such as the breakdown of organic material and the oxidation of sulphide compounds.

A four transmitter position fixing system operated by Tees and Hartlepool Port Authority was used for position fixing on all surveys.

In the study three sampling exercises were conducted. These took place in September 1987, September 1988 and March 1989. The disposal site and surrounding area was sampled in September 1987 over a 10 by 10km grid orientated north-east/south-west. Samples were taken at 1km intervals covering a physical area of 81km^2 centred on the disposal site. Samples were also taken over a finer grid with positions at 0.5km intervals located over the central 25km^2 of the coarser grid. Samples of the dredged material were also taken from the dredger hoppers at the time of the survey. The samples were split into four size fractions, <20μm, 20-60μm, 60-90μm and >90μm. The %mass of each fraction was found and the concentration of Co, Cu, Fe, Pb, Mn and Zn in each of the three finer fractions was determined.

In September 1988 the area was sampled over a 7 by 6km grid with similar sampling positions used for the 1987 survey extending over an area of 42km^2. The inner area once again was sampled at 0.5 km intervals. Samples were also obtained from the dredged channel of the River Tees and approaches at 150m intervals along the centre line of the dredged channel from Newport Road Bridge to the Fairway Buoy. In addition, a number of samples were also taken from the dredgers. The samples were split at 90μm and the finer fraction analysed for concentration of 10 metals Co, Cu, Pb, Mn, Fe, Zn, Hg, Ni, Cd and Cr. The percent mass <90μm was also found for each sample.

The March 1989 sampling grid covered the same area as the 1987 survey, however the distance between the sampling points was increased from 1km to 1.5km on the outer grid and from 0.5km to 0.75km on the inner grid, thus halving the number of samples. Samples were taken from a 7km dredged section of the estuary and also from the dredgers. Each sample was split at 90μm and the finer fraction analysed for metal concentration of 10 metals; Cd, Co, Cu, Pb, Mn, Fe, Hg, Ni, Zn and Cr. The percent mass of each sample <90μm was also found.

A number of samples from both the estuary and disposal site were selected for speciation analysis. The samples were analysed for the percentage distribution of Cr, Cu, Pb, Zn and Mn in 6 chemical phases.

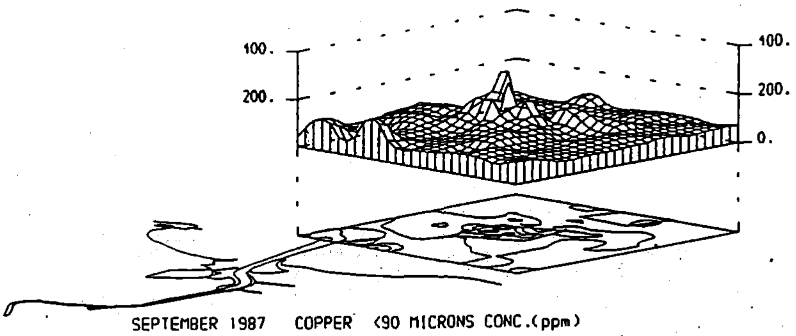
SPATIAL DISTRIBUTIONS

The concentrations of each metal and percentage of each sediment size fraction were represented by three-dimensional isometric projections for the survey grid area. This enabled a visual assessment to be made of the distribution of each metal in each survey.

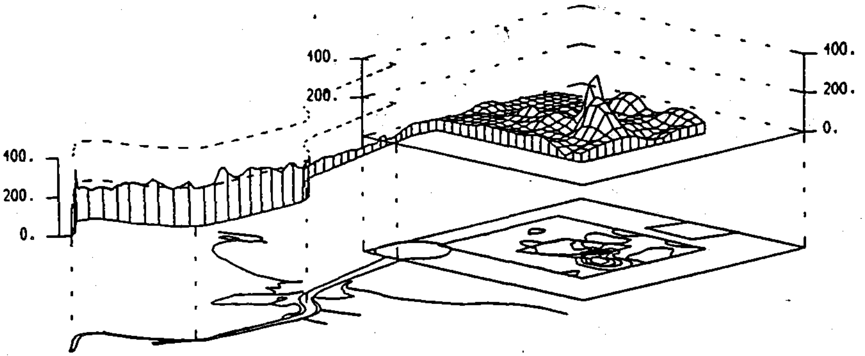
A representation of the metal concentrations along the centre line of the dredged channel was combined with the isometric projection for the March 1988 samples. The concentration of metal is denoted by height on the vertical axis. A running average of 3 samples was used.

Neighboring samples in the river often had widely different concentrations. To compare the concentration of each metal along the dredged channel the average concentration within the area of each THPA chart (Fig 2) was calculated.

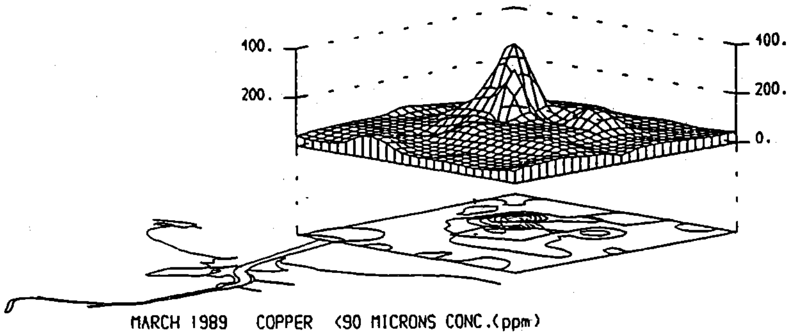
To enable trends within the disposal site and surrounding area to be seen more clearly the area was divided up into 9 smaller regions (Fig 2). These regions were: the disposal site, four inner regions (north east inner, north west inner, south east inner and south west inner) and four outer regions (north east outer, north west outer, south east outer and south west outer). The mean concentration of each metal in the <90μm fraction of the samples in each area was calculated.



SEPTEMBER 1987 COPPER <90 MICRONS CONC.(ppm)

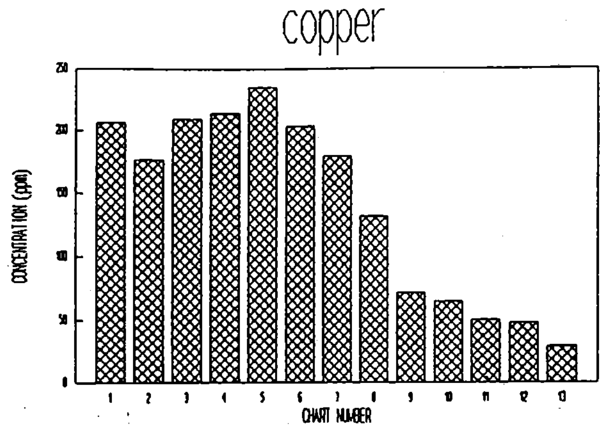


JUNE 1988 COPPER <90 MICRONS CONC.(ppm)

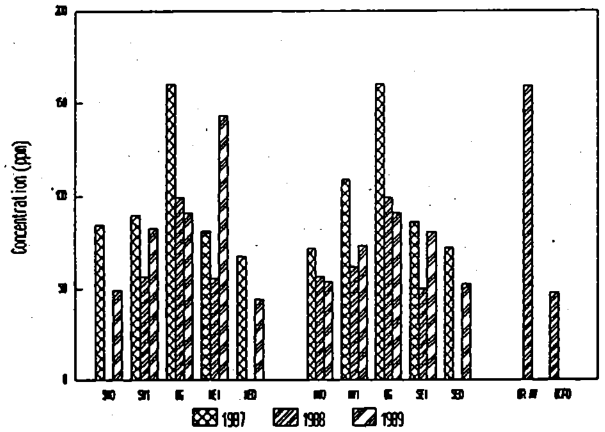


MARCH 1989 COPPER <90 MICRONS CONC.(ppm)

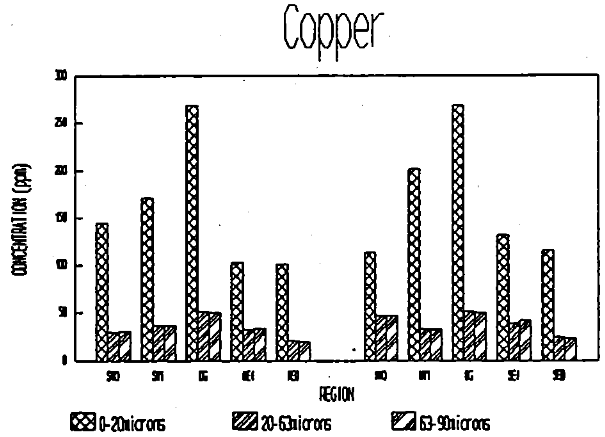
Fig. 5 Isometric projections of copper on <90 micron fraction



Distribution in dredged river 1988



Distribution in disposal ground and surrounding areas



Distribution of metal on each size fraction

Fig. 6 Averaged area histograms of copper distribution

SEDIMENT SIZE

The bed sediments of the dredged channel of the River Tees were composed principally of fine material (<90μm) except for an area around the mouth of the river where some of the samples consisted of below 20% fine material (see Fig 3). During storms large amounts of sand are deposited in this area. As a consequence the volume of material dredged from this section varies from year to year depending on the frequency and severity of storms.

The percentage of particles of <90μm diameter in the samples varied greatly over the surveyed area. The samples nearest the coast (south west) consisted of more than 20% <90μm. The bed became increasingly fine grained towards 7km off shore from which it became more coarse again towards the north east edge of the survey area. The inner disposal site had on average less fines than the north west and south east regions. The disposal site had the largest variation in particle size with samples containing under 20% <90μm to over 80% <90μm. The percentage less than 90μm at any particular point was found to vary from year to year.

The distributions of the 0 to 20μm, 20 to 63μm, and 63 to 90μm fractions showed similar trends in the survey area to that of the <90μm. The <90μm content of the samples varied from less than 5% on the south west edge of the survey area to greater than 75% south east and north west of the disposal site. The maximum proportion of the samples in the intermediate size ranges (20-63μm and 63-90μm) was approximately 40% .

The average percentage of <90μm sediment within each of the 9 regions (Fig 4) decreased towards the disposal site on a north west to south east transect. The north west inner region in which there are rock outcrops on the bed had around 25% fines. The percentage of fines was constant at approximately 30% on a south west south east transect except for the south west outer area (the area nearest the coast) where the percentage fines was between 10 and 20%.

METAL CONCENTRATIONS

Comparison of the averaged concentrations in the 9 regions of the disposal site and surrounding area showed that in general the concentration of Cu (Figs 5 and 6), Pb, Zn, Hg, Cr and Cd decreased with distance from the disposal site. The concentration of Fe, Mn (Figs 7 and 8), Co and Ni however, showed no tendency to decrease away from the disposal site. The concentration of Fe, Mn, Co and Ni had only slight variation from region to region.

The average concentrations of Cu, Pb and Zn were higher in the finest fraction than in the coarser fractions, by a factor of 5 for Pb, 3 for Zn and 2 for Cu. In contrast, the concentrations of Mn, Fe and Co showed less difference between size fractions of within a factor of two.

The implications of this distribution are that the total concentration on the <90 micron fraction is dependant on the size distribution of the particles. This is more so for Pb, Zn and Cu than for Fe, Mn, and Co. Samples with a high proportion of sediment of 0-20μm size fraction will have proportionally higher concentrations of Cu, Zn and Pb when presented as concentration in <90μm fraction.

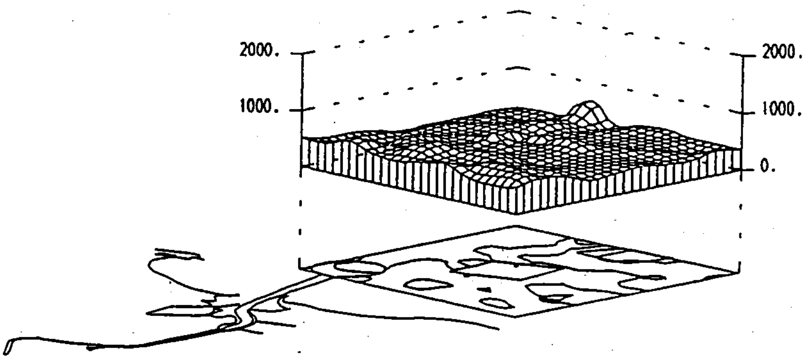
From the 1988 survey, detailed information on the metal concentration in the dredged river was obtained. This information was used to derive an average concentration of each metal on the dredged material. The average concentration of each metal on the dredged material was calculated from the 1979-1988 average dredged quantity and average metal concentrations for each section of the river, represented by a THPA chart number (Fig.2), using a weighted average method.

A background metal concentration of each metal was estimated from the metal concentrations in the samples from the dredged channel between the mouth of the River Tees and Fairway Buoy (ie chart numbers 10 to 13). This material was assumed to have originated from the coastal area and would be likely to be lower in pollutants than the river. The background metal concentration was assumed to be representative of the natural metal concentrations in the disposal site and surrounding area.

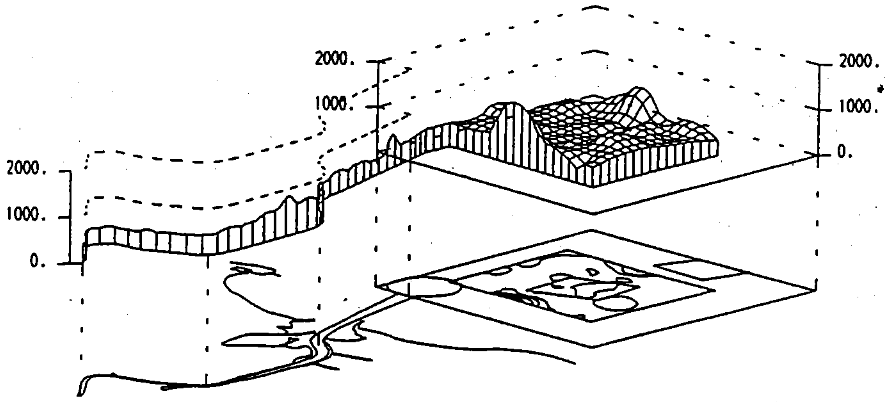
The average concentration of each metal in the disposal site was compared with the average concentration on the dredged material and the background metal concentration in order to evaluate the degree of dispersal or mixing.

The average concentration of Hg, Pb, Cu (Fig 6), Cd, Cr and Zn in the dredged material was far greater than the background concentration. The average concentration of Fe, Mn (Fig 8), Ni and Co on the dredged material was only slightly higher than the background concentration.

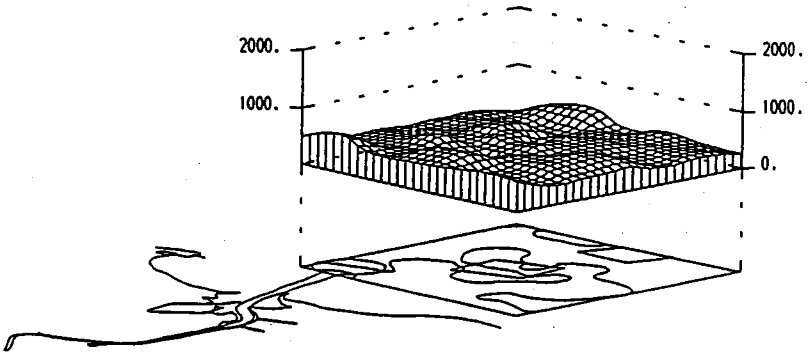
The average metal concentration in the disposal site for all the metals was between the average metal concentration on the dredged material and the background



SEPTEMBER 1987 MANGANESE <90 MICRONS CONC.(ppm)

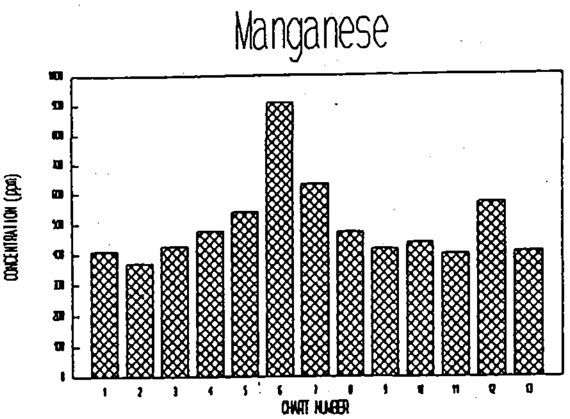


JUNE 1988 MANGANESE <90 MICRONS CONC.(ppm)

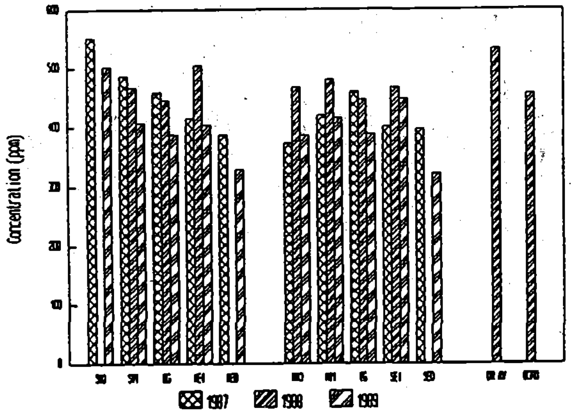


MARCH 1989 MANGANESE <90 MICRONS CONC.(ppm)

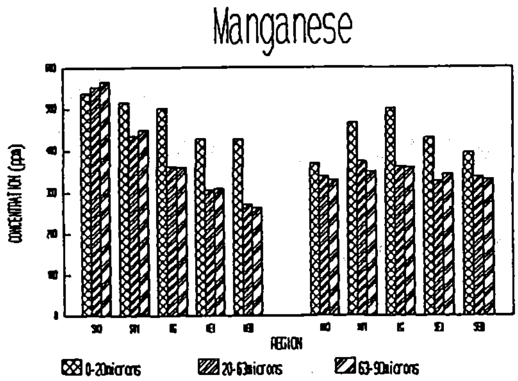
Fig. 7 Isometric projections of manganese on <90 micron fraction



Distribution in dredged river 1988



Distribution in disposal ground and surrounding areas



Distribution of metal on each size fraction

Fig. 8 Averaged area histograms of manganese concentration.

DISCUSSION

Natural spatial variation in the concentration of metals in bed sediments is expected. Variation in metal concentration within source material of the sediment, sorting of the sediment by transport processes, chemical and biological effects can all influence the spatial distribution.

The average concentration of the metals investigated (Cu, Zn, Pb, Fe, Mn, Co, Cd, Cr, Ni and Hg) were in the same order of magnitude as the natural occurrence concentration of the metals. Fe being present in highest quantities followed by Mn, Zn, Pb, Cu, Cr, Ni, Co, Cd and Hg. The chemical properties of each particular metal influence the concentration of the metal in each particle size fraction and the concentration of the metal in each chemical phase of the sediment. A high concentration of metal in the silt fraction of a particular sample does not necessarily indicate anthropogenic contamination, it may simply be due to natural processes.

Natural chemical effects can concentrate metals in the surface layers of deposited sediments. Metal ions can diffuse through and be transported by upward moving pore water in consolidating sediments. When the dissolved ions reach oxic surface layers of sediment a change in the chemical conditions results in precipitation of the metal. As the sediment deposits the oxic layer moves up within the sediment and the metals move up with it. Hence, surface layers of sediment very often have higher concentrations of metals than the underlying layers.

The particle size distribution in the dredged channel is in itself caused by a combination of both physical and chemical effects. Fine sediment will accumulate in the tidal part of the river where the hydrodynamic environment is less energetic than the river above the tidal limit and the wave influenced coastal area. The changing chemical conditions where fresh river water mixes with saline water can result in precipitation from solution of dissolved particles and the flocculation and deposition of suspended material adding to the fine fraction of the sediments.

In the disposal site and surrounding area a more even distribution of fine sediment would be expected if there was no disposal of dredged material since chemical and hydrodynamic conditions vary little over the area. The south west area nearest the coast had the lowest percentage of fine particles. This is most likely because it is the shallowest area and would consequently be subjected to the highest hydrodynamic energy from wave effects. The higher percentage of fines found in the north west and south east areas is less easily explained but is likely to be due to a combination of bathymetric effects and the characteristics of underlying material.

The most notable characteristic of the distribution of fine material was that the percentage of fines in the disposal site was only half that in the dredged material. This could be due to one or all of three factors: the dredged material is mixing quickly with the surrounding sediments; the dredged material is removed from the area by mass erosion; and, the true proportion of fines in the dredged material is far lower than that estimated. A combination of the first two is considered to be resulting in the observed effect.

The metals which have significantly higher average concentrations in the dredged channel compared with assumed background metal concentrations also have high concentration in the disposal site and surrounding area. This is most likely a result of the disposal of dredged material.

It was found that the areas of elevated concentrations of Hg, Pb, Cu, Cd, Cr and Zn were generally contained within the boundary of the 10km by 10km survey area.

The peaks of high concentration in and close to the inner and outer disposal sites were not consistent in size or position from one year to the next. This is possibly due to unrepresentative samples (in some instances the peaks were due to one sample). The change of position of the peaks could be accounted for by movement of the polluted sediment. The disappearance of peaks could be due to desorption of ions into solution, mass erosion of the polluted sediment or recent disposal of unpolluted sediment. Appearance of new peaks could be caused by disposal of polluted sediments or re-exposure of previously polluted sediment. It is unlikely that sediment containing high concentrations of metals is being brought into the area by natural processes.

Processes which can account for this are the release of metals from the sediment into solution or mass erosion of the polluted sediment out of the area.

In nature, the modes of occurrence and chemical behaviour of all the metals are broadly similar. The most common form of all the metals is as divalent or trivalent cations. Fe and Mn are exceptions in that they can change their oxidation state. They are stable in oxidation state 2+ at low Eh, whereas at high Eh, Fe is stable as 3+ and Mn as 4+. Fe and Mn are the most abundant of the metals studied and are usually in the form of hydrous oxides.

Common secondary minerals such as clay minerals and hydrous oxides of Fe and aluminium can incorporate ions of other metals within their lattice structure as they form as well as on surface exchange sites. Hence, samples with high proportions of these secondary minerals (present as fine particles) will also have relatively high concentrations of other metals, this would explain high correlations between Fe, Mn and other metals.

The correlation between Fe and Mn was consistently high and shows that both metals have similar distribution which was expected from similarity of their chemical behaviour described above.

The correlation of Fe and Mn with Co and Ni was generally also high. The correlation with the other metals Cu, Zn, Pb, Cr, Cd and Hg was much lower.

The metals with higher concentrations in the river than the background, Cu, Zn, Pb, Cr, Cd and Hg, had generally quite high correlation with each other in all data sets. The most likely reason for this is that the high concentrations are on the same samples in the river for many of the metals and that the paths of dispersion, once disposed are the same for all of the metals. The low correlation of Hg and Cr with other metals in March 1989 could be due to the disposal of material with exceptionally high concentrations of these two metals. Such material is found at the upstream end of the dredged channel.

CONCLUDING REMARKS

Copper, zinc, lead, cadmium, chromium and mercury had higher concentrations in the dredged channel of the River Tees compared to the background metal concentrations. The concentration of each of these metals was higher in the bed sediment at the 2km by 2.5km Inner Disposal Site compared to the background metal concentration, but, lower than the average metal concentration on the disposed dredged material. The concentration of each metal was also higher than background outside the disposal site. Except for mercury, the metal concentration decreased with distance from the disposal site to the background level within the 10km by 10km survey area.

Iron, Manganese, Cobalt and Nickel were found to have similar concentrations to the background in the dredged channel of the River Tees and in and around the disposal site.

The differences in concentration of Copper, Zinc and Lead were greater in the 0-20μm fraction. However, the overall trend was the same as in the <90μm fraction. The concentrations of Iron, Manganese and Cobalt showed no particular trend, i.e. they were reasonably constant across the survey area.

The study showed that the disposed material was transported from the disposal site. This was indicated by the distribution of <90μm fraction of the sediment. The high proportion of fines in the disposed dredged material was not found in the disposal site. Uncontaminated sediment was also being transported across the disposal site and mixing with the dredged material. The transport and mixing of sediment was considered to the cause of the reduction in metal concentration observed for copper, zinc, lead, cadmium, chromium and mercury with distance from the disposal site.

The change in speciation of metals on the sediments from the dredged river channel to the disposal site could not be accounted for by desorption or phase changes within the sediment. The increase in the residual fraction was probably due to the mixing with cleaner sediments and transport processes at the disposal site.

ACKNOWLEDGEMENTS

The cooperation and assistance given by the Tees and Hartlepool Port Authority in carrying out the sample retrieval and their general support throughout this study is gratefully acknowledged.

Carolyn Davis under the supervision of Dr Tom Stephenson carried out the metal speciation analysis at Teesside Polytechnic.

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WATERFLO - POLLUTO : A THREE - DIMENSIONAL MODEL FOR GROUNDWATER FLOW AND DISPERSION OF POLLUTANTS

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ABSTRACT

To predict the long term effects of the disposal of contaminated dredged material on the environment, a three-dimensional mathematical model for groundwater flow and pollution transport has been developed.
The model is based on the finite element technique and can be used in a dynamic and equilibrium state mode for any pollution dispersion problem.
The flow model calculates steady state groundwater flow, in a heterogeneous medium. The pollution program simulates pollutant transport, taking into account advection, dispersion, diffusion, and decay as well as sorption of contaminants. As such the package is utmost useful for environmental impact assessment of various sources of groundwater pollution.

INTRODUCTION

One of the main areas of concern for the environmental impact assessment of disposal activities with contaminated material is the long term effect on the surrounding groundwater layer. Due to its long term nature it is definitely impossible to evaluate the situation based on laboratory or in situ measurements only.
Modelling of all the interacting processes is a necessity to get an idea of the effects to be expected. This modelling process is quite complicated as one has to cope with a multidisciplinary problem :

- first there is a geohydrological aspect for the groundwater movement simulation.
- second there is a chemical aspect concerning the sorption processes and other chemical interactions;
- third there is a biological aspect concerning decay processes and bio-accumulations;
- fourth there is an hydraulic aspect concerning advection, dispersion, dispersion and diffusion of particles through the groundwater system.

It is obvious that a good model has to respond reasonably well to all these aspects. The first and the last one are well-known in hydrogeological modelling. Modelling the second and the third aspect is complex especially when the interaction between different pollutants and organisms has to be simulated.
In the POLLUTO model the number of pollutants is limited to one, and only adsorption/desorption and first-order decay processes are considered.

WATERFLO

General remarks

In order to respond to the most complex groundwater flow situations a three-dimensional simulation model was chosen based on the finite element method with special attention to the input-output procedures in order to realise a flexible and efficient tool for environmental impact analysis.
The program calculates the groundwater potentials for any steady state scenario properly defined in the data files. The flow domain can be heterogeneous and is considered to be isolated from the surroundings. Its properties also have to be specified in the data files. Interactions with the outside world can only take place in the nodal points, in the form of fixed groundwater potentials or predefined inputs or outputs of water in the nodes.

Theory

Defining the hydraulic potential H as a function of x, y and z, and Q_i as the discharge in node i (where i = 1, ..., n) the basic equation for steady state groundwater flow can be written as :

$$\nabla (K \nabla H) + \sum_{i=1}^{n} Q_i \, \delta_i = 0$$

with :

K	:	hydraulic conductivity	$[LT^{-1}]$
H	:	hydraulic potential	$[L]$
Q_i	:	discharges in the nodes	$[L^3T^{-1}]$
δ_i	:	Dirac Delta-function $\delta(x-x_i)\delta(y-y_i)\delta(z-z_i)$	$[L^{-3}]$

Solution method

By means of a finite element approximation and the Galerkin method a set of n algebraic equations is obtained, allowing to calculate all potentials H_i's in the nodes and inflow or outflow Q_i for the nodes with a fixed potential.

The set of algebraic equations is solved by an iteration process which is stopped when the maximum change in value of H_i is smaller than a tolerance TOLH, specified by the user.

The calculation of the water table forms part of the solution as its correct position is not known at the start of the calculation. This is done as follows : at the start of the calculations a series of nodes are defined as being on the water table. During a second iteration process the z-coordinate of these nodes is adjusted as follows :

$$z_i = H_i$$

expressing that the pressure potential in node i is equal to zero which corresponds to the definition of the water table. The iteration continues until the change between two successive values is lower than a user-specified tolerance.

The basic flow-chart of the model is given in fig.1.

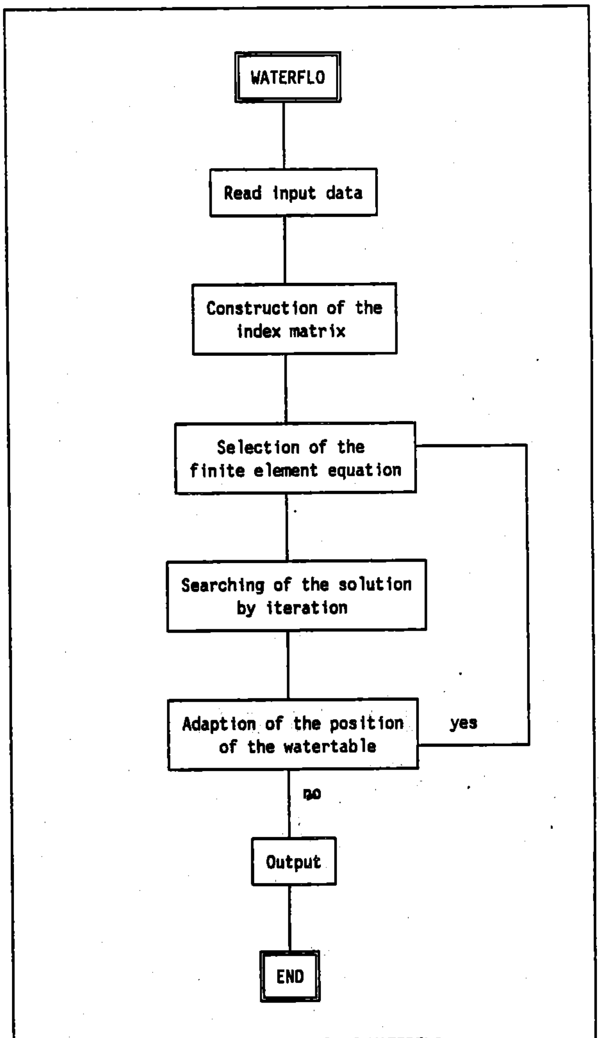

FIG. 1 : FLOW CHART OF WATERFLO

POLLUTO

Transport equation

The studied domain is considered to be isolated from the surroundings. Interactions concerning the transport of pollutants are supposed to happen in the nodes : the concentrations can be fixed, or there can be concentration inputs together with the input of water in the nodes (hence only with the positive Qi values).

Defining C as the concentration of the pollutant dissolved in the groundwater (mass of pollutants per unit volume of water) and S as the amount of pollutant adsorbed on the solid matrix particles (mass of pollutant per unit mass of soil) the basic equation for pollutant transport is :

$$n \frac{\partial c}{\partial t} + \rho \frac{\partial S}{\partial t} = \nabla (n D \nabla C) - q \nabla C + \sum_{i=1}^{n} Q_i^{+} (C_i - C) \, \delta i - \alpha_1 nC - \alpha_2 \rho S$$

with :

n = porosity [1]

C = concentration $[ML^{-3}]$

S = adsorbed concentration [1]

ρ = bulk density of the inert material $[ML^{-3}]$

D = dispersion tensor $[L^2T^{-1}]$

q = groundwater flux $[LT^{-1}]$; calculated with Darcy's law $q = K \nabla H$

Q_i^+ = positive water inputs in the node i $[L^3T^{-1}]$

C_i = concentration of the pollutant present in the water input in node i $[ML^{-3}]$

α_1 = decay reaction constant of the pollutant in the groundwater $[T^{-1}]$

α_2 = decay reaction constant of pollutant in adsorbed phase $[T^{-1}]$

δ_i = Dirac delta function for the nodes i $[L^{-3}]$

This equation expresses the mass balance of the pollutant. The terms on the left hand side give the total change of pollutant mass, while those on the right-hand side give the different mechanisms to which the pollutants are subjected. The first term is the hydrodynamic dispersion. The second term is the advection of the pollutant with the groundwater flow. The third term is the input of the pollutant in the nodes, while the last terms give the decay of the pollutant due to (bio-)chemical reactions, which are assumed to be first-order reactions.

Sorption equations

Soil sorption may be phenomenologically split into two separate processes : adsorption and desorption. Adsorption is here defined as the transfer of a chemical from a dissolved state in the water to a adsorbed state on the surfaces of the soil matrix particles, while desorption is defined as being the reverse process. The present model bases its treatment of sorption upon the following two assumptions. Considering the adsorption, it can be supposed that the number of particles adsorbed per unit time is directly proportional to the bulk aqueous concentration of pollutant, nC, and to the unfilled adsorptive capacity of the soil matrix. The sorption flux is then given by :

$$\Gamma_1 \, nC \, (1 - S/S_{max})$$

with :

Γ_1 = the sorption reaction constant

S_{max} = maximal adsorbed concentration

Considering the desorption, it can be supposed that this flux is directly proportional to the amount of pollutant present in the adsorbed phase, ρS, and that there is no limit to the solubility in the water phase. The desorption flux is then :

$$\Gamma_2 \, \rho S$$

with :

Γ_2 = the desorption reaction constant

Combining the two above expressions, we find the kinetic equation describing the sorption process.

$$\rho \frac{\partial S}{\partial t} = \Gamma_1 \, nC \, (1 - S/S_{max}) - \Gamma_2 \, \rho S$$

The second assumption is based on the fact that often the adsorption/desorption processes are so fast that the aqueous and adsorbed concentrations reach equilibrium almost instantaneously after any change brought about by other, slower processes. This allows to simplify the soil sorption equation by assuming that the adsorption and desorption fluxes are continuously in equilibrium.

$$\Gamma_1 \, nC \, (1 - S/S_{max}) = \Gamma_2 \, \rho S$$

Hence : $S = K_1C/(1 + K_2C)$,
in which K_1 and K_2 are constants

The equation states that, there is an equilibrium between the adsorbed concentration S and the aqueous concentration, C. This is called the Langmuir isotherm, and is represented schematically in fig.2.

The program

The transport and the adsorption equations are solved by the finite element technique for the space domain. Because both equations are non-linear the Euler-Heun finite difference technique has been used for the time domain.
When boundary conditions are properly specified all state variables are calculated from a known initial state. The time-step Δt is chosen so that the maximum change in C_i is smaller than

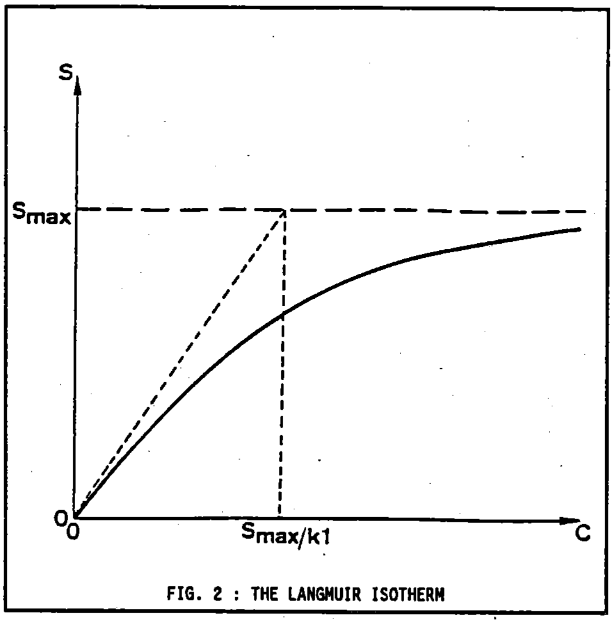

FIG. 2 : THE LANGMUIR ISOTHERM

the user-specified tolerance, TOLC. A first prediction of the situation at time t + Δt/2 is made with the Euler equation. Next, a correction is calculated with the Heun equation, leading an accurate prediction of the situation at time t + Δt.

This principle has been applied for both the equilibrium approach (POLLUTO 1) and the kinetic approach (POLLUTO 2). As far as long term effects are concerned the first approach is the most practical one because of the reduced calculation time. Fig.3 gives a simplified flow chart of the program.

INPUT - OUTPUT - PROCEDURES AND DATAFILES

One of the major advantages of the global programming package is the versatile structure of data files and programs, which enable a transfer of data and results between the programs WATERFLO and POLLUTO.

An overview of this structure is given in fig.4.

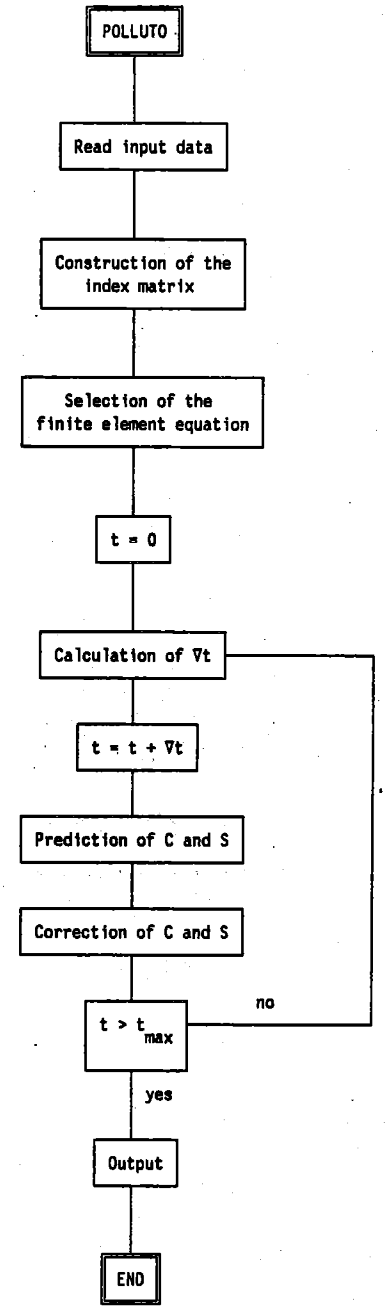

FIG. 3 : FLOW CHART OF POLLUTO

The following elements are included :

- GENERATO :
  a finite element mesh generator.
- CONDITIO :
  a program to define the physical properties of the porous medium and the boundary and initial conditions such as permeability, adsorption characteristics, density, fixed water potentials, in- and outflows, ...
- WATERFLO :
  groundwater flow simulation program.
- POLLUTO 1 :
  a program to simulate the transport of pollutants for cases in which the adsorption is described by an equilibrium isotherm.

- POLLUTO 2 :
  a program to simulate the transport of pollutants for cases in which the adsorption is described by a kinetic equation.
- GRAPHICO :
  a program to visualise the calculated results
- TRANSFO :
  program to transform data files into ASCII-files and vice versa.
- MESH.DAT :
  data required to generate the finite element mesh (used by GENERATO).
- CONDITIO.DAT :
  data concerning the physical conditions created by CONDITIO.
- MAIN.DAT, NODES.DAT, ELEMENTS.DAT :
  these files contain all information for a specific simulation. They are generated by GENERATO, adjusted by CONDITIO and used as input or output by the WATERFLO- and POLLUTO-programs; the files are random access files.
- GLOBAL.DAT :
  a standard ASCII file containing all model data.
- PLOT.DAT :
  results file, which can be read by a commercial graphics software package.

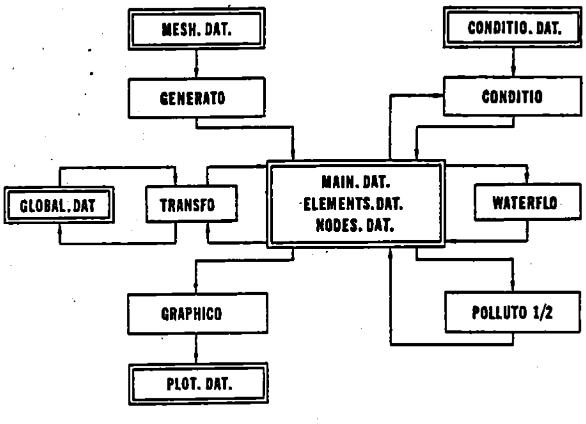

FIG. 4 : PROGRAMS AND DATA

APPLICATIONS

Simulation of the sorption phenomenae

One of the basic features of the model is the ability to simulate the sorption processes. In order to demonstrate the importance of this feature some simulations have been realised with the model.

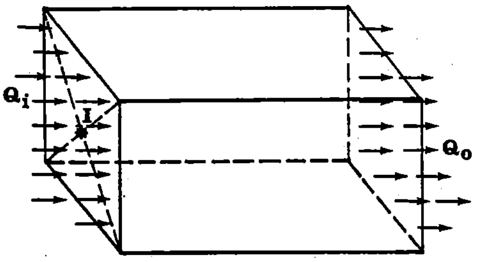

FIG. 5 : BASIC GEOHYDROLOGICAL CONFIGURATION

A simple geohydrological situation with a constant groundwater flow over the complete domain has been chosen as background (fig.5).
Within this system a single point source of a pollutant is simulated releasing a constant concentration of 5 ppm.
The dispersion of the pollutant has been calculated for three almost identical situations :
- first the dispersion during a period without adsorption
- second the dispersion over the same period taking into account a moderate adsorption process (K_D = 100)
- third the simulation period has been increased till 50 times the period with an identical adsorption process (K_D = 100)

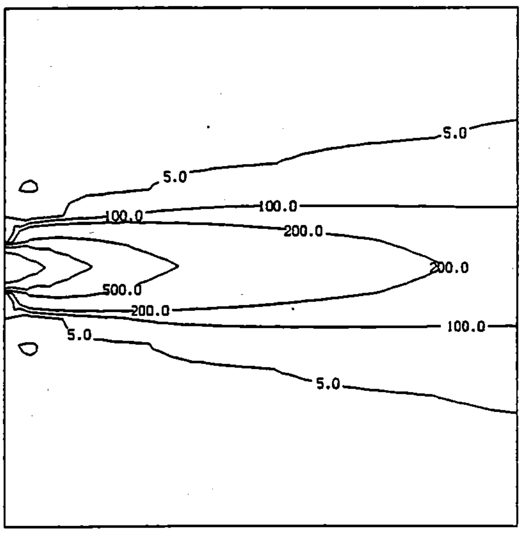

FIG. 6 : SIMULATION RESULTS (NO ADSOPTION)

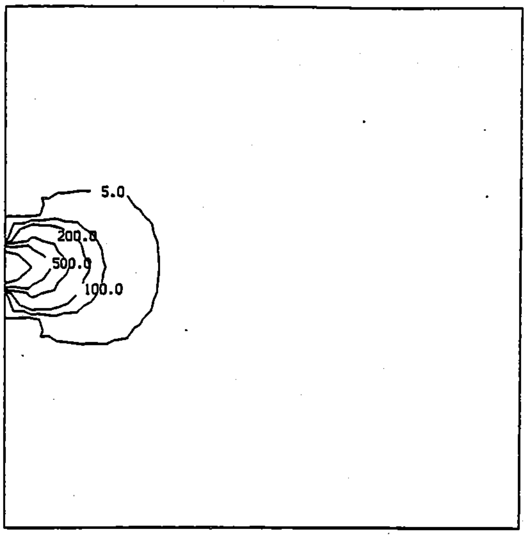

FIG. 7 : SIMULATION RESULTS (WITH ADSORPTION INFLUENCE)

Fig.6 to 8 give a cross sectional view through the point-source in the direction of the flow. From the figures 6 and 7 it can be seen that the adsorption phenomenae reduces the spatial contaminant dispersion by a factor 3 or 4 for a given period.

The third simulation (fig.8) gives an indication of the time scale of the adsorption process. Figures 6 and 8 indicate that the adsorption processes reduces the time scale of the dispersion phenomenae by a factor larger than 50.

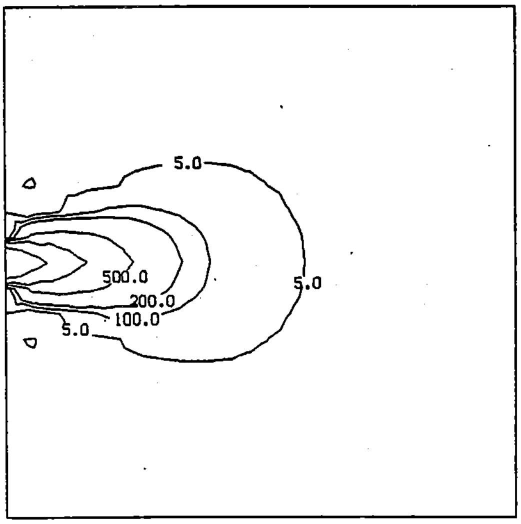

FIG. 8 : SIMULATION RESULTS (WITH ADSORPTION INFLUENCE ; SIMUALTION PERIOD = 50 ΔT)

The decay function

The influence of the decay process on the transport of contaminants has been evaluated with the same basic model as the sorption process.

Fig.9 gives the dispersion during the same period with a decay of 1% per day. A comparison with fig.6 indicates the considerable reduction of the contaminant dispersion due to the decay process.

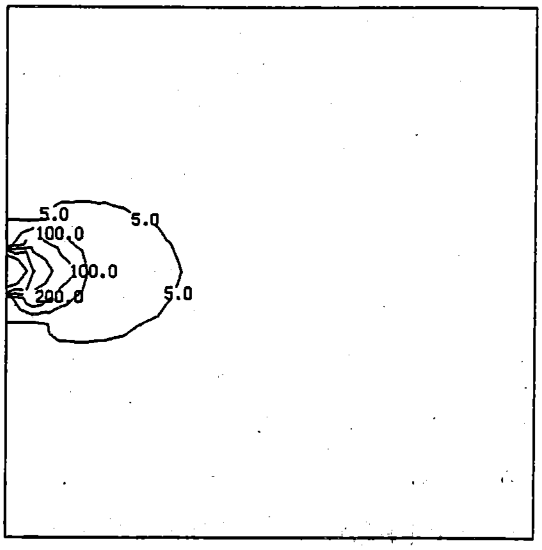

FIG. 9 : SIMULATION RESULTS (WITH BIOLOGICAL DECAY)

Capping efficiency

Another application of the WATERFLO and POLLUTO model has been the evaluation of the capping efficiency of an underwater disposal site. A schematic design of the disposal site is given in fig.10. Due to an optimal selection procedure of the disposal site an area was chosen in an almost stagnant groundwater layer. Therefore diffusion of the pollutants towards the overlying watervolume is the main process

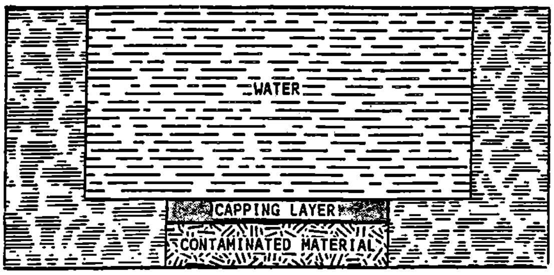

FIG 10 : DISPOSAL SITE - TYPICAL CROSS-SECTION of concern as indicated in fig.11 were the contaminant content of the water is given in parts per billion (ppb) after a 1000 year period taking into account natural sorption and decay processes.

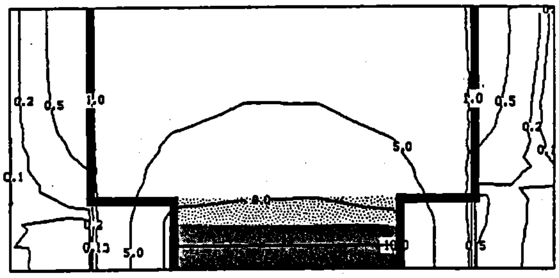

FIG. 11 : CONTAMINANT DIFFUSION WITHOUT CAPPING LAYER

In order to reduce the potential risk a capping layer has been proposed. The influence of a sandlayer has been evaluated with the POLLUTO model. The resulting diffusion values after a 1000 year period are given in fig.12.
Comparison of both figures gives a considerable reduction of the diffusion phenomenae to the overlying waterlayers by the capping layer.

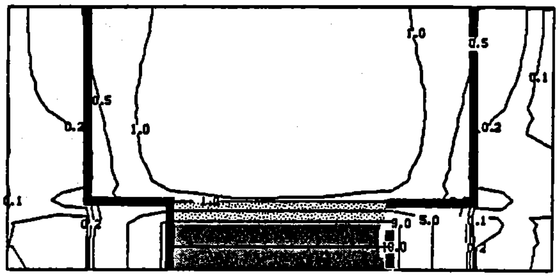

FIG. 12 : CONTAMINANT DIFFUSION WITH CAPPING

Evaluation of an underwater disposal site

The programs WATERFLO and POLLUTO 1 have been used to evaluate the long term effects of the underwater disposal of dredged material under the Doeldok on the left bank of the river Schelde. A detailed description of this prototype project including the modeling results can be found in ref. 1.
First the groundwater flow has been modelled on a regional scale. Fig.13 gives an impression of the results. A more detailed local model was used to simulate the groundwater flow in the vicinity of the disposal site. The results of this detailed model have been used as basic data for the POLLUTO simulation runs. These runs have been realised with Zn which was the most critical element in the disposed dredged material. Fig.14 gives an idea of the dispersion around the dock and the underlying disposal site after 10.000 years.
Both models proved to be an efficient tool to get a realistic view of the potential risks of the disposal site. Meanwhile a second study is underway for a similar project.

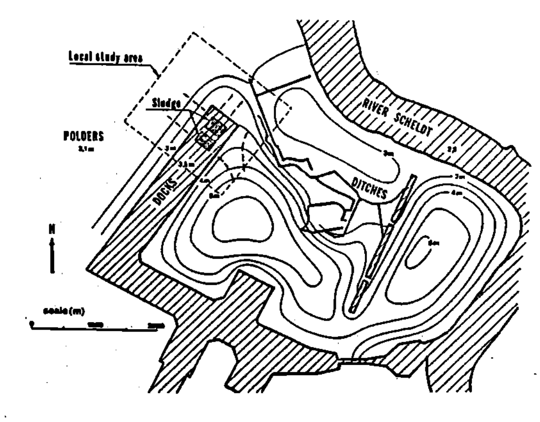

FIG. 13 : CALCULATED GROUNDWATER POTENTIALS

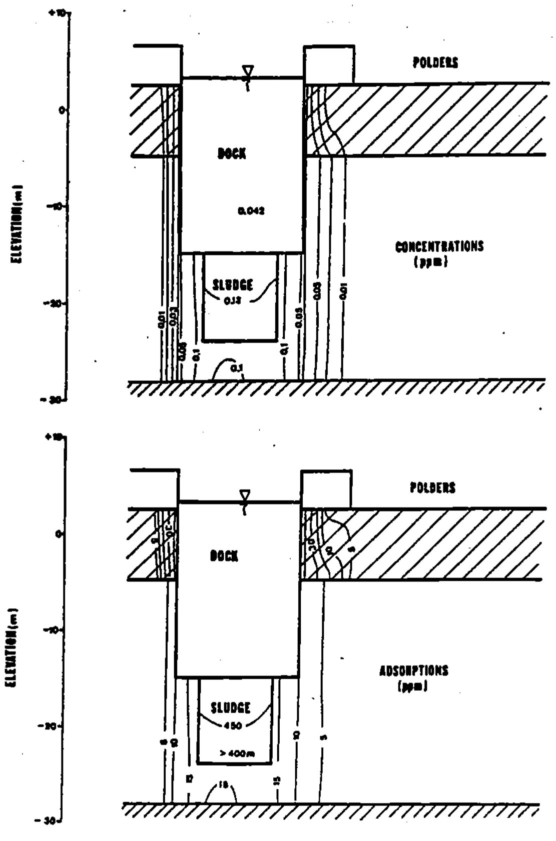

FIG. 14 : ZINC DISPERSION AFTER 10.000 YEARS

CONCLUSIONS

- Mathematical models are necessary for estimation of the long term effects of contaminant dispersion through groundwater layers.
- The simulation of pollutant transport in groundwater layers requires a multidisciplinary approach in which geohydrologists, modellers and geochemical engineers contribute to set up a realistic model.
- Flexible and precise input-output procedures are very important to model situations with large dimensions.
- A correct description of the sorption process and the biological decay is required for an adequate simulation of natural situations.
- WATERFLO and POLLUTO have proved to be versatile tools even for complex situations like the underwater disposal of dredged material under the docks on the left bank of the river Scheldt.

REFERENCES

1. C. Claeys, J. Van Hoof, L. Ponnet - "Underwater disposal of dredged material in Doeldok : Final evaluation of the pilot project" - CATS - 1991.

UNDERWATER DISPOSAL OF DREDGED MATERIAL IN DOELDOK : FINAL EVALUATION OF THE PILOT PROJECT

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ABSTRACT

In the "Doeldok" on the left bank of the river Scheldt a large scale pilot project has been executed for the disposal of dredged material in an underwater pit.
The project included the selection of dredging and disposal area, the executional method, a detailed monitoring programme and an environmental impact analysis including a three-dimensional mathematical dispersion model.

INTRODUCTION

Disposal of the sludge from maintenance dredging activities becomes more and more a precarious problem. There used to be many possibilities such as creation of industrial areas, filling of marsh-land, use as a fertilising agent in agriculture etc. However recently people became aware that a part of the maintenance dredge sludge is contaminated with traces of heavy metals and other resistant organic pollutants. Therefore new solutions and disposal methods have been worked out in order to prevent the mobilisation of polluting agents and their migration to the surrounding environment.
Underwater disposal, one of the most promising solutions, has been evaluated on a large scale prototype test with monitoring program in the Antwerp harbour (fig.1). The solution consists mainly in the creation of a considerable overdepth underneath one of the docks in the harbour on the left bank (fig.2).
This pit was filled with the dredged sediments by means of a diffusor. A monitoring program aimed to quantify the environmental effects of the method and to evaluate whether a capping layer of sand or clay would be necessary.
During the monitoring program new measuring and sampling techniques have been developed and tested.

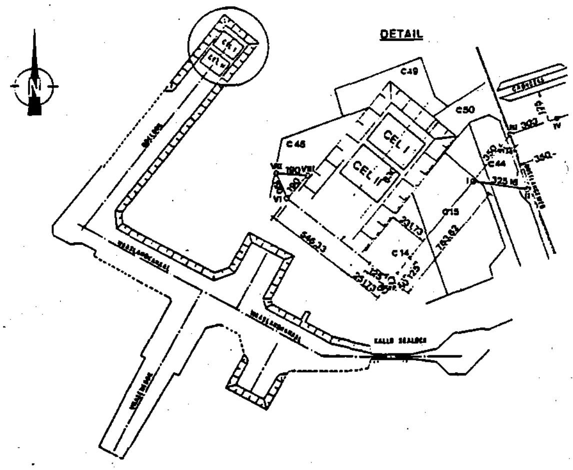

FIG. 1 : PILOT PROJECT LOCATION

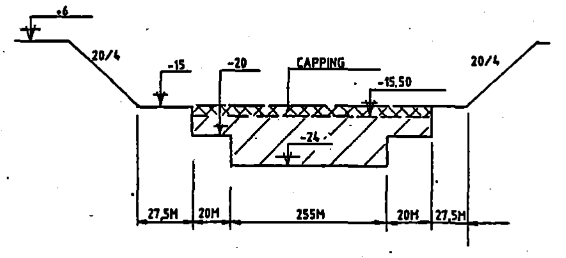

FIG. 2 : TYPICAL CROSS-SECTION

THEORETICAL BASE OF THE PROJECT

Based on a bibliographic study from parallel experiences in other countries as well as our own experiences in the field we can state that a very large part of the contaminating elements (especially the heavy metals) do have a strong compound with the soil particles; especially with the finer fraction of the dredged material. This combination prevents the contaminating elements from migrating to the surroundings by groundwater movements. Therefore a disposal method has to be designed which can guarantee an almost permanent continuation of the actual state of the dredged material. This can be defined as follows:

- the material to be dredged lies on the bottom of a river or harbour
- the environment has a very low oxido-reduction potential
- the pH is almost neutral (7 to 8).

When the dredged material is stored on land the oxidation process starts through the direct contact sludge-air. This oxidation process results on a medium to long term in an increased oxido-reduction potential and a reduced pH.
Both phenomena will reduce the strength of the chemical binding of the contaminating elements to the particles and liberate them partially, resulting in a migration to the surrounding groundwater table.
Furthermore surface run-off will take parts of the finest material with the draining surface water which will create a pollution of the surrounding ditches if no special measurements have been taken.
To circumvent these problems the idea was put forward to store this material in an underwater disposal site.

THE PROJECT

At the end of 1987 a first pit was realised in the Doeldok of the Antwerp Harbour with a capacity of 464.000 m^3. The excavated sand has been used to continue the creation of new industrial areas in the harbour. The pit has a depth of approximately 9 m and reaches up to the underlying impervious claylayer which proved to be an additional advantage to prevent vertical migration of the pollutants.
In 1988 the disposal activities were started simultaneously with a large scale monitoring program. A sludge with moderate contamination characteristics was selected for the pilot project in order to limit possible adverse effects if the project would be unsuccessful.
The disposal was realised with an underwaterdiffusor in order to create a non turbulent outflow of the silt at the disposal site (see fig.3). An in situ volume of 312.000 m^3 was dredged and disposed in this way.

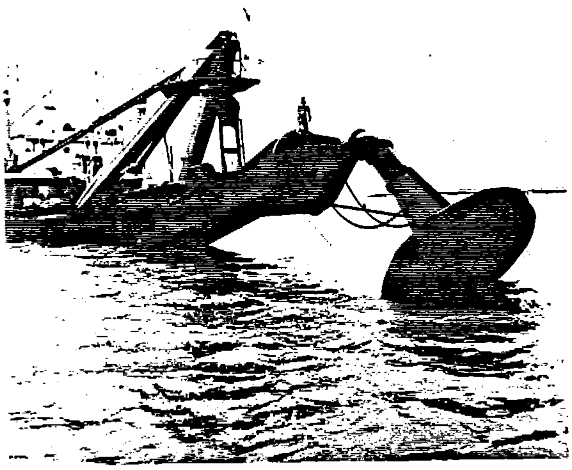

FIG. 3 : THE UNDERWATER DIFFUSOR

After a control program of one year the final report has been prepared and concluded that the method carries large possibilities for the storage of maintenance dredged materials from the river Scheldt and the port of Antwerp.

THE MONITORING PROGRAM

General remarks

The monitoring program is designed to identify all possible environmental effects of the dumping and storage of contaminated dredge sludge in an underwater disposal area such as:

- identification of the dredging and dumping sites;
- study of the direct effects of underwater dumping by means of a submerged diffusor (control of turbidity, spreading of the silt...);
- study of the settlement and consolidation process of the dumped fine-grained material;
- study of a possible spreading of contaminants to the environment (especially towards the nearby situated poldergrounds) via the groundwater layer;
- set up and calibration of a three-dimensional groundwater flow and dispersion model for contaminants;
- study of capping procedures.

A description of the different measuring campaigns can be found in ref 1,2 and 3.
For the monitoring program several new measuring equipment has been developed such as:

- the ECOPROBE test system is developed for the groundwater sampling program at fixed depths. The system consists of a modern electrical and automatic cone penetration equipment with a build-in pump to extract water samples at a well defined depth. High penetration and sampling rates are possible. The system can be connected with a mobile testing laboratory where instant chemical analysis of the groundwater samples can be done to acquire a first knowledge about the degree of pollution (see fig.4).

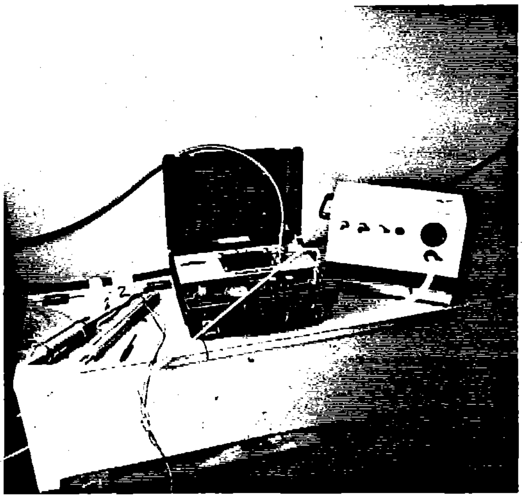
FIG. 4 : THE ECOPROBE

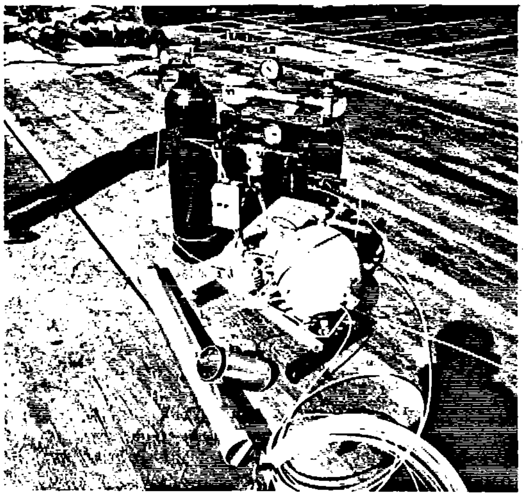
FIG. 5 : THE SILTCORER

- the SILTCORER (see fig.5) is developed to take undisturbed samples of fluid mud up till a density of 1.2 to 1.3 t/m^3. The equipment can be handled easily from a workship with a small hoisting frame or from a jack-up pontoon through a casing pipe when very accurate depth data are needed.

Apart from these other modern equipment has been used such as : nuclear density gauges, optical turbidity sensors, self registrating underwater buoys,....

<u>Control of the diffusor efficiency</u>

An indication of non-acceptable spreading of contaminants can be obtained by measuring an increase of turbidity in the dockwater. The diffusor was introduced in the project to minimize the creation of this extra turbidity. Therefore a program of turbidity measurements around the diffusor was realised.
Vertical turbidity and salinity profiles have been recorded at different distances from the diffusor (from 5 to 1000 meters). These measurements are realised one day per week in order to evaluate possible changes of turbidity as a function of the rising silt level in the pit.

Results:

The turbidity values before the start of the dumping operations were below the detection limit of the chosen probe (20 ppm).

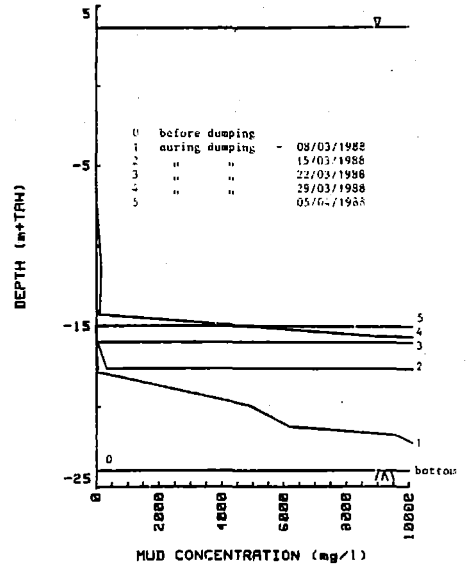

FIG. 6 : EVOLUTION OF THE TURBIDITY
ABOVE THE DISPOSAL PIT

During the disposal activities the turbidity levels remained equally below the detection limit of the probe for profiles situated outside the dumping area.Within the dumping area, the measured turbibity remained low for the higher waterlayers (above the normal harbour bottom). A typical series of profiles very close to the diffusor is given in fig.6.
As a conclusion we can say that the increase of turbidity was limited to the direct surroundings and below the diffusor. Spreading of large volumes of silt outside the area could not be detected. (A constant waterlevel is maintained in the harbour and there are no currents whatsoever in the dock).

Consolidation phenomenae

The consolidation process of the silt has been monitored by the following measurements:

- regular echo-soundings up till one year after the dredging works
- two in-situ density measuring campaigns
- two coring campaigns with a jack-up platform (one year interval)

Besides the in situ campaign a laboratory test program has been started with some settling and consolidation colums in order to evaluate their predictive value.

Results:
The initial bulking factor after disposal was 1.48 but the settlement of the silt was relatively quick as after one year a settlement of approximately 2 meter has reduced this factor till 1.05. A typical series of density profiles is given in fig.7 (two measurements with an interval of 3 months).

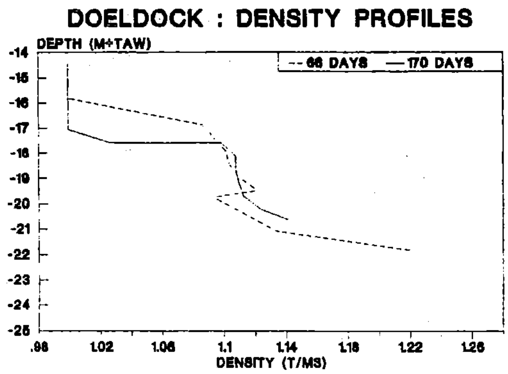

FIG. 7

The corings realised approximately 2 weeks after the dredging works showed an average density of 1.15 t/m^3 for the whole depth. The maximum density in the lower layers was 1.25 t/m^3.
Fig.8 shows the results of the laboratory consolidation tests which are a very good simulation for the evolution of the top silt level in nature.

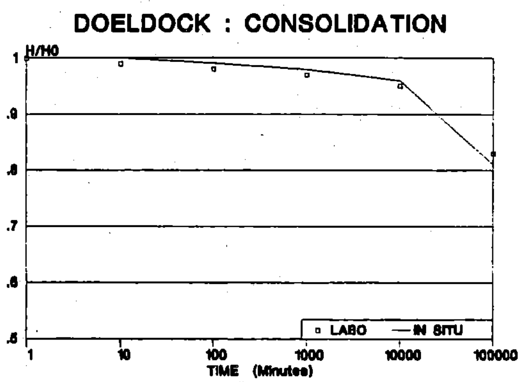

FIG. 8

Contaminaton measurements

Aims of the project

During the project two possibilities of contaminant dispersion were studied:

1) The dispersion of contaminated silt through the dockwater is controlled not only by turbidity measurements, but also by harbour bottom sampling before, during and after the dumping activities.
2) The dispersion of the contaminants through the groundwater around the disposal area is controlled by series of wells and by the Eco-probe testsystem.

The sampling program included both the bottom layers and the overlying water. The bottom was sampled with a Van Veen sampler. The water samples were taken with a small centrifugal pump. The samples have been transported to a specialised laboratory (I.H.E. - Institute for Hygiene and Epidemiology) where they were stored under controlled conditions and analysed within a short delay.
In order to limit the cost of the campaign the samples are subdivided in two series:

- A small number of samples which were analysed in detail for a large number of elements.
- A larger number of control-samples which were analysed for a limited number of

relevant basic elements (mainly heavy metals).

Dredged material characteristics

Samples have been taken in the dredging area by means of a vibrocore and in the disposal area with a Van Veen sampler for surface samples and with the siltcorer for deeper samples. The medium values for a few characteristical elements from each series of samples are given in table 1.

place	element			
	Cd	Pb	Cu	Zn
dredging area	0.8	27	7	59
disposal area				
- surface sample	1.8	26	14	133
- depth sample	1.1	46	18	157

Table 1 : Contaminant characteristics of the silt (ppm)

The contamination measurements give higher values in the disposal area than in the borrowing area. This is due to a segregation process of sand and silt in the disposal area. Indeed during the disposal activities a sand deposit was observed at the actual location of the diffusor and most samples are taken in the other zones where a higher silt and clay content could be expected.

During the coring campaigns a series of ECOPROBE samples have been taken at the disposal site to get an idea of the pore water characteristics of the disposed dredged material (results are included into table 2).

Water quality results

Parallel to the mud the dock and groundwater have been sampled before, during and after the disposal activities to control the variation of the contamination characteristics. A summary is given in table 2.

element	Cd	Pb	Cu	Zn
DOCKWATER				
- before disposal	0.1	1.3	13.6	42
- during disposal	<0.1	1.6	7.6	24
- after disposal	<0.1	<0.6	7.9	25
GROUNDWATER				
- before disposal	0.2	186	25	106
- after disposal	0.1	23	3	84
PORE WATER				
1° series	0.5	30	18	*
2° series	0.3	2.1	11	282

* no data available

Table 2 : Contamination characteristics of the water (µg/l)

The measurements indicate that there was no increase in contamination level neither in the dockwater nor in the groundwater around the dock. For the groundwater we can even note a decrease of contamination level. This phenomenon is probably due to seasonal influences.

The pore water measurements indicate a considerable reduction of the pore water contamination level during the first year after disposal. Most probably the contaminants are partly adsorbed onto the dredged material.

Dock bottom quality

To control an eventual dispersion of the mud out of the pit towards the surroundings of the disposal area three sampling campaigns of the bottom of the dock were realised. The contamination levels are summarised in table 3.

time	element			
	Cd	Pb	Cu	Zn
- before disposal	2.3	22	10	80
- during disposal	1.5	12	7	37
- after disposal	1.7	13	8	110

Table 3 : Contamination characteristics of the dock bottom (ppm)

The results indicate that there was no increase of the contamination levels at the dock bottom during the disposal activities.

Conclusions

From the monitoring program it can be concluded that the immediate and mean-term (1 year) impact of the disposal of dredged material in overdepths of the Doeldok were very limited.

The diffusor is an efficient tool to limit and even prevent turbidity generation around the disposal site. Consolidation of the silt continued for more than one year. Some differential settlement is caused by the sand-silt segregation proces during the disposal activities. Due to this differential settlement phenomenae it is advisable to delay capping activities where it is acceptable until the density in the pit has reached a sufficient value.

The contamination of the dredged material seems to be concentrated onto the finer elements which resulted into slightly higher contamination loads in some areas of the disposal site where the finer fractions were concentrated.

The quality of the surrounding dock and groundwater remains unaltered by the disposal activities.

CAPPING CONSIDERATIONS

Direct contact between the disposed material and the overlying dockwater will be one of the main sources for the dispersion of contaminating elements especialy when currents would cause erosion of the disposed material. In order to prevent this type of dispersion it is planned to realise a capping layer above the disposed material.

The study included the definition of the capping material. Therefor a mathematical scourmodel was used to predict the bottom velocities generated by some different types of vessels. At the actual situation only small workboats will enter the Doeldok but in the future it is planned to be used by big ships such as Ro-Ro. Bottom velocities will grow from 0.30 m/sec till more then 2 m/sec after full utilisation of the dock.

It is obvious that a sand capping layer cannot resist to these high velocities.

Therefore the following considerations are made:

- a specific erosion protection is required when the dock will become fully operational.
- consolidated silt has a higher erosion resistance than sand
- a sand capping layer is mainly useful from a biological point of view

Special techniques have to be developed.

LONG TERM EFFECTS

Introduction

To predict the possible long term (10.000 year) contaminant movements through the surrounding groundlayers, a three dimensional finite element dispersion model of the whole area has been set up. A measuring program to gather the data required for the calibration of the model was included:

- measurement of the different underlaying groundwater tables (21 wells)
- measurement of the in-situ permeability
- realisation of a few additional drillings and penetration tests in order to identify the geological profile of the area.

The in-situ permeability has been measured by a 7 days lasting pumping test combined with water level measurements in the surroundings.

The models

The groundwater model

The basic equations for the groundwater model are the following:

$$\nabla (K \nabla H) + R = 0$$

with :

∇ : Del-operator $\left(\frac{\partial}{\partial x} , \frac{\partial}{\partial y} , \frac{\partial}{\partial z} \right)$

K : hydraulic conductivity

H : groundwater potential

R : source and sink-term

The solution of these equations is calculated by a finite element model and the Galerkin method. The model is described in more detail in reference 4 and 5.

The pollution dispersion model

The basic equation for the pollutant transport model is the following:

$$n \frac{\partial c}{\partial t} + \rho \frac{\partial s}{\nabla t} = \nabla(n\ D\ \nabla\ c) - q\ \nabla\ c + R(c_0 - c)$$

with :

n : porosity

c : pollutant concentration of the groundwater

s : pollutant concentration adsorbed to the soil

D : dispersion tensor

q : groundwaterflux

R : sink/source term

For the adsorption/desorption phenomenae the model can utilise different alternatives such as the Langmuir and Freundlich equation or linear and exponential equations.

Again a finite element model with Galerkin solution has been used (see ref 4 and 5).

Application of the models

The regional groundwater model

Based on the in situ groundwater level measurements and the known waterlevels in the river Scheldt, the docks and the ditches of the polders a simulation model was used to

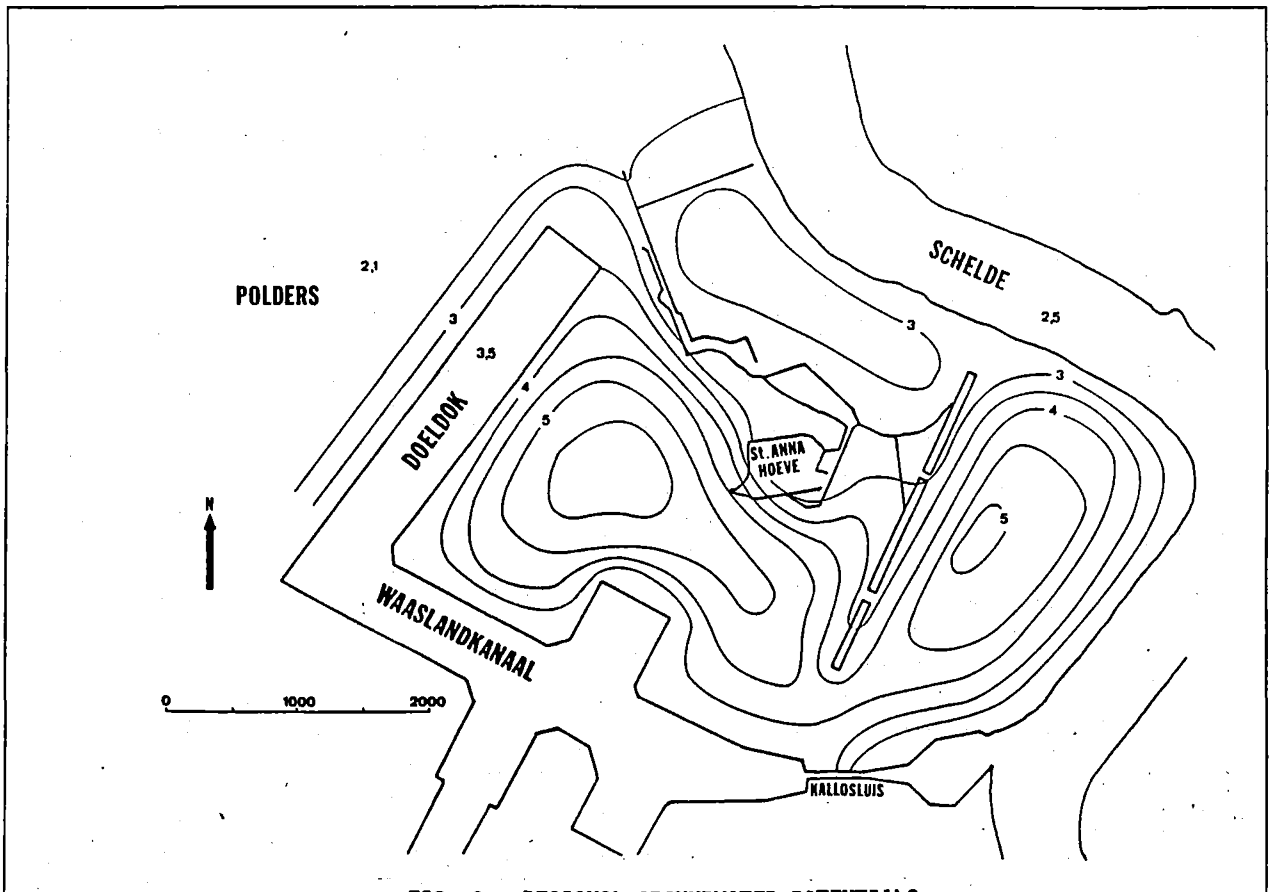

FIG. 9 : REGIONAL GROUNDWATER POTENTIALS

calculate the groundwater potentials and fluxes within the region.

A general view of the results is given in fig.9. From this model we see that the main groundwater flow goes from the reclaimed zone between the docks and the Scheldt through the Doeldok towards the polderzone.

The detailed groundwater model

As the transport of pollutants is a very slow and local phenomenon, it was decided to calculate the groundwater movements in more detail for a limited area around the disposal site in the Doeldok. The basic data at the boundaries of this model were produced by the regional model.

A vertical section through the disposal pit is given in fig.10 including the calculated groundwater potentials. From the figure it can be seen that under the dock there is an area with an almost constant groundwater potential of 3.5m. This is a typical characteristic for a zone with no groundwater flow which is very advantageous for disposal purposes as the only remaining transport mechanism is the very slow diffusion proces.

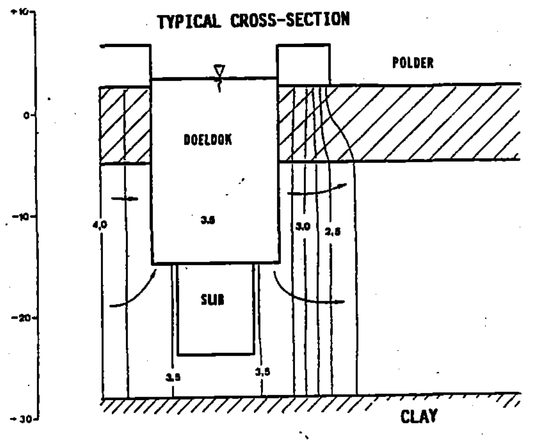
TYPICAL CROSS-SECTION

FIG. 10 : GROUNDWATER FLOW

The pollution dispersion model

With the results of the detailed groundwater model as boundary conditions a series of simulations for the transport of zinc have been run. The basic characteristics have been chosen from the results of the in situ measuring campaign:

- dockwater content of Zn : 0.042 ppm
- Zn adsorbed to the dredged material : 414 ppm
- pore water content of Zn : 0.134 ppm

During the selection of these basic data the worst cases have been selected in order to get a pessimistic view of the reality. The average values of the different parameters are much lower.

In a first stage the simulation has been done with no dredged material into the pit. The only pollution source is the dockwater whose quality was unaltered by the disposal activities.

The results are shown on fig.11 from which it can be seen that the limited pollution levels of the dockwater move very slowly to the west.

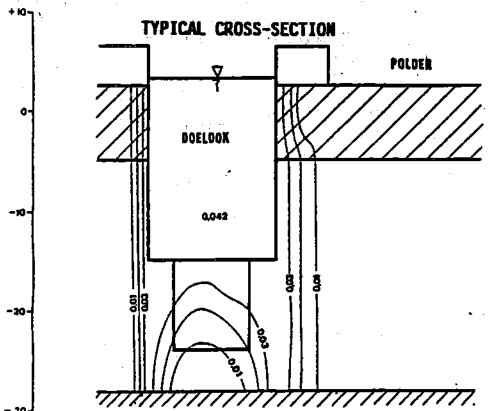

FIG. 11 : GROUNDWATER POLLUTION WITH AN EMPTY PIT

But even after 10.000 years the transport distance is less than 200 meters.

A second simulation run has been made with the dredged material into the pit. The results are given on fig.12. Again the same dispersion pattern can be seen. It has to be remarked that the additional dispersion compared with the first run is limited to a zone around the underwater pit. This additional influence remains below the Doeldok even after a period of 10.000 years.

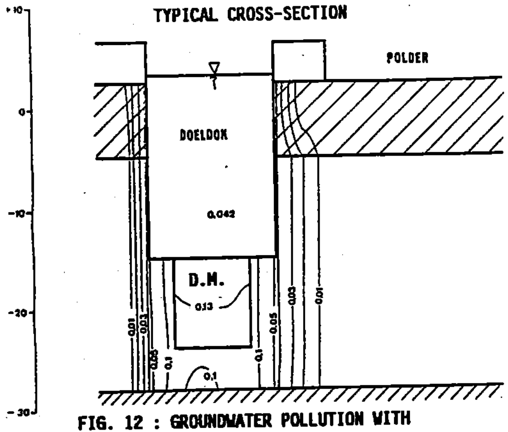

FIG. 12 : GROUNDWATER POLLUTION WITH DREDGED MATERIAL (D.M.)

GENERAL CONCLUSIONS

- Underwater disposal is a good solution for the storage of contaminated dredged material. On the average term (1 year) the contaminant content of the pore water will be reduced by adsorption phenomenae.
- A diffusor is a perfect instrument to fill underwater pits with fine grained material. The dispersion of silt around the site is minimal.
- The capping of underwater disposal sites within harbour areas has to be realised with a flow resistant material. A sandlayer will be eroded by propeller erosion.
- The site under the Doeldok has optimal conditions for the disposal of contaminated material because it is a zone with a very limited groundwater flow.
- The influence of the disposal site on the long term (10.000 years) is limited to a zone below the dock.
- A long term control measurement program is advised to check the conclusions of the study. It is advised to choose the measuring point relatively close to the dock.

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ESTIMATION AND TESTING OF ENVIRONMENTAL EFFECTS OF HEAVY METALS IN DREDGED MATERIALS

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ABSTRACT

Disposal of contaminated dredged material may result in pollution of surface waters by runoff, release of contaminants into the underlying soil and soil water, uptake by plants and incorporation of the pollutants into the food chain.

Laboratory tests can be used to estimate these effects, but exact predictions, even with complex mathematical models, will hardly be possible because a series of unpredictable factors may influence the diagenesis of a dredged sediment.

A simple mathematical model to estimate the extent of leaching of metals in the subsoil, based on uncomplicated laboratory tests, has been used. It is shown that even after land disposal of relatively contaminated sludge, migration of the metals considered is expected to be minimal. Uptake by plants however may constitute a more important risk in the case of land disposal.

A testing procedure to evaluate the environmental impact of dredged materials is proposed. When total element contents are higher than accepted levels, mobility under different conditions is used as an additional criterium.

INTRODUCTION

Sediments can be considered as both a carrier and a possible source of contaminants in aquatic systems. These materials may affect quality of groundwater and agricultural products when disposed on land 1).

Different ways for migration of heavy metals from a disposed dredged sediment can be discerned.

With runoff water, metals are dispersed over other areas or in surface waters. Skogerboe et al. 2) observed relative important transport of metals in runoff from freshly disposed as well as previously dried and oxidized sludge.

Upon draining of the interstitial water and leaching, metals in solution move into the underlying soil, where their migration will be slowed down by adsorption processes 3), 4), 5). Emmerich et al. 6) did not find significantly higher concentrations in a percolate from a 1 m soil column, where the upper 15 cm was mixed with contaminated sewage sludge. Risk for contamination of soil water should however not be underestimated when higher amounts of metals are involved.

Finally, metals accumulated in the upper layers of the soil are available for plant uptake 7).

For estimation and testing of environmental effects of land disposed dredged materials, easy and reproducible testing schemes, suitable for routine use, must be chosen. It will be illustrated how the results of relatively easy leaching tests, combined with an uncomplicated mathematical model, can be used to estimate at least the extent of possible migration of metals from a sediment, disposed on a given soil. An approach for testing dredged sediments prior to disposal is proposed, based on results of a study of metal behaviour in some flemish sediment samples 8).

MIGRATION OF THE METALS UPON LEACHING

Leaching from land disposed dredged materials is most likely the result of wet precipitation. The standard leaching test developed by the Netherland Energy Research Centre for studies on the leachability of combustion residues 9) is using demineralized water acidified to pH = 4. Only for simulating particular situations, more specific leaching agents are used. For estimating the migration of metals, leached under influence of rain, the results of a DIN 38414 10) test have been combined with mathematical modelling.

Experimental

The DIN test 38414 10) comprises three consecutive extractions at liquid/solid (L/S) ratios of 10 for 24 hours. In the filtrates, concentrations of Cu, Cd, Pb and Ni were determined using graphite furnace atomic absorption spectrometry. Concentrations of Zn were determined with flame AAS, but were lower than the detection limit (0.01 mg/l).

Mathematical model

When considering a soil column that is percolated with a solution containing the metals, the following relation applies to the movement of the concentration front when a step feed of Δc is applied on a surface unit of the column [3].

$$(\Delta a_v + \theta \Delta c)dx = \Delta c dV \qquad (1)$$

where: Δa_v = amount adsorbed per unit volume (kg/m^3)

θ = pore volume fraction

Δc = concentration of metal in step feed (kg/m^3)

x = elementary depth (m)

ΔV = elementary volume brought on one surface unit of the column (m^3/m^2)

For slow flow rates, equilibrium can be assumed, since equilibrium of soil adsorption processes is a matter of minutes [11].

Diffusion and dispersion are not considered in this equation. Therefore, the model will only provide an estimate of the average penetration depth of the metals, rather than predict the actual shape of the concentration profile [5].

The integrated form of this equation looks like:

$$\int_{x_i}^{x} dx = \int_{V_i}^{V} \frac{1}{\theta + \Delta a_v / \Delta c} dV$$

Since c remains constant under the assumed conditions (equal at c_f and dropping immediately at zero at the average penetration depth), and for x_i and $V_i = 0$, the following equation is obtained:

$$x = \frac{V}{(\theta + a_v/c)} \qquad (2)$$

a_v can be calculated from the equilibrium concentration, using an adsorption isotherm. Here, the Langmuir equation is used.

$$a = \frac{k_1 . c}{1 + k_2 . c} \qquad (3)$$

where: a = amount adsorbed per mass unit (mg/kg)

c = equilibrium concentration in solution (mg/l)

k_1 and k_2 are constants

Calculations

The laboratory results can be related to real scale predictions, once a particular situation is defined. Using this model and the results from the consecutive leaching test, the migration of metals leached from a hypothetical 1 m disposal of the investigated sample in the underlying soil may be estimated in the assumption that no major chemical changes would occur in the disposed sediment.

The bulk density of the dried sludge (d^*) was assumed to be 1500 kg/m^3, the annual precipitation 760 mm (Belgian mean average). Runoff and evaporation have been neglected. The estimation thus will refer to a maximal migration under the assumed conditions. The calculations were done for three different underlying soils, light, medium and heavy textured, for which the experimentally determined Langmuir adsorption parameters are given in Table 1.

Table 1. Langmuir-adsorption parameters for three soils [12] (k_1 in l/kg, k_2 in l/mg)

	Light (A)		Medium (B)		Heavy (C)	
	k1	k2	k1	k2	k1	k2
Cd	57	0.017	540	0.119	465	0.073
Cu	818	0.330	1096	0.285	10000	2.000
Pb	705	0.092	2039	0.246	12811	0.628
Zn	26	0.013	108	0.043	1250	0.250

The results of the calculations are given in Table 2. The liquid to solid ratios (L/S) of the experiment can be related to a time scale by estimating the time needed to reach the same L/S-ratio in the real scale situation. For the proposed example, this is done as follows:

After 1 year, 780 mm or 780 l of precipitation is assumed to percolate through a surface unit of the sediment disposal. As a 1 m^2 surface corresponds to 1500 kg of sediments (1 m deep), the L/S ratio reached after one year will equal 780/1500 = 0.52. The L/S-ratio 10 of the first fraction of the laboratory experiment is thus reached after 19 years.

The volume (V) which has percolated through a surface unit of the disposal at a given L/S ratio is obtained by multiplication with the mass percolated. The concentrations in the percolates (c) at L/S 10, 20 and 30 were experimentally determined. c_p is giving the concentration of the pooled fractions up to the L/S value considered. Using the Langmuir adsorption isotherm (equation (3)), the adsorbed quantities (a) in equilibrium with c_p are calculated for each type of soil, using the appropriate adsorption parameters (Table 1). Finally, the average penetration depth can be calculated using equation (2).

Table 2. Calculation of migration profile in the underlying soil (c = concentration in the fractions (DIN 38414 [10]), c_p = concentration in the pooled fractions; types of soils: A = light sandy loam, B = light loam; C = heavy clay)

Element	Total (mg/kg)	L/S	Time (Years)	Volume (l)	c (μg/l)	c_p (μg/l)	Adsorbed quantities (a) (mg/kg)			Depth (x) (mm)		
							A	B	C	A	B	C
Cd	13.2	10	19	15000	0.1	0.1	0.006	0.054	0.046	176	18	21
		20	38	30000	1.9	1.0	0.057	0.540	0.465	352	37	43
		30	58	45000	0.3	0.8	0.043	0.414	0.356	528	56	64
Cu	140	10	19	15000	11.6	11.6	9.46	12.67	113.30	12	9	1
		20	38	30000	8	9.8	7.99	10.71	96.12	25	18	2
		30	58	45000	6	8.5	6.96	9.33	83.90	37	27	3
Pb	178	10	19	15000	2.5	2.5	1.76	5.09	31.98	14	5	1
		20	38	30000	1.8	2.2	1.52	4.38	27.51	20	10	2
		30	58	45000	2.6	2.3	1.62	4.69	29.43	43	15	2

Discussion

From the graphical representation of the average penetration depth (Fig. 1), the important influence of the soil type is clear. Lighter soils that usually have a low adsorption capacity will allow metals to migrate deeper, resulting in lower enrichments in the soil. For soils with a more important sorption capacity, the enrichment in the upper layer can be very high, although very limited in depth.

When considering the absolute values it appears that migration of metals under the assumed conditions is very low. The enrichments in the underlying soil are very small and the penetration depths are limited to the first half meter for the lightest soil.

Higher leaching can occur under influence of chemical changes, induced by altering temperature and humidity regimes, microbial activity and eventually plant growth. Additional leaching tests are required to asses maximum possible release of metals under unfavorable, although more uncommon conditions, that still could be encountered in practice.

TESTING SCHEME FOR DREDGED MATERIALS

The possibilities for land disposal of dredged materials depend on its environmental qualities. Therefore, reliable testing procedures are needed allowing comparison of the results with accepted standards.

Total contents

Although from the total contents of a metal, only a fraction will have an ecological significance, results of a total analysis should be a first criterium in evaluating environmental quality of sediments. A broad screening identifies the elements that might cause problems. In a first approach, only those metals with contents higher than acceptable total levels should be further investigated. When total levels are lower, further testing is not necessary and special caution for the disposal of the sediment should not be imposed.

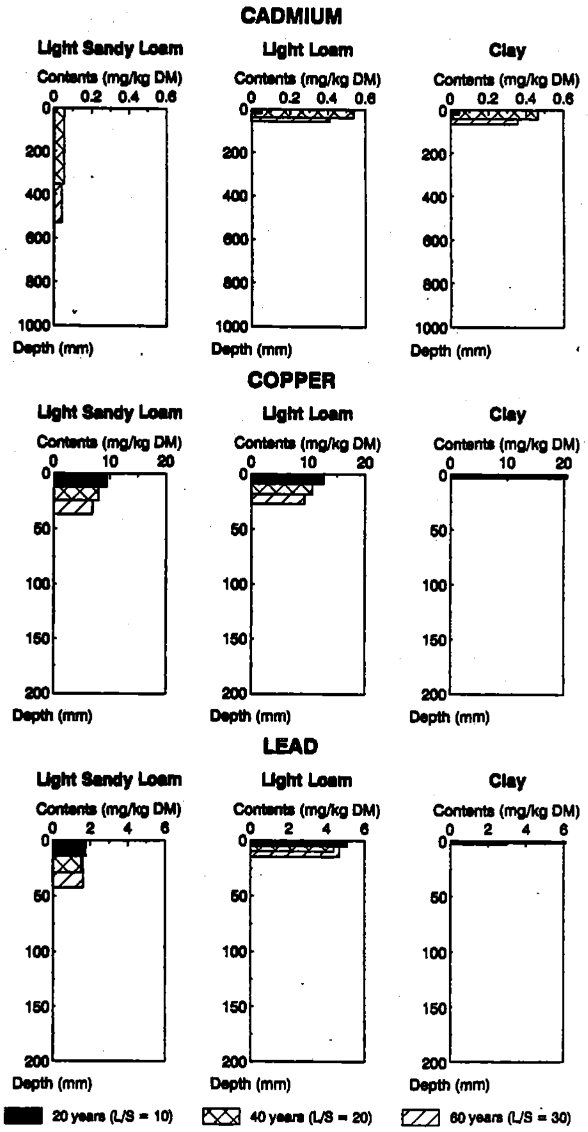

Fig 1. Graphical representation of adsorbed quantities (mg/kg DM) and average penetration depth at increasing L/S ratios

Because higher total contents of metals do not necessarily imply negative effects, a relaxation of these criteria could be allowed by considering also the mobility of the metals.

Mobility

When total contents of elements are higher than standard values, their potential release has to be assessed. If mobility is sufficiently low, land disposal can still be allowed, with exclusion of more critical areas as arable land, natural parks, rural residence zones, but with inclusion of industry soils, recreational zones, etc.

To be absolutely safe, one could require that any solution leaving the sludge should meet the quality criteria for surface waters. Leachability cannot be predicted precisely and is affected by alternating humidity regimes, temperature, microbial activity, plant growth, topological characteristics of the dumping site, etc. Laboratory leaching tests with water, eventually acidified to pH = 4, may allow to simulate specific situations. However, extrapolation to field conditions remains doubtful. A second leaching test may be chosen to asses maximal release of metals under the worst conditions that might be encountered in practice. A mixture of NH_4OAc and EDTA, a leachate with a lower pH (4.65), an important buffering capacity (about 500 meq/l) and exchanging and complexing capacities, may be useful to simulate the more unfavorable conditions.

The NH_4OAc-EDTA extraction imposes an additional criterium. Interpretation of the results may be based on a comparison of the extractable contents in the sediments and reference total contents for normal soils. As the total content in the sediments however may be relatively high, restrictions for disposal could be imposed to areas where a slight input of metals is not critical because background contents are already high or because there is no direct contact with vital compartments of the ecosystem (e.g. industrial zones, metropolitan areas, recreation zones). They can be called limited safe for the environment.

For sediments not meeting the criteria discussed up to now, free disposal is not allowed. These sediments are unsafe for the environment and should be disposed under controlled conditions or treated until criteria are matched. Further criteria can be worked out to distinguish between heavily polluted sediments that need a hermetically isolated disposal site and moderately polluted

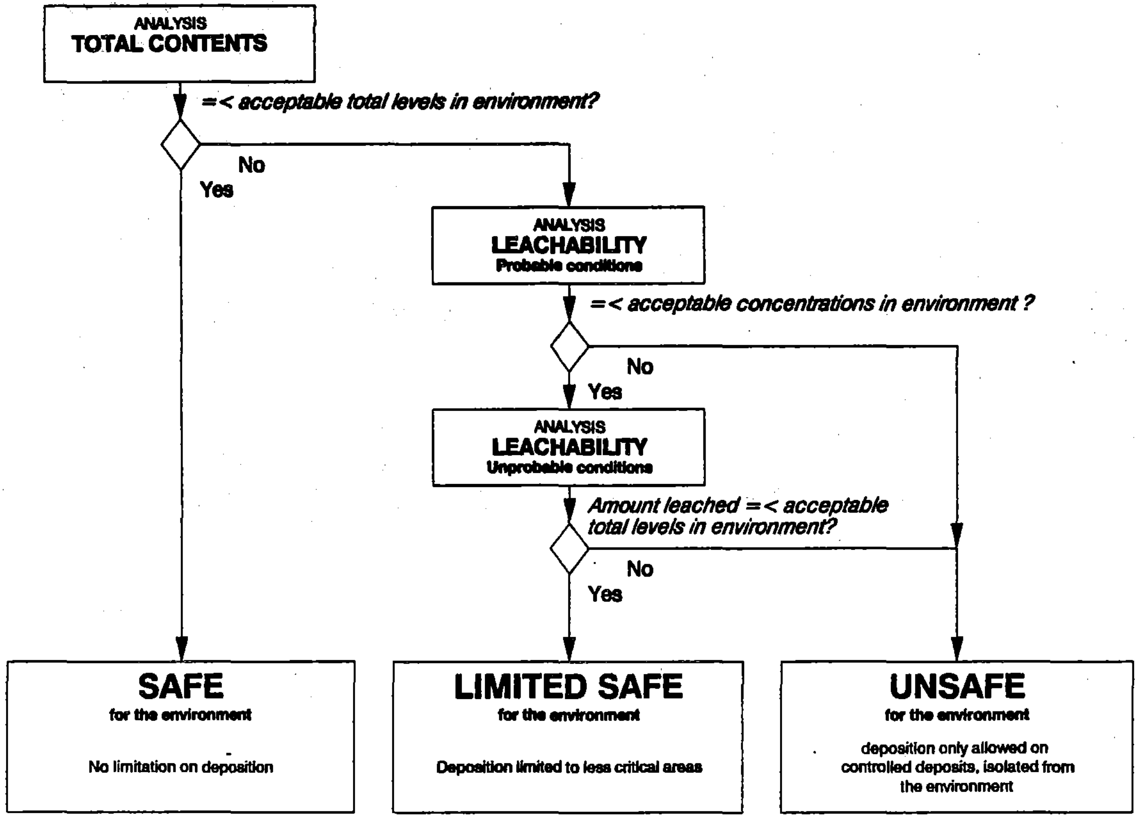

Fig 2. Flow chart for the classification of sediments

sediments, where protection from the environment do not has to be very rigid. This concept is visualized in Fig. 2.

SUMMARY AND CONCLUSIONS

Because of the limited predictability of factors influencing heavy metal release from disposed dredged sediments, laboratory tests only allow to estimate the possible release of metals. The results, coupled with mathematic models, can be used to predict the extend of migration of metals from a defined disposal site.

This was illustrated by the calculation of metal migration into underlying soils. The results indicate that migration is limited and strongly slowed down by adsorption on the solid soil phase, especially in heavier soils.

A testing scheme allowing classification of dredged materials as safe, limited safe and not safe for the environment, has been presented. Maximum allowable background concentrations in arable soil are used as criteria to indicate the eventual need for further investigation. A sediment is absolutely safe when total contents of all pollutants are below these values.

Further investigations consist of leaching tests with water and a more aggressive extracting agent (e.g. NH_4OAc-EDTA). Maximum allowable concentrations in unpolluted surface waters are used as references for the concentrations in the water leached fractions. Contents extracted by the more aggressive agent should be lower than normal total contents in soils. Sediments that meet those requirements are called limited safe and can be used in areas that are not sensitive to limited release of metals when conditions should turn unfavourably.

Sediments not meeting these requirements are unsafe and should be dumped in a controlled disposal site, isolated from the environment.

As important as assessing quality criteria for dredged sediments is taking measures for limiting and even eliminating input of heavy metals in the environment. Careful disposal and treatment of dredged sediments is only remedying to errors from the past. In the future, these errors should be avoided.

ACKNOWLEDGEMENT

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DESIGN OF A SILT TRAP AND DISPOSAL SITES FOR CONTAMINATED DREDGING SPOIL IN A DUTCH ESTUARY

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ABSTRACT

As part of the delta works in the south-west of the Netherlands, the estuary of the Hollands Diep and Haringvliet (e.g. fig.1) was closed in 1970. Material suspended in the waters of the Rhine and Maas rivers (silt) now settles in the delta as a result of the reduced flow velocity. This material is considerably polluted and large areas of the basin are now covered with contaminated sediments. The Dutch Government is considering measures for an environmental clean-up. Dredging and treatment of the sediments will only be effective if the supply of contaminated silt is stopped or greatly reduced. Thus in the short-term, measures are needed to reduce the inflow of contaminated silt.
A feasibility study was carried out on the construction of silt trap in the upstream section of the delta. The contaminated dredging spoil from the delta bottom and the silt trap would be stored in two underwater disposal sites in the mid-section of the delta. With the aid of a simulation model, it is estimated that approximately one million m^3 of silt would accumulate in the silt trap annually.

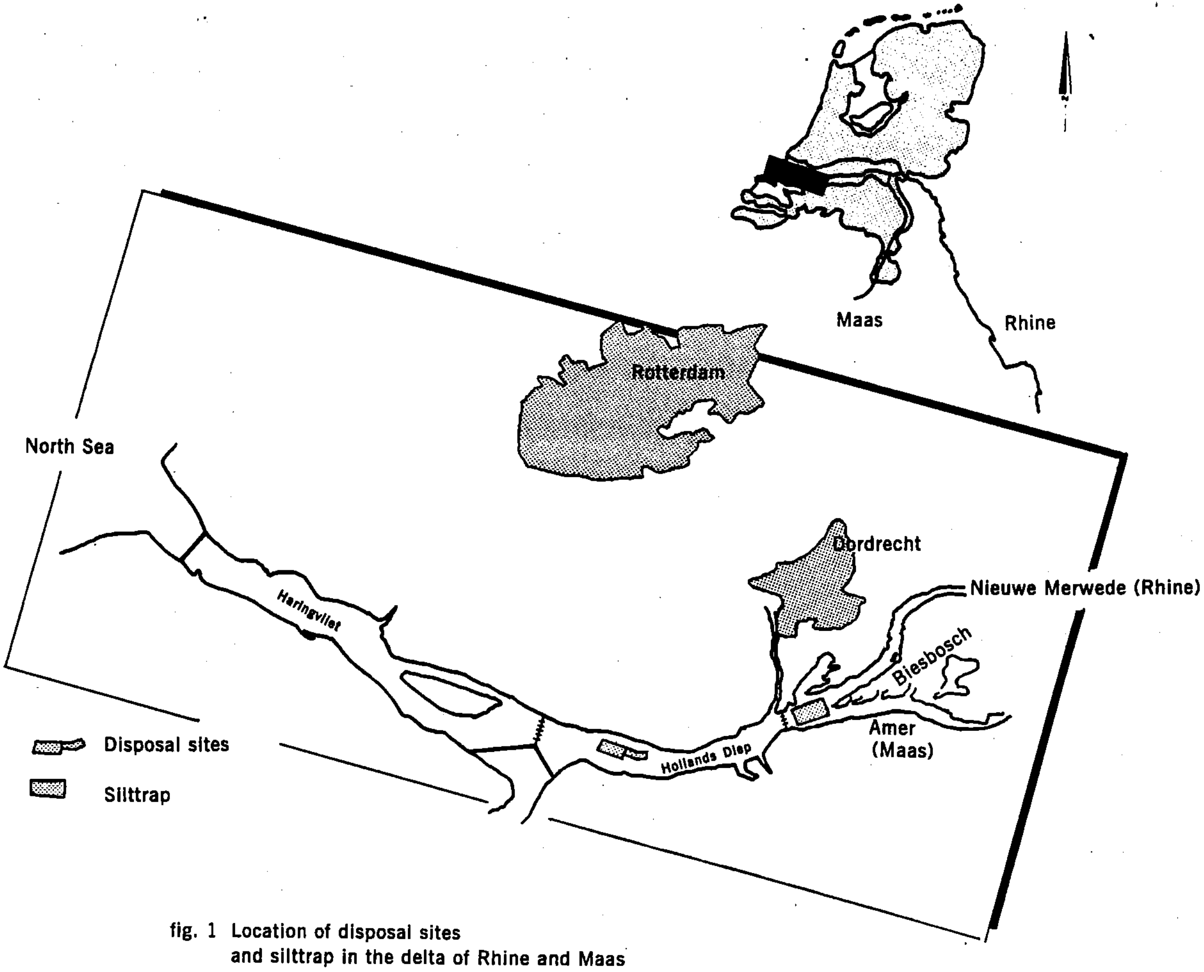


fig. 1 Location of disposal sites
and silttrap in the delta of Rhine and Maas

The bottom of the disposal sites is to be covered with a layer of clay to prevent infiltration of pollutants into the groundwater resources.
A cost-benefit analysis has indicated that sand exploitation required for construction of the silt trap and disposal sites would contribute to making these measures financially feasible.

INTRODUCTION

Silt at the bottom of delta of the Rhine and Maas rivers is polluted in many places (e.g. ref.2).
The contaminants enter the delta in solution and attached to small silt particles. Some of these particles pass through the delta into the North Sea, but most accumulate in the sediments at the bottom of the delta. The extent of pollution in the Hollands Diep and Haringvliet is shown in Figure 2.

As part of the delta works in the south-west of the Netherlands, the estuary of the Hollands Diep and Haringvliet was closed in 1970. Material suspended in the waters of the Rhine and Maas rivers (silt) now settles in the delta as a result of the reduced flow velocity. This material is considerably polluted and large areas of the basin are now covered with contaminated sediments.
The Dutch Government is considering measures to clean-up 'hot spots' and to store the spoil in controlled disposal sites (e.g. ref.3,4). Dredging and treatment of the sediments will only be effective if the supply of contaminated sediments is stopped or greatly reduced. Thus in the short-term, measures are needed to reduce the inflow of contaminated silt.

Efforts are being made at both national and international level to reduce the load of toxic substances in surface water from industrial, agricultural and domestic effluent. Improvements of the water quality and suspended material (silt) are considered to be the long-term approach. In the short-term, preventive measures need to be taken to reduce the quantity of sediments in the delta by minimizing the inflow of contaminated silt.
In many places in the Rhine and Maas delta, short-term measures are needed because of:

- the continuous supply of suspended and re-suspended contaminated silt in the Rhine and Maas river delta;
- a place is needed to store the spoil from dredging to maintain the navigation depth (maintenance dredging) in the shipping channel in the basin;
- some parts of the delta are so seriously contaminated that fauna are endangered.

Studies have shown that cormorant populations in a National Park in the delta area are seriously depleted.

FEASIBILITY STUDY

Witteveen+Bos consulting engineers of Deventer and Van Oord-Werkendam bv contractors of Werkendam carried out a feasibility study on ways to reduce the environmental impact on the Hollands Diep and Haringvliet, together with a solution for disposal of dredging spoil.

Specifically, the feasibility study prepared preliminary designs for:

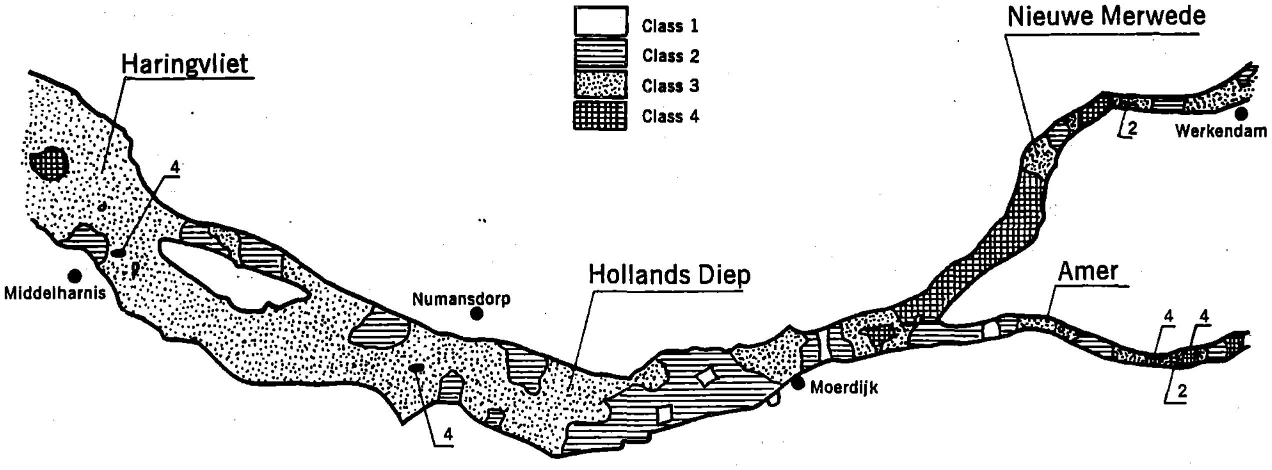


fig. 2 Contamination by polychlorinated biphenyls of the sediment in the Delta basin. The sum of the concentrations of all polychlorinated biphenyls in the sediment is plotted. The most polluted areas are in the Amer and the Haringvliet. Concentrations are represented by the classification as used in the Netherlands to decide on dumping for dredge spoils. Class 1 means concentrations lower than 0.02 ppm, class 2 means concentrations ranging between 0.02 and 0.2 ppm, class 3 means concentrations between 0.2 and 0.4 ppm, class 4 means concentrations higher than 0.4 ppm.

- a silt trap to reduce the load of suspended material in the waters of the delta;
- disposal sites for dredging spoil from construction and maintenance of the silt trap and from 'hot spots' elsewhere in the delta.

The silt trap is to be located in the most upstream part of the delta (e.g. fig.1) and the disposal sites in the mid-section of the delta.

A cost-benefit analysis was done in order to ascertain whether sand exploitation as a result of construction of the silt trap and disposal sites would contribute to making these environmental measures financially feasible.

SILT TRAP

The silt trap can be described as a widening and deepening of the river bottom to create a favourable location for the suspended silt to settle.
The proposed location and cross-section of the silt trap is shown in Figure 3 and 4. This is an area of about 270 ha which is to be deepened to about 15 m below sea level. Sand winning is economically feasible to this depth, because below this level, there is a hard clay layer of the Kedichem-tegelen formation.

During the building of the silt trap six million m^3 of polluted dredging spoil and 15 million m^3 sand will

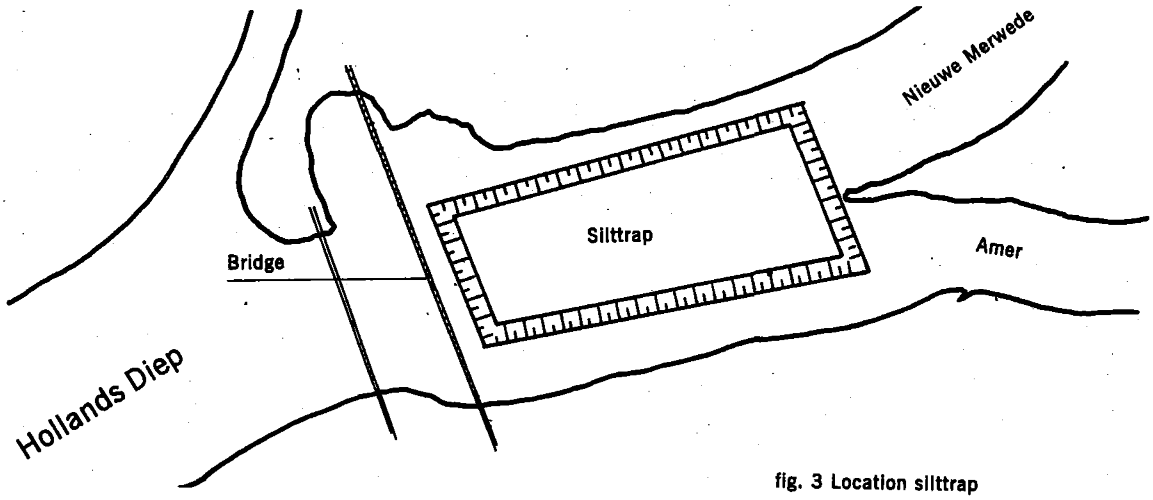


fig. 3 Location silttrap

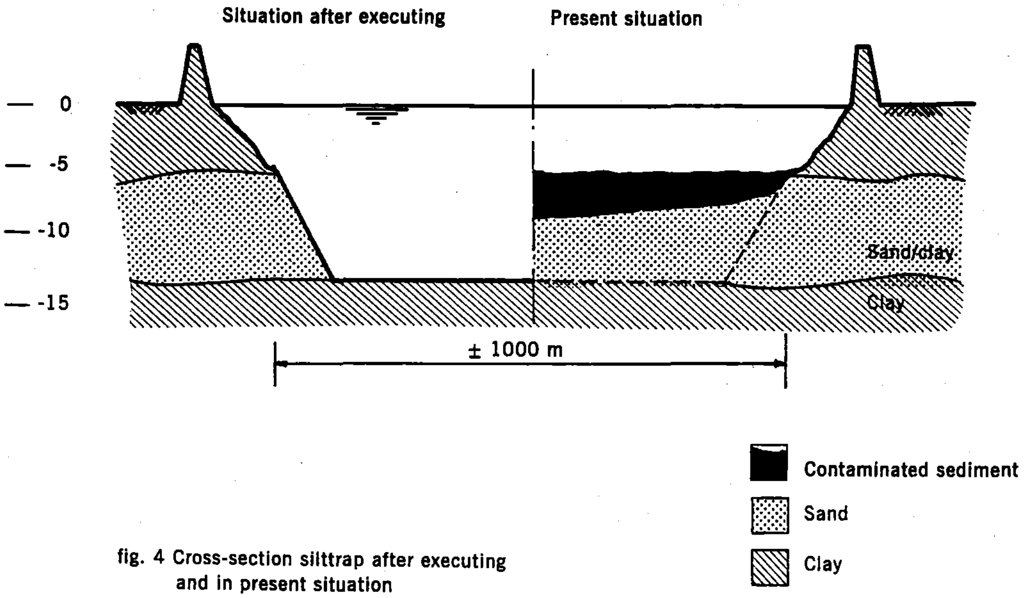


fig. 4 Cross-section silttrap after executing and in present situation

be displaced. Provision is made for construction of disposal sites for the dredging spoil.

Simulation model

A simulation model was used to estimate the effectiveness of these measures. For the purpose, the delta basin was divided into 25 units, each 2,000 m long. For discharge series, the weekly average discharge was used together with the concentration of suspended silt. The computer model SEBE (e.g. ref.7), which was adapted for this study, is based on a one-dimensional sediment equation of the sedimentation, re-suspension and consolidation processes.

The sedimentation transport equation is derived from a one-dimensional equation for suspended sediment transport. The equation takes into account the velocity of the particles, sedimentation chance (e.g. ref.11), the width of the silt trap, river discharge and the location.

The re-suspension term in the model was formulated by Partheniades (e.g. ref.10) and depends on the relationship between the sliding tension rate and critical sliding tension rate.

Consolidation of the silt is a time-dependent process. The consolidation equation takes account of a slow build-up of silt most recently placed on top. The model is based on the empirical relationships for consolidation of dredging spoil prepared by the Rotterdam Municipal authorities (e.g. ref.12).

The variables used in the model are partly dependent on the system. They were estimated with aid of data from the literature and after calibration of the model by comparing the sedimentation build-up in the period 1970-1985 (e.g. ref.8,9)with the calculated sedimentation build-up.

Calculation with the SEBE model indicates that over a period of approximately 25 years a large proportion of inflowing polluted silt will settle in the silt trap.

Each year some 4.4 million m^3 of silt enters the delta of which about 9 million m^3 flows into the North Sea and a part is drained by side branches out of the basin. The remainder settles in the delta basin. It is calculated that one million m^3 per year will settle in the silt trap, that is an efficiency of 30 to 40 %.

Advantages of the silt trap

The silt trap will reduce the environmental impact of polluted silt on the delta considerably.
The sediment will be largely concentrated in one place, thus preventing re-suspension in the most sensitive area. The advantage of locating the silt trap in the designated place is that the Pleistocience clay layer about 15 m below sea level limits the infiltration of pollutants into the groundwater, because the contact surface between the polluted silt and the permeable sand is 50 times smaller.
Reduction of the maintenance dredging required on the shipping channel in the Hollands Diep and exploitation of sand associated with the construction of the silt trap could lead to an overall reduction in costs.

Disadvantages of the silt trap

Both large and small silt particles will settle in the silt trap, but the fine particles will bypass the silt trap and settle elsewhere. The disadvantage is that on the one hand the fine particles containing most of the pollutants will not enter the silt trap, and on the other hand, covering the existing polluted sediments with less polluted sediment is slowed down.

DISPOSAL SITES

The starting point for the design of disposal sites is the creation of large-scale controlled storage locations for polluted dredging spoil from the Rhine and Maas delta.

Two disposal sites are proposed, one for class IV spoil and the other for class II/III spoil (e.g. fig. 6). Both sites will be underwater. The results of a recent study (e.g. ref.1) indicate that from the point of view of environmental impact, polluted dredging spoil is preferably stored in deep pits underwater. Because of the specific chemical (e.g. ref.5,6) and

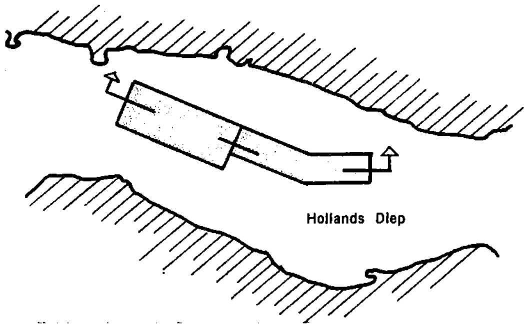


fig. 5 Location disposal sites

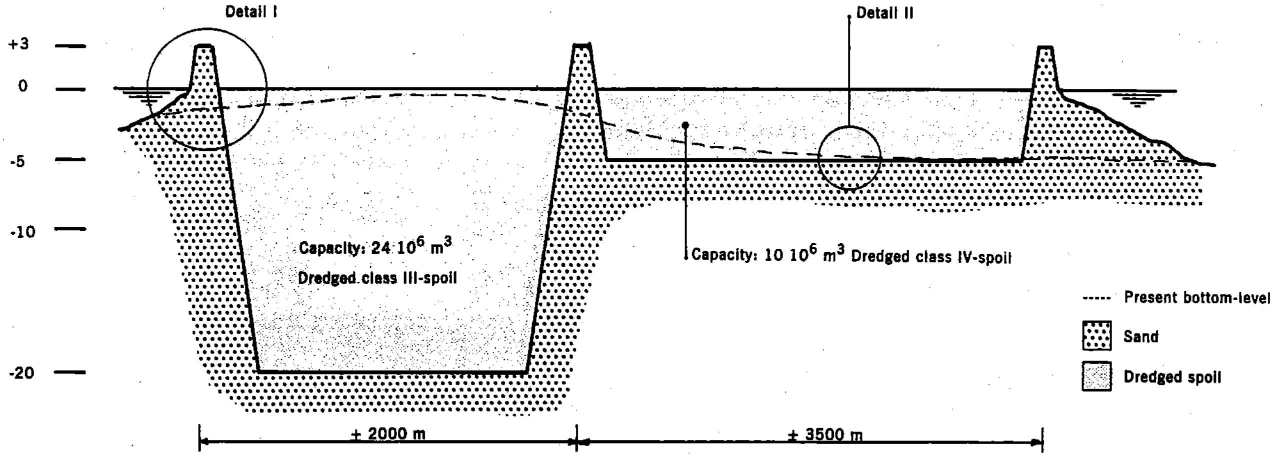
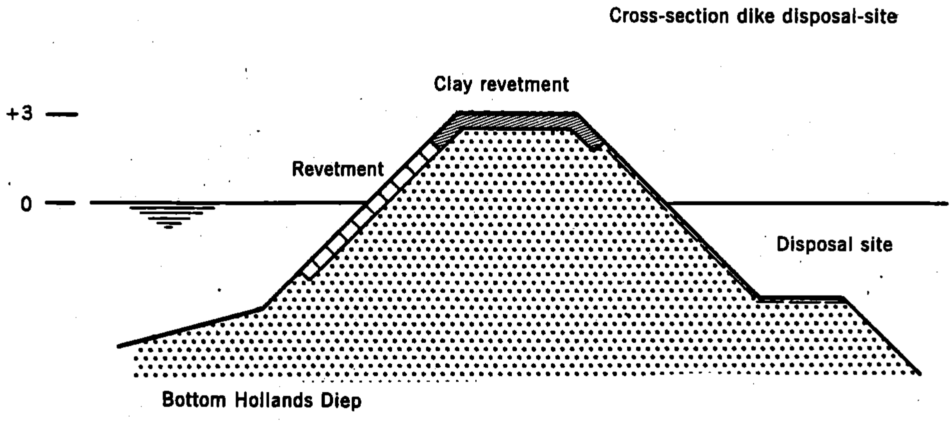
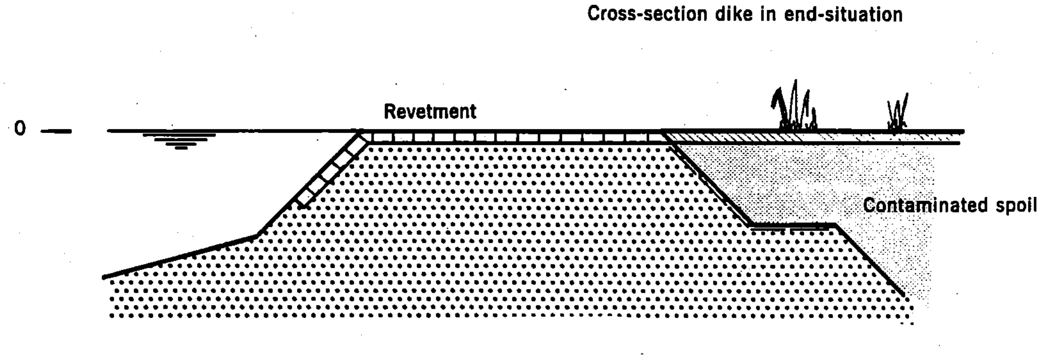


fig. 6 Cross-section disposal sites



Detail I



▬ HDPE-coating

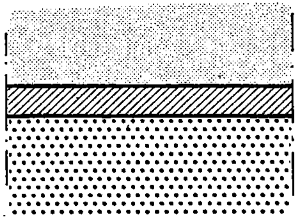
▧ Isolation layer consisting of geotextile and clay

⛶ Sand

▥ Revetment

▨ Clay revetment

Detail II



▒ Dredged spoil

▨ Isolation layer consisting of clay or not contaminated Dredged spoil

⛶ Sand

geohydrological conditions which prevail in underwater storage, the risk of dispersal of contaminants is reduced. The long-term effects of underwater deposition are probably more favourable than deposition at ground level.
The effects of diffusion and dispersion play an important role here.

In the selection of a location for the disposal sites the following considerations were taken into account:

- storage locations had to be in the area managed by the Department of Public Works (Rijkswaterstaat);
- minimal effect on the discharge regime of the Hollands Diep;
- minimal hindrance to commercial shipping;
- limiting the transport costs from dredging to disposal sites;
- limiting construction costs.

The most favourable location was close to the north bank as shown in Figure 5. A cross-section of the two disposal sites is presented in Figure 6. Details I and II (e.g. fig.6) present a cross-section of the ring dikes and the revetment. Each sites is 175 ha in area and they can store 24 million m^3 of class II/III spoil and 10 million m^3 of class IV spoil.
In constructing these disposal sites about 22 million m^3 of sand has to be removed.

After filling the disposal sites and consolidation of the spoil, ring dikes can be dug to the average water level in the Hollands Diep and the sites can be covered with sand and clean clay (e.g. fig.6, detail I). This will largely overcome any objections to the visual appearance of these disposal sites (atoll idea).

An additional advantage is that a clean-up of the polluted sediments in the nearby National Park being developed, 'de Biesbosch'(e.g. fig.2), is possible now that a disposal site is to be constructed in the immediate vicinity.

The plan fits into the Dutch Government policy to create a number of large scale disposal sites in The Netherlands. This policy is set out in the fourth Nota Ruimtelijke Ordening (physical planning) and the third Nota Waterhuishouding (water management).

DISCUSSION

A silt trap of the dimensions proposed in the study would catch about 30 to 40 % of silt entering the delta. In order to increase this proportion substantially, a wider and longer silt trap would need to be constructed. But this would not be possible in the present situation because of the intensive land use and the infrastructure in the area. A deeper silt trap would not improve the situation, however, because the relationship between the sedimentation rate and the flow velocity would not change.
The silt trap will contribute considerably to limiting the uncontrolled dispersal of poluted silt entering the delta from the Rhine and Maas.

The disposal sites are designed to store dredging spoil underwater instead, as is more commonly the practice, on land. Preferably, this sites should be constructed in the centre of wide waterways or estuaries because this reduced the infiltration rate to the groundwater resourses. The geohydrological situation of the site in the Hollands Diep is very favourable, because theoretically groundwaterinfiltration does not occur.

The detailed plan for a silt trap, disposal sites and sand winning is specially developed for the Rhine and Maas delta. However, this plan can be adapted for other deltas or parts of them.

CONCLUSION

From the study it appears to be possible to take measures in a delta area to improve the environmental condition of the water and sediments. By constructing a silt trap in the upstream of the delta, it is possible to reduce the environmental impact of polluted silt on the delta. By constructing disposal sites it is possible to store dredging spoil and the spoil from the silt trap. Furthermore, polluted spoil from the delta area can be stored in an environmentally acceptable way.

A cost-benefit analysis demonstrates that sand exploitation required for construction of the silt trap and disposal sites would contribute to making these measures financially feasible.

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MATHEMATICAL MODELS AS AN EVALUATION TOOL FOR THE EXPERIMENTS WITH CONTAMINATED DREDGED MATERIALS IN THE GEUZENHOEK DISPOSAL SITE

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ABSTRACT

At the request of the Belgian Ministry of Public Works a series of pilot scale disposal sites for contaminated dredged material were installed (1). By varying the isolation facilities (barrier systems) for the disposal sites the effect on the resulting spread of pollutants to the environment is evaluated.

The authors are instructed to create mathematical models to evaluate the data obtained from the monitoring network. The results of migration computations indicate that the response time of monitoring wells in the reference site (no barriers) exceeds the time span of the study. Therefore it is necessary to monitor the leaching processes in the unsaturated zone. Accordingly the appropriate sampling configuration was installed.

By performing calculations with a coupled model linking unsaturated zone transport with a model for simulating chemical equilibria in soil, it became clear that during the first 6 months of operation no breakthrough of the heavy metal zinc is expected. During this period zinc will be adsorbed on iron(III)hydroxides which are precipitated as a result of the initial oxic state of the unsaturated zone. However when this oxygen is exhausted reduction and dissolution of iron(III)hydroxides occurs with the subsequent release of adsorbed zinc. At this stage the zinc concentrations can exeed even the upper boundary concentrations.

The prototype model will be calibrated with the monitoring data. The resulting validated model may then be used for evaluating the environmental risks of large scale disposal sites and the operational efficiency of the different types of barriers.

INTRODUCTION

The silting up of estuaries, deltas and waterways is an inevitable phenomena and the need for dredging them to allow shipping access to the ports established there is an undisputed economic necessity. Unfortunately the material to be dredged is contaminated, often severely, with practically the whole range of chemical pollutants currently associated with the modern industrialized and agriculturally intensive hinterlands of these waterways. The disposal of these dredged materials in an economic and environmentally acceptable way has become one of the major management challenges of the port and waterway authorities concerned.

The issues involved are well known and require compromises between environmental impact, land use management and economic factors and between short term and long or even very long term advantages or dangers.

Modern disposal strategies depend on two main techniques that underpin the engineering design of the disposal facility:

1) Short term Risk and Cost Benefit Analysis.
2) Long term "fail-safe" design concepts for the site, even beyond the point of "loss of institutional control" (2).

In a major program designed to delineate the factors and parameters that can contribute to satisfying these two, often conflicting, design boundary conditions, the Belgian Ministry of Public Works has initiated a series of pilot scale disposal projects at the Geuzenhoek site near Gent. The main goal of this project is to evaluate the performance of different types of barriers and to assess the reliability of the risk assesment of sludge disposal sites. As part of this project, the authors have been instructed to construct a mathematical framework within which the results are to be interpreted.

In this paper a description will be given of the basis of the models and the preliminary calculations so far performed. As the project has just started it is anticipated that more information will be available in due course.

THE GEUZENHOEK PROJECT

Essentially the Geuzenhoek project is quite simple. Dedicated large scale lysemeter cells have been constructed within which a standard contaminated dredged material from the Gent-Teunessen canal can be pumped. These sites are lined with various propriatory barriers claimed to prevent the spread of contaminants from the cells by groundwater. One cell has been established without any special barriers to serve as the base line measurement. The cells and the soils under them are heavily instrumented and monitored. Furthermore the whole project is embedded in a total containment site so that all possible environmental impacts to the wider surroundings have been eliminated. The details of the project have been reported by Van den Eede (1).

In the project considerable attention has been devoted to the methodology of interpretation. It is anticipated that at least some, if not all (including the no-action base case), cells will have very high containment performances. The question then arises as to the value of a zero result expected in the monitoring strategy, did this occur because the barriers did indeed interdict the flux of contaminants, or were the measuring techniques themselves inadequate? This question can only be properly addressed within a verified model of the experiment as a whole, in which the processes involved are understood and related to each other in a practical manner. This is one of the functions of the so-called mathematical model for the experiment.

A second problem that arises is that of the applicability of the results from the pilot study to a full scale site. Obvious differences between the pilot study and a prototype are, for example, the embankment:base area ratio, the depth of disposed material and its associated consolidation parameters, the dredged material quality, both chemical and physical, the geohydrological setting and most importantly, the time scales involved. Again, through a detailed understanding of the processes involved and their integration into an overall model it is anticipated that this problem can be adequately addressed.

A final goal of constructing the mathematical models is that in due course, it will be possible to perform a sensitivity analysis, relating data base requirements, monitoring requirements and performance expectations, in a verified context. This will enable clear guidelines to be drawn up for performance assessment of new designs, for new sampling strategies and, from the environmental point of view the most important, the specification of the requirements of an adequate monitoring system.

THE ELEMENTS OF THE MODEL

The structure of the model is based on the Source-Path-Target subset of the risk analysis methodology (3). The system is considered to consist of three major units, the source of contaminants, in this case the dredged material, a target towards which the materials emitted from the source migrate, and a pathway connecting source and target.

The target is taken to be the various monitoring points in the system such as collection drains and stand pipes. These measuring elements are themselves active members of the system with their own response characteristics which have to be taken into account.

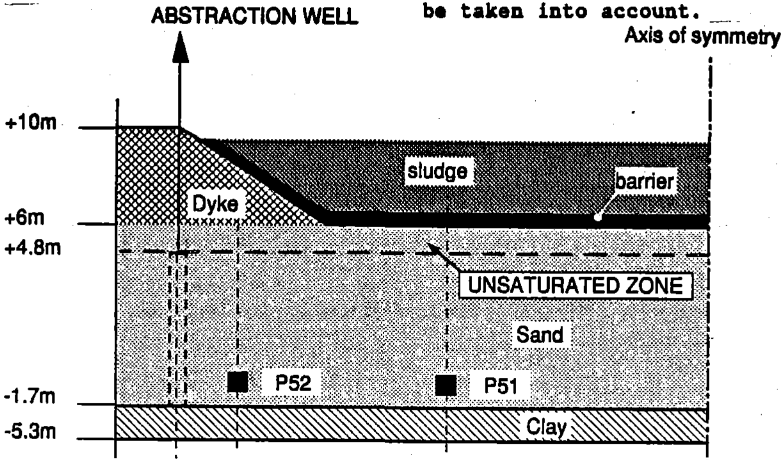

Fig.1 measuring option 1 - monitoring the saturated zone

The processes occuring in the dredged material are both physical and chemical. They include sedimentation, consolidation and possible aggregation as well as strongly changing pH and RedOx conditions. Pore water fluxes will be initially dominated by the excess transport of water and later by consolidation over-pressure gradients. Finally infiltration will be the major leaching mechanism. As it is intended to pump off any ponded water during the course of the trials, and to maintain an unsaturated zone under the site, the actual fluxes will be a function of the permeabilities of the dredged material and the liners. These will vary in time.

The model for the site is based on a quasi-one dimensional column driven at changing rates and assuming chemical equilibrium. A coupled convection-dispersion and chemical equilibrium code is used. At this point in time it is unclear whether or not a consolidation sub-model will have to be used as well. Equally it will depend on the uniformity of filling as to how many of these columns in parallel will finally be used to model a particular cell.

Five distinct pathways for the migration of chemicals from the site into the surroundings have been identified:

1) Wind erosion of dry contaminated material.
2) Wet erosion of the site.
3) Direct uptake in the biosphere.
4) Leaching through surface water run-off.
5) Infiltration and leachate through the site and into the geosphere.

The experiments have been designed to gain detailed information on barriers effective against the last pathway although some incidental information may be obtained on the fourth pathway.

The essential element in the system is the barrier, either engineered or natural between the dredged material and the sands underneath the site. Two aspects of the barrier have to be considered in the path model module. Firstly the efficiency of the barrier itself. This can be simply modelled as a one dimensional column transfer function again involving chemical and physical processes. However one cause for concern in these thin barriers is leakage either through cracks and fissures or by gross failure. The final transfer function can be generated by a quasi-parallel plug flow and by-pass reactor model.

By fitting the results of the study to the model it will be possible to assess the barrier efficiencies of the various processes both from a physical and a chemical point of view.

CURRENT STATUS OF THE PROJECT

At the time of writing, the project has progressed to the point where the cells have been constructed but not yet filled. Accordingly, the model results have been restricted to those needed for the design of the cells and the monitoring system.

One of the key questions to be answered at this stage is the expected time to response at a monitoring point for a system without any barriers. Breakthrough at the measuring point (target) has to be ensured within the two year time span of the experiment. Two measuring options are available:

1) via sampling in the well points in the saturated zone.
2) directly in the unsaturated zone under the barrier.

SAMPLING IN THE SATURATED ZONE

Simplicity, expense and similarity with the actual disposal sites favour the first option. Simulation studies were made using the target model described above for the unsaturated zone and the saturated zone separately and it has been shown that it is unlikely that significant concentrations will be measured there in the time scale of the tests. This is illustrated in fig 1, 2 and 3. Figure 1 shows a vertical cross-section of the experimental disposal site, with the harbour sludge, the barrier, unsaturated zone and monitoring wells in the saturated sandy layer.

The response curve at the phreatic surface of a conservative tracer, released from the barrier is computed by the unsaturated migration model ONZAT (4). The results for two sandy soils (5) are given in figure 2. The 50% breakthrough time is more than 2 years. Due to the lower water content of the medium fine sand the response is faster than the fine sand.

The spreading of a immision of a tracer at the phreatic surface after 2 years is illustrated by figure 3. The computations were performed with the 2-3D finite difference migration program VERA (6). The 10% iso-concentration line has not yet reached the abstraction well. In the monitoring wells P51 and P52 the concentration is less then 1% of the concentration at the phreatic surface.

The conclusion of these computations is that the response time of this measurement configuration is too large for the purpose of the experiments.

Accordingly a second sampling strategy was developed where filter mats are placed with a slope of 1.5% in the sand under the barriers or the base of the site (fig 4). These then lead into a central collection point in the middle of the site for sampling. The collection well volume can be varied to change the residence time in the sampling system. The results of simulations of this measuring system are shown in figure 5. As can be seen, with this strategy tracer breakthrough can be expected in the time scale of the test for a zero barrier system. This ensures that a zero breakthrough result for one of the proposed barriers will be a significant result. The filter mats have accordingly been installed.

However for a non-tracer case the situation is more complicated. Simulations which have taken into account the possibility of chemical interactions both in the unsaturated zone and in the mats have shown that in an initial period when oxygen is still present in the unsaturated zone, iron will precipitate and not be found in the sampling system and that, for example, zinc will be strongly adsorbed on the iron oxide precipitate. When the oxygen is exhausted, the iron will be reduced and the zinc will be released. This process is also illustrated in figure 5. The method of coupling chemical reactions and groundwaterflow is discussed in (7). It is assumed that the adsorption of zinc is linear with the zinc concentration in solution and with the concentration of precipitated iron(III)hydroxide. As a result of the adsorption on the ironhydroxide, the relative concentration of zinc is lower than the relative concentration of the tracer. After the depletion of the oxygen the iron(III) is reduced to soluble iron(II) and the accumulated zinc is released. The computed concentrations supersede the tracer concentrations. After 0.7 year the computed concentrations are even larger than the concentration near the inflow boundary.

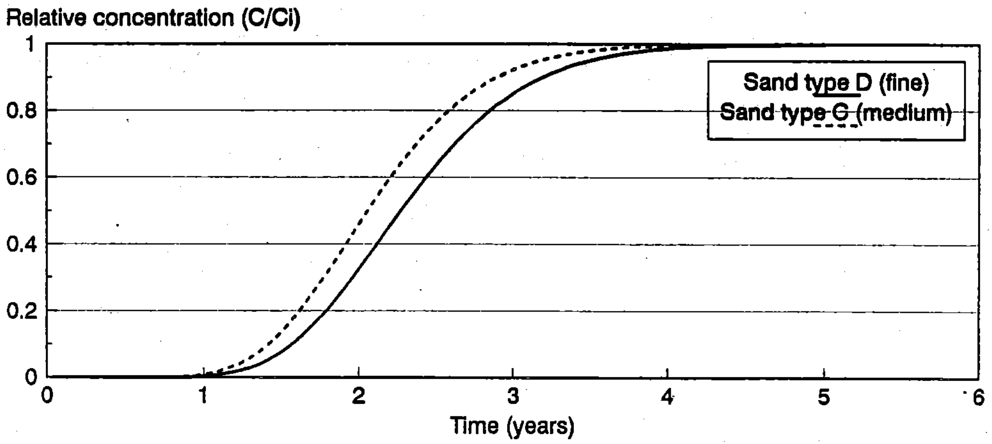

Fig.2 Response unsaturated zone
Proefstort Geuzenhoek - configuration 1

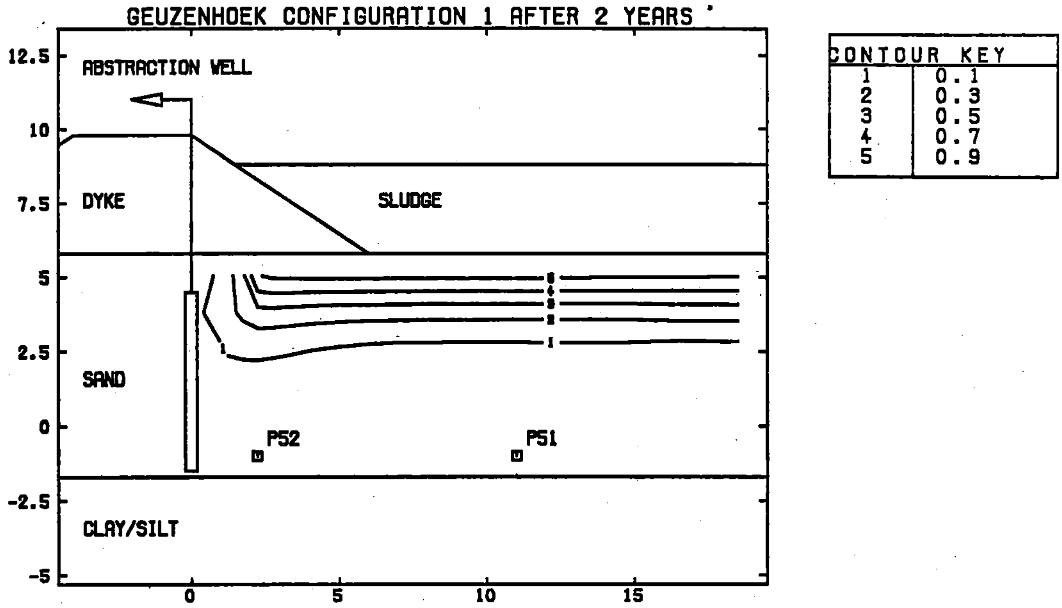

Fig.3 Migration of the tracer in the saturated zone
Boundary condition C=1 at T=0 at the phreatic surface .

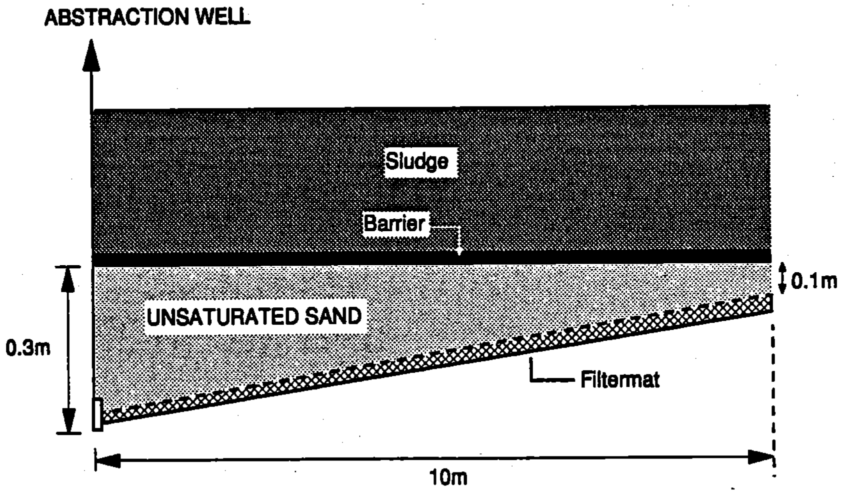

Fig.4 Schematic view of measuring option 2 - monitoring the unsaturated zone

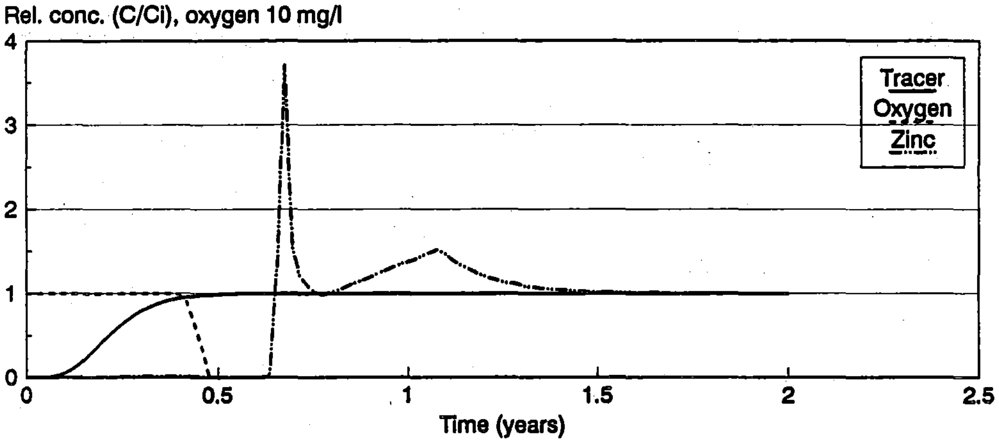

Fig.5 Response unsaturated zone + filter mat
Proefstort Geuzenhoek - configuration 2

DISCUSSION

These results, given here as illustrations, demonstrate that a presimulation of such a long term and expensive large scale experiment, is essential in order to avoid errors in design and to maximise the value of the data obtained. In the nearest future experiments on different scales (shake test, column experiments and the large field tests will be performed. Using the experimental results calibration and validation of (sub-) models takes place. These models can be then used for the evaluation of the effect of the barriers.

The validated models may also used for scale extrapolation of the field experiments. In this way reliable risk-assesment of disposal sites is possible.

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PROJECT STUDIES AND MANAGEMENT

THE CLEANING-UP OF CONTAMINATED SEDIMENTS IN THE NETHERLANDS

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ABSTRACT

About 150 - 200 million m³ of sediment in the Netherlands is heavily contaminated. The policy of the Dutch government pursues two tracks: prevention and clean-up. In 1989, a limited number of clean-ups were started in order to gain experience.

Concerning clean-up attention will be focused in the future to both storage and the application of treatment activities like separation and purification. The next years storage depots will be build and treatment techniques will be developed.

INTRODUCTION

The sediment in many water courses in the Netherlands is heavily contaminated, in such a way that these are risks to public health and environment. The degree of pollution differs from place to place and varies from slight to severe.

Contaminated sediment forms a source of diffuse environmental pollution.

The risks for the environment are mainly due to the absorption of these substances into the biological food chains and the further spreading of the polluted sediments into vulnerable regions, such as the North Sea, The Wadden Sea and the estuaries. Apart from this the quality of the ground water appears to be threatened.

In this paper an overview of the scope of the problem, the governmental policy developed in the last years and the governmental activities in the development of treatment processes for contaminated sediments will be given.

SCOPE OF THE PROBLEM

The Netherlands lies in the delta of the Rhine, Meuse and Scheldt rivers. A characteristic of deltas is that one or more rivers with various branches empties into the sea, and that the tidal rhythm can be felt a considerable distance inland. This tidal rhythm causes the sediment swept along by the rivers and the sea to settle.

Each year, a total of 50 million cubic meters of North-Sea sediment is deposited in the areas near the cost, while 12 million cubic meters of sediment from the major rivers is deposited in Dutch waterways. The pollutants in the water adhere to sediment particles. As a result, the sediment becomes contaminated. This is particularly the case with the sediment deposited by the rivers.

Some of the sediment deposits are found in areas where there are no applicable depth regulations. This sediment could be left to lie, if not for the fact that the pollution poses a serous threat to our environment.

From an exploratory examination of sediments in the national waters in the Netherlands an inventory was drawn up including more than a hundred large and small locations, presenting possible serious danger to public health and environment. Based on this inventory the quantity of heavily contaminated sediments in rivers, canals, lakes and harbours is estimated at 22 million m³ (figure 1)(1).

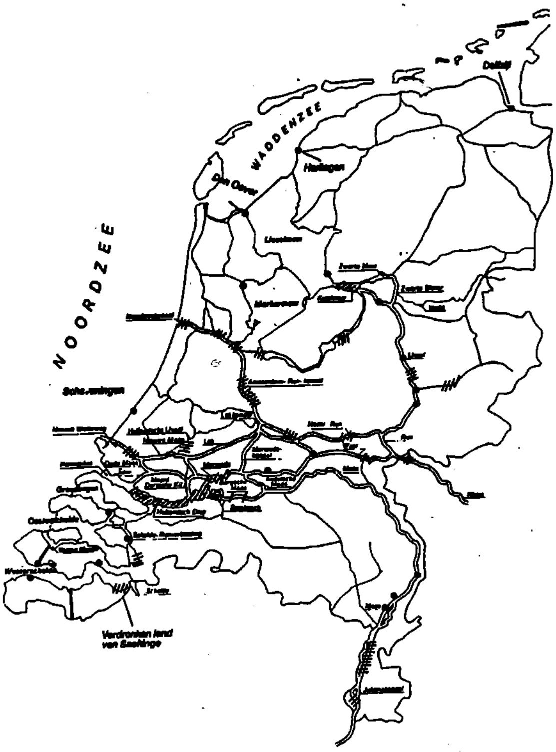


Figure 1: Contaminated sediments in the Netherlands (national waters)

Also the situation in regional waters was investigated: about 9 million m^3 of the sediment in lakes, city canals, polder waters, small canals, brooks and harbours are heavily contaminated.(2)

The majority of the sediment deposits are found in harbours and shipping waterways where the navigability is subject to regulations.
Large quantities of spoil (50 million m^3) are dredged every year to keep these water ways at a proper navigable depth. For many years this dredged material has been used for landraising or has been dumped into the sea. Nowadays only 40 million m^3 of lightly contaminated spoil is dispersed in the sea. The other 10 million m^3 is too heavily polluted that further treatment is needed. In the last year about 8 million m^3 could be stored in depots and 2 million m^3 was dredged because of the absence of solutions. If there are no such depots, maintenance stagnates, shipping traffic is obstructed and harbour activities experience difficulties.
The problem of polluted sediment can be calculated: for the next twenty years about 200 million m^3 spoil, dredged for environmental and navigable reasons, had to be treated.

The qualitative side of the problem can be summarized as follows. Table 1 contains concentrations of a number of pollutants, found in sediments of national waters. Also the number of times of exceeding the quality objective standards for the year 2000 (minimum protection level) is given in relation to the measured average, maximum of 90-percentile concentration.

Table 1: Contaminated sediments in the Netherlands (national waters).

	concentration in sediment				excess of standards (number of times)		
	average	90 perc.	max.	number of measurements	average	90 perc.	max.
arsenic (mg/kg)	24	45	421	2688	0,3	0,5	5
cadmium	6	18	185	2734	3	9	90
chromium	106	247	1494	2891	0,2	0,5	3
copper	84	180	5593	2723	2	5	160
mercury	2	4	155	2543	4	8	300
lead	157	325	7024	1347	0,3	0,6	13
nickel	38	67	681	2655	1	2	19
zinc	800	1778	58199	2873	2	4	20
oil	1515	3333	48462	2803	0,3	0,7	10
EOX	10	17	1516	2786	2	3	275
PCB 28 (µg/kg)	49	140	21429	2677	12	35	5300
PCB 52	32	128	2820	2676	8	32	700
PCB 153	30	127	4550	2677	8	32	1130
γ-HCH	< 4	9	483	1583		9	480
aldrin + dieldrin	< 5	15	5179	1774		1	130
fluoranthene(mg/kg)	4	7	481	3001	13	23	1600
benzo(k)fluoranthene	1	2	318	2887	5	10	1590

The table above shows that the desired quality objective is regularly exceeded by tens to hundreds of factors for many substances, particularly cadmium, copper, mercury, PCB and PAH (polycyclic aromatic hydrocarbons).
In the Netherlands the problems of the contamination of the sediment are nowadays fully recognized by society and politicians. For some years research programmes have been started concerning different aspects of the problem, e.g. monitoring, transport of sediment, behaviour of pollutants in aquatic sediments, effects on aquatic live, and preventive and remedial technologies (3). Dutch policy is nowadays concentrated on solving in stead of studying the problem.

POLICY ON CONTAMINATED SEDIMENTS

Water management

The policy concerning the problem of contaminated sediments is outlined in the "Third National Policy Document on Water Management" (4). The final goal is formulated as follows:

- *a sediment quality such that there are only negligible risks for the functioning of balanced aquatic ecosystems;*
- *dredging spoil quality such that dispersion and reuse are possible without question;*
- *aquatic sediment which is polluted to such an extent that it represents a serious danger to public health, the environment, the functioning of the aquatic ecosystems and the use of ground water, is cleaned up.*

It is assumed that the sediment and the silt carried along by the rivers will be clean again in about twenty years. To bridge the period the following interim goal for the year 1995 is formulated as follows:

- *a number of the most seriously contaminated sediment locations, where there is serious danger to public health or the environment, are cleaned up depending on the means available;*
- *at least two of the required large-scale storage depots for contaminated dredging spoil*

and spoil from cleaning operations are realized;
- *reuse of 2 million m^3 treated dredging spoil.*

These objectives mean that a two-track policy must be pursued: the track of prevention of water pollution and the track of cleaning up of contaminated sediments. Priority is given to preventive measures in order to prevent the problem lingering on for many years to come. Since the Pollution of Surface Water Act (1970) has been operative, a great deal has been achieved in this preventive area. The emissions of oxygen - consuming substances has been greatly reduced. In the Third National Policy Document on Water Management it is indicated that measures should be taken to reduce the emission levels further on, especially with regard to organic micropollutions. This means that for most substances pollutant sources will have to be reduced by 50%, and for some substances even by more than 90%. With the implementation of The Rhine and North Sea Action Programmes, beside others, we are on the right road to realize the above mentioned targets.

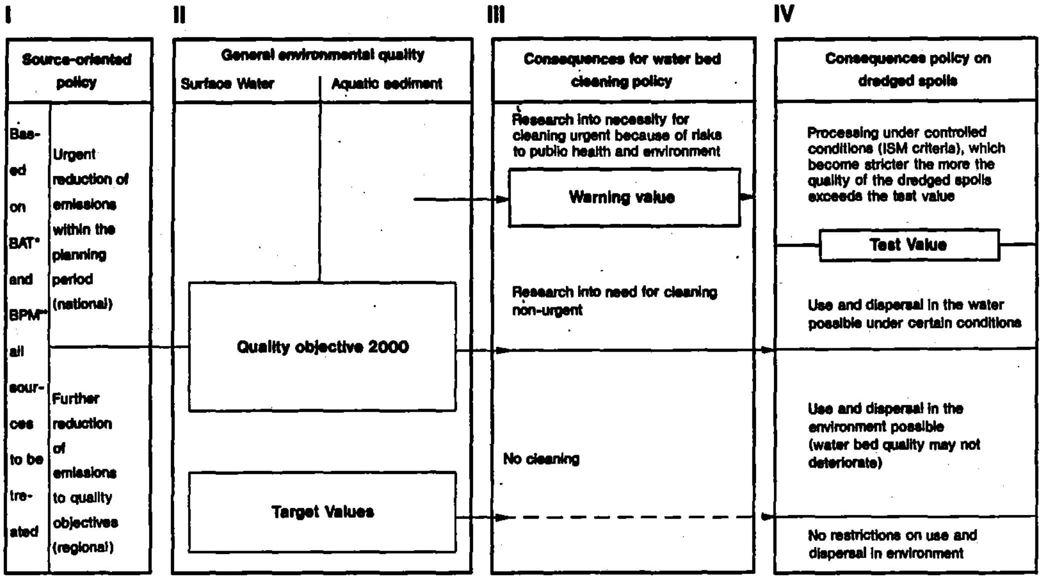
Concerning the second track of curative measures, attention will be paid to both storage in large spoil storage depots and treatment activities like separation and purification for the purpose of volume reduction and destruction of pollution in order to reduce the total amount of spoil to be stored.

Standards

For the practical implementation of aquatic-sediment cleaning-up and for coping with dredging spoil different standards are formulated. In figure 2 the relationship between general environmental quality, the test value and the warning value of sediment is illustrated schematically.

The following are explanatory notes to figure 2:

- *the direct emission approach (block I) is based, in accordance with the Water Action Programme 1985-1989, on cleaning at source with the aid of the best technical and best practicable means (B.T.M. and B.P.M.);*
- *the general environmental quality (block II) has a minimum protection level (quality 2000) and a target level for which the risks are considered to be negligible. This means that the target values should be attuned to the aquatic environment as well as to the soil. At present no soundly-based target values can be formulated;*
- *a warning value is given for the aquatic-sediment cleaning-up policy. If this value is exceeded then research into the necessity of cleaning is urgent;*
- *five categories are distinguished for the storage of dredging spoil (block IV);*
    - *spoil of a quality equal to or worse than the warning value for sediment must be stored under strict ISM conditions (Isolate, Store and Monitor). This means controlled dumping on the land or in deep under-water pits;*
    - *spoil of a quality falling between the warning value and the test value should, where possible and sensible, be stored under ISM conditions; the strictness of the conditions depends upon the degree of contamination of the spoil;*



* Best available technology

** Best practicable means

Figure 2: Relationship between general environmental quality, the warning value and test value for aquatic sediment (7).

- *spoil of a quality falling between the test value and the general environmental quality (quality objective 2000) can, under certain conditions and depending on the local situation, be dispersed or utilized in the water; an important principle here is that no worsening of the quality of the aquatic sediment must occur in the area concerned;*
- *spoil of a quality equal to or better than the general environmental sediment quality (quality objective 2000) can be dispersed in the aquatic environment, as long as no worsening occurs here either;*
- *spoil which complies with the target values can be used or distributed, without problem, on the land or in the water.*

In table 2 numerical values of the standards for a selected number of substances are presented.

Table 2. General environmental quality (quality objective 2000), test values and warning values for sediment (4)

sediment = content in sediment in water bed (in mg/kg), converted to standard sediment (10% organic matter and 25% lutum)

parameters	quality objective 2000	provisional test value sediment	provisional warning value sediment
cadmium	2	7.5	30
mercury	0.5	1.6	15
copper	35	90	400
nickel	35	45	200
lead	530	530	1000
zinc	480	1000	2500
chromium	480	480	1000
arsenic	15	85	150
PCB 28	0.004	0.03	0.1
PCB 52	0.004	0.03	0.1
aldrin + dieldrin	0.04	0.04	0.5
γ-HCH	0.001	0.02	0.5
benzo(k)-fluoranthene	0.2	0.8	3
fluoranthene	0.3	2.0	7

Financing

On the basis of the already observed effects caused by the contamination of sediments and mentioned inventories the Cabinet has reserved funds for the governmental period through 1994. 40 million Dutch guilders were available for the years 1989 and 1990. For the period 1991-1994 about 140 million Dutch guilders will be added.

Sediment Clean-up Programme 1988-1990

Execution of the policy described above is based on the Sediment Clean-up Programmes.
The first Sediment Clean-up Programme for the period from 1988 to 1990 comprises three types of activities:

a. cleaning-up of five contaminated sites
b. execution of the Development Programme Treatment Processes (phase I, 1989-1990)
c. drawing-up of a Report on the Effects on the Environment (REE) for contaminated sediment storage depots.

ad a

In 1989 the cleaning-up of contaminated sediments was initiated on a limited scale in order to gain experience for the clean-up planned in the 1990's.
Clean-ups take place if and when there is a serious threat to the public health or the environment.
Determining factors include:

- the nature and the concentration of the pollutants;
- the extent of local pollution.

In determining clean-up priorities, the following factors are taken into consideration:

- which use is made of the sediment and the water, for example: swimming, fishing, etc.;
- degree of risk of additional contamination as a result of the transportation of contaminated silt or absorbtion by organisms;
- influence on the quality of the surface water, ground water and drinking water.

Before deciding on a clean-up, the source of the pollution must be cleaned up and the new sediment must be of sufficient quality.

Five locations were cleaned up in the period from 1988 to 1990. At four of the locations, the polluted sediment was dredged and the sediment was deposited in a depot. In a number of cases, separation took place before storage.
Separation aims at separating the spoil into a relatively clean fraction and one or more fractions in which the pollution is concentrated.
Separation by hydrocyclones is a method frequently applied in practice. Separation takes place in a centrifugal field on the basis of size and density of particles. The process must be controlled in such a way that it results in a clean coarse fraction and polluted fines.

The following problems were encountered during the clean-ups:

1. the amount of spoil to be dredged proved to be considerably greater than had been originally calculated.
2. the spoil's granular composition proved to be different, resulting in a larger amount of fines to be stored after separation.
3. the coarse fraction after separation was still strongly polluted with tar-like sections.

These problems are partly caused by insufficient number of measures (horizontal and vertical) and by the absence of characterization of the pollutants. More and better preliminary investigation can contribute to a considerable savings in clean-up costs.

An aspect that has long been underestimated in the treatment of contaminated sediment is the way in which pollution is present in the sediment or is attached to the sediment. Certain metals, for example cadmium, adsorb to the sediment as sulfides, particularly to the lutum

fraction, or occur as separate ore particles among sediment particles.
Polycyclic aromatic hydrocarbons (PAH) can be absorbed into the organic dust fraction in the sediment. In the same way, PAH can occur as tar particles in the sediment. It will be clear that the different ways in which pollution occurs determine the process operation and the applicability of separation techniques.
From a technological point of view the hydrocyclone-process can be improved (5).

ad b
The Development Programme Treatment Processes 1989-1994 will be discussed in a next chapter.

ad c
It became apparent that it will be necessary to build about five large-scale storage depots in order to solve the problem of contaminated sediment, at least because of the large quantity of spoil and the costs.
The Ministers of the Environment and of Transport and Public Works have decided to draw up a governmental memorandum regarding national guidelines for the type and set-up of dredging spoil storage depots both on land and under water. A Report on the Effects on the Environment (REE) will be drawn up to support the decision on this. This report is expected in March 1991.
In the REE, attention will be paid not only to the set-up of different types of storage depots, but to the entire processing chain as well, such as: dredging, transport, separation, purification and depositing. In addition, attention will be paid to aspects such as the acceptance of the storage depots, management and maintenance of the storage depot, inspection and monitoring with respect to the environmental aspects, the future use of the storage depot and the after-care.
Realization of the depots involves a great deal of consultation with public authorities, apart from technical completion. It is expected that the first depots cannot be used before 1994/1995. From that moment onwards large-scale clean-up of contaminated sediments in the Netherlands can really be initiated.

Sediment Clean-up Programme 1991-1994

In July 1990 the final Sediment Clean-up Programme 1991-1994 was sent to Parliament (6).
This Programme contains the next items:

a. the clean-up of a few heavily contaminated sediments
b. further quantitative research to determine the nature and scope of the pollution
c. execution of the Development Programme Treatment Processes (phase II, 1991-1994)
d. construction of two large scale storage depots.

ad a
Only a limited number of locations will be cleaned up in the coming years. This is a result of the fact that insufficient storage capacity is available and that treatment techniques have not been adequately developed. Furthermore, additional research is required to determine the nature and scope of the pollution.

ad b.
Before the actual decision is taken for a location to be cleaned up, a phased procedure will be followed for reasons of efficiency.

Phase 1 Phase of Pre-orientation
On the basis of on-the-spot observation, historical information or reports by third parties, it is learned where the sediment is polluted in places. This information leads to the second phase.

Phase 2 Exploratory Research
In this phase initial global insight is gained into the nature and extent of pollution through specific sampling, and besides, a global assessment is made of the scope of pollution. (If the warning values are exceeded, this will give reason to proceed to phase 3).

Phase 3 Further Research
In this phase, research must indicate the risks for human and animal life in the light of environmental hygiene and public health. At the same time, the possible further spread of the pollution into the environment (ground water, surface water) will be examined. The clean-up decision (yes or no) will be based on this extended research. If clean-up is necessary, phase 4 follows.

Phase 4 Clean-up Research
This phase is in fact a method of approach for the actual clean-up. The amounts of spoil to be cleaned up are accurately determined. Clean-up measures, treatment processes and storage facilities are investigated. A time schedule is established and the financial consequences are brought into sight. When the clean-up research is finished, a clean-up plan can be formulated in principle.

Phase 5 Clean-up

Phase 6 Evaluation of Clean-up

DEVELOPMENT PROGRAMME TREATMENT PROCESSES FOR CONTAMINATED SEDIMENTS (1989-1994)

Introduction

If it is decided that polluted locations must be cleaned-up for environmental or nautical reasons, a number of treatment processes is, in principle, available.
Treatment processes are combinations of the following treatment activities:
dredging, separation, dehydrating, purification, immobilization (and storage).

The activities can be carried out in a variety of combinations, resulting in a total treatment process. An example of a treatment process is as follows:

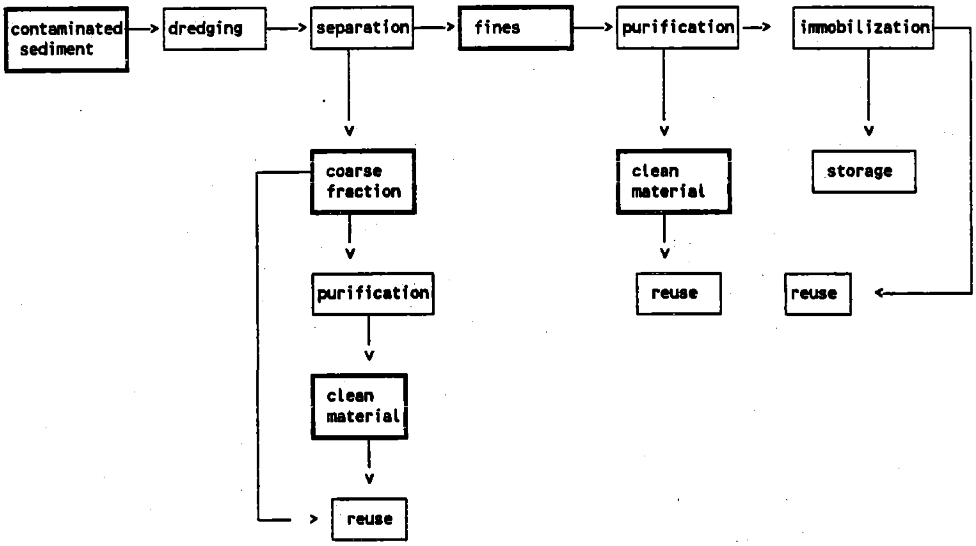


Figure 3: Example of a treatment process for contaminated sediment

Separation techniques are applied in an attempt to concentrate the further treatment on one small, polluted fraction, leaving one ore more clean fractions. The polluted fraction thus created can then be cleaned. In principle, a variety of methods can be used for this purpose: biological, chemical and thermal techniques (figure 4,table 3). In addition, immobilization techniques can be used to isolate the remaining pollution in such a way that it does not pose a short-term or long-term threat to the environment. Finally, fractions which cannot be cleaned must be stored.

It is of vital importance that treatment is considered an integral process of mutually related treatment activities.
The nature and the extent of pollution, but most particularly the manner in which pollution is present in the sediment determine the sequence of treatment activities and, therefore, the treatment processes that are possible in the end.
To be perfectly clear: one singular treatment process for all contaminated sediments in the Netherlands simply does not exist.

Development Programme
A wide range of technologies is available for the various processing operations. Many of these are not yet operational. In fact, the information required about essential parts of the processing methods is lacking, although this information is needed for well-founded policy decisions. Both financial and technical information are lacking. Last year it was decided to set up a research programme with industry to provide information about these matters.

The general objectives of the project are as follows:
1. Determining, through demonstration scale research, the feasibility of the different treatment activities in terms of efficiency (extent of the reduction of the contamination or quantity reduction) and costs.
2. Proposing feasible integrated processing methods for types of contaminated sediment on the basis of research results obtained for treatment activities, which are also aimed at the recycling of at least 2 million m^3 of dredging sludge in 1995.

The following activities will be required to implement the objectives of the development programme:
1. arranging demonstration remediation projects
2. developing specific processing methods at the laboratory, semi-laboratory and pilot scale (applied research)
3. arranging feasibility studies
4. arranging basic research
5. evaluation of past and present clean-up projects

This division into stages of the activities is based on the fact that a processing method has to go through a number of stages from basic research to demonstration project, this being the last stage before a product can be introduced on the market. To fulfil the objective of the project a processing method has to be fully understood, i.e. it should be possible to predict if and when the method can be applied. It should be avoided that the research obtains too much of a "black box nature" due to too rapid scaling up.

The Development Programme is divided into two phases:
Phase I (1989-1990)
Phase II (1991-1994)

Phase I is currently being undertaken and includes the following projects:
- separation
- chemical oxidation by H_2O_2 (PAH and oil)
- electroreclamation (heavy metals)
- bioreactor (PAH and oil)
- landfarming (PAH and oil)

- aerated lagoon (PAH and oil)
- extraction by means of acid/complex-formers (heavy metals)
- biological leaching (heavy metals)
- immobilisation (desk-study of available techniques).

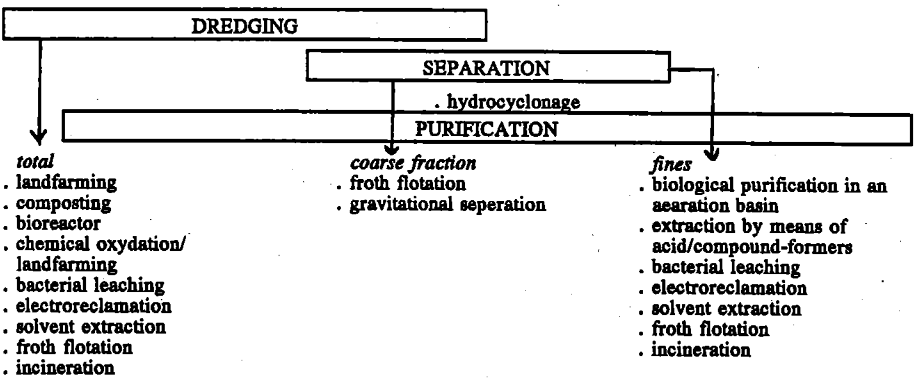


Figure 4: Purification methods for contaminated sediments

The reports about phase I will be presented in the first half of 1991. The results of phase I will provide direction to further research in phase II.

The government has made 3 million Dutch guilders available for phase I and 30 million Dutch guilders for phase II.
The budget will be supplemented by contributions from industry. Industry has contributed 1 million Dutch guilders to the budget for phase I, thus bringing the total budget for phase I to 4 million Dutch Guilders. The business sector will also be participating in Phase II.

Table 3. Purification methods for contaminated sediment.

Purification method	area of application		development stage
biological			
land farming	L	OMIPO	P
composting	L	OMIPO	P
aerating basin	L	OMIPO	P
bio-reactor	S	OMIPO	P
bacterial leaching	L/S	HM	L
chemical			
oxidation w/ hydrogen peroxide	L/S	OMIPO	L
electro-reclamation	L	HM	L
extraction by means of acid and compound-formers	L/S	HM	L
solvent extraction	L/S	OMIPO	L
physical			
froth flotation	L/S	OMIPO,HM	P
thermal			
incineration	L	OMIPO	O

L = large-scale
S = small-scale
L = lab investigation
P = pilot study
OMIPO = organic micro-pollutants
O = operational
HM = heavy metals

CONCLUSIONS

1. About 150-200 million m^3 of heavily contaminated sediment in the Netherlands should probably be cleaned-up in the next twenty years.
2. The policy of the Dutch government pursues two tracks: prevention and clean-up. In 1989 the clean-up of contaminated sediments was initiated on a limited scale. For clean-up during the period 1989-1994 180 million Dutch guilders are available.
3. For the next coming years attention will be focused to both storage in large spoil storage depots and the development and application of treatment activities like separation and purification.
4. Treatment is considered an integral process of mutually related treatment activities like dredging, separation, purification, immobilization (and storage).
   The nature and the extent of pollution, but most particularly the manner in which pollution is present in the sediment determine the sequence of treatment activities and, therefore, the treatment processes that are possible in the end. One singular treatment process for contaminated sediments simply does not exist.

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TOPSOIL FROM DREDGINGS - DEWATERING PROCEDURES REQUIRED TO RAPIDLY FORM A TOPSOIL PRODUCT FOR LAND RECLAMATION

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ABSTRACT

The conversion of dredgings into topsoil has usually been achieved through the long term ripening of the upper layers at confinement type disposal sites - a process occurring over many years.

A three year research project completed at the University of Strathclyde has established the technological and economic feasibility of rapidly producing (in 2-3 months) commercial quantities of a dredged topsoil product 'Clydesoil' from River Clyde dredgings. The project has determined the physical and chemical characteristics of the dredgings, and has established methods for handling, dewatering, desalination and amelioration at a soil factory.

This paper describes the research undertaken in developing methods to accelerate the dewatering process. The work involved examination of the dewatering behaviour in the laboratory and in the field, using appropriately scaled test plots and full scale trials. This led to the development of a mathematical model of the evaporative drying process, which was validated against the test data and used to describe the drying process under laboratory and field conditions. Consideration of all test results and modelling data led to the optimization and implementation of dewatering procedures at the soil factory throughout the calendar year.

INTRODUCTION

Considerable advances in the understanding of the behaviour of dredged materials have been made in the last twenty years, particularly in the Netherlands and the USA. The Dutch experience relates to reclamation of low lying lands and the disposal and recycling of dredged materials, de Glopper and Smits, (1974) and van Driel, (1984). The US Army Corps of Engineers have assessed the beneficial uses of dredged material and the environmental impacts of dredgings disposal, US Army Report EM 110-2-5026, (1986). In most cases and when undertaken, the recycling of dredgings to form a topsoil product is slow, often taking 2-3 years.

The processes and potential problems involved in converting dredged saline sediments into a topsoil product are indicated in Figure 1. Given the process requirements, there is a need to establish the methodology and guidelines for rapidly processing natural soils for land reclamation. The three year study at the University of Strathclyde has demonstrated that material removed from an industrial harbour can be successfully recycled to rapidly form a landscaping soil. This paper concentrates on the dewatering aspects. The other aspects in Figure 1 are described elsewhere (Riddell et al, 1989; de Silva, 1990; Thomas 1990).

DEWATERING BEHAVIOUR OF FINE DREDGINGS

The US Army Corps of Engineers examined physical, chemical and biological techniques for dewatering contained fine grained dredgings. The techniques are compared in Table 1 with the following methods considered applicable to thin layers (initial material heights less than 0.75 - 0.50m):-

- Surface trenching) may be used individually
- Periodic material rotivation) or more commonly, in
- Underdrainage) conjunction with one
- Evaporative drying) another

Given the requirement to rapidly dewater dredgings to form topsoil, the most favourable methods seemed to be the use of under-drained thin layers and evaporative drying, with surface trenching and rotivation. This represents a reversal of previous research trends.

To achieve rapid dewatering the following must occur during the manufacturing process:-

i) effectively decrease inherently high moisture contents as rapidly as possible from the as-dredged (sludge) state to a semi-solid (soil) state, enabling the material to be handled and placed by standard earthmoving and agricultural machinery, such as wheeled loaders, dump trucks and rotivators. (The minimum moisture content for handleability is the sticky limit, which defines the moisture content at which 'clay' adheres to metal tools).

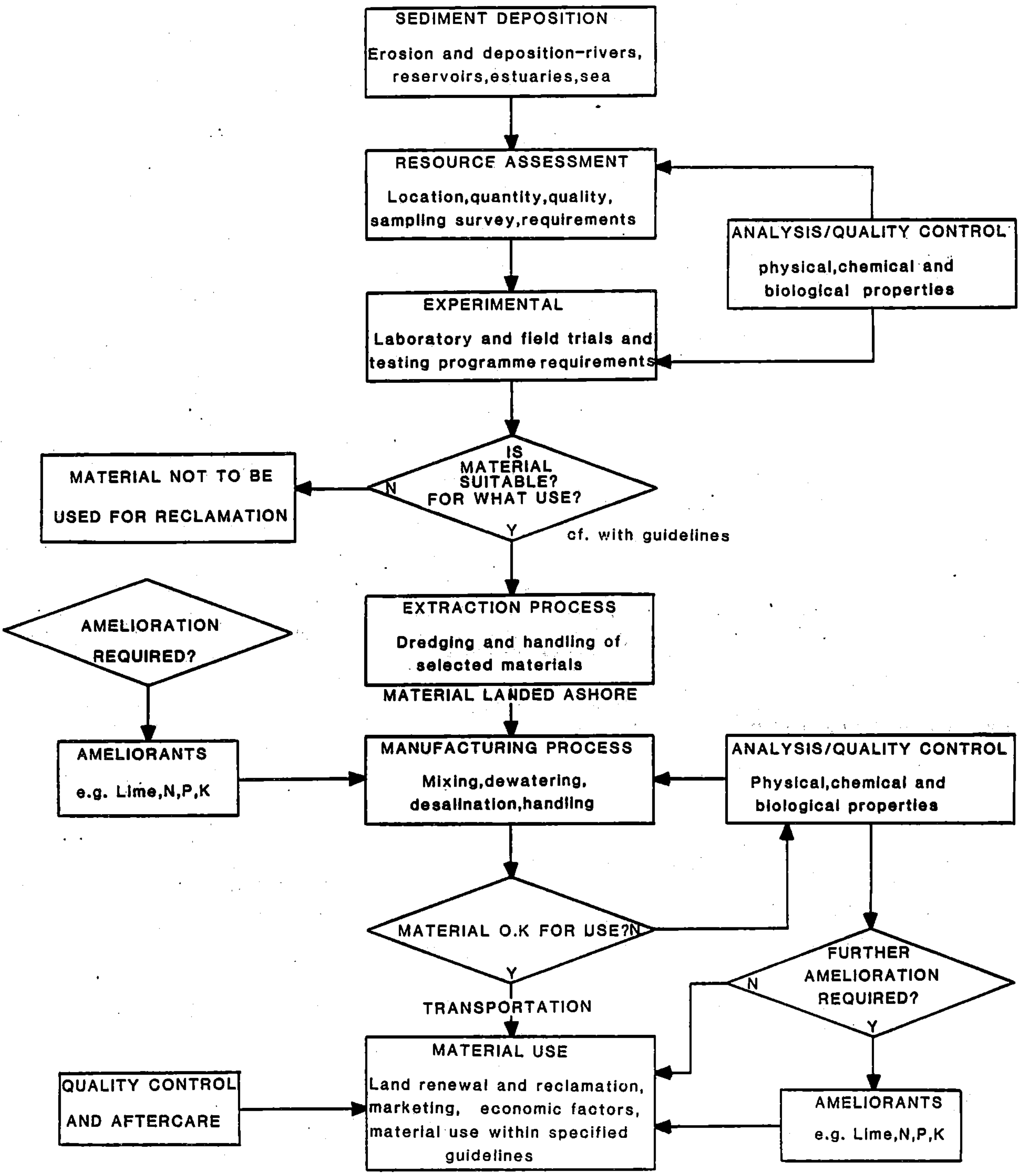


Figure 1. **Topsoil Product From Dredged Sediments (Processes Involved)**

	THICK LAYERS (>0.75 <2.5m)		THIN LAYERS (<0.75m)	
Dewatering Method	Technically Feasible/ Practical?	Estimated Cost[1]	Cost Effective?	Applicable to thin layers?
Surface Trenching	Yes	0.10-0.15	Yes	Yes[2]
Vacuum well-point Dewatering	Yes	2.80	No	No
Sand Slurry Injection	Yes/Maybe	0.28	Yes	No
Periodic Material Rotivation	Yes/No	0.24	Yes	Yes
Underdrainage (Gravity/Vacuum)	Yes	0.26-0.75	Yes	Yes[3]
Electro-Osmosis	No	-	-	No
Dike Raising	Yes	0.25-0.30	Yes	No
Vegetative Dewatering	No	-	-	Maybe[4]
Evaporative Drying	No	0.25-0.35	Yes	Yes

Notes:-

1. Dike raising is basis for cost comparison.
2. Required to remove surface water/aid ripening.
3. Only for site with pervious base, or artificial drainage layer (sand) provided.
4. May exceed time requirement for dewatering.

(Modified after Haliburton, 1979)

Table 1. Comparison of Effectiveness of Various Dewatering Methods and Their Applicability to Thin Layers

(ii) improve soil texture and structure by controlled mixing of selected fines, coarse materials and soil ameliorants, if required. Mixing by rotivation increases air and water permeability, thereby aiding dewatering and desalination and increasing oxidation rates, converting the initially anaerobic material into material suitable for plant growth.

(iii) remove excess salts by natural or induced desalination (leaching) methods, to levels acceptable for plant growth.

The following types of River Clyde dredgings are referred to in this paper:-

Fines - typically medium to coarse organic clay-silts.
Coarse - fine to medium to coarse sand with occasional gravel and silt.
Mix - 50% fines: 50% coarse by weight.

The mix material complies with accepted standards for topsoil, BS3882 (1965). Other mixing, textural and quality control requirements may apply for other sites, and will require appraisal during the resource assessment.

Laboratory and Field Dewatering Tests

The dewatering behaviour of fine and coarse dredgings was examined at three scales under constant and variable evaporation in order to observe and quantify the dewatering behaviour of River Clyde dredgings:-

i) Full scale field trials - Initial field trials indicated that low initial moisture contents and thin layers would be required to achieve rapid dewatering. Monitoring of a full scale trial at Babcock Basin (Fleming et al, 1987) involving approximately 6,000m^3 of suction-dredged silt placed in a lagoon at about 1.2m height indicated minimal consolidation effects with evaporative drying affecting mainly the top 0.20m after 400 days (see Figure 2). Primary consolidation settlement was complete after 37 days. After 400 days moisture contents remained above the liquid limit below 0.20m depth, and further dewatering could not be achieved without rotivation and mixing with coarse material. In comparison, 0.40m of grab dredged fines placed upon 0.40m of sand on a Clyde quayside dewatered from moisture contents of 136% to 50% in 50 days. The further research therefore concentrated on field dewatering trials using thin layers and laboratory tests.

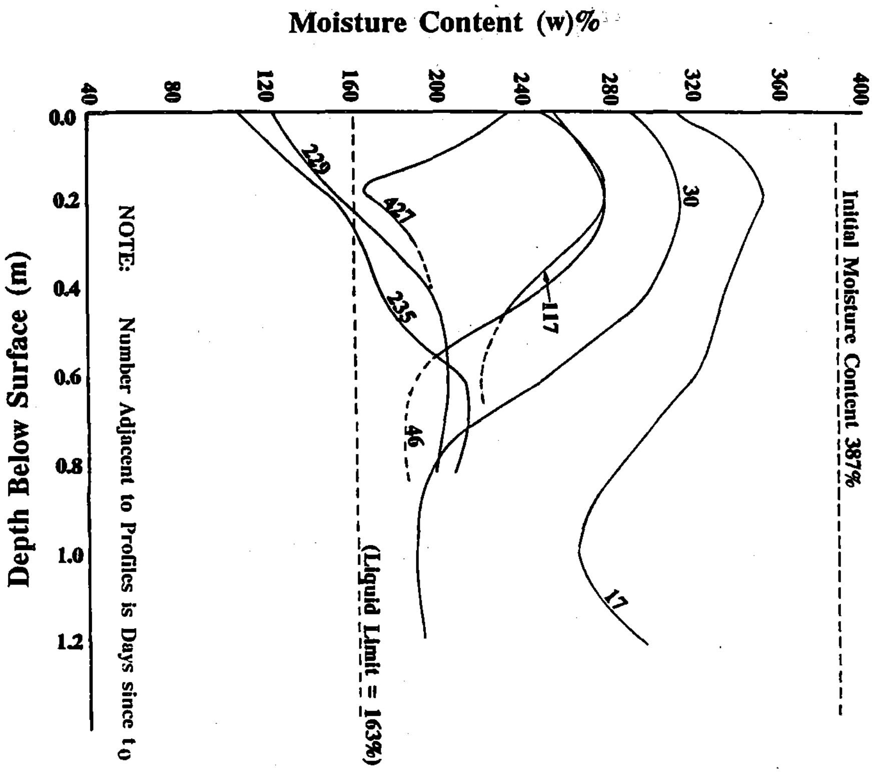


Figure 2. Moisture Content Depth Profiles VS Time At Babcock Basin

ii) Field drying plots - Twenty-six purpose built drying plots each of plan area 1m^2 containing initial dredged material heights of 0.75m, 0.50m and 0.25m were monitored to examine controlled field dewatering behaviour. The plots contained fines and mixed dredgings and indicated greatly improved dewatering behaviour for the mix. Evaporative dewatering was not effective for plot heights of over 0.50m for the fines, but up to 0.75m height could be used for the mix. The provision of sand under-drainage aided dewatering for both material types.

iii) Laboratory tests - Seventy-two plastic pots of 0.10 - 0.44m height and 0.10m diameter were used to determine the dewatering characteristics of various dredging mixes where test conditions closely resembled those in reality, but with drying under constant evaporative demand which reflects the moisture movement properties themselves rather than external influences (see Thomas, 1990 for details).

The Evaporative Dewatering Model

A constant rate evaporation model developed by Benson and Sill (1984) described the laboratory evaporative drying of dredged materials following consolidation. This model uses an integral method solution to the governing equation for evaporative drying of moist solids and provides the total and profile moisture contents of the entire layer for both the constant rate drying period and the falling rate drying period. Input data is readily obtainable using laboratory drying samples and the model output parameters can be readily interpreted in terms of drying parameters which are of use in practice:-

M_o, t_o - initial volumetric moisture content, initial time)
M_{cr}, t_{cr} - critical volumetric moisture content, critical time)(cm^3/cm^3, days)
M_e, t_e - equilibrium moisture content, equilibrium time)
m - volumetric moisture content)
γb - bulk density (Mg/m^3)
t_h - time to achieve handleability (taken as m less than sticky limit) (days)
t_f - time for drying profile to reach base of drying layer (days)
PE - potential evaporation (mm/day)

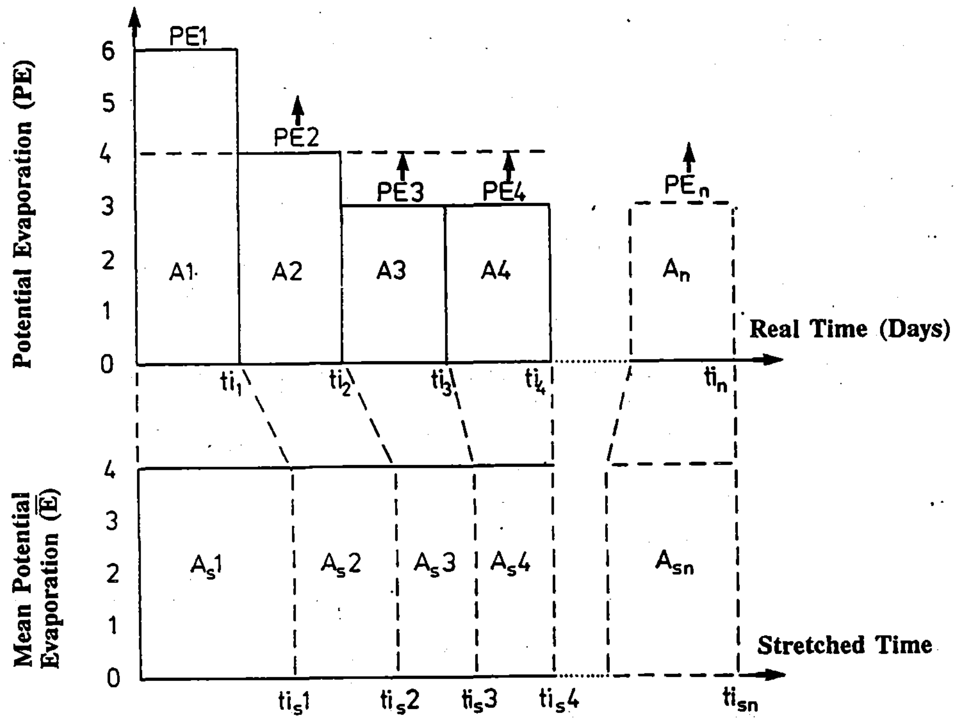
The laboratory dewatering model was successfully calibrated against 86% of the laboratory drying tests (sixty-four out of seventy-four drying tests) indicating that the model gives a good description of the evaporative drying process in the laboratory.

Development of the Dewatering Model and its application in the field environment

The laboratory model could not be used in the field situation except where the constant rate drying period is less than 1 month using mean monthly potential evaporation. This led to the development of a dewatering model which could describe dewatering under variable evaporation potential in the field. The application of a "laboratory" model to the field environment required that scaling laws be satisfied, and it is the accuracy of the field tests that count. In this respect sample size and evaporation were the important factors. The laboratory model was successfully calibrated with eleven out of fifteen 1m^2 field plots with t_{cr} less than 1 month indicating that simulation from a 100mm diameter laboratory sample to a 1000mm wide field sample is satisfactory.

The principal development of the Benson and Sill model allows for variable evaporation input with other material parameters initially constant. To ensure continuity, it is necessary to force linearity of the drying model over the constant rate drying period by "time-stretching", then solving for the time dependancy for moisture content, by stepwise advancement. Linearity is achieved by forcing the potential evaporation per time increment to equal the arithmetic mean potential evaporation ($\bar{E}$) over time, with the area under each time interval constant. The time stretching method is shown diagrammatically in Figure 3. The mean evaporation rate over incremental time is used to calculate for moisture diffusivity, and hence t_f and t_{cr} with $\bar{E}$ calculated up to the nth time interval in which t_{cr} occurs. The time dependency is now in "stretched-time", which can be greater or less than the "real-time" per time increment, but is linear. Cumulative time adjustments are required after t_{cr} for converting back to "real-time" output.

The variable evaporation model was verified mathematically and was successfully calibrated against eight out of ten field plots using derived potential evaporation for the Glasgow area. Figure 4 shows actual and simulated drying curves for grab dredged fines material spread at an initial layer thickness of 0.25m. The model development and calibration is described by Thomas (1990).



Where: A = Area Under Time Interval ti (ti_1 to ti_n)

A = Area Under Stretched Time Interval ti_s (ti_s1 to ti_{sn})

Total Time (T) $= \Sigma_1^n ti = \Sigma_1^n ti_s$

$\bar{E} = \frac{1}{n} \Sigma EI$ I = 1, 2, ---- n

Figure 3. Time Stretching Method Used To Evaluate Time Dependancy For Variable Rate Evaporation

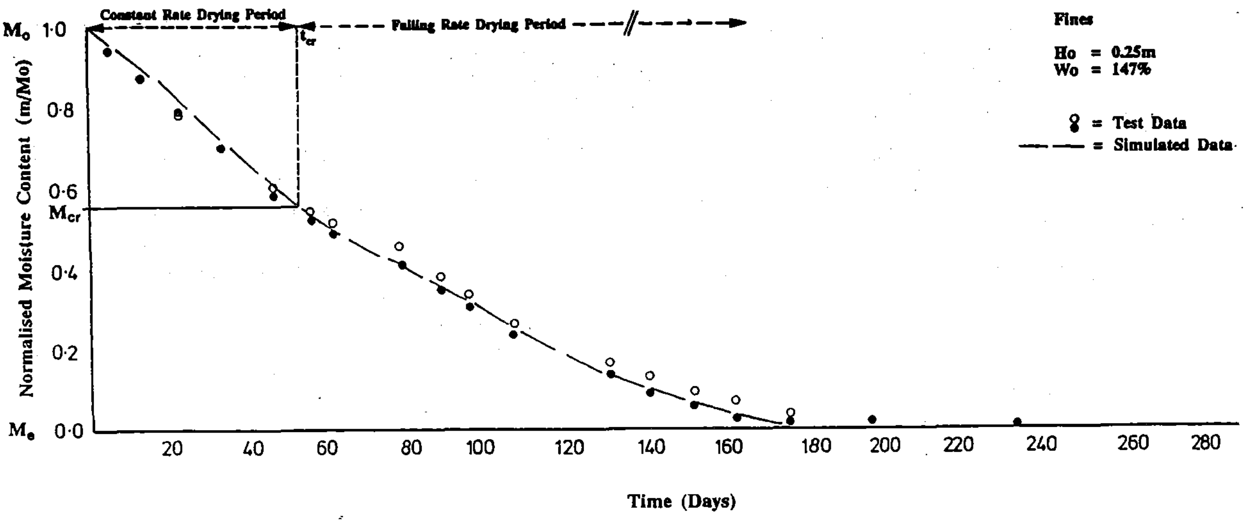


Figure 4. Actual & Simulated Drying Curves for Fines Dredgings

Predictions of Dewatering Behaviour

Based upon the results obtained, the developed model was considered suitable for predicting the field evaporative dewatering of thin layers of fine grained dredgings and dredging mixes. Prediction runs using the developed model were undertaken using the following test permutations:-

- Initial dredgings height, Ho = 0.10, 0.25, 0.50, 0.75m
- Initial moisture content, Wo = Fines 136% - 252%, Mix 44% - 193%
- rotivation/no rotivation (where applicable)
- dewatering starting at monthly intervals throughout the calendar year.

Figure 5 shows simulated 12 monthly drying curves for fines dredgings at 0.25m initial height with an initial moisture content of 136%. For this example drying rates increase from December to June and July and decrease from August to September. The poorest drying months are October and November as t_{cr} exceeds 150 days, with the most rapid drying occuring in May to July as t_{cr} is less than 30 days. Each test run permutation will generate a similar family of seasonal drying curves.

The optimisation of dewatering procedures requires a measure of dewatering efficiency to be applied to the simulated results. Dewatering efficiency is defined as;-

> "Production of the maximum material mass in the minimum time to a moisture content and textural condition which enables handling by standard earthmoving plant".

Measurement of dewatering efficiency requires consideration of time, mass and dewatering characteristics. A dewatering efficiency classification was developed by plotting the dimensionless drying intensity parameter (N) against layer thickness in material co-ordinates (L) where:-

$N = PE.L/Mo.D$
$L = Ho/(1+Mo)$ (metres)
where D = soil moisture diffusivity (m^2/day)

Figure 6 shows the dewatering efficiency plot for fines and mix dredgings using actual and simulated results. Considering Figure 6, it can be seen that for a given drying intensity, L mix is generally greater than L fines. For example, for the fines for N = 1.0, L = 0.02 - 0.09 (v. low to low-medium), whilst for the mix L = 0.03 - 0.25 (v. low to high-medium) indicating that the mix material is a more efficient dewatering medium than the fines under the same evaporation potential.

The next step was to identify the optimum dewatering conditions for drying throughout the calendar year. The prediction runs were summarised using the dewatering efficiency plot and the time taken to achieve handleability using a practicable upper limit of 120 days. The best monthly dewatering options thus obtained are summarised in Figure 7.

CONCLUDING REMARKS

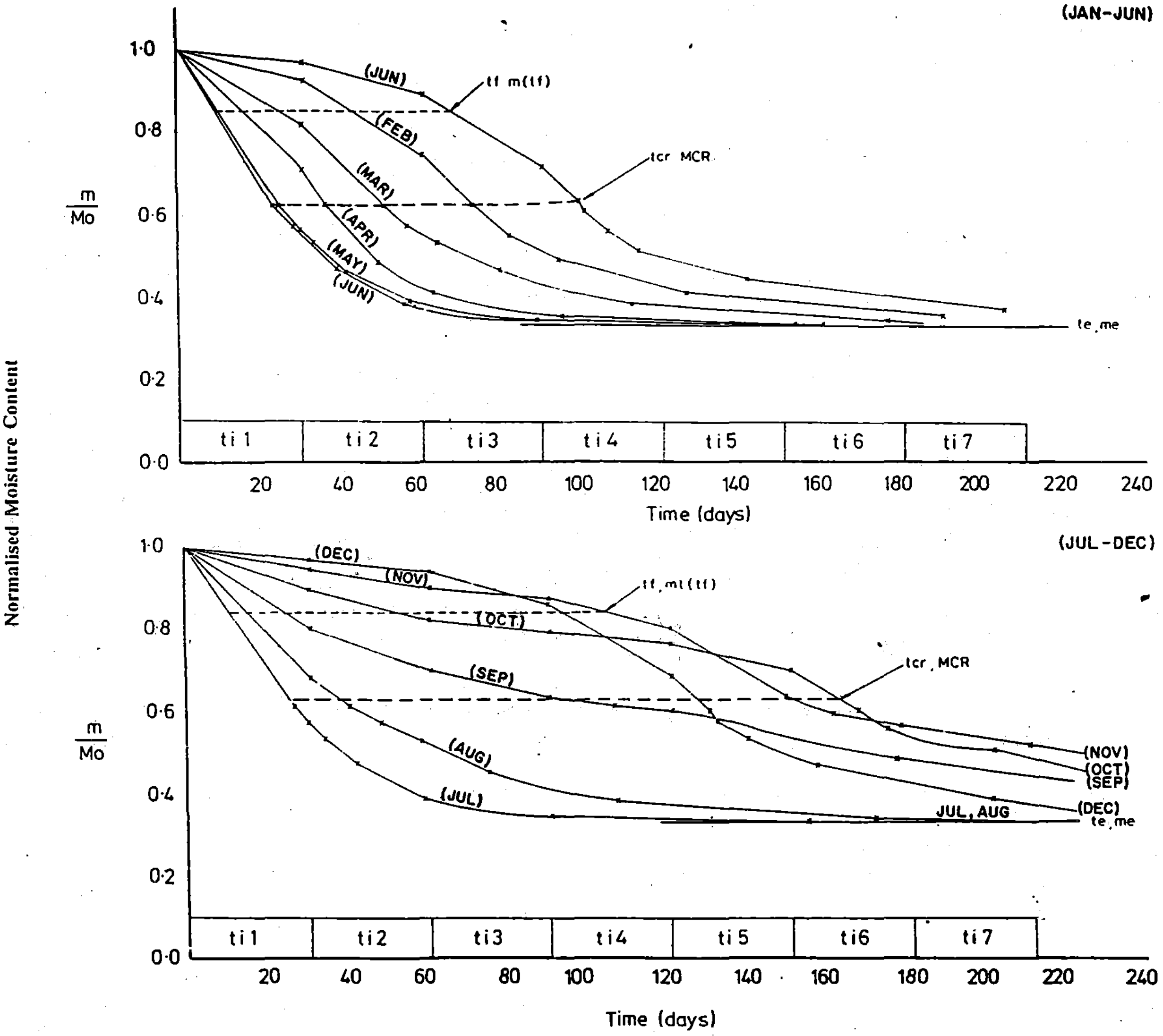
This research has proved the practical and commercial viability of manufacturing a topsoil product "Clydesoil", from dredged material recovered from an industrial harbour on the River Clyde. The success of the research was demonstrated by the use of approximately 27,000 tonnes of Clydesoil for structure planting at the 1988 Glasgow Garden Festival Site, followed by the recent establishment of a commercial soil factory at Merklands Quay in Glasgow, with a potential throughput of 100,000 tonnes/year. This is a radically new approach to the beneficial use of dredged materials whereby a dredged topsoil product can be dewatered and manufactured in 2 - 3 months with a 6 month lead-time. In addition to dewatering, desalination to plant tolerable levels is required prior to use in land renewal and reclamation projects. The study has shown that careful management and quality control of all stages is necessary.

CONCLUSIONS

A variable evaporation dredgings dewatering model was developed and verified mathematically, prior to calibration against field test plots in the Glasgow area. The model was used to predict the optimum field evaporative dewatering behaviour of thin layers (less than 0.75m) of River Clyde dredgings throughout the calendar year.

The principal findings of this work are that for controlled material heights, initial wet mixing of 50% fines : 50% sand dredgings placed upon around 0.30m of sand under-drainage gives a considerable improvement in drying efficiency throughout the drying year compared to dewatering fines dredgings only. Initial wet mixing increases air and water permeability, aids oxidisation and ensures compliance with end product specifications.

Implementation of the above findings at the topsoil factory will optimise production procedures and throughput of Clydesoil.



Material Parameters

Ho = 0.25m
Wo = 136%
Mo = 3.897
Mcr/Mo = 0.632
Me/Mo = 0.331
Mh/Mo = 0.329
γb = 1.225

Note:

Evaporative Drying Assumed To Start At Beginning Of Indicated Month

Figure 5. Simulated 12 Monthly Drying Curves for Fines Ho = 0.25m, Wo = 136%

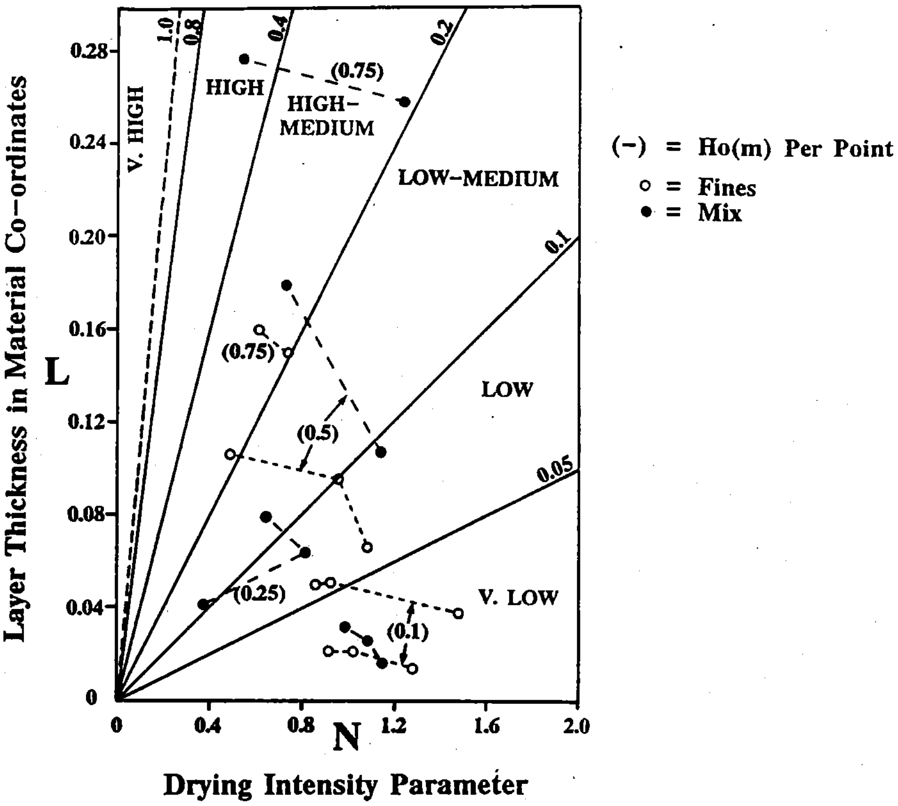


Figure 6: Dewatering Efficiency Classification For Fines/Dredgings & Mix

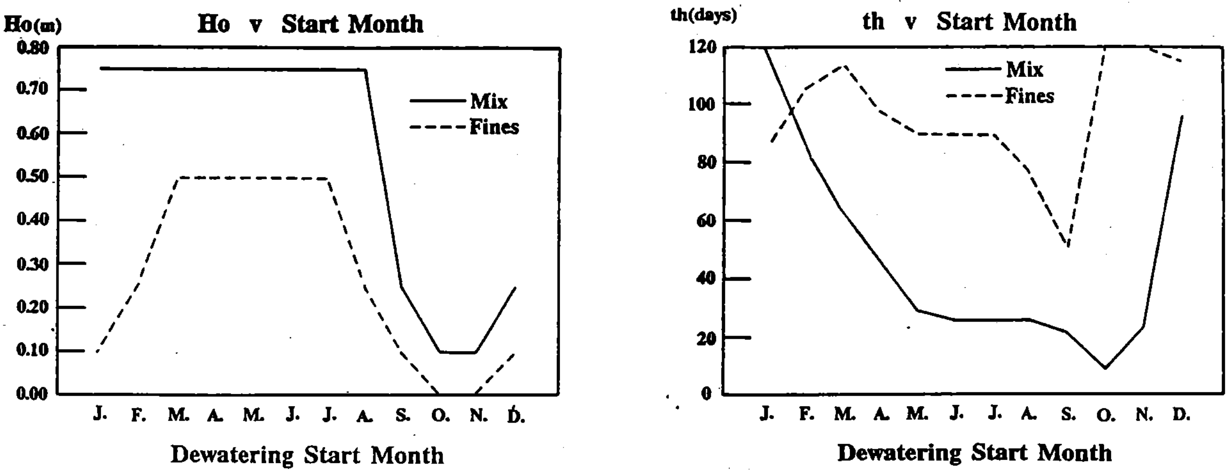


Figure 7: Predicted Best Monthly Dewatering Options For Fine & Mix Dredgings

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	THICK LAYERS (>0.75 <2.5m)		THIN LAYERS (<0.75m)	
Dewatering Method	Technically Feasible/ Practical?	Estimated Cost[1]	Cost Effective?	Applicable to thin layers?
Surface Trenching	Yes	0.10-0.15	Yes	Yes[2]
Vacuum well-point Dewatering	Yes	2.80	No	No
Sand Slurry Injection	Yes/Maybe	0.28	Yes	No
Periodic Material Rotivation	Yes/No	0.24	Yes	Yes
Underdrainage (Gravity/Vacuum)	Yes	0.26-0.75	Yes	Yes[3]
Electro-Osmosis	No	-	-	No
Dike Raising	Yes	0.25-0.30	Yes	No
Vegetative Dewatering	No	-	-	Maybe[4]
Evaporative Drying	No	0.25-0.35	Yes	Yes

Notes:-

1. Dike raising is basis for cost comparison.
2. Required to remove surface water/aid ripening.
3. Only for site with pervious base, or artificial drainage layer (sand) provided.
4. May exceed time requirement for dewatering.

(Modified after Haliburton, 1979)

Table 1. Comparison of Effectiveness of Various Dewatering Methods and Their Applicability to Thin Layers

GENERAL STRATEGY OF THE WATERWAYS OF THE FLEMISH REGION FOR HANDLING AND DISPOSAL OF CONTAMINATED DREDGED MATERIAL

J. VAN HOOF, Ministry of the Flemish Community, Department of Environment and Infrastructure, Waterways Administration, B

ABSTRACT

Maintenance dredging work in the access channels to the Flemish harbours and in inland waters is of vital importance to the Belgian economy in general and to that of the Flemish Region in particular. When it comes to necessary dredging operations, Belgium is one of the leading countries in regard to the amounts of dredged sediments. Largely most of it is dredged by the appropriate authorities of the Flemish Region. This gives rise to the special problems since a part of the dredged material is contaminated. Disposal on land becomes more and more difficult by reason of stringent regulations, public opinion and most of all by lack of sufficient free spaces.

The Flemish Waterways Administration, which is in charge of these particular dredging operations, developed an effect-orientated procedure called Environmental Impact Procedure (EIP), which must lead to the disposal decision, taking into account the degree of contamination of the material to be dredged as a function of the disposal facility and of the final destination of the disposal site.

During recent decades many studies and pilot projects, covering nearly all aspects of dredging, handling, treatment and disposal of dredged material have been carried out. To coordinate all these actions a special technical working group was established.

This contribution gives an overview of the efforts of thise coordinated actions and of the philosophy on which all these actions are based.

INTRODUCTION

When solving mathematical equations, we follow a step by step procedure to reach our goal. Every step that is taken, is well-known and well defined and the solution is found through pure logical thinking.

There are problems which cannot be solved that way. In that case the decision making process is based on reasonable suppositions, which means that the full impact of every step that is taken, to come to an acceptable solution, is not known.

To achieve our final goal we have to make assessments. This process is called management, while management procedures are dictated by a strategy.

One of those problems is the relationship between the degree of contamination of dredged material and the disposal conditions. There exists no single procedure to determine this relationship and in order to find a solution we work out a general strategy.

CONTAMINANTS

In order to understand the nature of the problem we are dealing with, we should define the word "contaminants". Except for some man-made chemical combinations, contaminants are pure chemical substances found everywhere in nature in different forms. Nature cannot exist without them. However, through human activities, an abundant quantity of them was spread out in the environment thus increasing the natural concentration of some chemicals in one place in such a way, that they risk becoming harmful to plants, human beings and animals.

The irresponsible and uncontrolled discharges of concentrated waste waters polluted many of our surface waters. The contaminants were spread out over very large areas, causing indefinable damage to biological life in practically all our waterways and in the access channels to our sea harbours.

In a way, as nature defends itself, we are fortunate that the concentration of the pollutants in the surface water is reduced by the presence of the natural sediments. The contaminants become attached by fixation to the alluvial sediments in our waterways. If this process, in which chemicals move from the water and accumulate in the sedimentation, were not to take place, nearly all life in our rivers and even in the sea, would already be wiped out.

However, this system is resulting in an increased concentration of contaminants in the natural sediments, where aquatic life is threatened. This causes new problems, especially when dredging operations should try to maintain both navigational depths and enough wet section to assure the evacuation of upstream water. People became aware that the disposal of these sediments could become harmful to the environment. National and international regulations were introduced for handling and disposal of contaminated dredged material. In many cases these regulations were so strict that a lot of dredging operations became almost impossible, with serious economic problems as a consequence.

Many regulations could be described as an emotional reaction to the statement that contaminated dredged material should be considered as a waste and should be treated as such. However this material, contrary to many real industrial or human wastes, is and stays a natural product.

CLASSIFICATION OF CONTAMINATED DREDGED MATERIALS.

Dredging operations result in dumping the dredged material back into the rivers or the sea or in disposal on land. The latter can be done on the land surface (upland disposal) or in pits. When dealing with CDM, the question to be asked in the first place is, whether the dumping or disposal could cause harmful effects to the environment and if so, to what degree, and consequently, which precautions should be taken to protect the environment in an effective way.

To answer these questions many countries started to build up a kind of classification system based on total chemical analysis of the sediments. The results of this analysis were compared with standards, defining different classes of protective measures regarding the disposal site and disposal conditions, as a function of the testing results. This approach seems simple and logical as the problem of contamination is of a chemical nature. On the other hand, the relationship between chemical contents and real environmental impact is, for different reasons, very questionable.

First the physical and chemical characteristics of the material to be dredged can differ drastically form place to place and may vary with depth and time. As the silt and organic fractions are mostly determining the uptake capacity of contaminants, the degree of contamination of sediments caused through contact with the same pollutants, may differ considerably from place to place.

Besides this statement, the environmental degradation in the vicinity of the disposal site is mainly caused by the transmission of the pollutants to the water phase, and through this phase moved and distributed to the various environmental sections. The solubility, and the rate thereof are very dependent on external conditions, such as PH, temperature, atmospheric pressure, oxygenation, etc... This means that the conditions of the disposal facilities (under water or on land) are very important in the assessment of whether a contaminated material with determined characteristics can be allowed in one particular disposal site, where as it should be forbidden in another one.

We conclude that the results of total chemical analysis can never reflect all these different circumstances and only allows the comparison between the actual chemical state of the sample and the normal background values as they are, and if these can be determined, as they are supposed to be.

Actually this says nothing about the real environmental impact as the chemical contents practically never reflect the amount of contaminants which are biologically available to the environment.

Therefore the main question to be answered is: what and in which degree are contaminants available for uptake by plants, animals and human beings; how harmful are they and if so, is this acceptable?

BASIC PRINCIPLES.

The problem in general does not start with the dredging of the contaminated sediments but with the disposal of them. We are convinced that the protection measures (e.g. drainage, monitoring, sealing systems) now prescribed by the appropriate authorities for the sealing of the disposal site are much too severe, compared to the degree of contamination. Mostly the same standards are in force as for industrial wastes. This leads to overprotection at too high a cost for society and an uneconomic use of the available spaces in the Flemish Region. If we are right, these spaces are more suited to the storage of heavy industrial wastes.

We can understand the prescribed measures. They originate from the fact that the actual state of science does not permit an evaluation which is concordant with reality. In fact, the actual technical measures are taken as a precaution, which leads to the first basic principle: "Precautionnary action", immediately followed by the second one: the use of the "Best Available Technology" on which our strategy is based.

The acceptance of these two principles is in conformity with international regulations governing the treatment and disposal of wastes in general. They were stated in the International Ministerial Conferences of the North Sea and are reflected in the Guidelines for dredged material disposal at sea editted by the Oslo Commission.

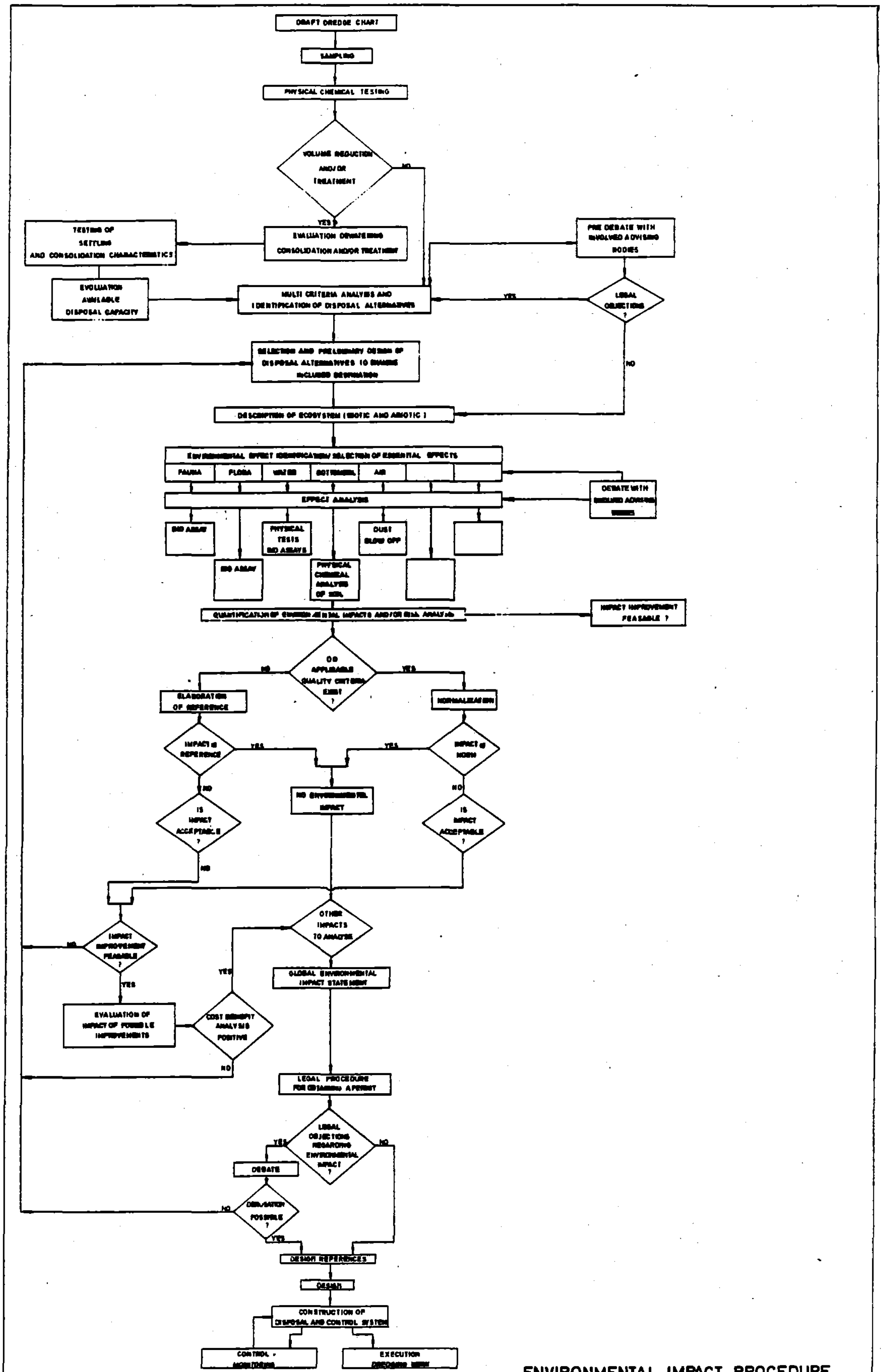
The application of these two principles supposes that in this rapidly advancing matter, a high degree of flexibility should be built in to adapt our evaluation and actions concerning treatment and disposal of contaminated dredged material, to the evolution of science. A one way classification system, where the disposal of contaminated dredged material characteristics, fixed in legal standards, are in fact contrary to the needed flexibility.

This means that all dredging and disposal situations should be studied case by case, using an assessment procedure, to evaluate the appropriate kind of disposal action, considering the degree of contamination of the CDM in relation to all the characteristics and final use of the disposal site.

In fact we should be glad that as yet in Belgium there are no fixed legal standards for the disposal of contaminated dredged material, which relate the disposal conditions to exact chemical characteristics. If this were the case necessary dredging actions could become impossibly expensive and unaffordable in the actual budget. A law which leads to unbearable costs for society is unexecutable, remains a dead letter and will not lead to any results.

DISPOSAL OF CONTAMINATED DREDGED MATERIAL AT SEA.

The disposal of dredged material at sea is subject to the regulations of the Oslo Convention for the prevention



ENVIRONMENTAL IMPACT PROCEDURE
FLOW CHART

of the pollution of the marine environment. These regulations are described in the guidelines which specifically address the disposal of dredged material by dumping.

The guidelines already incorporate assessment procedures as requested by the conclusions of the Third North Sea Conference. The guidelines establish an environmental assessment procedure, which in fact is an effect orientated procedure, examining all possible environmental effects of the dumping of dredged material on a case by case basis.

In the application of the regulations of the Flemish Waterways Administration and the authorized National Ministry, cooperated in the elaboration of a comprehensive report on the ecological impact of the dumping of dredged material in Belgian coastal waters and on the Belgian Continental Shelf. This status report is open for discussion and is sent for advice and comment to interested parties such as the scientific community, the harbour authorities and non-Governmental ecological organisations. A revised status report, incorporating any relevant comments received, will be published ub the middle of 1991.

This report is discussed in more detail in the paper "Ecological impact of dredged material disposal in Belgian Coastal Waters" (ref. 1,2).

DISPOSAL OF CONTAMINATED DREDGED MATERIAL ON LAND.

Environmental Impact Procedure

Aware of the fact that the traditional classification systems, using comparative standards, are not leading to accepatbale conclusions, the Flemish Waterways Administration has developed, what is called the "Environmental Impact Procedure" (EIP) (ref. 3,4). This procedure should allow the assessment of whether a certain contaminated dredged material can be stored in a chosen disposal site. The procedure must also be conclusive with regard to the necessary precautionary or monitoring actions, which should be taken to protect the environment from the negative influences of contaminants residing in the disposed material.

The Environmental Impact Procedure is a decision-making process based upon the physical, chemical and biological properties of the dredged material.

In the procedure, the following requirements must be fulfilled :

- to be applicable for all disposal alternatives ;
- to evaluate unequivocally all potential environmetal effects of the dredging and disposal operations ;
- to be based upon the standarized sampling and test procedures which fit into national and international legislation (London Dumping Convention and E.E.C. directives...)

Based on these requirements, the EIP flow-chart was worked out and is presented in figure 1.
The EIP consists of five phases, each of which describes a logical succession of activities.

- Phase 1 : programming of the necessary dredging works and of the sampling campaign ;
- Phase 2 : evaluation of the necessary requirements and the available disposal capacity, eventually including a cleaning or treatment operation of the contaminated dredged material.
- Phase 3 : selection of the disposal alternatives;
- Phase 4 : environmental impact identification and decision procedure ;
- Phase 5 : control procedures and execution of the dredging operation.

To evaluate the effectiveness of the EIP, the procedure will be worked out for two test-cases, one in the Canal Bruge-Ostend and the other one in the acces channel to the Kallo Lock. In both cases, considerable amounts of contaminated dredged material have to be removed. The study-program will last for two years.

Biological approach.

Following the Environmental Impact Procedure we investigate in the first phase the physico-chemical properties of the contaminated dredged material which leads to a first judgement of the material, whether there should be any reason for worrying about possible environmental consequences.

However, and as already mentioned, the importance of the chemical concentration of pollutants in contaminated dredged material is very relative. It is important to know what part of the chemical combinations will be set free and which fraction is potentially biologically available. This question cannot be solved by physical or chemical science alone but requires a multi-disciplinary approach.

Solving the first part of the problem requires standard testing procedures to determine the possible leaching of polluants caused by natural circumstances. This requires extraction techniques which can simulate the processes acting in the natual environment.
Consequently, the final disposal circumstances must be taken into account. The techniques used should be different for marine, land and aquatic disposal sites.

However these test results only give some indication of the hazard assessment of the contaminant pollutants, and in what amounts these could become biologically available. Therefore, the chemical test results must be linked to biological test producers, which must be integrated into the different steps of the Environmental Impact Procedure, following a tiered system.

The bioassays and testings have the purpose of quantifying the following aspects :

a) Bioavailability of contaminants determines how these components evolve in the ecosystem and is determined by environmental parameters such as Ph, redox potential, salinity, type, etc.

b) The assimilation is the physical process whereby substances in dredged material are assimilated by "eaters", with the consequence of a possible spreading of these contaminants in the biological part of the ecosystem.

c) Bio-accumulation is a process whereby some substances accumulate in organisms with the effect of a possible significant increase of the concentration of particular contaminants in these organisms.

d) Bio-magnification is the progressive increase of concentrations of chemical substances in organisms in the course of the trophic cycle.

e) Eco-toxicity is defined by a certain level of contamination which has a measurable influence, inhibition or cessation of metabolism.

Each phase of the Environmental Impact Procedure requires a new evaluation, supported by physical, chemical and not least, biological testings. As the procedure advances, more specific and thorough testing will be required to come to the final evaluation of the real environmental impact of the final product in the disposal area.

Three kinds of biological testing procedures have to be applicable or have to be developed :

- Acute Single Species tests, which are short-term biological signal tests.
- Chronical Single Species and bioaccumulation tests which are mid-long term tests ;
- Multispecies tests, (mesocosmes) or long-term research implicated by the study and interactions with the other environmental disciplines.

Beside these test procedures, bioremedial methods can give solutions for the treatment of specific contaminated materials. The different kinds of biological testing procedures, the application of which is considered most desirable, will be executed at the different stages of the Environmental Impact Procedure.

As far as the biological single species tests are concerned, some valuable methods were developed at State University of Ghent (R.U.G.) Most notable are the MICROTOX and RODTOX test procedures. The RODTOX test for example is a test on a bacterial population of the "active silt"-type, reacting after only 30 minutes on acute toxicity or on an abundant demand for oxygen. The single species test should be applied at the first evaluation of the contaminated dredged material.

After the disposal of contaminated dredged material, it is most desirable to evaluate the long-term effects of the disposal. This can be done by biomonitoring, which includes a long-term research program.

The importance of biological test procedures is accentuated in the guidelines of the Oslo Commission where it was stated that these procedures may contribute to reasonable judgement of eventual undesirable, chronic or acute toxic effects on marine organisms or human health, wether or not arising from their bioaccumaulation in marine and especially in food species (ref. 5).

The biological approach is completed by bioremedial systems. These systems are mostly based on the ability of active bacteria to break up organic contaminants. One of these methods is biofixation. These methods were applied in specific locations in Oudenaarde, Ghent and Zeebrugge (ref. 6,7).

In order to come to more justified and therefore more economical solutions in the matter of handling, treatment and disposal of contaminated dredged material, the Flemish authoritites decided to intensify all biological research programs which might contribute to more valuable solutions in this complicated matter.

GENERALISATION OF THE ENVIRONMENTAL IMPACT PROCEDURE.

The Waterways Administration developed the Environmental Impact Procedure for navigable rivers and canals. However we must be aware of the fact that the pollution of our rivers already starts in the ditches between rural fields which are connected with minor watercourses and unnavigable rivers. Most of the different elements of the waterdrainage system are falling under the competency of different authorities. It is evident that global management should be performed. Therefore at this moment the Environmental Impact Procedure as drafted for the navigable waterways, is being examined for its applicability to unnavigable watercourses. We are aware of the fact that, in view of the scale difference, other rules for samling and testing should be applied. However, it is important that the same philosophy in the approach to the problems caused by contamination of riverbottoms, navigable or not, should be worked out.

SANITATION OF RIVERBOTTOMS.

Until now, dredging operations were carried out to ensure the navigability of our waterways or for reasons of discharging upstream water. At the same time, these dredging operations have incontestably a very advantageous adjoining effect. By removing the contaminent contents, accumulated in the riverbottom sediments, the dredging operation becomes a real sanitation dredging project. The contaminant contents of the sediments has decreased to the level of normal background values at the sites where very intensive dredging operations were carried out.

As long as the voiding of contaminants in our waterways continues, the only positive effect of the dredging operations consists of the fact, that new quantities of contaminants can be bound in the cleaned riverbottom. This effect reduces considerably the contaminant load in the surface water. Due to budgetary reasons and a lack of free space for the disposal of contaminated dredged material in the Flemish region, this circular course must be stopped. The filth must be tackled at the source.

The real problems will arise from the moment that water quality objectives are achieved and the quality of surface waters elevated to acceptable standards.

Contaminated silt, covering the waterbottoms will then be a new source of contamination for the cleaned water. How the mechanism of the transfer from contaminated dredged material to the clean water phase is working and what interaction exists between these two matters, is not yet established. Immediate further research in this field is indispensable. We must not forget that the decision to carry out sanitation dredging works will depend on the results of this investigation.

The budgetary impact of the decision to start the sanitation of the riverbottoms by big scale removal actions of the contaminated sediments, will be difficult to survey, and creates a new spatial problem for the disposal of the contaminated dredged material on land.

Before taking such ponderous decisions, the scientific need to remove the contaminated sediments must first be proved.

This investigation cannot be separated from the biological effects the contaminated material will have on the cleaned water-phase. Once more, a multi-disciplinary approach on a case by case basis should be followed. If there exists an important interaction, then it would make little sense to clean surface waters without taking notice of the riverbottom contamination. A global approach to this problem is needed. Therefore the Flemish Region has decided to intensify all research programs concerning the interaction between bottom and surface-waters.

PILOT PROJECTS OF THE WATERWAYS DEPARTMENT

During the last few years, the Flemish Waterways Department has made great efforts by executing coordinated large scale research programs and pilot projects, covering nearly all fields of dredging, disposal and treatment of contaminated dredged material. During this congress my collegues are reporting on some of these pilot projects. For more details I refer to their contributions to this congres :

To be mentioned are :

- Pilot-project "Grote Geul" on the Left Bank of the river Scheldt :
  - Ecological impact of underwater disposal in the docks on the Antwerp Left bank (ref. 8)
  - Large scale separation and consolidation techniques for on land disposal of fine grained dredged material (ref. 9, 10)
  - Riverbottomsanitation and landscaping (ref. 11)
  - Separation plant on the left Bank of the River Scheldt (ref. 12)
- Pilot-project "Geuzenhoek" near Ghent :

  The disposal of heavily contaminated dredged material from the Canal Ghent-Terneuzen required special disposal facilities. A large scale pilot project was started to examine adequate disposal techniques, lining, screening and accelerated consolidation. (ref. 4, 13)

  The experimental disposal facilities were designated for investigation of :

  - efficiency of natural and mineral liners
  - diffusion of contaminants
  - bioavailibility of contaminants
  - accelerated consolidation.

  The program, which started at the end of 1990, will last for two years.
- Other projects

  Other projects were carried out or are in execution. Their purposes are :

  - reducing the amounts of sediments to be dredged by using advanced dredging technologies, location and control systems ;
  - alternative uses of dredged silt (e.g. artificial gravel) ;
  - mechanical separation techniques (e.g. hydrocyclones, elutriators) ;
  - beneficial uses of dredged material (e.g. afforestation projects on disposal sites).

CONCLUSION

The Flemish Waterways Administration has made great efforts to come to sensible solutions for the problems posed by contaminated dredged material. A considerable amount of the annual budget is spent on different projects. The problem is far from solved, but we are convinced that, when following management, based on a logical strategy, we can reach ecologically and economically justifiable solutions.

To reach this goal, the Administration is prepared to go on simulating research in different disciplines which might give positive contributions.

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THE OPERATIONAL AND ECONOMICAL ASPECTS OF THE VERY SUCCESFUL BOTTOM CLEANUP OF THE APELDOORNSCH KANAAL

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1. SUMMARY

As market leader in soil sanitation by chemical/physical technology Heijmans Environmental Technology Ltd was somehow disappointed by the first invitations to tender for waterbottom cleanup as received from the Ministry of Public Works in the Netherlands mainly due to the problem of sludge disposal. The public invitation to tender for the cleanup of part of the Apeldoornsch Kanaal looked far more attractive as the disposal of the contaminated sludge was arranged for. Heijmans Environmental Technology Ltd in combination with Dredging Company Holland Ltd therefore made up an attractive bid and invested a lot of effort to make this cleanup project as succesful as possible.

We feel we have succeeded to execute a waterbottom cleanup project according the quality and timing envisaged by the client.
This paper describes the work as contracted and as executed and looks back aiming for a contribution in the ongoing discussions between the parties involved which should lead to a mature aquatic soil sanitation market. Mature in our opinion should mean a reasonable price for a well defined product such that both the client and the contractor are satisfied and eager to continue to contribute in the total cleanup of the Dutch water bottoms and stimulate other European authorities to make up their mind with respect of the necessary cleanup of aquatic soils they are responsible for.

2.INTRODUCTION

2.1 The pollution

As not uncommon in the past a paper factory next to the Apeldoornsch Kanaal has disposed of her waste water without proper cleaning. As discussions between the authorities and the management of the factory concluded in investment into a waste water treatment plant the next logical step was to look into the cleanup of the bottom of the Apeldoornsch Kanaal.
A geotechnical survey and subsequent laboratory testing revealed the bottom material contained mainly mineral oil. In addition heavy metals (approximately 275 mg/kg dry matter) as chromium, arsenic, nickel, zinc, copper, mercury and lead were found. As our technique is a wet process not leading to any air contamination the safety measures according the lightest safety class called 1T were sufficient. This means only proper clothing to prevent contact with the contaminants and hygienic measures as not eating, drinking or smoking during the actual work.

The contract only requested separation of the bottom material into clean sandy material and dewatered silty/clayey material.

The dewatered sludge containing in a concentrated form all the contaminants originally hold in the total bottom material was planned neither to be cleaned nor immobilised but to be disposed of at a controlled deposit.

2.2. The contract

In 1989 of the 16 bidders to the Ministry of Public Works, Directory of the Province of Gelderland, Holland/Heijmans appeared lowest bidder at nearly 1,5 million Dutch guilders for the sixth pound of the Apeldoornsch Kanaal.

This figure can roughly be split up in the following activities;
- removal of the bottom material transport to the separation plant processing of bottom material
  1 million Fl
- transport of dewatered sludge
  0.1 million Fl
- preparation of a section at the disposal site including supply of foils and drains
  0.4 million Fl

The contract was constructed as a bill of quantities to be paid for according actual measurements for the 1.1 million guilders part with fixed sums for mob/demob and all activities at the disposal site.

In addition to pricing the bill of quantities the contractor had to add a reclamation scenario showing the work procedures as envisaged by him. The technology proposed by Heijmans Environmental Technology Ltd was based on the routine applied in the gravel and sand cleaning installations developed and exploited since 1983. The actual setup of the separation plant was designed and built tailormade for this project but mainly consisted of more or less standard equipment available on the market.
The technology proposed by Dredging Company Holland Ltd was based on routine equipment with a special selfclosing grab to ascertain a clean dredging procedure without spoil of bottom material.

3.OPERATIONAL PROCEDURES ENVISAGED

3.1. Dredging

The amount envisaged was 16 m3/ml on a average over a length of 2,100 m and a bottom width of about 20 m which means 33,000 m3 in situ. The bottom material consists of consolidated silt; nobody can remember any previous dredging work done at the canal.

A dredging pontoon of 160 tonnes with winches and a hydraulic crane fitted with a special selfclosing grab sized 1250 l operated at short intervals. This resulted both in a high accuracy with respect to the horizontal and a clean dredging procedure. An additional advantage of the use of a grab is the minimal volume change of the original bottom material resulting in a minimal amount of suspended material. Vertical accuracy was obtained using a backhoe-monitor. In general movements of the dredging pontoon was done by winching using a small tug for the bigger relocations. Reconstruction of the side slopes according contract and detailed work around bridges, quay-wall, jetties etc. also is easily accomplished with the equipment used.

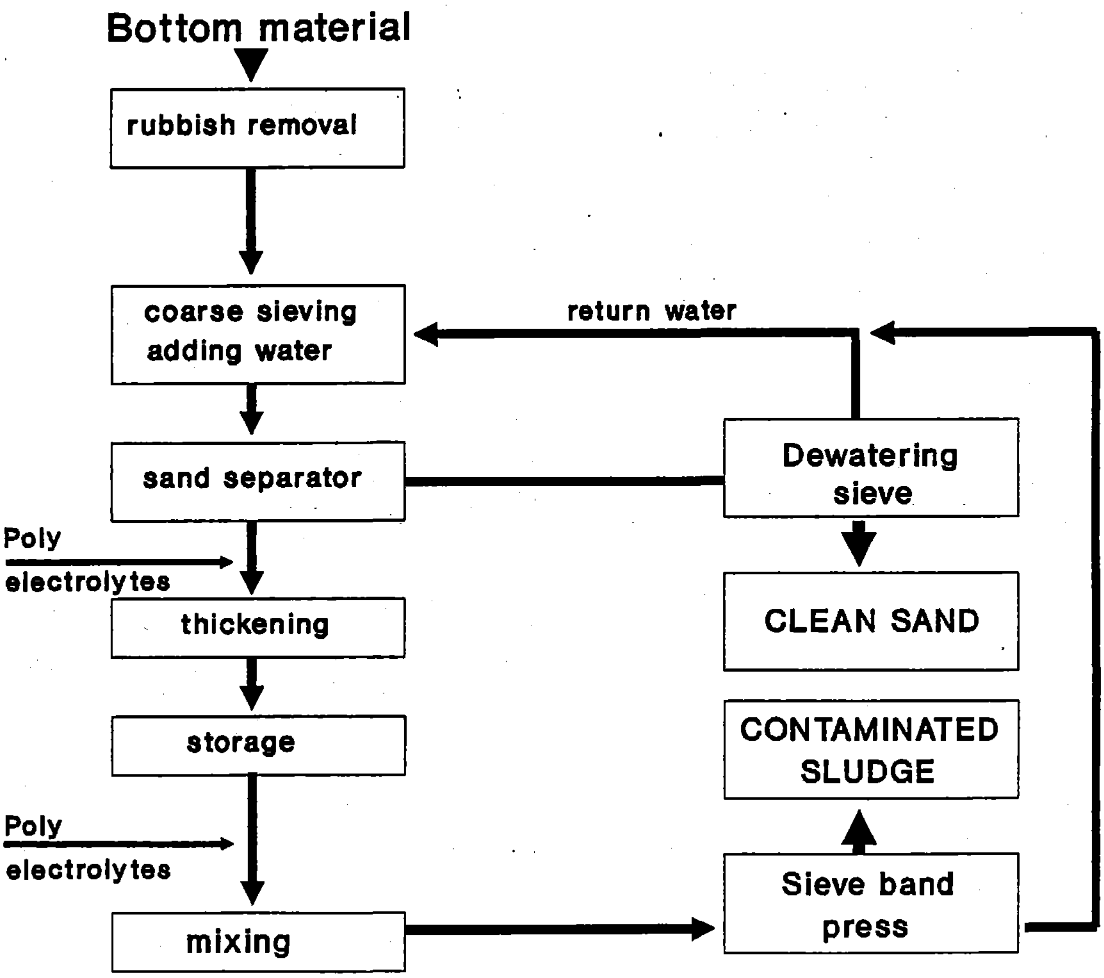
Transport of the dredged material to the processing plant was done with two small barges of 110 m3 each. The barges were only loaded up to 90% of their capacity to prevent overflow during loading, transport and unloading.

Regular measurement of the canal bottom profile was executed both by hand and using an echosounder.

As it was expected private and illegal dumping of obsolete houshold had taken place in the past a coarse screen which could be moved over the top of the barge was foreseen resulting in the well know Dutch byclicles and other semi-antiques. This scrap can not be handled in the separation plant and was disposed of at the municipal waste deposit.

3.2. Separation

After arrival at the plant the barge acts as entry container.
An additional barge acts as water container for proces water recycled in the separation plant. The separation plant is a closed system. Only some surplus water due to the dewatering of the original bottom material was disposed of decanting from the water container barge after settlement of the last fines. Separation was done at 63 micron resulting in a clean sand with sizes above this diameter and polluted sludge below same diameter. Both outputs of material were stored temporarily at the plant site using foil as bottom protection.



typical process diagram

The process flow started with a coarse screen to prevent stones and concrete elements to enter with next wet sieving off all parts above 5 mm diameter adding abundant process water.
In a hydrocyclone the material was separated into a sand part which after sieving resulted in a clean material output and the silty fine part suspended in the process water. Adding poly-electrolites resulted in fast and complete sedimentation of these fines. The overflow of water was recycled via an oil separetor. The sedimented fines were mixed with a second poly-electrolite to stimulate the dewatering in the sieve band press. This latter part of the plant is the most expensive and most critical part of the total plant and determines the total capacity of the installation.

3.3 Disposal

The client had arranged for acceptance by the local municipal waste deposit of the contaminated sludge with the restriction the amount of mineral oil should not exceed 5000 ppm dry material. As the amounts of heavy metals were low no restrictions were formulated for these.
The contaminated sludge should be isolated using HDPE foil all around with a sand drainage layer under the sludge to allow for removing of possible contaminated water minimising the risk for penetration into the subsoil.

If the sand would be cleaned below the so called A-value it could be used for any purpose. If beyond the A-value but below the B-value we are only allowed to use it in our asfaltic materials.
The sand was cleaned up till around the A-value and was be sold to a local camping.

4.ACTUAL WORK PERFORMED

The timing of 26 workable weeks was based on treatment of 300 m3/day. Due to a higher percentage of fines in the beginning we could not process more than 250 m3/day; the sieve band press is the determining factor in this case. We therefore decided to increase the workforce increasing the production hours with 25%.

On an average the percentage of fines over the total project appeared to be about 54% instead of the envisaged 41% of the dry material. On the oter hand the amount of dry material as a percentage of the dredged material was about 34% instead of the 51% envisaged. This resulted in total amount of fines approximately as envisaged.
As anticipated in our planning we lost a number of weeks in the beginning of 1990 due to flooding of the working area.

As the total amount of material removed appeared to be approximately 30% higher than stated in the contract roughly the same additional operational period was needed.
This increase was partly due to clients request to extend the contract somewhat further north and partly due to the fact that the actual clay lining of the canal was not according the as built drawings from the past. The actual bottom of the canal was measured accurately but during operations it appeared the cross sectional shape of the canal probably has changed since it was built.

This change of the original cross section in addition resulted in dredging of parts of the original clay lining subsequently leading to more fines. After consultation with the client it was agreed not to stick to the originally assumed cross section but to limit removal of material to sedimented soils leaving the original clay liner intact.

The limited pre-contract survey apparently not revealed the actual amount of fines.
In this case it has only lead to some contractual discussions as the contractor requested additional payment.
However if the (due to costs always somewhat limited) survey does indicate percentages of fines which during operations appear to be much higher it not only will lead to discussions regarding payments. In acquatic soil cleanup projects it may lead to the more principal question what we are winning by separation of clean sand from the contaminated sludge as the envisaged volume reduction of material to be disposed of may not warrent the additional costs for said separation. The volume reduction is only due to recycling of the sand. The sludge to be disposed of after dewatering still contains

about the same water content of around 50% as the original material does. We feel today the sieve band press is the best technique in the sense of reliable in operations and a reasonable cost versus dewatering result. If better, in the same sense, techniques will become available this will result more projects to be feasible.

At regular intervals samples were taken to determine the contaminant content of the sludge. The heavy metals did not pose any problems as envisaged. Once the content of mineral oil appeared too high but after a second round of sampling and testing this sludge could be deposited also at the municipal waste deposit.

5. CONCLUSIONS AND RECOMMENDATIONS

Not new in the dredging industry is to recommend a proper pre-contract survey revealing the total amounts and the characteristics of the aquatic soils. The characteristics of environmental dredging are determined by the amount of fines, to a lesser extend the characteristics of these fines in relation to the stimultated separation and sedimentation and last but not least the contaminant type and concentration.
The amount of fines will determine the environmentally added value of the separation techniques which should be payed for above the costs for the total disposal solution.
The types of fines and contaminants will effect the contractors price due to required flocculants needed for the sedimentation and the effectiveness of the dewatering.

The average and also the variations in content and type of contaminants are required for pricing the work first. In addition both the total load of contaminants and the peaks of contaminant content determine the potential acceptance of the polluted sludge at nearby waste deposits. It may seem logical to define a maximun content for each contaminant, however as in most cases it is requested by the client to encapsulate the contaminated sludge it seems more logical to agree on the total allowable load of contaminants. Prior agreement with respect to the acceptance of the contaminated sludge furthermore is in our opinion the most important factor affecting any cleanup project for aquatic soils.
The contractor can not bear the risk of ending up with the sludge without an accepted and agreed option for the disposal; the client as the original problem-owner should accept his responsibility in this respect. As the client in many cases is one of the public authorities they in addition are in a better position to arrange for this. In our project the client did so which appeared to be a major succes factor in this project indeed.

Looking into the future the aquatic soil remediation industry needs a clear attitude from the client (mainly the authorities at different level) with respect to their financial appreciation of the environmentally added value of separation of polluted sludge from the potentially recycleble sand. Cleaning of the contaminated sludge may be a further step in the worldwide cleanup scenario but will require even much more money. As in addition it will be questionable wether we can find economical application of this cleaned sludge it furthermore seems more interesting to look into immobilisation of this sludge in such a manner that the end product of this immobilisation will be accepted by the regulating bodies as an alternative construction material. The present attitude of many very capable people tends too much to a zero risk scenario resulting in a wait and see scenario for the cleanup industry.
We would welcome a more flexible approach allowing for practical solutions contributing to the improvement of our aquatic environment already now before we can guarantee a 100% solution but accepting a good solution for an acceptable price.

RIVERBOTTOMSANITATION AND LANDSCAPING BENEFICIAL USE OF FINE GRAINED DREDGED MATERIAL FROM THE ANTWERP REGION

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ABSTRACT

The paper describes the results of a study that searched for the possible utilisation of the fine grained maintenance dredged material from the Scheldt river and the Antwerp Harbour. The retained project consists of accelerated dewatering techniques followed by the beneficial use of the dewatered material for landscaping projects. The study includes a technical description of the retained solution, a planological evaluation of the selected sites and propositions for the further destinations of the retained sites.

INTRODUCTION

Maintenance dredging works are vital for the accessability of the port of Antwerp. During the past decennia different trends have been observed concerning these works :

- the volume is increasing with the navigation depths
- the grain size on the Belgian bars is decreasing
- the concern about existance of contaminating elements is growing

These trends have led to increasing problems to find acceptable solutions for the disposal of the dredged material from the Antwerp region (Belgian part of the river Scheldt and the Antwerp Harbour - fig 1). Therefore a study project was started in order to inventorise the possible solutions for the beneficial use of the dredged material in landscaping projects (ref 1).

This paper summarises the main problems which were encountered as well as the proposed solutions for the coming decennia including volumetric quantification, cost analysis and site selection.

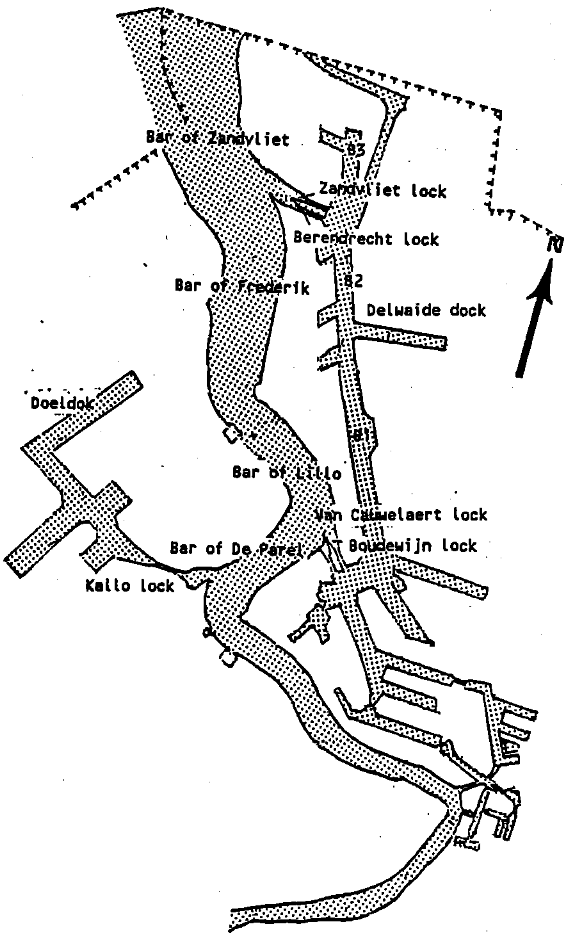

FIG. 1 : DREDGING AREAS IN THE ANTWERP REGION

PROBLEM IDENTIFICATION

One of the first problems met during the study project was how to estimate the volumes to be removed annually from the area, especially for the silty material. Of course there are detailed statistics available about the annual maintenance dredging volumes but as an important part of these volumes has to be dumped back into the river recirculation phenomenae exists even after a very careful selection of the dumping sites. These phenomenae became more and more important as the possible alternatives became restricted during the recent years :

- dumping on Dutch territory is not allowed
- reclamation on land is reduced due to decreasing space and decreasing geo-technical quality (grain size, bearing capacity) of the reclaimed material.

Therefore the study team has made an inventory of the morfological and sedimentological studies for the whole Scheldtbasin. The most general approaches of the problem can be found by R. Wollast and A. Maryns (ref 2) and J. Nihoul and R. Wollast (ref 3). These studies result into the following conclusions : in the river Scheldt between 60 and 100 km from the entrance the annual sedimentation can be estimated at 2.000.000 tons of dry material from which between 500.000 and 600.000 tons of fine grained material. Taking into account the difficulties to compare dredged volumes measured in cubic meters with these quantities in tons and the fact that the study area contains the brackish water zone of the estuary with a very important amount of suspended sediment it can be concluded that the actual dredging volumes (ref 4) confirm these theoretical values. Both results have led to the conclusion that annually some 650.000 tons of fine grained material has to be taken out from the natural system in order to create a stable morfologic environment.

As far as the sand is concerned the problem is far less critical as the recirculation problems are less important and sand remains a valuable raw material for the reclamation of industrial areas within the harbour both from a geotechnical as well as an environmental point of view.

DREDGING OF THE SEDIMENTS

As the sandfraction of the sediments is only a minor problem for which there are different beneficial uses available the study was concentrated onto the finer fraction only.

The first problem is the separation of both fractions. After a detailed analysis of all available data it was decided that the natural system of the Scheldt estuary is an almost ideal separator with the finer silty material mainly concentrated in the acces-channels to the entrance locks of the harbour and the coarser material on the main bars (see table 1). The annual volume of siltaccumulation in the two main acceschannels (ref 5) is larger than the requirements therefore no special installations are required for this phase of the process.

Dredging area	Fraction (%)				
	<2µ	<20µ	<63µ	<120µ	<200µ
Bar of Zandvliet	-	7	12	23	96
Bar of Frederik	-	18	24	34	97
Bar of Lillo	-	27	50	67	99
Bar of De Parel	-	7	14	24	90
Bar of Krankeloon	-	1	2	5	89
Acces channel Kallo	32	71	91	100	100
Acces channel Zandvliet-Berendrecht	39	68	89	100	100

Table 1: Grain size distribution of the sediments in the Scheldt river.

As far as the dredging process is concerned the study outlined a few topics to be taken into account by the selection of the most appropriate equipment :

- For the river Scheldt (channels to the entrance locks) large capacity selfdischarging trailing suction hopper dredgers should be utilised during the wintermonths. The dredged material should be discharged directly into the dewatering fields at a high density. Therefore degassing installations and specific dragheads will be required.
  The rest of the year normal maintenance procedures with the sweapbar and underwaterploughs will be sufficient.
- For the Antwerp harbour the available dredging capacity is not sufficient to follow the same procedure. When possible the direct discharging method into the dewatering fields will be utilised (November - February). During the rest of the year the dredged material will be stored in a bufferpit which will be emptied in the winter season.

SILT TREATMENT SYSTEM

The main problem for the utilisation of fine grained dredged material is the very long dewatering and consolidation period to come to a geotechnically acceptable product which can be used for different purposes. A reduction of this period is a giant step towards an acceptable long term solution.

Of course there exist also an environmental problem due to the contaminant load of the fine sediments. But in the long term this problem will be reduced or even solved by a better implementation of the global waterpurification program for the whole Scheldt catchment area (North of France, Flanders, Walloons, Brussels, Netherlands). Additionally there are a whole series of laboratory and pilot tests running for the cleaning of polluted dredged material.

The proposed treatment system which consists mainly of an accelerated dewatering system is designed in such a way that an additional treatment step can be included before or after the dewatering. However it is doubtful that an industrial and economical feasible system will become available within a few years especially for dredged material with a relative low content of a large number of contaminants and with high adsorption characteristics.

The dewatering system the study is looking for should fit the following requirements:
- large capacity (650.000 tons/year)
- immediately available
- technical feasible with high reliability
- flexible to adapt and to integrate further yet still unknown) treatment steps
- limited costs

After a detailed analysis of all the available systems (both natural and mechanical) it was decided that at this moment only the natural methods reach a sufficiënt level of technical reliability (ref 6, 7). The mechanical systems are still in a testing phase as far as the large industrial plants for silt dewatering are concerned (ref 8).

Within the natural system a one-year cycle has been selected in order to limit the required surfaces. In order to realise this objective the following boundary conditions are put forward :
- limited load in the dewatering fields (500 kg/m^2)
- good underdrainage (either natural or artificial)
- careful removal of the overlying water (limited surface per field, ring ditch,..)
- maximalisation of the evaporation through a regular turning of the silt in the dewatering field.

A final choice concerning the optimal design and treatment methods will be done based on the results of the pilot program which is in execution within the Ministry of Public Works and Traffic. The program is reported in another paper of this congress (ref 9).

To minimise the investment costs a systematic approach has been designed based on modules containing 4 dewateringfields each (see fig.2). These modules are designed with special attention to :
- minimalisation of the dikeconstructionworks
- minimalisation of the length of the required dewatering ditches
- minimalisation of the required length of discharge pipeline
- optimalisation of the acces of the fields by dumpers for the further transport of the dewatered silt

Each module has a surface of approximaterly 18.4 ha and an annual througput of 72.000 tons of dry material.

To treat 650.000 tons of dry material annually 9 modules will be necessary. Therefore 200 ha will be required including some additional space for secondary activities such as: supervision, stock of construction material, testing area for alternative dewatering techniques or additional treatment steps, ...

BENEFICIAL USES

Taking into account the very dense population of the flemish region it becomes more and more difficult to find areas which can be used for the reclamation of dredged material especially because the low lying areas which were considered of poor value in the past become important from a nature conservation point of view.

Therefore the basic filosophy is changing from a pure disposal strategy towards a recycling policy in which the dredged material is used as a raw material for other purposes. It is obvious that our study fits into this change of ideas; therefore the dewatered silt is considered as a raw material with the following characteristics :
- large volume
- limited geotechnical stability characteristics

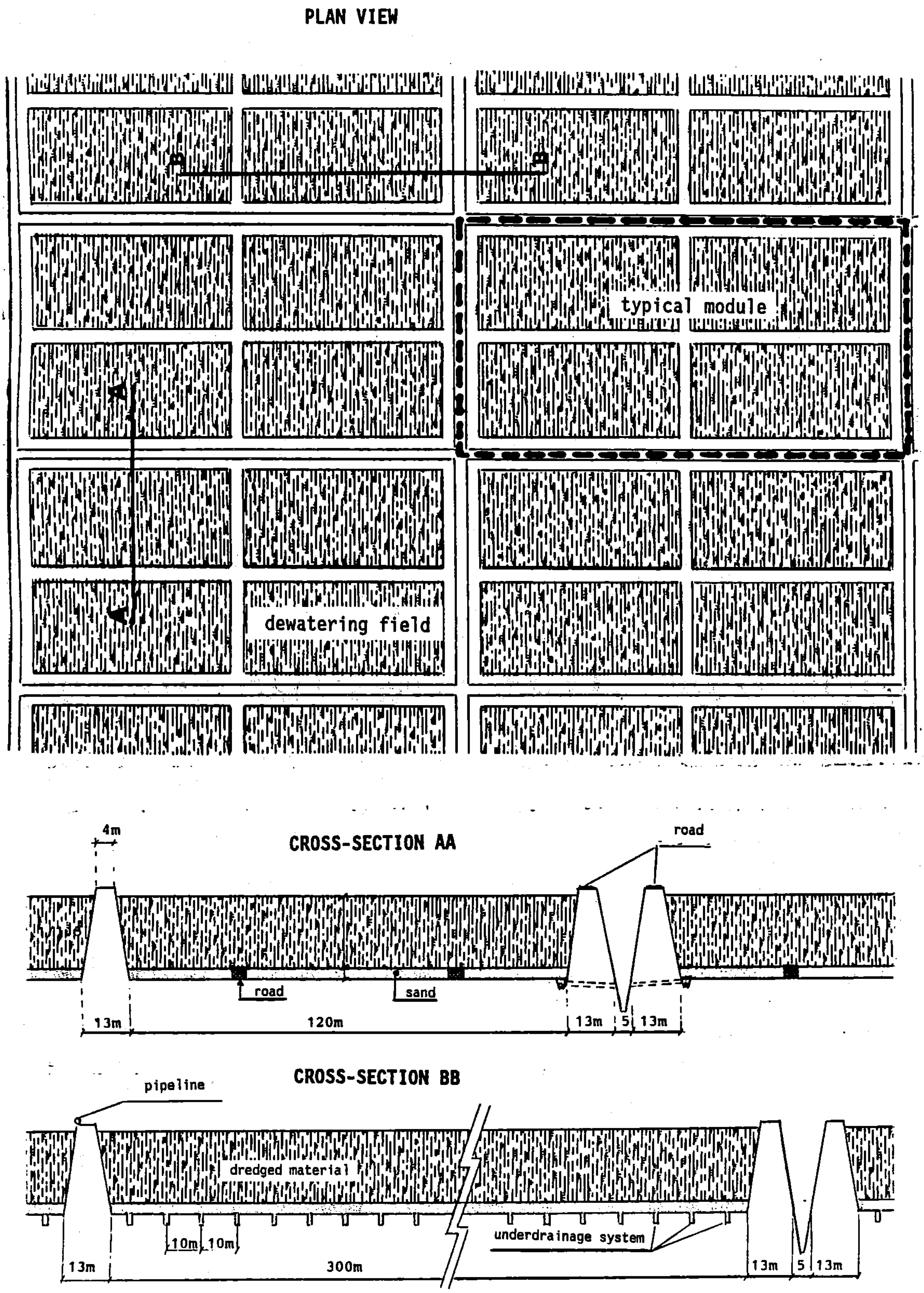

FIG. 2 : MAIN CHARACTERISTICS OF THE DEWATERING FIELDS

- fine grained material
- relative important watercontent

Taking into account these characteristics especially the enormous volumes of silt (650.000 ton/year) the utilisation of the dewatered material as a low quality construction material for landscaping projects is selected as the best solution for short and mean term projects. More sophisticated recycling projects such as the utilisation of the dewatered silt as a raw material for the ceramic industry are questionable due to the high costs and the low social acceptance of the final products.

Starting from the retained solution a basic analysis has been made of the special care measurements to be taken with the utilisation of dewatered fine grained dredged material in a large scale landscaping project :

- sufficiënt drainage capacity to evacuate the remaining pore water during further consolidation and settlement,
- stable slopes with a geotechnical poor quality material,
- controlled water and contaminant exchanges of the material with the surroundings.

Based on these requirements* the following constructional elements are integrated in the basic design (fig.3)

- an impervious underlayer (natural or artificial) to separate the fill from the surroundings in order to control water and contaminant migration,
- a drainage system of intermediate sandlayers to evacuate the excess pore water,
- slopes limited to 1/10.

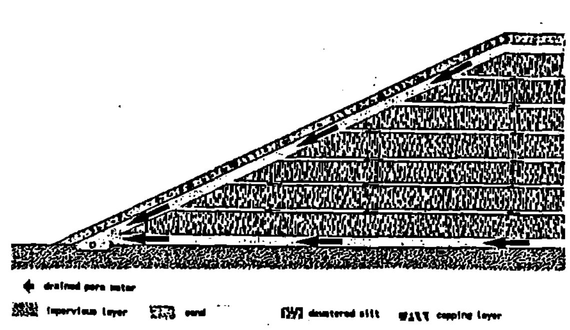

FIG. 3 : BASIC DESIGN OF A LANDSCAPING PROJECT

It is obvious that these requirements will be adapted to the results of a detailed environmental impact analysis of each selected area. This environmental impact study will start soon after the evaluation of the forlying reports by the regional authorities.

ENVIRONMENTAL CONSIDERATIONS

As far as the environment was concerned the study concentrated on the inventorisation of the available date and a first judgement of the quality of the dredged material. Additionally the basic design of the different installations is made in such a way that control and additional safeguarding steps can be included in a cost-efficient way if they should be required in the detailed environmental impact analysis which will be ordered soon. The inventorisation of the environmental data led to the following conclusions :

- the sandy material is only slightly polluted (highest levels for the elements Ni and Cd);
- the pollution levels of the silty material in the acces channels to the locks are higher but remain acceptable for landscaping projects if some basic measurements will be taken.

To meet the requirements the following measurements are proposed in the study :

- Controled dewatering of the treatment site with a system of ditches. If necessary a waterpurification step can be included at a central point.
- Quasi impervious layer (natural or artificial) underlying the dewatered material in the destination sites in order to prevent uncontrolable migration of water and contaminants to the surroundings.
- Controled dewatering systems by drainage layers for the excess porewater and by ditches for the surface run-off water. Again a waterpurification stage can be included if necessary.
- Capping of the whole volume with a layer of 2 meter of high quality material in order to prevent migration through plants and trees growing onto the site.

These measures are proposed based on rather limited information; therefore they will be adapted, enhanced or reduced based on the detailed environmental impact study which will be realised during the next stage of the project.

SITE SELECTION

The site selection has been realised based on a multicriterial analysis with a wide variaty of basic criteria such as :

- technical criteria : storage area and volume, transport distance, availability of watertransport; ...

- social criteria : social acceptance, distance to housing estates, recreational needs, ...
- planning criteria : acctual and future destination of the area and the surroundings, ...
- hydrogeological criteria : underlying groundlayer, surrounding groundwater-situation, soil characteristics,...
- environmental criteria : contaminant dispersion risk, traffic noice generation, ...

Based on these criteria two different types of site have been selected :

- sites for the dewatering and treatment installations close to the dredging sites (large surfaces are required);
- sites for the beneficial use of the dewatered material : more limited surface, longer acceptable transport distances, places with landscaping needs or potentials, environmentally more restricted.

A first search has been realised in order to define a few large areas where a more detailed search would be useful. Fig.4 gives a review of these areas.

Within each of these four areas a detailed study resulted into the one or two most appropriate places based on the above mentioned criteria :

- the sites for the dewatering and treatment installations ly within the actual or future harbour area, both on the left and right bank of the river Scheldt (see fig.4);
- The sites for the final use of the dewatered material are :
  - * A planned buffer area between the new industrial harbour zone and the surrounding agricultural land on the left bank of the Scheldt river (Beverenpolder).
  - * An extension of an area for industrial waste treatment within the existing harbour on the right bank of the Scheldt river (Walenhoek).
  - * An old clay excavation area near the Rupel river where the original landscape will be restored (Morenhoek).
  - * A clay excavation area north of Antwerp near an existing navigation canal where a new relief will be realised additional to the filling of the excavated volume (Het Blak).

A review of the main characteristics of the retained areas is given in table 2.

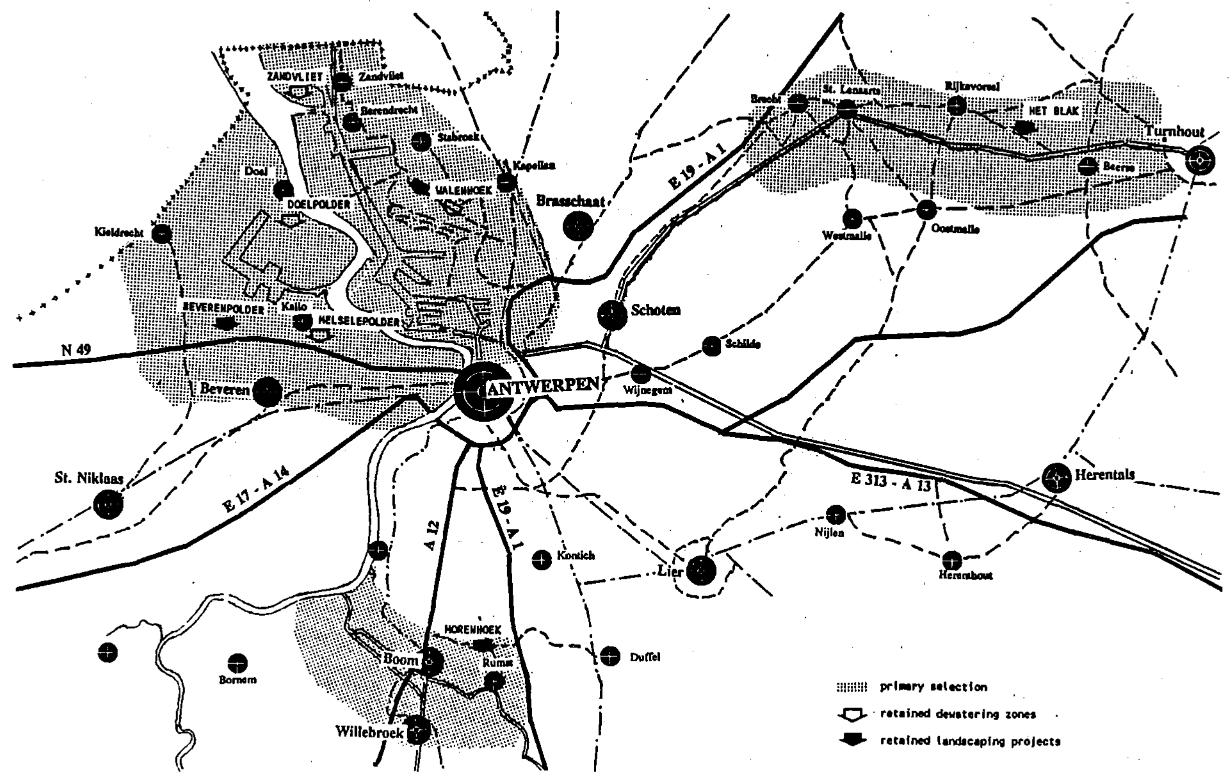

FIG. 4 : SELECTED AREAS

Area	Surface (ha)	Capacity 10^6 t	Impervious layer
Beverenpolder	201	19,3	polder clay
Walenhoek	84	8,8	polder clay
Morenhoek	123	19,7	clay of Boom
Het Blak	149	17,9	clay of the Kempen

Table 2 : Main characteristics of the retained areas.

For each of the selected sites a detailed analysis has been made of the landscaping possibilities and of the potential social needs of the region which can be fulfilled by a proper design of the project.
From this analysis resulted a wide variety of planning destinations such as :

- A visual buffer function between the harbour area and the nearby agricultural zone. (Beverenpolder)
- A recreational and nature conservation function. (Morenhoek)
- An integration with nearby industrial waste treatment installations by the use of the dewatered material as sanitation cover product. (Walenhoek)
- A recreational function for specific sports. (Het Blak)

COST ESTIMATE

One of the most important criteria for the decision whether to proceed with a proposed treatment method and where to implement the method is the cost estimate. Therefore much effort has been paid to this aspect of the problem with detailed attention to the following topics :

- pumping towards the dewatering fields
- construction of the dewatering fields
- accelerated dewatering procedures
- excavation and transport of the dewatered material
- construction of the destination site(s)
- filling of the destination sites

A review of the results is given in table 3.

From the cost estimate we learn that even when the material is dewatered the transport distance remains of crucial importance and the most nearby places are the cheapest ones.

	River sediments		Harbour sediments	
Treatment site	Doelpolder	Melselepolder	Zandvliet	Walenhoek
Destination site				
- left bank harbour	1115	1050	-	-
- right bank harbour	-	-	1150	1110
- Rupel	1285	1300	1300	1490
- Kempen	1505	1520	1520	1660

Table 3 : cost estimates (Bfr/ton)

CONCLUSIONS AND RECOMMANDATIONS

- In order to solve the increasing siltation problems of the river Scheldt 650.000 tons of fine grained material have to be removed annually from the system.
- Due to the decreasing deposition possibilities under water as well as on land a long term solution has to be based on the beneficial use of the dredged material.
- A first requirement for this beneficial use is an efficiënt and accelerated dewatering proces.
- Dewatering fields are the most economical solution for this problem. The fields have to be provided with an underdrainage system (natural or artificial).
- Accelerated dewatering techniques should result in a one year cycle.
- A basic solution for beneficial use of the dewatered dredged material are landscaping projects such as restoration of the original groundlevels in excavated areas or the construction of physical barriers between different social activities.
- For the dredged material of the Antwerp region the four most promising alternatives are :
  - a visual barier between the industrial harbour area on the left bank of the Scheldt and the surrounding poulders;
  - an extension of the industrial waste treatment installation with the proposed silt treatment installation in the harbour area on the right bank (the stored material can be used as capping material for industrial waste);
  - the restoration of the original landscape in a clay excavation zone near the river Rupel. The area can be used afterwards

for recreational and nature conservation purposes;
  - the restoration of the original landscape in a clay excavation zone near Brecht. Eventually a new landscape can be made for specific sport applications.
- On the long term this beneficial use can be replaced partially and/or gradually by processes with a higher added value.
- The utilisation of the dewatered silt has to be done in such a way that the geotechnical and environmental stability of the area remains guaranteed.
- The final decision on the process and location should be made based on a detailed environmental impact analysis of the different sites. In this stage environmental considerations played an important role in the basic design of the system in order to get any potential problem reversible at minimal costs.
- The cost of the whole process is estimated between 1050 and 1500 Bfr. It is advisable from an economic viewpoint to reduce transport distances as much as possible. The estimated costs are exclusive dredging costs for the silt and sand.
- The solutions with a beneficial use within the harbour area remains the most economical.

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PHYSICAL TREATMENT AND STORAGE OF AMSTERDAM CANAL SLUDGE

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ABSTRACT

Maintenance of the famous Amsterdam canals requires dredging of 100,000 m^3 of sludge annually. The sludge is mainly contaminated with lead, mercury, mineral oil and polycylic aromatic hydro-carbons. Due to environmental restrictions only 50,000 m^3 is allowed to be dumped into a deep harbour basin. Recently the remaining, contaminated 50,000 m^3 is treated in a sludge treatment plant. The plant successively consists of machineries separating coarse material, hydro-cyclones separating the sand fraction > 40 - 50 μm, pre-thickeners and a belt filter press, dewatering the sludge to a dry solids content of 35 - 40 %. The sludge cake is stored temporarily in a depot alongside the plant. The surplus of process water is treated in an upflow sand filter installation.

This paper describes the design of the plant and depot, and concludes with some practical experiences and recommendations.

1. INTRODUCTION

The inner city of Amsterdam possesses a total length of 110 km of canals which have to be maintained. Proper maintenance requires dredging of 100,000 m^3 of sludge annually. Chemical analyses of the sludge frequently indicated high concentrations of lead, mercury, mineral oil and poly-cyclic aromatic hydrocarbons (PAH's).

In the past the sludge could be dumped into a former deep sand winning pit (the Nieuwe Meer) and into the basin of the Amerika harbour. Due to strict environmental regulations dumping into the Nieuwe Meer had to be stopped, while dumping in the Amerika harbour was permitted only for lightly contaminated sludge, corresponding with a volume of 50,000 m^3 annually. Other solutions had to be found for the remaining, heavily contaminated 50,000 m^3 of sludge.

An experiment on vacuum extraction, aiming in situ thickening of the sludge, was not successful. Meanwhile maintenance dredging needed urgent solution. Therefore Amsterdam has chosen for storage of the contaminated sludge in a temporary land depot near the Jan van Riebeeck harbour. In view of the limited storage volume, the volume of sludge needed to be reduced to a minimum.

This paper describes the sludge treatment plant consisting of separation of reusable materials as metals, rubble, sand, etc., and dewatering of the sludge. The chosen treatment method is described within a broad context of sludge cleaning methods. The design of the temporary depot is also described. The paper concludes with some practical experiences and recommendations derived from the tests which have been carried out since june 1990.

2. GENERAL CLASSIFICATION OF SLUDGE CLEANING METHODS

Compared to soil, dredged sludge is characterized by a high water content (appr. 75 vol%) and a high content of fine mineral particles (fraction < 16 μm up to 80 % of mineral particles). The bond of contaminations to mineral particles is stronger as the size of particles decreases. Therefore the treatment of contaminated dredged sludge requires other means than applicable for the sanitation of soils.

The cleaning of contaminated dredged sludge can be divided into four main groups [ref. 1]:

1. Methods to separate a rather clean sand fraction from the sludge, after which a slurry of heavily contaminated fine particles remains. The technique of hydro-cyclonage belongs to this group.

2. Methods to separate contaminations from fine sludge particles by means of

extraction or evaporation. Various means of extraction can be applied for separation of PAH's and heavy metals. Evaporation is very effective for the separation of mercury.

3. Methods to clean the extraction agent of method 2. Representative of this group is ion exchange. The combination of acid extraction and ion exchange is an applicable method for the cleaning of sludge contaminated with heavy metals.

4. Method of bio-degradation to disintegrate contaminations of PAH's, in particular.

3. PHYSICAL AND CHEMICAL COMPOSITION OF AMSTERDAM CANAL SLUDGE

Since 1984 physical and chemical analyses of sludge samples are regularly made. Each canal has therefore been divided into sections of 100 - 150 m. A representative sample of a canal section is created by mixing ten samples taken from the particular section. Table 1 shows the concentrations of chemical contaminations. The last colomn of table 1 shows the so-called signalling value (S.V.). Whenever the S.V. is exceeded by at least one of the substances, the dredged sludge from the particular canal section has to be stored in depot under special conditions or has to be cleaned. According to table 1 very high concentrations of mineral oil, PAH, extractable organic chlorine (EOCl), nickel, mercury and lead are present. Appr. 50,000 m^3 of sludge dredged annually is contaminated in such a way that it has to be treated by one of the methods given in the previous chapter.

Table 2 shows the physical composition of the sludge. From both table 1 and table 2 it can be concluded that the quality and composition of the sludge varies a great deal. Sometimes even samples taken from neighbouring canal sections showed very different concentrations. Due to the large volume concerned and its variety of composition, at present the contaminated sludge cannot be treated properly yet by methods 2, 3, and 4. The technique in which a reusable sand fraction is separated from the contaminated sludge (method 1) followed by dewatering of the sludge, has been applied successfully [Hamburg, ref. 2]. Several practical tests also proved the applicability of this technique for the treatment of Amsterdam canal sludge.

Table 1
Concentrations of contaminations in Amsterdam canal sludge [ref. 3]

ubstance	Concentration [mg/kg d.s.]		
	Min.	Max.	S.V.
Mineral oil	168	16000	5000
PAH	0.2	200	17
EOCl	0.3	100	20
chromium	4	320	1000
nickel	3	465	200
copper	2	400	400
zinc	15	3000	2500
arsene	1.0	100	150
cadmium	<0.5	40	30
mercury	0.1	40	15
lead	10	1800	1000
PAH (total Borneff series)			

Table 2
Physical composition of sludge [ref. 4].

Substance	Unit	Concentration		
		Min	Max.	Average
mineral particles	% d.s.			84
lime (calcium)	% d.s.			6
organic material	% d.s.			10
lutum content (< 2 μm)	% m.p.	1.5	31	16
fraction < 16 μm	% m.p.	2.5	60	
fraction > 63 μm	% m.p.	4	89	45
dry solids content	vol%	15	30	
d.s. = dry solids content m.p. = mineral particles content				

4. THE SLUDGE TREATMENT PLANT

General

The sludge treatment plant at the Jan van Riebeeck harbour consists of four main sections:

A. Separation of coarse material
B. Separation of the sand fraction
C. Sludge dewatering
D. Treatment of process water

With the help of the process scheme of Fig. 1 the plant is described in detail below.

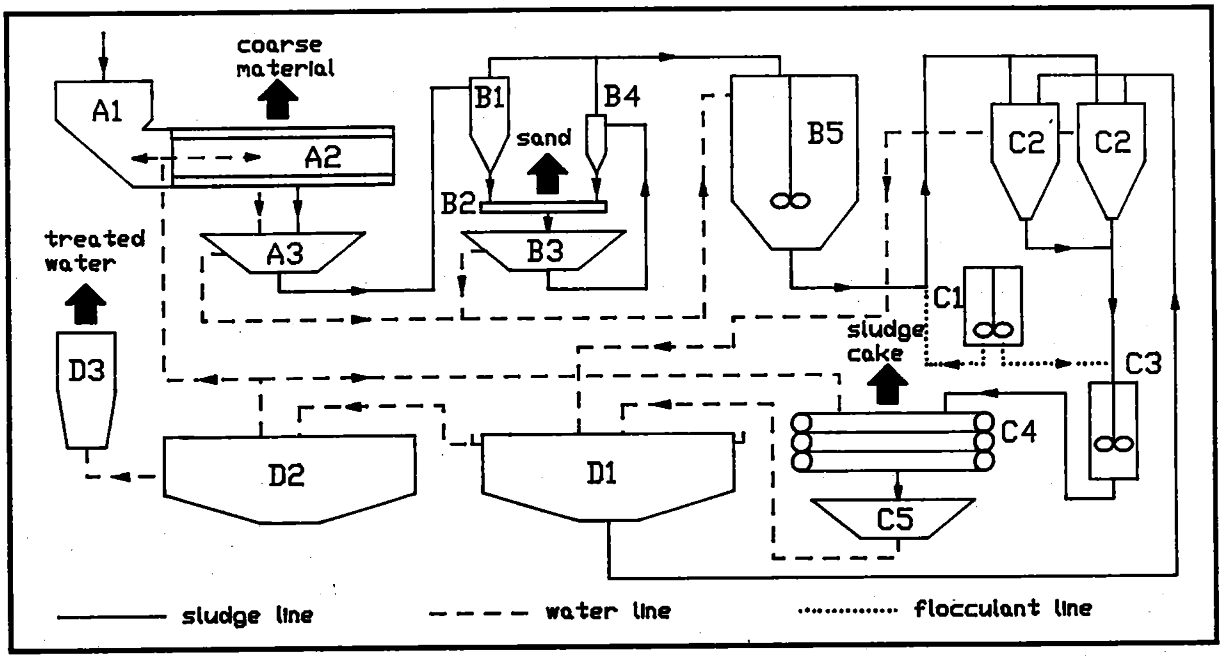

Fig. 1 Process scheme of the sludge treatment plant.

A. Separation of coarse material

The raw sludge is supplied by barges, which have a volume of 35 m^3. The capacity of the treatment plant is designed for a maximum of 350 m^3 of raw sludge per day, corresponding with ten barges. A grabbing crane dumps the raw sludge into a funnel (A1), which has been provided with a washing unit and a screen (width of mesh 0.50 m) at the bottom to seperate very coarse material as tires, cycles, etc. Next the sludge passes a rotating double-walled cylindrical drum (A2) including washing unit, with successive mesh widths of 50 mm and 8 mm, to separate the coarse and medium sized material, respectively. All the material remaining on the sieves is washed and stored separately. The sieved sludge and sand is collected in the receiving bin (A3) beneath the cylindrical drum in which it is mixed with the washing water.

B. Separation of the sand fraction

The mixture of sludge, sand and washing water (appr. 15 % d.s.) is pumped towards the primary hydro-cyclone (B1) which has a capacity of 100 m^3/hr. The underflow of the hydro-cyclone contains a sand fraction of diameter bigger 40 - 50 μm. The sand is dewatered on a shaking screen (B2) with mesh size 200 μm. It is expected that 10 to 15 % of the mineral particles of diameter between 45 and 200 μm will flow through the screen. To increase the yield of sand the leakage water is pumped towards the secondary hydro-cyclone (B4) which has a capacity of 25 m^3/hour, also separating at 40 - 50 μm. The underflow of the secondary hydro-cyclone is spread out over the sand layer remaining on the shaking screen. The yield of reusable sand is estimated on 32 m^3/day.
The upper flow of both hydro-cyclones containing fine sludge particles < 45 μm, flows into a buffer tank (B5)in which a stirring device keeps the content in suspension. Also the surplus water from receiving bins A3 and B3 containing fine sludge particles, is stored in tank B5.

C. Sludge dewatering

Prior to the process of pre-thickening, flocculant is added to the sludge. The flocculant dosing is executed by an automatic flocculant preparation and dosing installation (C1), which has a capacity of 8 kg per hour. The sludge flocks settle down in two coneshaped pre-thickeners (C2). The settled sludge flocks (d.s. content 18 - 20 %) are again mixed with an addition of flocculant (mixtower C3) and finally dewatered in a belt filter press (C4). The design capacity is 8 ton d.s./hour. The sludge cake (d.s. content 35 - 40 %) is stored in the temporary depot alongside the plant.

D. Treatment of process water

The raw process water from the pre-thickeners and the belt filter press is pumped into the settling tank (D1), which has been provided with an overflow gutter. The clear water from the overflow is collected in a clear water tank (D2). This water is used for washing of coarse material on the sieves (A1 and A2) and for cleaning of the belt filter press (C4). The surplus of clear water is treated in an upflow sandfilter installation (D3: capacity 40 m^3/hour). The treated water flows into the Jan van Riebeeck harbour. Regularly samples are taken from the water to analyse the concentrations of contaminations, which have to be lower than the concentrations stated in the discharge permit (see Table 3).

5. DESIGN OF THE TEMPORARY DEPOT

The temporary depot occupies an area of appr. 26.000 m^2. In total a volume of 172.000 m3 can be stored, corresponding with a filling period of appr. 10 years. The bottom of the depot has been built up of a 20 cm layer of sand, a geomembrane liner of 2 mm high density poly-ethylene (HDPE), and a 50 cm layer of sand (Fig. 2). The drainage system in the top sand layer consists of HDPE Ø 0.08 m ribble drain provided with a poly-propylene covering. The distance between drain tubes is 5.0 m. Each drain tube is provided with a purging unit on top of the embankment. Along the inner toe of the embankments the drainage water is collected in a HDPE Ø 0.16 m collecting drain. All drain tubes lay in a bed of coarse sand. The collected drainage water passes an oil separator and is collected in the raw process water buffer tank (D1) of the plant. The core of the embankments has been built up of the original soil of the depot site. The surface of the inner slope consists of the same layer system as the bottom of the depot. In addition the top sand layer has been stabilized with cement. Slopes of the embankment have been constructed at 1 : 2. Height between depot bottom and top of embankment is 4.0 m.

6. PRACTICAL EXPERIENCES

In june 1990 the sludge treatment plant was put into operation. The first tests showed good performances of the sieves and the hydro-cyclones. The d.s. content of separated sand varies from 80 to 90 % according to design specifications. The quality of the sand is acceptable for the construction of road embankments. The capacity of the pre-thickeners appeared to be insufficient to thicken the sludge to a d.s. content of 18 - 20 %. Only 9 - 12 % d.s. was attained. The low d.s. content is caused by the great fluctuation of composition of the sludge and the relatively large content of organic particles in comparison with mineral particles. Due to the poor performance of the pre-thickening process and in order to get a sludge cake of d.s. content 35 - 40 %, the velocity of the belt filter press had to be slowed down to a capacity of 2.5 - 3 ton d.s./hour. Due to the volume reduction the average concentration of contaminations in the sludge cake is about 3 times greater than originally.

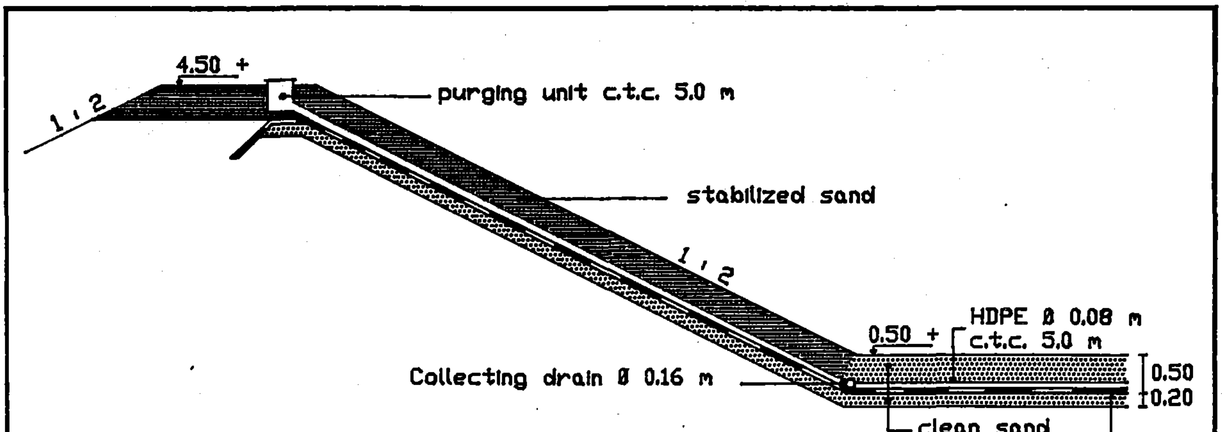

Fig. 2 Cross-section of the depot.

The test period has not been finished yet. Therefore the plant is still subject to minor changes. The tests proved that the capacity of the pre-thickening installation has to be increased. Moreover pre-thickening requires flocculants suitable for a wider spectrum of sludge composition. Additional tests already have selected a suitable flocculant. The water quality meets the requirements of the discharge permit except for the concentration of Kjeldahl-nitrogen (N_{kj}), which is 1.5 - 3 times too high (Table 3). The high concentration of N_{kj} is mainly caused by the fraction of suspended particles.

Table 3
Concentrations of contaminations in treated process water.

Substance	Unit	Concentration	
		Treated water	per-mit
C.O.D.	mg/l	46 - 96	100
N_{kj}	mg/l	33 - 61	20
EOCl	µg/l	3 - 34	100
Mineral oil	µg/l	50 -211	5000
suspended particles	mg/l	2,7- 10	25
PAH-Borneff	µg/l	0,2- 0,5	10
sum of heavy metals	µg/l	25 -141	1000
Mercury	µg/l	0,1- 0,3	1
Cadmium	µg/l	0,1- 0,5	10
C.O.D. = chemical oxygen demand			

7. DISCUSSION

The sludge treatment plant and the storage of the sludge cake at the Jan van Riebeeck harbour offers a temporary solution for the maintenance of Amsterdam canals. The plant offers an environmental friendly reduction of the sludge volume in which recycling is pursued.

Prior to construction of a sludge treatment plant sufficient practical tests have to be carried out on techniques of separation and dewatering. For the greater part the capacity of the plant is dependent on the dewatering process. It is therefore recommended to install an overcapacity of pre-thickening installation, in particular when the composition of raw sludge varies to a great extent.

Since the sludge has been compacted and collected in depot, cleaning methods as extraction (method 2) in combination with ion-exchange (method 3), or bio-degradation (method 4) will become more attractive. The attention should now be focussed on cleaning of the sludge cake.

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RECULTIVATION OF JAMNO LAKE

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ABSTRACT

The removal of bottom sludge from Lake Jamno is considered basic step in its recultivation.
The main sludge component is calcium carbonate. The sludge will be used for agricultural purposes. The secondary sewage treatment plants are under operation or construction in order to prevent lake eutrophication and Baltic Sea pollution. The recultivation procedure is designed for 5 yrs.

INTRODUCTION

Jamno Lake is situated close to the Baltic shore north of the city of Koszalin. It has a short connection with Baltic sea, which causes periodical sea water intrusion into the lake. The lake area is 22 km^2 and mean depth - 1.4 m. Catchment area of the lake has 502.8 km^2, with 1 city /Koszalin over 100 tausend inhabitants/, 27 towns and villages. There are also 3 tourist resorts situated between lake and Baltic sea on a strip of land /1 km width and 10 km long/.

The tourist resorts are constantly inhabited by 4000 people. During sommer time there is over 25000 tourists. The catchment area is in 30% forested and 60% of the area is in agricultural use. The lake has polimictic and polisaprobic character with no thermal and oxygen stratification, strongly eutrophicated due to the man made pollution.

POLLUTION OF THE LAKE

The sewage from Koszalin are now discharged without treatment to the river / primary and secondary sewage treatment plant is under construction/. The sewage treatment plant for 3 tourist resorts has been operated since 2 years. Other towns have no treatment plants, and villages-have no sewerage systems. There is also a pollution load from the farming land. The pollution load of discharged sewage 50000 m^3/d is 8700 kg BOD/d, and 5000 kg BOD/d from farming land and other disspersed sources. The lake recives 169 t/a of phosphates from discharged sewage. Total load of phosphates discharged to the lake is about 170 t P/a. The atmospheric pollution adds to the lake pollution. The mesurements of air born pollution performed in 1967 reveiled the load of phosphorus 1.1 t P/a and 24 t/a of ammonia nitrogen. Now the air born pollution load is much higher.

Since 1967 the lake is under constant investigation. The degradation of the lake is evident. It is proved by physical-chemical and biological components of water and by increase in bottom sludge thickness. The biomass concentration of the lake is over 50 mg/l, the pH approaches the value of 10 and the water is oversaturated with oxygen. The oxygen deficits however were stated in the estuary of the river transpositing the untreated sewage of Koszalin to the lake. The total concentration of phosphorus and nitrogen in the lake water are 0.9 - 2.1 mg P/l and 5 mg N/l. Mass algae growth decreases the light transparency of water. The bacteria concentration in water is so high, that since 1972, the lake has not been used for recreational purposes.

During last 10 years there is evident increase in BOD, total nitrogen and phosphorus, phenols and bacteria concentration in the lake. Phytoplancton organisms concentration was in the range of 2.2 to 3.7 · 10^6 org/l. with predominance of blue green algae. Zooplancton organisms were not numerous, probably due to excessive development of blue-green algae and generally because of the lack of ecological balance in the lake.

Total dissolves solids TDS concentration of the lake water ranges between 0.5% to 0.5‰. The higher concentrations are caused by inflow of Baltic sea water, which usually takes place during automn and winter storms /70-90 days annually/. The water exchange rate in the lake is 6.3 annually.

RECULTIVATION STEPS

The recultivation of the lake requires several steps which include: secondary sewage treatment plants construction with phosphorus and nitrogen removal for towns in the catchment area; improvement of selfpurification processes in the tributaries and in the lake by construction of Bio-Hydro-structures; removal of bottom sludge leyer from the lake.

For the recultivation purposes only 0.50 m sludge leyer shoud be removed. The removal 2 m of the sludge is suggested for the improvement of agricultural production on sandy and acidic soils predominating in the vicinity of the lake. Upper leyer of bottom sludge accumulates nitrogen and phosphorus compounds, which are diffused into the water from anoxic zone of the sludge especially during storms.

The sludge removed from the lake will be transported to the sludge lagoons and then pumped onto the fields or to the sludge processing plant. The mechanical sludge dewatering is designed ahead of thermal dewatering and packing. Part of the sludge will be enriched with dolomite powder. The water from sludge dewatering will be used for crop irrigation during vegetion season or after iron coagulation discharged to the lagoons and lake. The efficiency of phosphorus removal by iron coagulation of the water was $\sim$85%.

The total operation of sludge removal is designed for 5 yrs. Part of the sludge /30 to 50%/ will be used in the vicinity of the lake without dewatering, and part will be transported to the farmers and mainly gardeners in the coutry after processing.
The economical analysis proved that the sludge value will cover the cost of lake recultivation.

THE SLUDGE CHARACTERISTICS

The bottom sludge leyer was increasing at a rate of 1 mm/a until 1960 and after-the rate was increased tenfold. In 1947 the calculated volume of the bottom sludge was 44.6 mln cm^3, whereas in 1989 the bottom sludge was evaluated on 50 to 60 mln m^3. About 80% of the sludge are anorganic components, with increased concentration of organic matter in the upper sludge leyer.

There is also in the upper 10 cm sludge leyer 70 to 95% of total nitrogen and phosphorus present in the lake water. During storm the upper sludge leyer /5 to 20 cm/ is intermixed with water causing turbidity and diffusion of nutrient back to the water.

It is presumed that the removal of the sludge leyer will decrease the concentration of nutrients as well as turbidity. It will also affect the algae and zooplancton population leading to ecological balance in the lake. One may axpect also the increase in the population of bottom organisms. The zone of rooted aquatics is planed in the estuary parts of the rivers in the lake. The bottom sludge 1.0 m deep is 100 yrs old and consist of calcium carbonate mainly. The old sludge has much lower concentration of phosphorus in comparizon with the newer leyers. It is expected that during sludge removal from the lake the concentration of phosphorus will decrease due to sludge sorption capacity. Total amount of sludge removed will be 30 mln m^3, which is 3.5 mln ton of dry solids, with 1.14% P_2O_5, 1.5% N, 0.20% K_2O, 0.5% MgO and 22% CaO.

There are also microelements in the sludge /Mn, Zn, Cu, B, Mo/. The concentration of heavy metals in the sludge g/kg is: Zn - 0.08-0.288; Cu - 0.012 -0.052; Ni - 0.013-0.057; Pb - 0.014 -0.071; Cd - 0.0001-0.0003. The heavy metal concentration is lower than maximum permissible concentration for the sludge used in agriculture.

The research performed by the Institute of Soil Science defined the doses of sludge and the increase in agricultural productivity on the land in the lake vicinity.

DISCUSSION

The basic element of the Jamno Lake recultivation is sludge removal, which shall proceed with sewage treatment plant construction, lagoons and bio-structures in the rivers and lake. The bottom sludge can be economically used in agriculture, and cover the cost of recultivation.

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HEAVY METALS IN CANAL SEDIMENTS OF THE HAGUE (THE NETHERLANDS) : AN INVENTORY AND USE OF ACID EXTRACTION TREATMENT

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ABSTRACT

Sediments are primary sinks for contaminants. In our study, dredged canal sludges from 130 sites in The Hague often showed too high metal contents as compared with the existing sediment standards in The Netherlands. Elements most frequently exceeding the standards were Cu, Zn and Pb; the latter element has been the main emphasis of our study.
Extraction with strong acids is a feasible clean-up technique; in 24 hours laboratory experiments, 80-100% Pb removal was attained at pH < 1.5, using HCl as an extractant. H_2SO_4 was shown to be far less efficient. Practical applications of these, and alternative techniques (e.g. ion exchange, microbial conversions) are briefly discussed here.

INTRODUCTION

Dredging of waterways is a common practice for the improvement of navigability as well as for water quality management purposes. In the last few years, large problems have arisen in the storage and clean-up of polluted dredged material. A temporary solution is storage in large reservoirs on land, as has become the case for the harbour sludge of Rotterdam, The Netherlands. The storage basin has to accomodate 5-10 million m^3 of polluted dredged sediment per year (1), and its full capacity will be reached by the year 2005. On the longer term, therefore, further measures will be inevitable in order to reach acceptable sediment qualities that would allow unrestricted disposal. Additionally, it may become necessary to locally clean up polluted sediment sites.

There is no universal method for the treatment of the different types of organic and inorganic pollutants in sediments. Dredged material from different locations can vary widely in composition; important factors that determine the sediment quality are (i) particle size distribution, (ii) water and organic matter content and (iii) the history of pollutants loadings from point and non-point sources.

Our research has dealt with an inventory of the levels of metals in dredged canal sediments from 130-133 sites in The Hague (Den Haag, The Netherlands), and studying possible clean-up methods for these sludges. The sediments were classified according to "pollution classes", as are being applied in The Netherlands. Statistical correlations between the various constituents were examined as well.

For sediments from a relatively polluted site in the centre of the Hague, the efficiency was investigated for removal of lead (Pb), a priority pollutant at that site. Extraction with strong acids is a promising technique, which was examined under different laboratory conditions (type of acid, pH, extraction time, pre-treatment, etc.).

	Number of samples	median	min.	max.	No. of samples in pollution classes	
					III	IV
Organic matter (%)	133	6.1	0.6	36	-	-
Lutum (< 2 µm, %)	133	4.5	0.4	26	-	-
Cd (mg/kg)	130	0.9	0.4	13	1	0
Cr (,,)	130	11	2.4	50	0	0
Cu (,,)	130	38	2.9	330	37	3
Hg (,,)	130	0.2	0.05	4	7	0
Pb (,,)	133	100	3.6	3000	2	2
Ni (,,)	130	11	1.9	290	10	1
Zn (,,)	130	240	19	2900	20	2

Table 1. Sediment characteristics and metal contents in 130-133 sludge samples from The Hague canals. For criteria of classes III and IV, see Table 2.

POLLUTANTS IN CANAL SEDIMENTS OF THE HAGUE

A comprehensive research on the canal sludge qualities at some 1000 sites in the Hague is at its final stage; our paper provides preliminary data on metal contents at 130-133 sites in The Hague.

Table 1 presents sediment characteristics and metal contents at the sites; for detailed results, see (2). Sludge samples had all been taken from the upper 50-100 cm of the sediment layer, under which the original sand bed could be found.

	Class I	Class II	Class III	Class IV
Cd (mg/kg)	< 2	2-7.5	7.5-30	> 30
Cr (,,)	< 480	< 480	480-600	> 600
Cu (,,)	< 35	35-90	90-400	> 400
Hg (,,)	< 0.5	0.5-1.6	1.6-15	> 15
Pb (,,)	< 530	< 530	530-1000	> 1000
Ni (,,)	< 35	35-45	45-200	> 200
Zn (,,)	< 480	480-1000	1000-2500	> 2500

Table 2. Classification of dredged sediment qualities in the Netherlands in four pollution classes (see text). Measured data for sludge samples have to be corrected with respect to a standard sediment (25% lutum, 10% organic matter) with the help of the formula:

$$N' = N \frac{a + b*25 + c*10}{a + b*\%\ \text{lutum} + c*\%\ \text{organic matter}}$$

in which N' and N are the corrected and uncorrected contents, respectively, and a,b and c are correction factors:

metal	a	b	c
Cd	0.4	0.007	0.021
Cr	50	2	0
Cu	15	0.6	0.6
Hg	0.2	0.0034	0.0017
Pb	50	1	1
Ni	10	1	0
Zn	50	3	1.5

The governmental authorities of The Netherlands make use of guidelines for assessing sediment qualities, dependent on the possible uses of the material. The procedure defines four sediment pollution classes (Table 2). Dredged material from class I is of acceptable quality for all uses. Class II sludges may be introduced into the aquatic environment under certain restrictions, whereas for class III and, most urgently, class IV sediments, storage in reservoirs on land under strictly controlled conditions is necessary (1); these latter sediments may pose a serious threat to aquatic ecosystems and to public health.

According to the above guidelines, all sediment data have to be standardized with respect to a "standard" sediment, *i.e.* a sediment with an organic matter content of 10% and a lutum (< 2 µm particle size) content of 25%. For the different chemical compounds empirical correction formulae are available for non-standard sediments, which take into account the enhanced cation exchange capacity (CEC) of the soils (related to increased adsorption capacity) under higher organic matter and lutum contents, see Table 2. Thus, pollutants contents in sandy sediments poor in organic matter may have to be corrected by a multiplication factor of 1.5 to 3, dependent on the soil characteristics and pollutants under consideration. The reverse holds for sediments relatively high in lutum and organic matter.

The data in Table 1 have been classified according to the above guidelines. The results show a large variation in the pollution levels for the different sludge samples (*i.e.* locations in The Hague canals). Relatively bad sediment qualities were found for the elements lead, zinc and copper, for each of which 2-3 samples (1.5-2%) were in class IV. Further, a large number of the samples (for Cu some 30%) were found in class III, necessitating future sanitation.

	Zn	Ni	Pb	Hg	Cu	Cr	Cd	lutum
org. matter	+	-	-	+	-	-	+	-
lutum	-	-	-	-	-	+	-	
Cd	+	-	+	+	+	+		
Cr	+	-	+	+	+			
Cu	+	-	+	+				
Hg	+	-	+					
Pb	+	-						
Ni	-							

Table 3. Statistical correlations between sediment parameters in 130-133 canal sludge samples from The Hague. + = significant correlation at 99% confidence level;
- = less or non-significant.

Table 3 presents results for the correlation analysis between the various components in the sludges; the different metals, except Ni, were usually significantly correlated, with typical correlation coefficients of 0.4-0.7 (2). It is remarkable that the values of the above parameters hardly show any relationship with the sediment parameters organic matter and lutum contents. Due to their higher CEC's , one would expect higher pollution levels for the muddy, organic rich, rather than for the coarser, organic poor sediments . *E.g.* Förstner and Wittman (3) reported 90-95% of the adsorbed Pb to be found in the sediment grain size fraction < 60 µm, which constituted only 30% of the overall sediment weight.
It should be realized, however, that the pollution loads at the different locations in

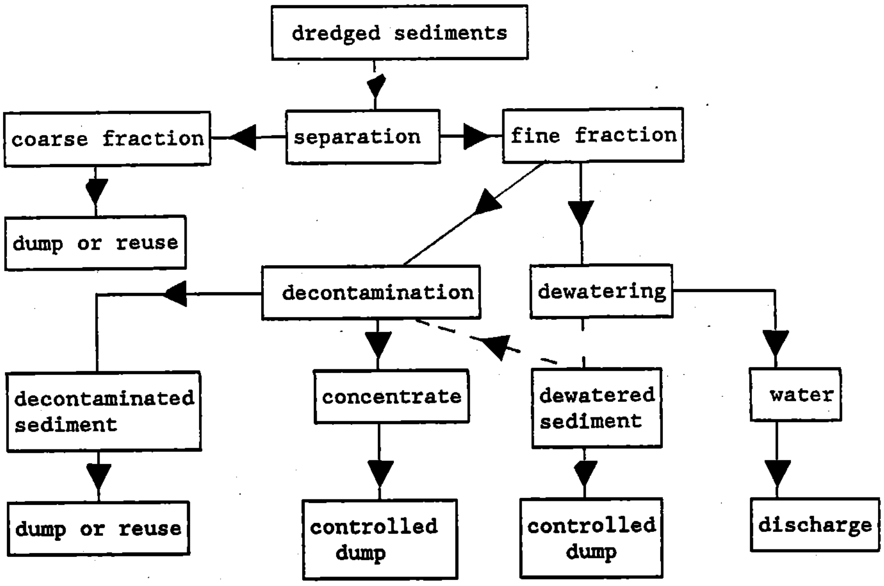

Fig. 1. Scheme of treatment steps for polluted sludge

the canals of The hague is quite uneven, *viz.* strongly dependent on the presence of local waste water discharges, run-off of street dirt and presence of busy traffic (emitting lead from exhaust gases). The historic evolution of the pollutants loadings, with its spatial and temporal fluctuations, appear to be a more critical factor in the determination of the pollution levels of the sediment fractions, than the (slow) process of natural redistribution of the pollutants between the fine and coarse fractions.

SLUDGE TREATMENT METHODS

The most suitable method for removal of the different pollutants in dredged materials will, amongst others, depend on the sludge type (lutum and organic matter contents, median grain size, etc.) and the pollutants levels in the material. Fig. 1 gives a scheme for the process steps involved.
Usually, efficient (pre-)treatment is the separation of the dredged material into a coarser and finer fraction, after which the coarser, in general relatively unpolluted, fraction can be dumped or reused. For this separation use could be made of a hydrocylone, which is based upon centrifugal separation of the different grain sizes in the sludges(4). The efficiency of separation is especially good for mud/sand mixtures, for which typical efficiencies of some 80% were found for the removal of the fraction > 200 μm. A disadvantage of the method is its relatively high water use, leading to a bulky end product which needs dewatering. Also, the high water supply with accompanying high turbulences involved may give rise to a net redistribution of the pollutants from the finer towards the coarser sediment fractions (3).

Some potentially attractive treatment methods for sludges are (5):
- extraction with acids and/or oxidants
- complexation with EDTA or NTA
- separation in ion exchangers
- magnetic or electrochemical separations
- (micro)biological conversions

For the moment, extraction with strong acids, together with ion exchange, are the most practicable of the above techniques. Magnetic and electrochemical separations are currently under development. These methods are however complex and rather unspecific with respect to the different toxicants vs. non-toxicants; *e.g.* also chlorides and carbonates are being attacked, causing a low efficiency for the removal of the toxicants proper.
Microbiological conversions are a promising method for organic micropollutants under the condition that the bacteria are adapted to the environment. Also, in some cases metal ions can be concentrated after which post-treatment can follow. An example form the bacteria of the genus *Thiobacillus* which, under appropriate oxygen and sulfur supplies and low pH values can quantitatively dissolve metal ions from sediments.
Cation as well as anion exchangers are at the moment commonly used for the removal of metals from sludges. The technique generally includes a pre-treatment of dissolving the metal ions from the sludge matrix in order to supply a relatively "clean" solution to the exchangers. For Rotterdam harbour sludges, Gommers *et al.* (6) found overall good results for the removal of heavy metals, with the exception of lead. Disadvantages are the large use of ion exchange material by competing, less harmful ions such as Ca^{2+} and Mg^{2+}, and the disposal problems for the regeneration brines.

Fraction	Extractant	Extracted component
Exchangeable	1M NH_4Ac, pH 7	Exchangeable ions
Carbonatic	1M NaAc + HAc , pH 5	Carbonates
Easily reducible	0.1M NH_2OH HCl + 0.01M HNO_3	Mn-oxides
Moderat.reducible	0.1M Oxalate buffer, pH 3	Amorphic Fe-oxides
Sulfidic/organic	30% H_2O_2 + 0.02M HNO_3, pH 2 extracted with 1M NH_4Ac in 6% HNO_3	Sulfides together with detrital organic matter
Residual	hot HNO_3 conc.	Lithogenic crystalline minerals

Table 4. Fractional extraction procedure (see ref.(7)) for different lead binding forms in sediments; in contrast to ref.(7), no exclusion of air-oxygen has taken place in our experiments.

In our experiments we tested the potential applicability of treatment of The Hague canal sediments with the help of extraction with strong acids, in combination with oxidants and some pre-treatment steps. Also the possible use of ion exchanger as a post-treatment method was investigated.

LABORATORY EXPERIMENTS

MATERIAL AND METHODS

We investigated the extraction of metals with particular focus on lead from The Hague canal sediment with the help of strong acids. The process parameters under consideration were:

- type of acid (HCl or H_2SO_4) and acid consumption
- pH
- contact time
- pre-treatment and use of oxidants

Also, a preliminary research was made on the applicability of cation exchanger for the removal of lead from the canal sludge.

The sludge samples came from the Hofvijver pond in the centre of The Hague. Samples had been taken with a 4 cm diameter sampling tube. The samples had a length of about 40 cm. Below this the original sand bed was found. The samples were well mixed and stored in 250 mL polythene bottles at 4° C.
All sediment analyses, with the exception of dry solid and lead contents were carried out according to standard procedures by Al Control laboratory, Raamsdonksveer. The Pb content of the dried, ground sludge was determined after destruction with boiling 32% HCl/65% HNO_3, followed by treatment with H_2O_2 and boiling HCl (for details, see ref.2).
The lead contents were determined with flame atomic absorption on a Perkin Elmer 360 AAS at 383 nm, with deuterium background correction.

For an investigation of the different binding forms of lead in the sediment, a selective extraction scheme as suggested by Kersten and Förstner(7) was followed, see table 4.

ACIDS CONSUMPTION: EXTRACTION TIME: PH

The extraction experiments on the sediment samples were carried out at room temperature, for fixed, adjusted pH values; for these values the effect of extraction time was then investigated. A weighed amount of wet sediment was transferred to a 300 mL erlenmeyer flask after which the necessary amount of acid to attain the particular pH was slowly added. Use was made of either 5 M HCl or 2.5 M H_2SO_4. During the experiments the pH, as monitored on a Metrom Herisau E 512 pH meter, was kept constant by adding (usually minute) amounts of the acid.
The erlenmeyer flasks were continuously stirred. Samples were taken at regular intervals, centifuged and then filtered over a Whatman GF/C 1.2 μm glass fibre filter. Analysis on Pb was done with AAS (see before).

For the preliminary experiments with ion exchanger, the cation exchanger IRC 718 (Baker) was first activated by rinsing with 2 M HCl. The wet exchanger was then transferred into a a 1.3 cm diameter glass column (empty bed volume about 15 mL). Then 250 mL standard $PbCl_2$ solutions, with a concentration of 50-250 mg Pb^{2+}/L and pH 6-7 were passed through the column with a transfer rate of about 1 L/hr. Apart from standard $PbCl_2$ solutions, use was also made of the supernatant liquid after the previously mentioned acid-extraction experiments; for this about 100 mL was passed through the column with a percolation rate of about 1 L per hour.

All chemicals (Merck or Baker) used in the experiments were of "analytical grade" or "extra pure quality". The (borosilicate) glass ware was always acid-rinsed and dried before the experiments.

RESULTS AND DISCUSSION

The sediment consisted for the greater part of very fine material (72% < 43 μm) with a high organic matter content (Table 5). The mineralogical composition as determined by X-ray diffraction was as follows: SiO_2 (quartz) and $CaCO_3$ (calcite) both 35%; FeS_2 8%. Dominant clay material was shown to be anorthite ($CaAl_2Si_2O_8$): 12%. Data in Table 5 further indicate that the canal sludge was especially high in lead (class IV).

Dry solids (%)	23	
Organic matter (%)	15	
Grain size distr. (%)		
< 2 μm	16	
< 16 μm	29	
< 43 μm	72	
Calcite (% d.w.)	25	class
Cd (mg/kg.d.w.)	4	II
Cr (")	28	I
Cu (")	390	III
Pb (")	2600	IV
Ni (")	25	V
Zn (")	2100	III

Table 5. Sedimentological qualities and metal contents in The Hague (Hofvijver pond) canal sediment; averages over 5 to 11 samples. For the pollution classes, see table 2.

The specific binding forms of lead, as determined by the extraction procedure of Kersten and Förstner [7] are shown in Fig.2. The larger part (63%) of lead is bound onto the carbonate fraction, mainly as coprecipitate with $CaCO_3$. The 22% "reducible fraction", associated with iron and manganese hydroxydes, will especially be susceptible to changing redox conditions in the sludge, leading to enhanced Pb release rates under anaerobic conditions[3]. About 7% of Pb is bound onto the sulfides and organics in the sediment, whereas a final exchangeable fraction of 7% may be considered to be loosely bound onto the clay fraction.

According to these data, dissolution of the carbonates with the help of strong acids may potentially release at least 60 % of the lead fraction from the sludge material. Extraction of the other phases, except the "exchangeable phase" may be more difficult.

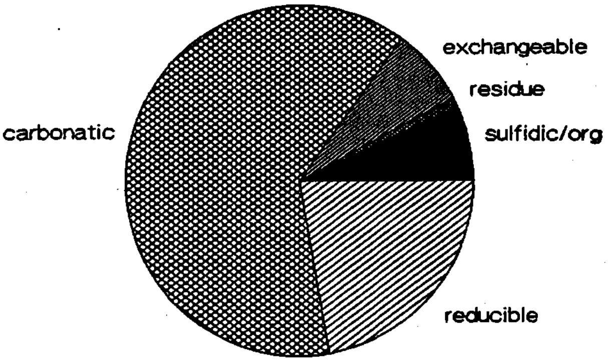

Fig. 2. Different Pb binding forms in The Hague (Hofvijver pond) canal sediment; see text

EXTRACTIONS WITH HCl AND H_2SO_4

It should be pointed out that the extractions with acids in our experiments have always been carried out on non-dried sludge samples; drying of the sludge as a pre-treatment caused some 60% lower Pb release rates during the subsequent acid extractions. This is probably due to irreversible changes in the different lead binding forms.

Results of the experiments [2] on the effects of acid type, pH and extraction time on the lead mobilization (Fig. 3) show the following:

- A continuous increase in the lead release occurs in the course of the experimental period (24 hrs); in some cases equilibrium had not been reached even after this time. The long extraction time is apparently necessary to allow the acid to penetrate into the sludge, where it will gradually dissolve the carbonate and organic phases, thus releasing the adsorbed and bound Pb from the soil matrix.
- In the experiments with HCl we found markedly enhanced Pb release rates for the lower pH values. In general 100% lead release was found for pH values < 1.5 within 24 hours. Release values > 100% (Fig.3) must apparently be due to variations in the total Pb contents of the sludge samples.
- Sulfuric acid was found to be a far less efficient extractant than hydrochloric acid. Even at pH=1 only some 20% of the lead could be extracted with H_2SO_4 in 24 hours . This result is in accordance with earlier reported investigations [6,8]; probably precipitation reactions with (i) formation of Ca/Mg sulfates, leading to less accessibility of the soil matrix and (ii) formation of $PbSO_4$ play an important role here.

We also examined the effect of a 3 hour pre-treatment with 30% hydrogen peroxyde, H_2O_2; the pre-treated samples showed 150% increased lead mobilization in the subsequent 3 hour acid extraction, compared to a "conventional" 6 hour acid extraction . Also the other metals, with the exception of Cr, showed release percentages > 75% (Table 6). Apparently the oxidation of organic compounds by H_2O_2 makes the soil matrix more accessible for the acid.

Under practical conditions, these improved extraction results should certainly be evaluated with respect to the higher investment and chemicals cost involved.

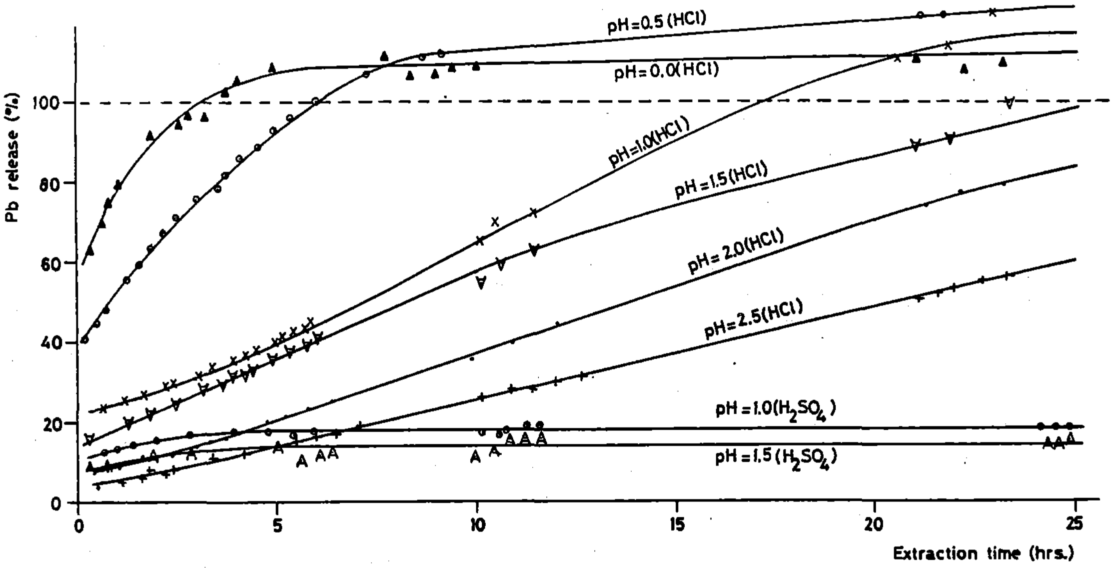

Fig. 3. Pb release rates in acid extraction experiments with The Hague (Hofvijver pond) canal sediment; for the experiments use was made of either 5.0 M HCl or 2.5 M H_2SO_4

Metal	Release (%)
Cd	89
Cr	31
Cu	91
Pb	100
Ni	78
Zn	93

Table 6. Metal realease from The Hague canal sediment (Hofvijver pond) with the help of a 3-hour extraction with H_2O_2 (30%) followed by a 3-hour extraction with 5 M HCl (pH = 1.0).

POST TREATMENT METHODS

In order to remove the metal ions permanently from the sludge, concentration techniques may be applied. A conventional method is separation of the solid and wet fraction by sedimentation, followed by treatment of the wet fraction with hydroxides, in order to precipitate the metals. Alternatively, ion exchangers may be used for removing the metals from the liquid phase.
Some experiments were carried out on the latter technique. Results for the cation exchanger Baker IRC-718 indicate that 100% efficiencies for lead removal could be reached for a throughput of at least 15 empty bed volumes of standard 50-250 mg/L Pb^{2+} solutions. With the supernatant from the sediment extractions (after sedimentation) we only found removal efficiencies of max. 65%.
More research is still needed to evaluate the efficiency of cation and anion exchangers as a technique for heavy metal removal from dredged materials.

CONCLUSION

It is evident that the best abatement technique for polluted sediments is pollution prevention, *i.e.* source control of waste water discharges. However, 100% sanitation will never be reached in view of uncontrollable non-point sources. Diffuse dissipation of Pb will largely be controlled by further mandatory use of unleaded fuel.
Technical clean-up of sediments to remove adsorbed heavy metals will be expensive, whatever method is applied. For our experiments with acid extraction of heavy metals from dredged sludges, we estimated that about 200 kg HCl (30%) per m^3 sludge would be necessary to reach efficient extraction at pH = 1. Most of this would be consumed by the simultaneous dissolution of $CaCO_3$. Additional post-treatment with NaOH (neutralization) would roughly use the same amount of chemical. The finally yielded treated sludge is rich in chloride, causing serious problems in reuse. Other techniques such as microbiological conversions and ion exchange, or a combination of the above techniques, may be attractive future alternatives.

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A BALANCED REMEDIAL DREDGING PROGRAMME

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ABSTRACT

Many water authorities have to contend with contaminated aquatic sediments in harbours, navigation channels and lakes. At present the removal of these bottom sediments seems to provide the only solution to this problem. To remove the material in a environmentally acceptable manner it is obviously important that in the first place the correct nature and extend of the contaminants must be determined in situ. Secondly the dredging must satisfy a certain number of environmental criteria so that a "clean" bottom can be provided without placing an unnecessary burden on the environment or the storage capacity. After this selection of appropriate companies to carry out the work must be made on a qualitative basis, whereby the financial aspects must play a minor role although the financial possibilities are not of course unlimited. Only the adequate education and training of all the parties involved in the work can guarantee an environmentally friendly solution to the problem. If all the aspects mentioned are taken into account one can say: Dredging is a cleaning technique.

INTRODUCTION

Many lands throughout the world are increasingly confronted by contaminated underwater sediments in rivers, harbours and lakes. In water where there is little or no flow over the bottom sediments the contaminants bond themselves to suspended particles. Contaminated bottom sediments are found not only in areas where the harbours and channels have to be maintained at a stipulated depth for navigational reasons but also in drainage canals, lakes and ponds. In this contribution the arguments for and against the removal of the contaminated sediments are not considered. The starting point here is that a particular underwater sediment must be removed. In principle, there are three methods by which a water bottom can be restored:

A rendering the contaminant harmless by cleaning it in situ;
B rendering the contaminant harmless by isolating it in situ;
C removing the entire contaminated bottom sediment (remedial-dredging).

This order of priority is the personal view of the author. If it is possible, within acceptable financial limits for the protection of the environment, that the contaminants can be left in situ (option A), preference should be given to this method. Isolation in situ (option B) is possible in places where there is sufficient depth for navigation but, from an environmentally technical point of view it is not always easy to achieve. The removal of the contaminated bottom sediments (option C) is one method currently used in the Netherlands in those areas where a specific depth is required for navigational reasons. Studies in relation to possible means of removing thin contaminated layers from the beds of lakes and ponds are present in progress. It is not yet clear by which means and at what rate the removal of the contaminated aquatic sediments will be carried out on a large scale when navigational requirements are not involved; it will plainly depend on the experience acquired during previous remedial works and the financial and technical prospects. This contribution considers option C: the removal of the contaminated aquatic sediment for both navigational and environmental reasons, in other words, remedial-dredging.

From figure 1 it appears that there are various possible ways to treat the dredged material which has been removed. After the exact nature and extent of the contamination has been determined and the sediment has been removed there are a number of options. The options depend on the financial and technical possibilities and the values which have been attributed to the environment by the management concerned. The most simple method is to remove the sediment and dispose of it. Financially this method is the most attractive but, in relation to the environment it is the least acceptable.

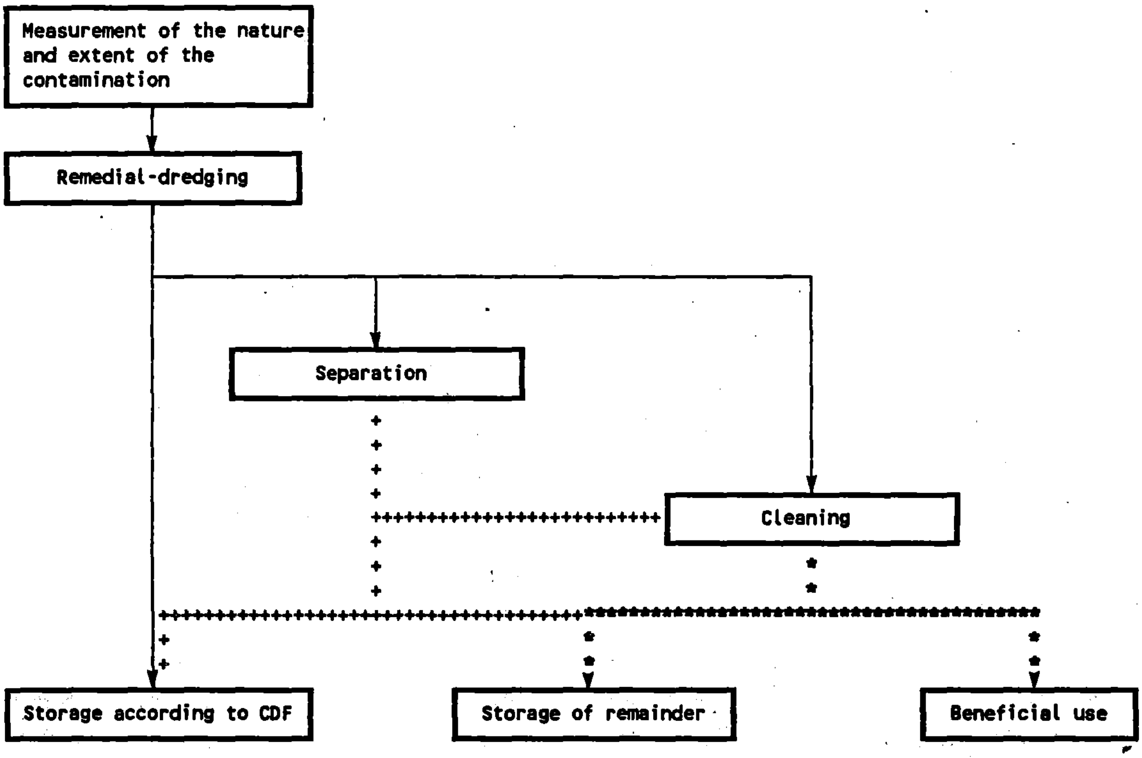

Figure 1: Treatment procedure for contaminated aquatic sediments

In most cases the contaminants are not evenly distributed in the aquatic sediment. The first saving can be made by the selective removal of the sediments because the less contaminated material can be handled in a cheaper storage depot. If, depending on the type of soil and the technical possibilities, separation of the dredged material is considered, three alternatives arise. The most contaminated soil is placed in an CDF (Confined Disposal Facility) depot, the less contaminated in a cheaper depot and the clean material can be re-used. After the cleaning process, clean ground for reuse and partially cleaned ground has been produced.

PROBLEM DEFINITION FOR REMEDIAL DREDGING

After the management which is responsible for the quality of the water has made a decision that a harbour or part of a waterway must be cleaned up, remedial-dredging is one of the three previously mentioned methods which may be used (cleaning in situ, isolating in situ or removal) to solve this problem. Remedial-dredging is also necessary if a heavily contaminated bottom sediment has to be removed down to the nautical depth for navigational reasons (maintenance dredging). Before remedial-dredging can be started it is essential to determine the precise position of the contaminated layer in both horizontal and vertical directions at the location in question. Furthermore whether there is a clear variation in the pollution grade which demands a different method of treatment or storage of the dredged material must be determined. It will be clear that this is not simple and that it is expensive.

If remedial-dredging is used it is necessary to be able to remove the contaminated bottom sediment both accurately and selectively. With the currently used dredging techniques it is possible to dredge accurately but not at the same time in an environmentally friendly way - think of a cutter suction dredger or a bucket dredger. These can execute accurate dredging but at the same time cause great dispersion of the contaminants. On the other hand remedial-dredging is a clean up technique, which must ensure that the end product is a "clean" bottom. In the following paragraphs the criteria which remedial-dredging must meet are described. In addition there is an indication of how these can be measured and how the assessment and evaluation are carried out.

Technical boundary conditions

When, for navigational reasons, it is necessary to deepen a waterway that has contaminated aquatic sediments, the following general technical boundary conditions apply with regard to remedial-dredging:

- the dispersion of the contaminated soil to clean or less contaminated areas must be prevented;
- the contaminated material must be removed separately from the clean or less contaminated material;
- because the dredged material will be treated according to the level of contamination, layers with a level of contamination must be removed separately;
- in certain cases the dredged material to be treated or disposed of must have the smallest possible volume;
- the environs, human and natural, must not be adversely affected by the technical consequences of remedial-dredging.

For the cleaning up of aquatic sediments, in other words the removal of the entire contaminated layer, the following boundary condition also applies:

- that the site, including the inaccessible places, must be "clean" or as clean as the surroundings.

If bottom sediments are to be entirely or partly removed in an environmentally friendly way the boundary conditions mentioned must be taken into account. Thus the following important elements can be derived:

- accuracy and selectivity;
- increase in turbidity;
- spillage;
- mixture concentration;
- safety.

Criteria for remedial-dredging

Accuracy and selectivity

The accuracy of the dredging depends on the ability to position the dredge head with precision in both horizontal and vertical directions. Many conventional stationary dredgers can do this. Selectivity is a new idea in the dredging world, certainly when, in the vertical sense, it involves the removal of layers varying in thickness between, for example, 10 and 40 cm in an environmentally friendly way. "Selective" implies that only that material is removed which according to previously determined guidelines should be removed. Sometimes it may happen that different classes of material exist side by side. In this case the layers of a different class will be removed selectively, class by class.

Increase in turbidity

It is not the initial turbidity which is so important but the increase in turbidity as compared to the background turbidity which results from natural current and tide movements and, not to be forgotten, from the movements of shipping. The turbidity is the amount of soil particles in suspension expressed in mg/l. The increase in turbidity is of importance to the environment itself because particles may settle in the place where remedial-dredging is in process. After some time this sedimentation builds up to a thin layer of spill on the clean bottom. When remedial-dredging is being carried out for navigational reasons this sedimentation on the site of the dredging activity is less troublesome because the underlying layer is probably also still contaminated. However the soil particles which have come into suspension must be prevented from being dispersed by current to less contaminated areas.

Spill

Spill is loosened soil which fails to enter the soil transport system and, after some time, settles on the bottom. Two types of spill with different characteristics can be distinguished. On one hand, an excavation tool disturbs the soil, failing to carry some of the soil into the vertical transport system while, on the other hand, part of the soil is carried into suspension (turbidity) only to settle on the bottom once again. In the latter case a weak layer of spilled material is formed which, because of its properties, is easily distinguished from the undisturbed soil. The spill which arises from particles which have not been resuspended is certainly important to remedial-dredging. The rest of the spill can be compared to the turbidity.

Mixture concentration

The concentration of the dredged material depends on the processes which follow the dredging. If the material is treated in a separation installation the mixture must be homogenous and have a certain low concentration. All hydraulic dredging techniques satisfy this condition. With mechanical techniques an extra treatment phase is needed to dilute and homogenise the dredged material. Some types of storage depot or specific cleaning techniques, however, may require a high concentration of the dredged material.

Safety

Personal contact with the contaminants must be kept to the absolute minimum. There are official stipulations for every situation but, in practice, it has been demonstrated that people are inclined not to take these safety regulations seriously. Some dredging techniques are safer than others; a hydraulic method (suction dredger with pipeline) is a controlled closed system and is thus safer than a mechanical method.

Possible applications

Remedial-dredging sites are often small harbours with quays, jetties and sloping constructions. Many conventional dredgers have difficulty in removing the bottom sediments from these inaccessible places. Which technique is most suitable will depend on the local conditions. This also applies to shallow lakes where thin layers of contaminated material must be removed from the lake bed.

Reliability in relation to coarse refuse

In the harbours requiring remedial-dredging there is much coarse refuse - from plastics, steel wires, and rubble to bicycles and refrigerators. The presence of the coarse refuse disturbs the dredging process in the sense that when blocked the dredge head is lifted up through the water column and the coarse refuse is removed manually. Dispersion of contaminants and reduction of the concentration of dredged material is the result. It must be clear that an accurate technique with a low increase in turbidity is not sufficiently environmentally friendly if the technique is repeatedly disturbed by the presences of coarse refuse.

Assessment of dredging techniques

In principle, there are two ways to evaluate: one absolute and one relative. Absolute assessment demands clear standards with which the techniques must comply. To date there are no fixed norms, at least as far as is known to the author so one must make do with the relative assessment. In this method comparative norms are derived from conventional dredging techniques (adapted to environmental requirements) which have already been used for remedial-dredging.
The comparative norms will eventually lead to the definite norms for the future. The fixed norms are indispensable. Conventional dredging techniques are those which would normally be used in a specific location. In the current cleaning up of harbours and navigational channels a grab dredger within a silt screen is often used. Whether this is the technique for remedial-dredging in the future remains to be seen. In the current clean up work in the Netherlands, such as that in the Geulhaven in Rotterdam and in the Oosterschelde harbours monitoring programmes are being carried out in order to assess the remedial-dredging work.

REMEDIAL DREDGING VERSUS TREATMENT

The further treatment of the dredged material depends on the local conditions, the soil properties, the degree of contamination, the technical possibilities, and the available finances of the management in question. When contaminated sediment is being removed for navigational reasons the dredged material is often taken straight to and ISM storage depot. Financially this is the most attractive solution but it is not the most environmentally friendly one. One problem may have been solved: the harbour is once again accessible to shipping, which, in its turn is important to the economy of a country. An additional environmental benefit is that the contaminants are no longer dispersed by the effects of shipping movements because the water is now sufficiently deep. If a contaminated aquatic sediment has to be removed for reasons other than navigation it seems better not to take the cheapest method of treatment. It is important to ensure that the problem is not merely relocated. The complete treatment path consists of the following stages:

* I	Identification of contaminants
* R	Remedial-dredging
* T	Transport
* S	Separation
* D	Dewatering
* C	Cleaning
* St	Storage
* B	Beneficial use

There are numerous possible combinations for the treatment techniques. In this paper only a very short (I-R-T-St) and a long (I-R-T-S-D-C-St-B) path are followed.

Short treatment path I-R-T-St

As earlier stated, this treatment path is often followed when the aim of dredging is to remove contaminated sediments for navigational reasons. The identification of the contaminants is the first step and is very important because it may have a strong influence on the following stage, the remedial-dredging, in both positive and negative senses. The more accurately the contaminants can be identified in advance, the smaller the amounts of material which have to be dredged, transported and stored. The quantity naturally depends on the accuracy of the dredging technique. On the other hand there is no point in identifying the contaminants to a greater degree of accuracy than that to which they can be removed. The further the transport distances or the higher the storage cost the greater the attention that must be paid to accuracy in identifying the contaminants.

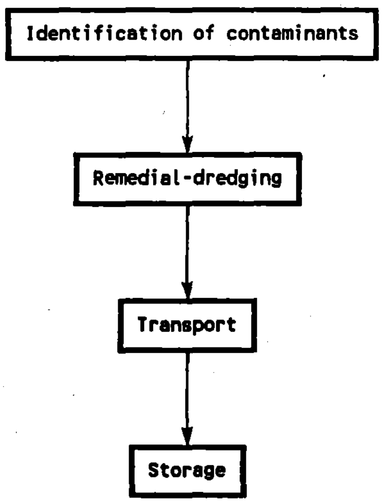

Figure 2: Short treatment path

Long treatment path I-R-T-S-D-C-St-B

If the management of a harbour or navigation channel only requires that the sediment in the location involved is removed, in other words the site must once again acquire a clean bed, the short treatment path will suffice (I-R-T-St). The bed of the waterway is then indeed clean but in fact the problem has merely been relocated. If the manager really wishes to prevent a new problem developing he will have to do more with the dredged material than merely store it elsewhere. In theory there are many possibilities. The choice depends, on the one hand, on the value attached by the management to an improvement in the environment and, on the other hand, on the technical possibilities. For the long treatment path (I-R-T-S-D-C-St-B) also, the identification of the contaminants is the first step and certainly a more important step than for the short. The following steps are greater in number and, in relation to financial consequences even more important. The financial share of the remedial-dredging for a treatment path with a cleaning technique is relatively small (ca. 10 à 20%). Even so remedial-dredging may have a big influence on the total cost. If it is possible to provide an accurate estimate of the nature and extent of the contaminants in the sediments, including the differences in contaminant classes, the total volume of dredged material to be treated depends on the execution of the remedial dredging. By dredging selectively it is possible to use other cheaper methods of treatment for part of the aquatic sediment. Every clean m^3 of bottom sediment that is removed by inaccurate dredging has to be treated at a high cost.

In the scheme shown in figure 3 the transport is linked to the remedial dredging, but in fact this occurs more often in the path. After the separation, dewatering and cleaning, depending on the location of the treatment installations, transport and possibly one or more transshipment of dredged material may be necessary. Dewatering is linked to the separation because in most cases the dredged material must be mechanically dewatered after separation. Beneficial use is added to this because it must not be underestimated. It is the only technique in this row which does not cost any money, on the contrary, it yields money or is of social value. Under certain monitorable conditions, the use of less contaminated dredged material can be included under beneficial use.

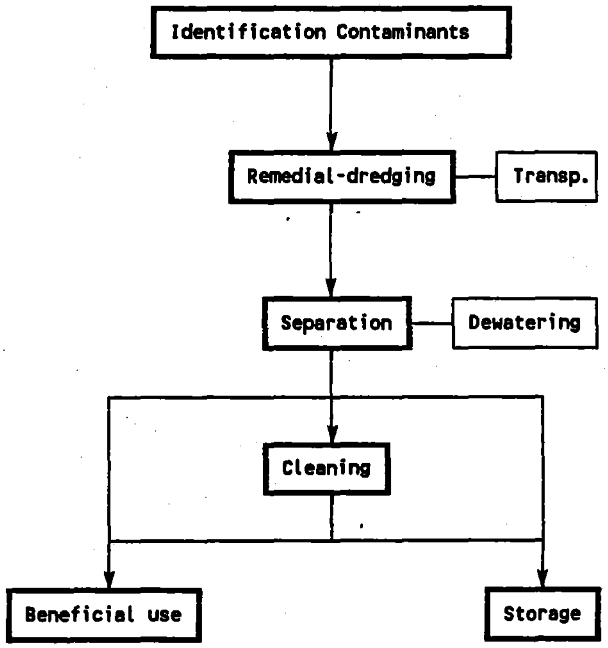

Figure 3: Long treatment route

Relation between remedial-dredging and the treatment techniques

Relations exist not only between the remedial dredging and the treatment techniques but also between the treatment techniques themselves. The relationships involve the amount of dredged material to be processed and the actual techniques. In the following diagram the relationships between all the treatment techniques are shown and the explanation gives further information about the relations between the remedial-dredging and the remaining techniques.

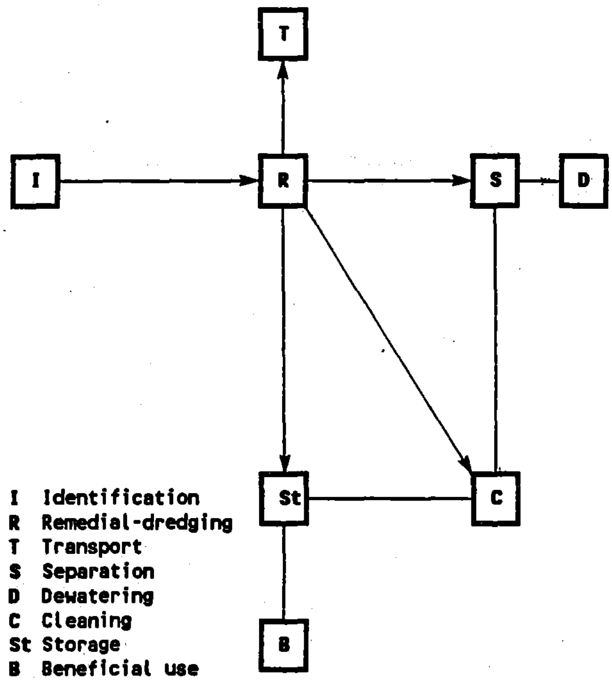

Figure 4: Relation with the treatment techniques

Explanation of the scheme

The identification of the contaminants (I) has a direct relationship only with the remedial-dredging (R). The identification process determines in situ the amount of material that is necessary to remove. The remedial dredging (R) is related to the transport (T), the separation (S), the cleaning (C) and the storage (St). The remedial-dredging also has a technical relationship with the same treatment processes. The hydraulic dredging method (suction dredger) demands transport of the dredged material via a pipeline. With a mechanical dredging method (grab dredger) transport in barges is most suitable. A hydraulic process is especially suitable for a separation installation because the dredged material produced is homogenous and contains comparatively little coarse refuse. For recycling techniques too, the hydraulically dredged material is easier to handle because of the homogeneity. Both hydraulically and mechanically dredged material is suitable for storage on land. The choice depends more on the local conditions such as over the introduction of dredged material into an underwater storage, only the hydraulic methods can be used.

EXECUTION OF REMEDIAL DREDGING

When the most suitable offer has been selected we can start the execution of the remedial-dredging project. In this chapter we will deal such aspects as choosing the right scenario, co-operation between employer and contractor and the possibility of carrying out research work.

Scenarios

In contrast to the procedures which are usual for normal dredging work in clean or even virgin soil, remedial-dredging operations require a complete scenario. In this document the contractor will set out how he intends to carry out the work within the existing boundary conditions. The contents of this scenario formed the basis for the selection of the proposals. Now, in the realization phase, the scenario will also serve as a guideline for execution.

In the future it would seem worthwhile to include a type of risk analysis in the basic procedures. The employer should indicate at what places certain risks may be encountered and what will happen if the proposed working methods are not able to deliver the desired results. There must be provision for possible alterations and their financial consequences. Acceptance of a scenario and the fact that the proposal has been well received does not give the contractor licence to carry out the remedial-dredging work in an unsatisfactory manner.

Co-operation between employer and contractor

Both the employer and the contractor should take a different attitude when they are undertaking remedial-dredging works. Clarity is of uttermost importance. If a contract stipulates that spills must be avoided, the parties to the contract normally cannot do too much about it in actual practice.

Both parties should realize that it is better to prevent things from happening than to cure the results. It is now rather useless to work with sanctions against a contractor after, for example, pollution of surface water or dispersion of contaminants having taken place and cannot be made undone by any means.

The working methods have been agreed upon beforehand, but their application in practice is sometimes a bit complicated and human error can also play a role. Not only the contractor but also the employer should have qualified staff on the job to check the work that has been carried out and during its execution. Measuring equipment of great reliability must be used. This applies in particular to those parts of the remedial-dredging job which constitute risks to the environment as given in figure 5.

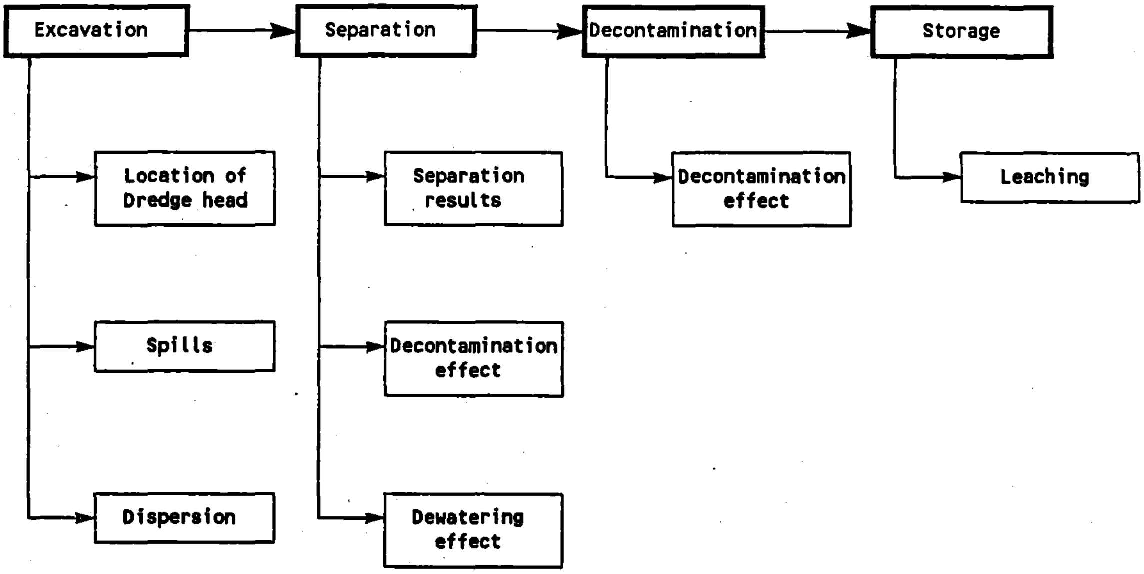

Figure 5: Survey of measurements which may be critical for the environment.

It is recommended that, in addition to the site supervisors, specific members of the principal's as well as the contractor's management teams should be nominated to follow the progress of the work from a distance.
The people on the site will soon notice that their work is under close scrutiny and is not a routine matter. The remote supervisors at management level are directly involved in the job and can, if necessary, make course corrections faster. Ultimately, it should be pointed out that the only purpose of the extra support is to:

- create a real collaboration between both parties so as to arrive at the best possible result within the extant boundary conditions and prevent things happening which cannot be undone.

Monitoring and research during the work

It goes without saying that monitoring on the job is an essential part of a remedial-dredging projects. The three most important aspects are:

(1) Monitoring for process control.

(3) Monitoring for the purpose of assessment.

(1) Monitoring for process control is mainly undertaken by the contractor himself since he is in the first place responsible for the quality of the product. This type of monitoring goes on continuously.

(2) Spot checks are of particular interest to the employer but, when a normal dredging operation is concerned he seldom needs to check something immediately but will do it later. If the work has not been carried out in agreement with the boundary conditions the contractor will be obliged to meet his obligations later.
For remedial-dredging operations however the sensitivity of the environment has become the decisive factor. An immediate check may be necessary in case direct action may be required because when dispersal or leaching of contaminants are causing pollution, the process cannot be reversed.

(3) To monitor the work for the benefit of the assessment is of extreme importance to both parties. The employer will have to test the boundary conditions which he formulated earlier for their general validity or possible shortcomings. If it turns out that the remedial-dredging has not so improved a polluted aquatic site that it meets the boundary conditions or if that result can only be achieved by additional effort, i.e. by more work at higher cost, it may well be that the boundary conditions as drawn up in advance had some shortcomings.

Possibly, the soil sampling methods have been inadequate or the specification of the job gave the contractor too much leeway to do the job the way he did it and for which he may have had his reasons. The contractor can evaluate the efficiency of his working methods and check the techniques used on the job. Has he achieved the planned production and have certain new working methods had the expected results? This assessment is of paramount importance to both parties, in particular with a view to future remedial-dredging projects.

Research during execution

Carrying out some types of research work has little connection with the realization of the ongoing remedial-dredging job. The data collected come too late to influence that project but it is essential that during the execution of the project the possibility to undertake some practical research on a 1 to 1 scale should exist.

It is unsatisfactory to include a provision for research in the specification and budget and then not to use it, so the contractor must make allowances for that possibility. Of course, he is entitled to undertake practical research on his own initiative.

In the Netherlands a report exists (Ref. 1) which is based on a programme which covers all aquatic sites which might qualify for remedial-dredging. This research programme has been jointly paid for by principals and contractors, for it is only by scientific research that we shall find ways to execute future projects more efficiently and develop new techniques on which to base an improved policy with even more regard for our environment.

SCIENCE, ENGINEERING AND MANKIND

A harmonious interplay between science, engineering and mankind is now of vital importance to the success of our further undertakings. The word vital is not lightly chosen, for that is what this is all about. The most advanced techniques are useless if mankind cannot handle them or is not motivated to do so.

<u>A motivated and experienced man with a lower technical standard can achieve better results than people with the best technology in their hands who are not motivated or just not educated enough to see the job that needs to be done.</u>

At present the development of new engineering techniques is high on every one's agenda. But we tend to stress them to such an extent that we forget to educate and train those who should use them.

We spend millions of guilders or dollars (or whatever) on research and development but we find it difficult to allocate one-tenth of that kind of money to education. It is true also that the distribution of participants in the education programme is rather lopsided. You will find middle management trying hard to broaden its horizon by participation in conferences, symposia, workshops and seminars but those at other levels do not get similar opportunities. This applies to all parties involved in the process, such as principals, dredging companies, consultants and equipment builders and all who have an interest in the ports industry. But not to all echelons in those organisations; obviously the people in the field seldom get a chance to participate in education and training events. We are also sadly lacking the participation of the people up there, in the Board Room. We are living in difficult times and should take steps to ensure that the available information reaches everyone who needs it, on his own level and in his own language. We need an education scheme for which Government and private enterprise will design the curriculum. Government should give a large financial contribution because society stands to profit from more efficiency in the port industries.

The programme should address some of the following points:

- The first priority would be to increase general awareness of the serious nature and worldwide importance of the environmental problems.
- Instruction material for all employees, staff and management.
- Safety and health risks.
- Switching from a <u>volume-oriented (m^3)</u> approach to a greater appreciation of <u>quality</u>.
- Educated use of new working methods and techniques.

This education programme will cost some money, but rather more effort and something like this is inescapable if our endeavour is to remain directed towards:

- The restoration - with due regard to the environment - of every useful aquatic site.

EVALUATION AND PUBLICATION

The <u>evaluation</u> of projects which have been completed, together with the associated techniques and results, is currently normal practice. Even so I would like to place emphasis on this. In normal dredging for the purpose of maintenance or deepening harbours and navigation channels, assessments are carried out in order to gain knowledge for later projects. The learning effect generally involves economic questions such as more efficient execution. If we are concerned with the removal of contaminated sediments for navigational reasons or with the cleaning up of contaminated aquatic sediments the evaluation of the economic effects is of course, still also very important. It can possible save the community much money in the future, but the environmental effects are much more important. Has a proposed method and its final execution fulfilled expectations? Perhaps millions have been spent and the location in question is still not clean. We shall indeed have learnt something from this, but it is a very expensive lesson. An essential aid to the evaluation is a well set up and executed monitoring programme. The evaluation must cover the entire project from the preparation up to and including the after care. The subjects of this are:

- soil investigation into the nature and extent of the contaminants
- information package for the companies involved
- pre-investigation of most suitable techniques
- environmental yield versus cost
- monitoring programme
- research during execution
- contracts with clearly defined responsibilities, fixed norms and sanctions
- involvement of industry (tendering)
- schedules with safety regulations
- the evaluation and selection of tenders from industry
- the execution of remedial-dredging and further stages of treatment
- the supervision of the execution by the client
- results of remedial-dredging and stages of treatment
- technical deviations with regard to the original plan
- after-care

All these subjects must be separately assessed so that the adjustment of each part is possible. Both the client and the companies carrying out the work should be involved in the assessment.

A second important point is <u>publication</u>. It often occurs that the results of a certain completed project remain known only to a small circle, certainly when the results are adverse. We all benefit from the wide distribution of the results of experience gained during remedial dredging. All results should be accessible to any interested party. Within a country it should be compulsory to report to a central body. In fact within the EC we should have such a central body from which information could be made available to others. Only through the exchange of knowledge and experience we will be able to clean up contaminated aquatic sediments in an environmentally friendly and socially acceptable way.

DISCUSSION

The formulation of a good policy for the treatment of contaminated dredged material is a of great importance. If, for example, the policy indicates large scale disposal sites above or below water, less stringent demands are placed on the dredging than when the policy stipulates treatment of the dredged material. This aspect should be discussed very soon. A second important discussion point is: how can one stimulate industry to develop environmentally friendly techniques. Only when it is known what the financial and technical consequences of specific methods are a good policy can be formulated.

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ECONOMIC ASPECTS OF PROCESSING DREDGED MATERIAL

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ABSTRACT

The silting up of our ports and watercourses is becoming an increasingly severe problem.

Hitherto this material was dredged up and then either returned to the watercourse in a place where there were no draught problems or in a conventional on-shore dump. Consequently the disposal of dredged material remained relatively low. However, it has become increasingly difficult to adopt such disposal methods for a variety of reasons.

According to the most recent figures, the Flemish Region will in future have to dispose of ± 6,5 million tonnes of dredging spoil every year. Moreover at present the figures are still rising.

In the long term this constitutes an enormous <u>physical planning</u> problem. Regional plans make no provision for the disposal of dredged material and various studies have shown that the space available for this purpose is limited.

A further problem is that a portion of this dredged material is <u>to a greater or lesser extent contaminated.</u> Dredged material which would normally be returned to the river will in future have to be subjected to additional precautionary measures first.

For the portion which is stored on-shore further technical measures will have to be implemented in order to prevent the further dispersion of the pollution in the soil via the groundwater.

In the lower reaches of the Estuarine Scheldt the problems also assume an <u>International dimension</u>. If Belgium is to meet the WVO (Water Pollution Law) legislation now in effect in the Netherlands, it will have to take measures relating to dredging in and the disposal of material from the lower Estuarine Scheldt.

Of course all these measures tend to push up the cost of a number of alternative disposal methods which may or may not be combined with specific treatments.

I. INTRODUCTION

The growth of environmental awareness has made this a problem of current concern in recent years and it has been realized that any environmentally safe method of disposing of dredged material is going to cost more. This change in attitude has resulted in extensive study of ways of solving the problem of disposing dredged material in the most efficient and environmentally safe way possible. They have been primarily directed at reducing the volume of material to be dredged, special techniques for the separation of polluted fraction and controlled disposal and treatment techniques.
Studies have been carried out in the following areas:

- DREDGING TECHNIQUES

The optimization of dredgers and techniques are aimed first of all at reducing the quantity of material dredged and introducing environmentally safe dredging methods. Secondly, sophisticated techniques make it possible to limit the physical effects, such as an increase in turbidity in the water column. A cutter suction dredger is much less suitable for use in environmentally sensitive applications than a leak-proof grab, although the output of the latter is much lower, which tends to increase costs.

In recent years spectacular improvements have been to trailing hopper suction dredgers. They have among other things, been equipped with devices for dredging with low specific density, adjustable anti-turbidity overflows, controlled by the most recent electronic position finding devices, etc. All these improvements permit environmentally safer and more precise dredging, which results in the dredging of smaller quantitites in order to achieve the same, usually nautical, objective.
The operating costs of dredger will however rise significantly when a procedure is imposed which is aimed at achieving specific environmental standards. The maximum output, and thus minimum costs, characteristic of a specific dredger, can no longer be achieved (eg by the installation of anti-turbidity screens). The various classes of dredger have a variety of different environmental characteristics. When special attention must be paid to environmental standards, a dredger will be chosen which represents a compromise between output and acceptable environmental effect in clearly specified conditions.

or example, generally speaking, a trailing hopper uction dredger causes relatively little turbidity in ie water column, while the dredging costs remain elatively low.

dredging technique based on the water injection r fluidization principle on the other hand does core low for environmental safety. Indeed factors uch as greater turbidity, precision of working and pilling, make this method much less suitable for the erformance of environmentally safe dredging operations (see ref.1).

Table 1 provides an appraisal in environmental terms of a number of types of dredger used in normal conditions.
Figure 1 indicates the relationship for various dredgers between turbidity in the water column and the associated dredging costs. The high score of the trailing hopper suction dredger is striking (low turbidity, relatively low cost, high environmental efficiency). The same conclusion can also be found in the study mentioned in ref. 1.

VOLUME REDUCTION

The problem of the disposal of dredged matter can be minimised when the volume of the matter to be disposed can be significantly reduced. Various techniques have been developed for this purpose. Reductions in volume can be achieved by separating the sand fraction, which can be used for other purposes, from the dredged material. The volume of remaining fraction (= silt) can then be further reduced by lagooning and mechanical compression methods.

- DISPOSAL TECHNIQUES

The creation of a gigantic offshore dump ("the environmental island"), which could also be used for the disposal of other forms of waste has been under consideration for some time.

Similary the disposal of dredged matter in overdepths at sea, in docks, rivers and canals is a widely applied (eg. in the USA and the Netherlands) and environmentally safe technique, and often offers a short-term and medium-term solution.

- RECYCLING TECHNIQUES

Finally, there has also been a great deal of research into the recycling of dredged matter, so that the problem of disposal no longer arises. However, most of this recycling technique are either not yet operational or their high cost discourages their application.

The aim of this contribution is to summarize the various processing and disposal methods for dredged matter, whether polluted or otherwise, and then to analyze them in terms of cost. In this way we can analyse the cost-effectiveness which permits the technical and economic comparison of the various methods.

As many cost factors are influenced by local conditions, we will consider concrete examples wherever necessary. The extent of pollution also plays an important role, for this reason we assume that the dredged material is moderately to heavily contaminated.

First of all the study will provide a cost description of the conventional methods of dredging and disposal, after which the costs of supplementary technical provisions required by reason of the degree of pollution of the matter derived from maintenance dredging will be estimated.

The next step consists of analysing the costs of the various methods of reducing volume and the creation of alternative silt dumps.

Finally various recycling techniques are described and estimated in terms of cost. Here it is by no means the intention to provide exact cost calculation, but merely to make a comparative study of the various methods and to indicate the decisive cost factors.

BASIC ASSUMPTIONS

The cost calculation is based on the specific characteristics of the dredged matter : we assume that this dredged material has an in-situ density of 1.2 t/m3 with a dry matter (DM) content of 30%.

It is assumed that mechanical dewatering will raise density to 1.36 t/m3, with a corresponding dry matter content of 40%.
Summarized this means :

a) <u>in situ</u>
1 m3 (30% DM) = 0.36 tonnes of dry matter
Dewatered this gives 0.59 m3 - 0,36 tonnes of dry matter = 0.8 tonnes of silt (40% DM)

b) <u>dewatered dredged material</u>
1 m3 (40% DM) = 0.61 tonnes of dry matter

Conversion of Costs :

BF 100/m3 in situ = BF 280/tonne DM
(conversion factor 2.8)

BF 100/m3 in situ = BF 125/tonne 40% DM
(conversion factor 1.25)

BF 125/m3 40%DM = BF 280/tonne DM
(conversion factor 2.24)

	Turbidity	Spill	Accuracy	Density	Total score	Cost factor
Crane with grab (sealed grab)	8	6	6	8	7.00	++
Bucket dredger	6	6	8	7	6.75	+
Backhoe dredger	5	6	7	7	6.25	+
Trailing suction hopper dredger	6	7	6	5	6.00	-
Sidecasting dredger	6	4	4	4	4.50	--
Cutter suction dredger	3	4	5	3	3.75	--
Water injection dredger	2	2	5	2	2.75	--

Score Turbidity 10 = minimum turbidity
Spill 10 = minimum spill
Accuracy 10 = maximum accuracy
Density 10 = in-situ density during dredging
Cost factor + = relatively high cost
- = relatively low cost

Selection table for environmentally safe dredging

TABLE 1

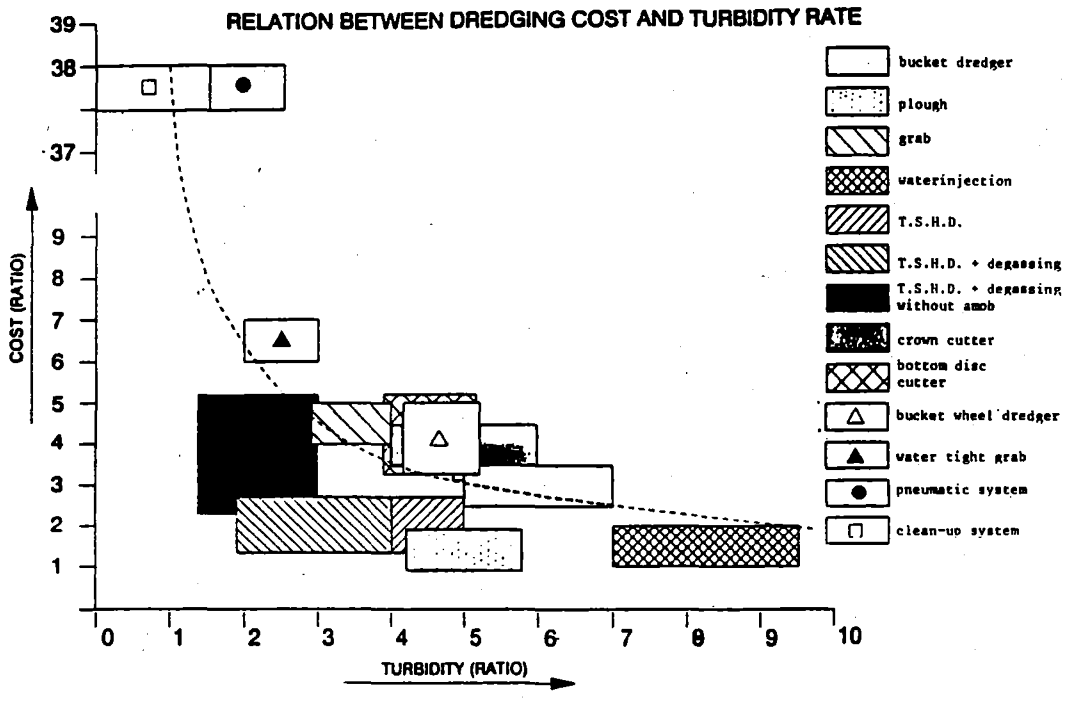

FIGURE 1 (see ref.1)

II. CONVENTIONAL DREDGING AND DISPOSAL METHODS

In the past the dredging cycle was usually as follows: the material was dredged by the most economically efficient dredger, carried in the well or in dumb barges and dumped at sites in the watercourse where this was considered to be nautically or hydraulically permissible. If no such places were available in the watercourse being dredged, a disposal site with sufficient capacity was sought close to the watercourse. This was either filled directly or filled from the well of the dredger. The only technical arrangements made for these dumps were dump dykes intended to prevent water and silt spreading over a larger area as well as dumping shuttering for regulating the water level on the site during filling.

Obviously these were the cheapest methods, with underwater dumping clearly leading the field in cheapness in those cases where the travelling distance was not too great. The fact that these procedures will also have to be used to a large extent in the future has already been indicated above ; there are, however, a number of problems in terms of physical planning and the pollution of the material.

As long as sites are available and if a cheap way of preventing dispersion into the environment can be found, these methods continue to be the cheapest, easiest, and most satisfactory solution.

In order to enable a cost ratio for other methods to be drawn up we have assumed that the order of magnitude of the cost of the conventional method, that is without additional technical measures and including the dredging work, can be set at BF 150/m3 or BF 420 per tonne of dry matter.
The dredging work itself can be estimated at BF 100/m3 or BF 280 per tonne of DM.

III. CURRENT SITUATION

In the Flemish Waste Decreet dated 2nd of July 1981 dredged matter is considered to be a special waste product. This has far-reaching implications :

The simple dredging and disposal methods cannot now be applied to polluted dredged matter without further ado. Final disposal on land must be in a licensed waste dump holding the required permits. The sludge must be disposed of on a site whose classification corresponds to that of the pollution as required by licensing authority. In order to keep disposal costs to a minimum one may first consider subjecting the material to a series of treatments, which may include extensive dewatering, which results in a marked reduction in volume.

When polluted matter is dredged, this must take place in an environmentally safe way, without unduly disturbing the bottom and taking steps to prevent the pollution being taken up again in the water phase and thus becoming dispersed over a wide area. The dredging work must be carried out with a high degree of accuracy and with a minimum of spillage.

Dredging works performed by conventional methods usually results in the bed being severly disturbed and with increased turbidity in the water column as a result. If it is wished to limit this phenomenon, this will, because of the lower output, tend to raise costs (eg a grab compared to cutter suction dredger). This is most certainly the case when the dredged matter is then subjected to a physical and/or chemical treatment. Indeed the output of even large-scale treatment installations are significantly lower (twice to ten times) than the corresponding outputs of dredgers. This makes it difficult to design a satisfactory on-line installation.

As the sand fraction is usually not a bearer of pollution, the first step in reducing volume may consist of the separation of dredged material into a sand and a silt fraction. The sand can then be used for useful purposes.. Separation into fractions can be carried out by means of hydrocyclones, followed by the dewatering of the silt by means of filter belt presses. Assuming a basis cost of BF 280/tonne DM for conventional dredging works, these operations can be estimated at a total of BF 2000 to 4000/tonne DM . Here it should be pointed out that these installations can only be used "on-line" with low output dredging equipment.

The residual product will then for example, have to be disposed of on a Class I dump, for which the costs, including environmental levies come to between BF 2350 to BF 4,300 per tonne/DM. The costs of a Class II dump come to BF 1,450 per tonne/DM.

SUMMARY TABLE FOR SEVERELY POLLUTED DREDGED MATTER

Dredging	:	BF 280/tonne DM	3 - 8%
Cycloning and/or dewatering	:	BF 2,000 - 4,200/tonne DM	± 50%
Dumping costs and environmental levy	:	BF 1,450 - 4,300/tonne DM	± 45%
		BF 3,730 - 8,780/tonne DM	100 %

The dredging work is thus a tiny fraction of the overall cost (3-8%).

Should the standards imposed by the licensing authorities be adopted at all dredging sites, the price will be ten to twenty times higher than the costs of conventional dredging and disposal methods in the past. The result may be that a large number of watercourses can no longer be dredged for financial reasons, particulary when public authorities are confronted with this problem.
The classification of dredged material as a special waste by the government has in the first place meant that the public authorities responsible for clearance have been put in a very difficult situation. Requirements which result in intolerable expenditure for the community will simply not be applied.
A more sophisticated approach to disposal requirements is therefore urgently required.

CASE STUDY
TREATMENT OR DISPOSAL OF POLLUTED DREDGED MATERIAL

As an exercise we may make an estimate for the dredging of a silted canal in an urban environment. It is assumed that the canal is only accessible to small dredging vessels with a low draught such as a bucket dredger with a bucket capacity of 200 litres. The dredged material must be disposed of at a dump site where the standards, imposed by the licensing authority, are strictly applied. As we shall see this has a very significant impact on the ultimate price per tonne.

There are two basic premises, according to which we assume that the polluted material is subjected to two different processing and treatment techniques, namely :

- the polluted dredged matter will be disposed of after transport by water in a licensed mono-dump, located ± 50 km from the dredging site.
- the polluted matter will after treatment, be carried by road to a class I dump, about 100 km from the dredging site.

The mono-dump is specially laid out for the recirculation of the press water, so that it is totally isolated from the environment (see figure 2).

In order to keep the costs to a minimum the contractor ensures that the dredging is carried out as efficiently as possible, that is with a minimum of mixing with the water in order to keep the volume as low as possible, and to limit the necessary dewatering and volume reduction to a minimum. Extensive mechanical dewatering reduces the volume by 25 to 30% in order to minimize transport and dewatering costs.

On the basis of the above assumptions calculations indicate that costs fall in the following order of magnitude :

(see table : Alternative 1 : monodump, transported by water)

ALTERNATIVE 1 : MONODUMP, TRANSPORTED BY WATER

- Preparation and construction of the mono-dump	BF 700/t DM	15%
- Dredging, transport and dumping of the material	BF 1,340/t DM	29%
- Processing and treatment of the material + monitoring on the dump site according to the legal standards	BF 2,410/t DM	51%
- New layout for the dump site after completion of the works according to the legal standards	BF 250/t DM	5%
	BF 4,700/t DM	100%

The order of magnitude of the cost for the proposed dredging and treatment plant comes to BF 4,700 per tonne of DM. The dredging price is BF 1,340/tonne of DM. This takes account of the great transport distance for the matter and the inaccessibility of the dredging site, which means that small dredging units must be used.

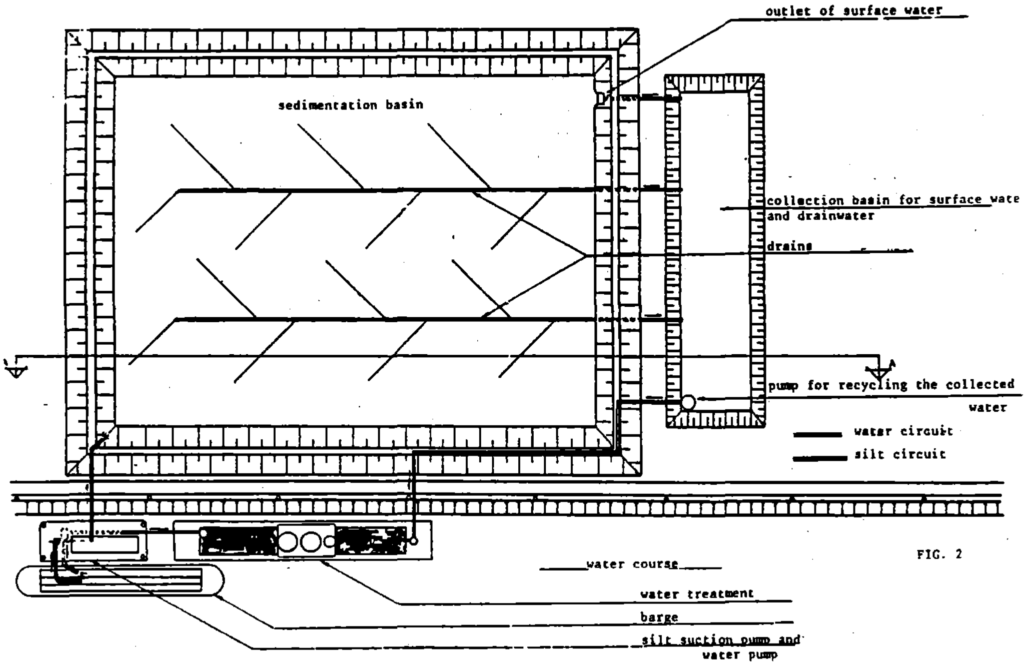

FIG. 2

Moreover the output of the dredger must be matched to that of the treatment installation. Even when a high capacity mechanical dewatering plant (a series of filter belt presses working in parallel) is used it will only be possible to use the dredger during a single shift, whereas a double shift will be necessary for the treatment installation. The dredger can therefore only work at half its normal capacity, thus considerably raising the price.

The dredging work itself costs only BF 420 per tonne of dry matter. The pollution of the dredged material thus gives rise to an increase in the overall dredging price of 1,000 %, or in other words the dredging and treatment costs are ten times the former dredging costs.

ALTERNATIVE 2 : CLASS I DUMP - TRANSPORTED OVERLAND

- Dredging of the spoil	BF 420/t DM	5%
- Transport of the spoil	BF 980/t DM	12%
- Processing and treatment of the spoil	BF 4,200/t DM	48%
- Dumping costs and environmental levy	BF 3,080/t DM	35%
	BF 8,680/t DM	100%

The assumptions here indicate that the treatment of the pollution entails an increase in price of ± 2,000 %, or 20 times the original normal price. The environmental levies and dumping costs are ± BF 3,090 per tonne of DM, representing 35% of the total price.

The total price suggested here is totally hypothetical and is of course dependent on local factors and the nature of the pollution. In other cases, transport costs, disposal costs, dredging costs, etc. will play a different role in relation to the specific situation. This theoretical example can therefore be in no way generalized, but does give a good indication of the order of magnitude of prices when it is decided to proceed to treatment or disposal on a protected disposal site of severely polluted dredged matter in comparable conditions and taking account of current standards.

CLEANSING POLLUTED DREDGED MATERIAL

Another alternative is to clean severely polluted dredged matter.

The current costs of known cleaning methods lies between BF 8,000 and BF 20,000 per ton of DM. Obviously then, such solutions can only be adopted for treating small quantities of severely polluted material. It is therefore still cheaper to store this problematic material at a protected and licensed dump.

IV. SOLUTIONS FOR THE FUTURE

In recent years intensive studies have been carried out or the effectiveness and feasibility of a number of alternative disposal and treatment methods. In the following paragraphs a number of solutions are examined, ranked by cost, technical and economic feasibility and duration. Here the feasibility of the various solutions are a function of the degree of pollution of the material which is to be disposed of.

IV 1. OVERDEPTHS IN DOCKS AND WATERCOURSES

Overdepths in docks and watercourses have also been used in the past as the ultimate destination of dumped dredged material. Formerly, however, this was never done in any controlled way.

Underwater disposal has the great advantage over on-shore disposal in that the polluted material is disposed of in controlled conditions, which markedly diminishes the likelihood of leaching, particularly of heavy metals.

In order to prevent the surrounding groundwater from nevertheless absorbing the leachable fraction, the protection of the surroundings is useful and in some cases is essential.

For this reason it is desirable for there to be a continuous layer of clay under the bottom of a cell, as this tends to prevent the creation of vertical flows of pollutants in the soil. This procedure was followed in the underwater disposal in the Doel Dock (ref.10).

If necessary, after filling and allowing a sufficient period of time for settlement the upper surface of the cell can be provided with a sealing layer or "capping". This capping may consist of a course of clean sand or dewatered clay which is dumped on top of the consolidated material.

Another technique, which is now in intensive development, is DCM or Deep Chemical Mixing. Here a tin upper layer consolidated material is mixed with a composite additive (such as fly ash, cement or bentonite) which creates a thick and compact protective layer.

The filling of the overdepths is carried out by means of a "submerged diffusor". With this device the turbidity in the water column is kept to a minimum during the filling of the cells. The filling work is carried out by a converted cutter suction dredger, which is a craft with a high production rate. In this connection we refer to ref. 10 where the results of an extensive test programme are reported, and where the work was monitored during and after the filling of the cells.

When designing deep sites in docks sufficient attention must be given to the stability of the overdepths themselves and of the surroundings (embankments, and quay walls). Soil studies and associated soil mechanical tests will then have to be carried out in advance.

Figure 3 shows a cross-section of an overdepth of this sort in a dock.

The system offers the advantage that when overdepths are dredged sand material is released which can be turned to good account when preparing sites on the left bank for industrial installations. In this connection it has been borne in mind that because of the negative sand budget, relatively large areas still cannot be completed.

The technique moreover offers a solution at a favourable price and the operation raises no drawbacks of a physical planning nature.

The disadvantage is that this system can only offer a solution in the short or medium term; after a while there will be no room left for the construction of additional overdepths in docks or canals.

Case study

Compared with the first case study this solution offers a relatively cheap alternative. If there is space available, the filling of excess depth in docks and watercourses offers an extremely attractive solution both in ecological and in economic terms.

To estimate the cost we assume a deep site with a capacity of 1,000,000 m^3, and an average fill depth of 8.5 m. The results are given in Bf per tonne of DM, where it is assumed that the material resulting from maintenance dredging has an in situ density of 1.2 tonne per m^3.

- dredging, transport and environmentally safe disposal of the material in the deep spot	420 Bf/tonne DM	65%
- creation of the deep spot	280 Bf/tonne DM	35%
- capping		p.m.
TOTAL :	Bf 700/tonne DM	100 %

IV 2. NATURAL SEPARATION AND DEWATERING SYSTEMS

The treatment of large volumes of dredged material which may or may not be polluted can be carried out by means of separations and dewatering in large basins. This procedure which can usually be integrated in to the dredging process, offers favourable economic prospects.

Combined with the environmentally safe disposal of dewatered dredged material these techniques can be used as elements of a large treatment unit for dredged material.

- Separation Basins

A separation basin is an elongat[illegible]ump which is supplied with a sand/silt mixture from one side. The flow which is then established in the basin and which is dependent on the dredging unit used ensures that the sand particles sink first, while the other material is driven forward through the basin and is carried into a catchment basin. When the material is polluted the greater part of the pollution, which normally adheres to the fine fraction, will be concentrated in the catchment basin. The residual sand fraction can then be dug out by normal methods and adopted for normal uses. Recent trials and studies indicate that this technique is only economically effective if the sand fraction in the sand/silt mix exceeds 20%.

- Dewatering Lagoons

In order to make the most effective use of the available space, the material in the catchment base will, before being finally disposed of, be reduced in volume by using an accelerated dewatering technique.

Dredged material easily contains up to 85% water. This must be reduced to about 60% so that it can be transported and handled as dry matter.

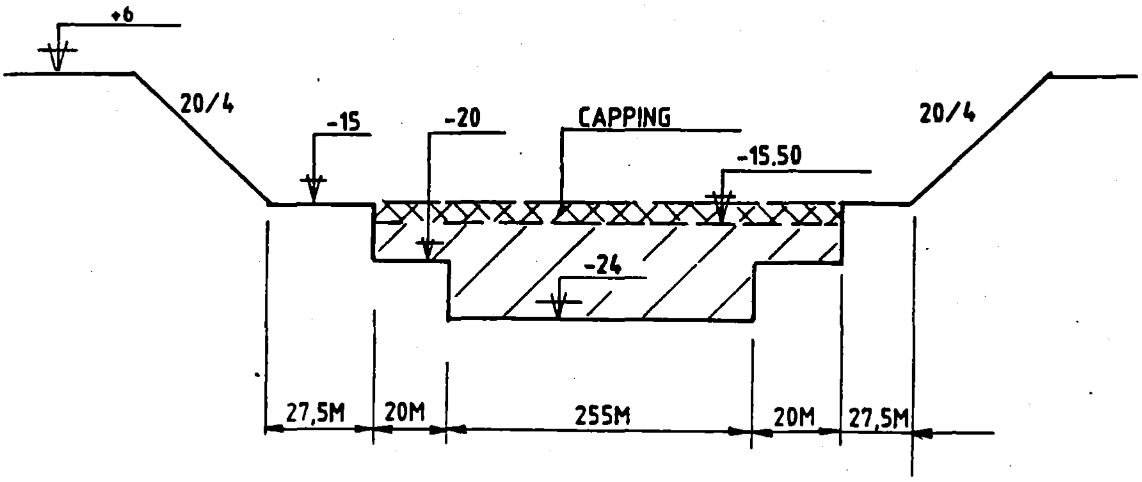

Figure 3

Accelerated consolidation takes place in lagoons. The bottom of the lagoon is provided with a layer of draining sand and possibly drainage pipes as well in order to permit the accelerated drainage of water on the underside of the basin.

To facilitate accelerated drying various surface treatments are applied, such as seeding with deep-rooted plants, digging ditches for draining off surface water, and the turning over of the material with diggers in order to encourage evaporation, etc.

- Landscaping

The dried dredged material can be used for landscaping when laying out recreational areas and green zones.

This approach is described in greater detail in the article "Large scale separation and consolidation for disposal on land of finegrained dredged material" (ref. 11).
The advantage of this approach is partly that it makes it possible to keep pace with the output of suitable dredging equipment and partly that it offers a relatively cheap solution which offers significant advantages from the physical planning point of view. Pollutants in the dredged material do not necessarily constitute an obstacle if they are taken into account during the design and construction of landscape features.

Case study

- dredging and transport	Bf 420/tonne DM	25%
- separation and dewatering and excavation	Bf 450 to 550/tonne DM	34%
- transport to destination area	Bf 120 to 350/tonne DM	21%
- works in destination area	Bf 230 to 325/tonne DM	20%
TOTAL	Bf 1220 to 1645/tonne DM	100%

IV 3. MONODUMPS

Because the material resulting from maintenance dredging work is regarded as special waste in Flanders, the licensing authorities consider the sites where it is dumped as special waste disposal sites, a fact which is reflected in the terminology used in the foregoing.

Only waste materials of a single sort are admitted to monodumps, to the exclusion of all others. Such dumps are not subject to general licensing conditions, but are governed by special licensing arrangements which are dependent on the specific nature and origin of the waste.

In the case of dredged material, which in our view are only subject to moderate leaching, less severe requirements could be imposed for the design and layout of the disposal site than is for example the case with a Class 1 tip for industrial waste. This of course implies that the costs of laying out such sites could be reduced.

In the longer term the disposal of material from maintenance dredging in monodumps raises land-use problems in Flanders, simply by reason of a lack of space. This problem could at least be partly solved by considering such monodumps as buffer dumps awaiting a final solution in the form of technically and economically feasible recycling or clean-up procedures.

The cost of disposal varies from Bf 4,200 to 5,600 per tonne of DM, depending on the pollution, the disposal conditions imposed, local conditions, etc.

IV 4. TREATMENT OF THE MATERIAL ON BOARD THE DREDGER

This solution appears to be somewhat futuristic, but would nevertheless result in a reduction of the dredged material problem in the long run. The research currently being carried out is aimed at increasing the precision of the dredging operation, and more efficient positioning systems, both of which would tend to reduce costs. This would result in the more precise definition of the areas to be dredged. Other studies are aimed at separating the silt from the sand fractions in the hopper well itself.

Such studies should result in a minimum volume of material being dredged combined with the effective removal of a maximum volume of dredged material. The advanced automation of the dredging process and the treatment of dredging spoil on board the dredger itself will require much more time and further research.

The following possibilities are currently under examination:

- Registration and automation of all dredging and position-finding data during the dredging cycle provide improved and more accurate management and control over the dredging process. Dredging efficiencies are improved by linking this information directly to the sounding data. Remote transmission technology for use between dredging units and between ship and shore, adapted from aerospace applications, is in full development.

- If a material with a very high silt content is being dredged, every effort must be made to achieve maximum densities by equipping the hoppers with degassing installations and suitable suction heads; cutters can be equipped with high density pumps and modified suction intakes.

- Methods are currently being developed for dredging sand/silt mixes which either separate the sand and silt fractions on board or measure the mixture in function of sand and silt contents during dredging and dump it selectively in different compartments of the well.

  The sand which is then separated from the silt, could then be returned to the watercourse. The silt fraction can be stored on land. This would reduce the volume of silt brought ashore, thus reducing the physical planning problem.

Such measures would result in a minimum volume for a maximum of material to be effectively removed. However, a great deal of research and time is still necessary before such advanced automation and on-board treatment becomes daily reality.

IV 5. RECYCLING

Recycling methods can be considered as long-term solutions. Recycling techniques are being developed which will make it possible to use dredged material for artificial gravel, construction materials, or as a soil improver by mixing it with formulated fertilizers. Pilot projects are currently under way.

These techniques result in a final solution for the problems posed by dredged material. They make it possible to consider dredged material not as a classified waste by as a raw material. At present the cost of these methods is still fairly high, largely because of the high energy costs. Further extensive studies should bring greater understanding.

IV 6. THE ENVIRONMENTAL ISLAND

In the past the idea of constructing an environmental island has been suggested more than once. The idea recently returned to the news because it was proposed to combine it with other activities which could make a positive contribution to the economics of an island of this sort. A recent study concluded that the construction of such an island to act as a depository for industrial waste and dredged material would be the most economic and feasible solution. The overall cost was estimated at Bf 500 per m^3 of dredged material (40% DM) where 50% should be regarded as fixed costs and 50% as variable costs (dredging, transport, and volume reduction).

The dewatering would take place on shore, at the prices indicated above.

This would give the following table :

- dredging and transport	Bf 420/tonne DM	± 20%
- separation and dewatering and excavation	Bf 450 to 550/tonne DM	± 25%
- transport and deposit on the	Bf 1000 to 1300/tonne DM	± 55%
TOTAL	Bf 1870 to 2270/tonne DM	100%

There is, however, considerable social resistance to this solution. Moreover when the overall supply of dredged material and the relatively small volume of polluted fraction requiring special treatment is taken into account there are a number of other solutions which are economically more advantageous.

V. COMPARISON OF ALTERNATIVE SOLUTIONS

An analytical review and classification (see tables 2, 3 and 4) of all the proposed solutions was drawn up so that an appraisal of the various solutions could be made. The following elements were considered in the review.

Cost : This was estimated for every solution. In this connection it should be noted that the costs are indicative but can nevertheless be used as a basis of comparison.

Timing:

Timespan during which solution can be used :

Usually the period during which a solution is offered is a logical consequence of the nature of the solution. Even so it was not always easy to set limits. For example landscaping should probably be regarded as a medium term solution, rather than a long-term one.

We still do not have a full inventory of the sites in Flanders which could be considered for this purpose.

Moreover the technique of building mounds of consolidated silt has not yet been adequately researched. A fullscale pilot project should make more reliable forecasts possible.

Physical planning :

The nature of the solution has a clear impact on land use.

Environmental impact:

The appraisal of the environmental impact of each case was based on studies which were carried out in the past. Of course an individual approach will be adopted for each particular case.

Treatment on board the dredger was not taken up in the classification because this solution is more of an intermediate stage in the development of other solutions : first of all a reduction of volume must be achieved, and then a final destination must be found for the consolidated material.

Natural separation and dewatering techniques, like mechanical techniques can likewise serve as an intermediate step in other approaches such as monodumps, transport to an environmental island, and even for disposal in overdepths.

The word "landscaping" here is used in the sense of the natural approach to landscape development.

TABLE 2 : REVIEW OF PROPOSED SOLUTIONS IN TERMS OF DECIDING FACTORS

Deciding factor	Cost	ST or LT solution		Physical planning	Environmental impact
Solution		When practicable	Period of applicability		
Overdepths	++	ST	MT	++	++
Natural approach landscaping	+	MT	MT/LT	0	+
Treatment on board dredger	+	LT	LT	+	+
Disposal in monodumps					
Severely polluted	-	ST	ST	--	0
Mildly polluted	-	ST	ST	--	+
Recycling	--	LT	VLT	+	+
Environmental island	0	MT	VLT	++	++
Current state of affairs	--	ST	ST	--	-

++ = very favourable
\+ = favourable
0 = neutral
\- = unfavourable
-- = very unfavourable

ST = Short term
MT = Medium term
LT = Long term
VLT = Very long term

TABLE 3 : CLASSIFICATION OF SOLUTIONS

by price :

1. Overdepths
2. Landscaping
3. Environmental island
4. Monodumps
5. Recycling

by when practicable

ST 1. Overdepths
ST 2. Monodumps
MT 3. Landscaping
MT 4. Environmental island
LT 5. Recycling

by impact on the environment

1. Recycling
2. Environmental island
3. Overdepths
4. Landscaping
5. Monodumps

by duration of applicability

VLT 1. Recycling
VLT 2. Environmental island
LT 3. Landscaping
MT 4. Overdepths
ST 5. Monodumps

by impact on land use

1. Recycling
2. Environmental island
3. Overdepths
4. Landscaping
5. Monodumps

overall classification

1. Overdepths
2. Landscaping
3. Environmental island
4. Recycling
5. Monodumps

TABLE 4: DIAGRAM OF POSSIBLE PROCESSES

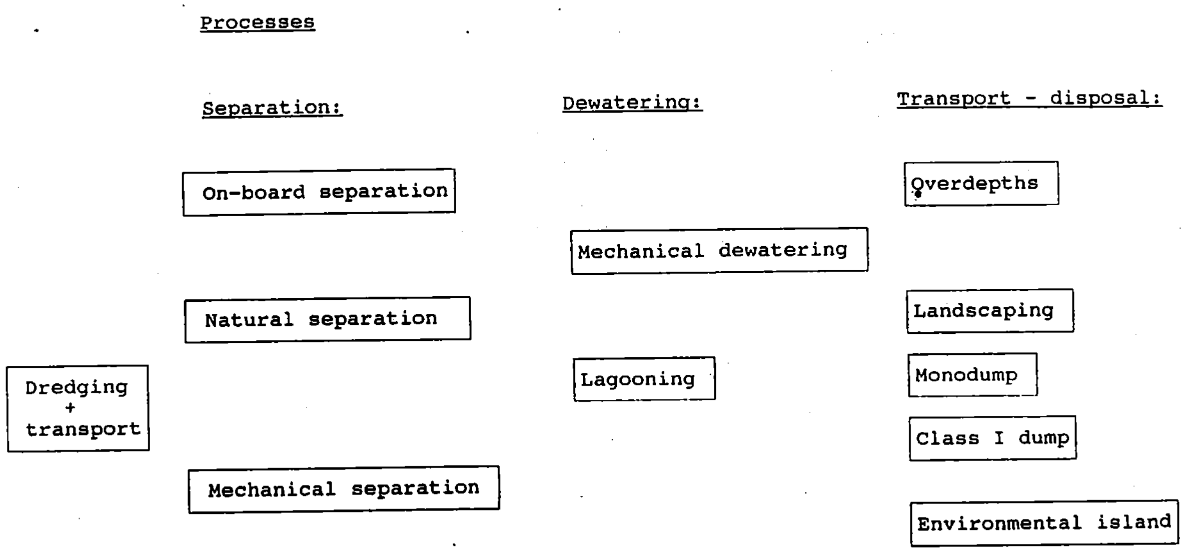

TABLE 5 : DECISION CHART/PROCESSING COSTS FOR DREDGED MATERIAL

	COST FACTOR	FOR	AGAINST
Past	1	cheap, simple	environmentally harmful no longer acceptable to society too little disposal capacity → cannot be sustained
Overdepth	2 - 3	can be realized in ST environmentally safe very cheap	ST solution (capacity used up after 10 to 20 years)
Landscaping	4 - 5	creation of recreational areas relatively cheap	only for unpolluted or mildly polluted mat ST solution (capacity used up after 20 to 25 years)
Environmental island	6 - 8	environmentally safe LT solution possible alternative uses (storage industrial waste) the ideal solution to physical planning difficulties	unacceptable to society technically difficult high investment costs
Monodumps	15 - 20	provision solution if no other alternatives	temporary solution extensive limited capacity social objections
Recycling	30 - 60	no environmental burden or land use problems	expensive no economic use of recycled materials difficult at the moment

VI. CONCLUSION

All studies of accelerated consolidation of the silt raction of dredged material must be encouraged. Savings resulting from the technical improvement of he dredging process, enabling higher outputs to be achieved, can be used in part to compensate higher environmental costs. It is doubtful nevertheless whether the savings will be enough to cover the total environmental cost. The above considerations have shown that these costs can be very high indeed. This is particularly so in the case of recycling, which, although offering a final solution, preferable above all others, is at present so expensive and availability still so far in the future that it does not stand up to comparison with other methods. Economic recycling must therefore be seen as a long-term project.

If a decision must be taken on the basis of the available data of what method is most suitable both now and in the future, an answer must be given to the following question: Which method, with the lowest acceptable price in relation to environmental impact and land-use questions, and taking into account the social acceptability of the proposed solution, can be achieved within a realistic period of time and to what extent can the processing capacity corresponding to this method keep up with the supply of dredged material?
In the special case of the Antwerp region it would seem to be advisable to dispose of the bulk of the material in overdepths in the docks on the Left Bank. In other cases where the provision of such overdepths is not possible, monodumps can offer a temporary solution. We have, however, already seen that the construction of monodumps runs into considerable social opposition.

This becomes particularly difficult when after a certain period of time the disposal capacity thus created is exhausted. Here landscaping, possibly after separation and accelerated consolidation of the polluted material, could offer a solution, but here society's willingness to accept this solution will, because of the NIMBY syndrome (not in my backyard), again be a key factor.

For the Antwerp region it will be important to develop the landscaping method in the immediate future. The overdepths in docks and watercourses can be used as a temporary solution for dealing with the current supply of dredged material. However, after a period estimated at between 20 to 25 years, the available capacity will be entirely used up.

Virtually all the methods described here are based on a reduction of the volume of the dredged material after it has been dredged. <u>It is, however, far more important to reduce the volume of polluted material at the source.</u> A drastic reduction at source of the of industrial and household waste water would make a great contribution to reducing the volume of sediment currently deposited in our rivers. Furthermore natural sedimentation would then no longer be loaded with contaminants, which would in turn make a broad range of choices again possible. <u>Programmes aimed at keeping water and soil environmentally clean are thus crucial</u> if a lasting solution to the problem is to be found.

Should such a clean-up of our watercourses not be achieved within a reasonable period of time, the construction in the long term of an off-shore environmental island will have to be given serious consideration.

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CLEANING THE HEAVILY CONTAMINATED GEULHAVEN AT ROTTERDAM

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ABSTRACT

The Geulhaven at Rotterdam has been heavily contaminated in the past by oil derivates and hydrocarbons. A total of 260.000 m^3 of contaminated harbour silt had to be dredged. Most silt was to be treated by hydrocyclones to extract the sandfraction for reuse. The remaining silt and clay fractions, containing the pollutants, were to be stored in special depots, in the "Slufter" depot class III and class IV in the "Papegaaiebek" depot for later treatment. The slope protection was to be cleaned first after which the dredging with closed grabs within a screen to prevent dispersion could take place.

The working plan as originally envisaged had however to be reconsidered completely due to the following problems:

- Inadequate representation of reality by the original borings and chemical tests.
- Larger quantities and higher degree of pollution than anticipated.
- Cleaning slope protection proved more costly than foreseen.

Methods for improvement of the sand separation process and cleaning of the slope protection were considered and tested, some with succes:

- Repeated separation by hydrocyclone.
- Separation by fluidised bed.
- Biological treatment of the sandfraction and silt.
- Cleaning the slope protection with a "jetbox".

The paper highlights the original working method, problems encountered, newly developed equipment for slope cleaning, test results and chosen solutions for use in final execution.

INTRODUCTION

Dredging alone is hardly ever a problem, but the dredging, treatment and storage of contaminated soil is however often a mayor problem. Much research has been done to find alternative methods of dredging in order to prevent the pollution of the waterbody and the spread of contaminated material to neighbouring clean area's. The anti-turbidity screen and the closed grab or the visor closed bucket are examples of this.

Treatment of contaminated dredged material has been mainly concentrated on separation techniques to extract a reusable sand fraction in order to reduce the costly storage capacity demands for the contaminated fines fraction.

The Geulhaven project is one of the 10 locations for which the Dutch Ministry of Public Works issued in 1987 a demand for restoration schemes. Mid 1989, five of the jobs were let by Rijkswaterstaat on the basis of a mix of quality/price considerations. The Geulhaven project was acquired by HAM/VOW in joint venture with Dolman bv and Witteveen and Bos Consultants.

PROJECT DESCRIPTION

The Geulhaven is situated at the mouth of the "Botlek" complex in the Rotterdam Port Area. A small part is used as a tugboat harbour but the main part is in use for transfer of oil products and tank cleaning. The location is as sketched in fig. 1.

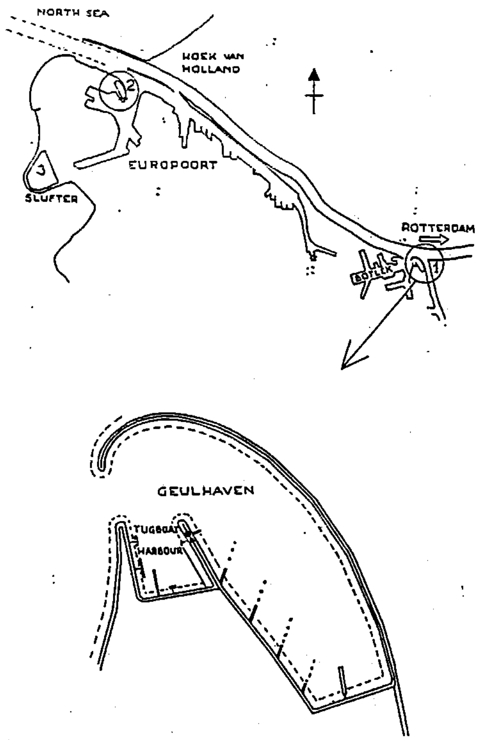

Fig.1. Location Geulhaven Project

In the early eighties the sediment in the harbour proved to be very contaminated to such an extent that special measures were required instead of normal maintenance dredging; so dredging was postponed. Normal dumping at sea or even storage in the slufter depot for part of the material was not allowed because of the extreme high degree of pollution.

In order to reduce the quantities to be stored, separation in a clean sand fraction and a contaminated silt fraction was to be preferred. Contaminated slopes had to be dredged and cleaned first. Turbidity caused by dredging had to be avoided in order to prevent pollution of clean areas. Consequently overflowing of barges or hoppers was not allowed. Safety measures for the operational crew had to be applied according to the Dutch regulations.

THE INITIAL PROPOSED WORKING METHOD

Fig.2 shows a schematic diagram of the initial proposed method.
The process starts with bulk dredging by closed grabs within a screen from waterface to bottom (fig.3) In the final stage accurately clean up dredging within the screen will be done with the specially designed HAM visor backhoe bucket. (fig.4) The dredged material is stored in barges and transported to the separation plant near the Papegaaiebek depot.

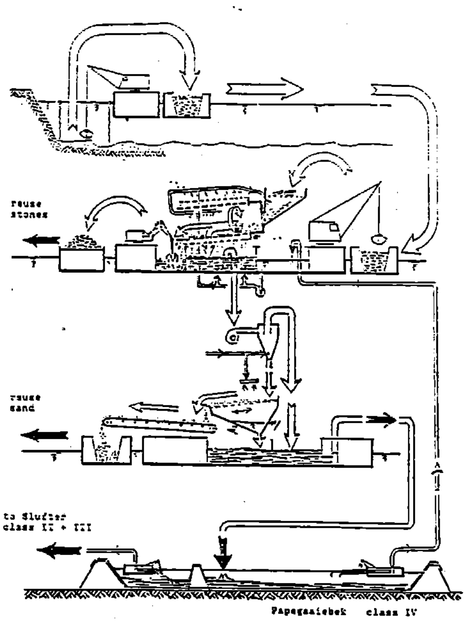

Fig. 2. Schematic diagram of the operation

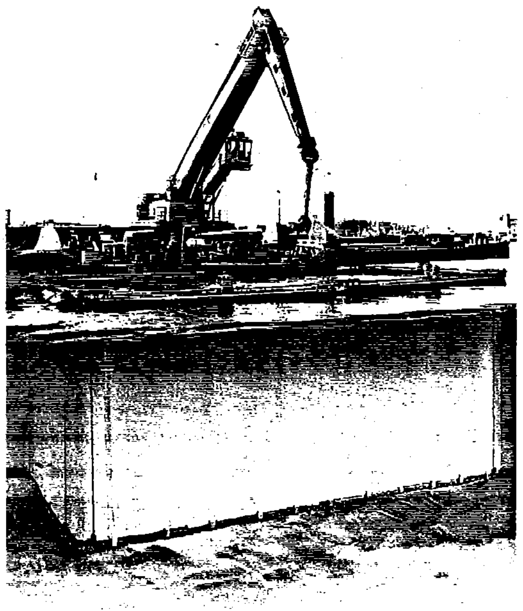

Fig.3 Dredging within anti turbidity screen

After the treatment in the separation plant, the clean sand fraction will be stored in barges for further transport and reuse elsewhere. The silt class IV will be stored in the Papegaaiebek depot, while the class II and III silt is to be stored in a temporary diked off section of this depot.

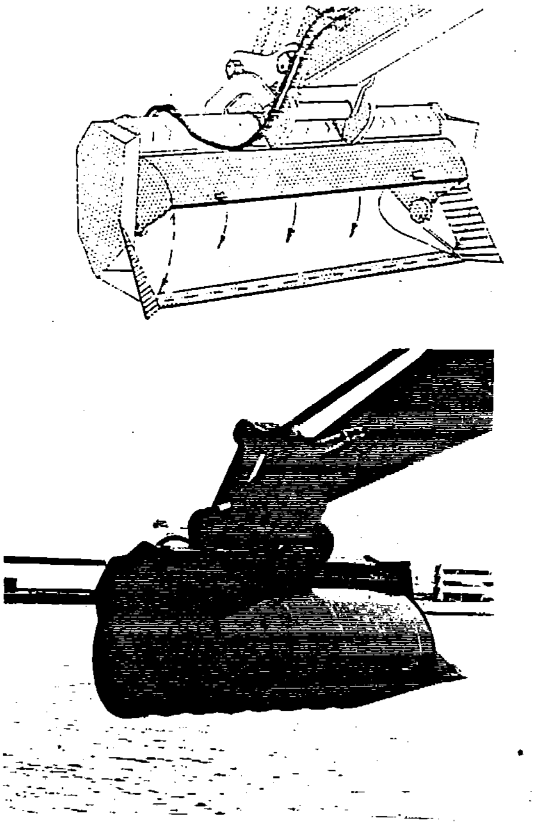

Fig.4 HAM Visor backhoe bucket

After sedimentation of the silt all required process water is pumped from the surface of this depot to the treatment plant by the HAM 254 wormwheel dredger.(fig.5) Finally the silt class II and III will be carefully re-dredged by the wormwheel dredger to the much larger and per volume unit cheaper Slufter depot.

Fig. 5 Thin layer wormwheel dredger HAM 254

The coarse material and debris separation plant was mounted on a pontoon with a bucket grab for loading the dredged spoil on top of a grizzly screen above a loading funnel. At the lower end of this funnel the loaded material enters a heavy rotary double screen with inside openings of 5 cm and outside openings of 1 cm.(fig 6.) With the use of jets, in combination with the rotary action, possible clayey lumps are being disintegrated and the silt is separated from the course fraction .

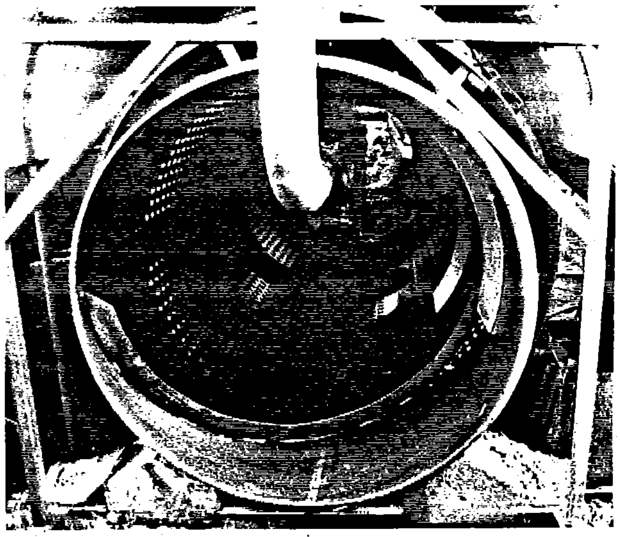

Fig. 6 Rotary double screen sieve

The silt passing the screen is pumped to the separators of the separation unit (fig. 7) on the other pontoon and the course material is collected in a storage bin from where it is loaded on a barge by using a small grab. The separators are in fact hydrocyclones with a underflow controlled by a rubber flap in combination with an adjustable underpressure at the top outlet.

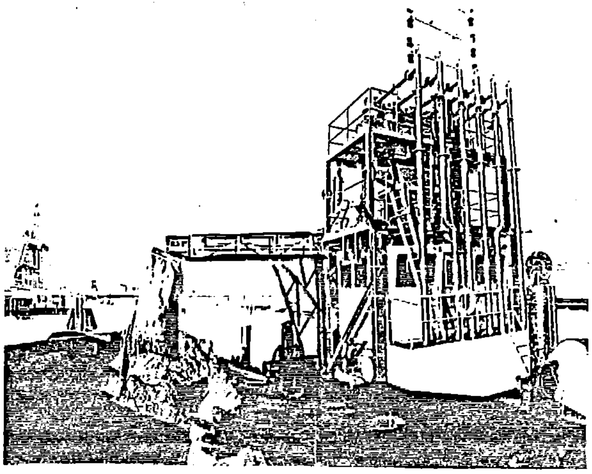

Fig.7 Separation unit DBV 9

The top effluent of the hydrocyclones is pumped to the Papegaaiebek depot while the underflow is dewatered on a vibrating sieve. Finally the dewatered sand is transported by conveyor belt into a barge.

PROBLEMS DURING EXECUTION

a. Soil survey:

The degree and type of pollution and grainsize distributions for tender purposes were determined from the analyses of about 20 samples.
The quantities of contaminated silt, as given in the tender, were based on excavation up to the original harbour bottom assuming clean soil below this level.

The contractor started an intensive soil investigation in order to properly plan the dredging operation. Due to an excessive amount of overdredging during maintenance the quantities of contaminated soil appeared to be much greater. In many places the possible extractable sand content proved to be lower than the figures based on the original samples and moreover the degree of pollution was erratic.

Because of these events the contract and planning of the project had to be severely revised . Effective separation was endangered by hydrocarbon percentages as high as 10 %. In addition local low sand contents made the storage reduction by using separation techniques questionable.

b. Slope cleaning:

The slope cleaning was planned as a secondary activity before the main dredging. Cleaning the 1 in 3 slopes however became a main issue when the execution started in the autumn of 1989. The slope protection consisted of willow mattresses covered with stones 10 to 80 kg. and construction rubble, intermingled and overlain by fresh contaminated sediments below M.S.L. The visible stones proved to be covered with a tarry substance from H.W.L. downward.

The stones had to be cleaned for reuse. Therefore it was decided to clean the stones in a large rotating sieve which was however originally planned to be used only for the debris separation of the dredged silt prior to the separation process. The wear was considerable and the throughput capacity had to be reduced in order to increase the time for washing the stones properly.

A great difficulty was the potential clogging of the outer sieve with 1 cm openings by the broken pieces of willow wood from the mattresses which were also picked up by the grab dredge. This clogging problem happened also at the suction entrance of the several immersed pumps in use.

The execution was suspended after the most contaminated part of the slopes had been cleared. At that time the budget was well exceeded and a better solution for the cleaning of the slopes had to be found. In the mean time the research department of HAM developed the so called "Slopecleaning Jetbox" which will be explained in a later section of this paper.

c. Separation:

The use of the separation technique had to result in a reduction of the necessary storage capacity. The separated sand fraction however contains a high percentage of coal-tar particles up to 4 mm size to such extent that the sand must be considered as class IV contaminated material. These particles mainly consist of mineral oil and PAC's (polycyclic aromatic carbonhydrates)

Repeated treatment with the installed separators on a prototype scale did not produce the desired results. Pilot plant scale tests with several different types of hydrocyclones and fluidized bed columns were also as ineffective as the repeated treatment.

HAM research department did some further tests using bacteria in a 200 l. percolation cell ,simulating a possible situation in a depot, to breakdown the pollution in the separated sand. After about 20 days the breakdown of the main contaminants appeared to be only about 50%. The main reason for this limited succes is most likely the low availability of the contaminants for the bacteria in the waterphase. The bacteria used in this test are the same as those in the tests reported in [1].

The problem of tarcoal particles is still under study. Because of these results only the soil types with low tarcoal content and high sand content will be separated.

THE SLOPECLEANING JETBOX

The slopecleaning jetbox is based on the idea of cleaning the top layer of a slope with the use of water jets in a confined space under water. The jets will erode the siltation up to a depth of about 0.25 m. in the slope protection layer. The mixture created in this way is sucked up into a settling basin. The water for the jets is extracted from the same basin thus creating a closed circuit in order to prevent unnecessary use and contamination of clear water.

In fig. 8 a top view and cross section of the prototype is given . The box is 0.6 m. high and about 8 m. long and 3 m. wide. Inside the box there are 65 nozzles divided in 4 sections. Each section has 3 or 4 rows of 5 nozzles and can be seperately supplied with jetwater. A special feature is the presence of six large sliding doors in the roof of the box. These will be opened when the box is lowered on or lifted from the slope surface in order to reduce the water displacement at the moment of tough down or lift off. In this way the stirring up of contaminated material which can pollute new or already cleaned areas is reduced to a minimum.

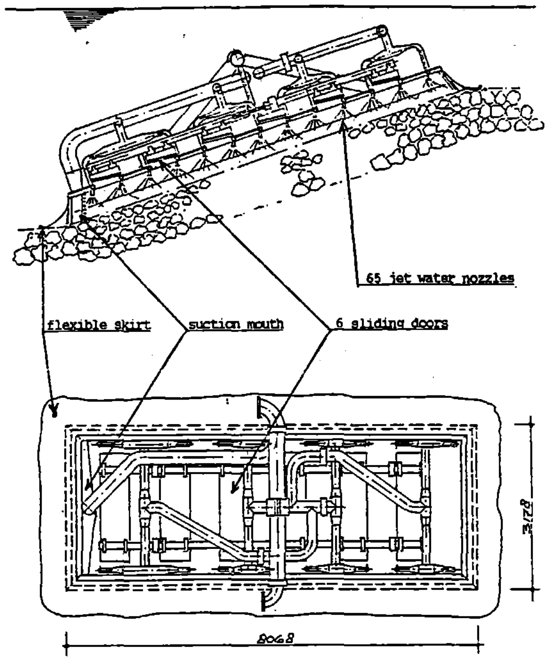

Fig.8 The Slopecleaning Jetbox

At the moment of writing this paper the jetbox has been constructed but is not yet in use. The box will be secured to a backhoe dredge mounted on a pontoon. Fig. 9 shows a schematic diagram of the dredge spoil discharge from the jetbox and jet water supply to the jetbox.

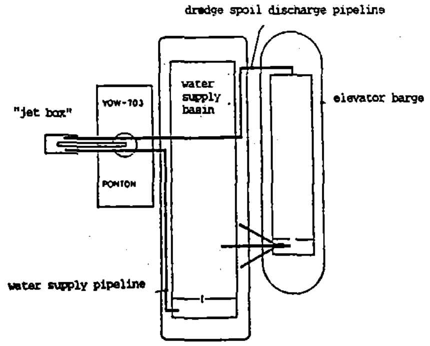

Fig. 9 Schematic diagram of the spoil discharge and watersupply

The submerged suction pump with a flexible suction pipe from the jet box is attached to the backhoe pontoon. The mixture will be discharged in an elevator barge which serves as a settling basin. If necessary floculation can be applied. The overflow will be pumped into a second barge which serves as a final settling and water supply basin for the water jets.

CONCLUSIONS:

- Soil surveys and sample analyses for contracts in contaminated sediments should in view of the often erratic distribution of the contaminants be very intensive . The costs will be much higher than the normal 1% of the dredging cost and can be between 10% and 30%.
- The accuracy of the determination of the vertical and horizontal position limits of contamination is very important. It is however futile to prescibe a dredging tolerance which is much smaller than the accuracy of the probable geografic boundary between contaminated and clean soil.
- Environmental dredging and subsequent treatment of contaminated sediments are still in a development stage. The relationship between client and contractor should leave ample room for joint development by client and contractor. In this way sufficient experience and expertise will be acquired by both client and contractor to enable them to jointly formulate new standards and procedures for environmental dredging projects.

References:

[1] J.De Fraye , Y.Kreps-Heyndrikx : The use of selected bacteria in the treatment of contaminated sludge, CATS Congress, Gent, Belgium, 1991

HARBOUR SLUDGE : FROM FERTILE SOIL TO CONTAMINATED WASTE

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ABSTRACT

The purpose of this article is to show the development of growing knowledge in the field of the contamination of dredged sludge from the Rhine and the harbour of Rotterdam.
Over the years sludge has been deposited in the Northsea and on land. Governmental legislation has now led to a stop on disposal of contaminated sludge in the Northsea. Landdisposal is restricted. Sediment quality criteria have labelled large quantities of sludge as contaminated. Therefore large landdisposal areas were created on the "Maasvlakte", near Rotterdam. Investigations have been conducted concerning former sludge disposal sites in Rijnmond. At least 150 sites have in the past been levelled up with sludge.
The health risk of contaminants from former sludge disposal sites has been investigated.

INTRODUCTION

Over more than hundred years until the nineteen-eighties sludge from the rivers and harbours of Rotterdam was used to level up polderlands.
Untill 1977 about a total of 21 million m^3 of harbour sludge was dredged every year$^{1)}$. Annually six million m^3 was disposed on land. About 70% of the dredged material was of marine origin and returned to the sea. This holds for the outer harbours close to the sea.
Dredged material from the inner harbours was and is to the present day more severely polluted and is deposited on land.

This article deals with the approach in solving the problems of disposal of harbour sludge and the growing insight in the qualitative aspects of the dredged material. Former sludge disposal sites were subject of an investigation which dealt with the possible health risks by consumption of foodcrops.
Some results of environmental studies of former sludge disposal sites, the Broekpolder and the Steendijkpolder, are presented here.

DISPOSAL OF DREDGED MATERIAL

Till the 1970's no attention was given to the pollution problem caused by disposal on land of dredged material.
The situation changed in 1975 when the question came up whether the dredged material in the top layer of former disposal sites could cause health effects through the uptake of contaminants by food crops grown on these disposal sites$^{2)}$.
Concern about the possible health effects led to the foundation of a Steering Committee "Disposal of Dredged Material" (SGBB). In the SGBB were represented the province of South Holland, the Public Authority of Rijnmond, the Municipality of Rotterdam and the Ministry of Transport and Public Works.
The purpose of the SGBB was to develop a policy concerning the problems related to the discharge and handling of dredged material.

Lack of disposal sites was the mean reason for establishing a Coördinating Committee for the Disposal of Dredged Material (CCBB), who had the task to define where and under what limiting conditions the dredged material in the long and short term could be disposed of.
In their first report the CCBB (1977) considered the necessary short term disposal sites. In this report many uncertanties arose concerning the environmental consequences of the disposal of dredged material.
Consultation of the municipal authorities within whose boundaries disposal sites were planned, were not very successfull.
Therefore a policy plan was set up to find a solution for the disposal problems. It was decided that an Environmental Import Report (EIR) had to deal with the environmental problems for the disposal of dredged material.

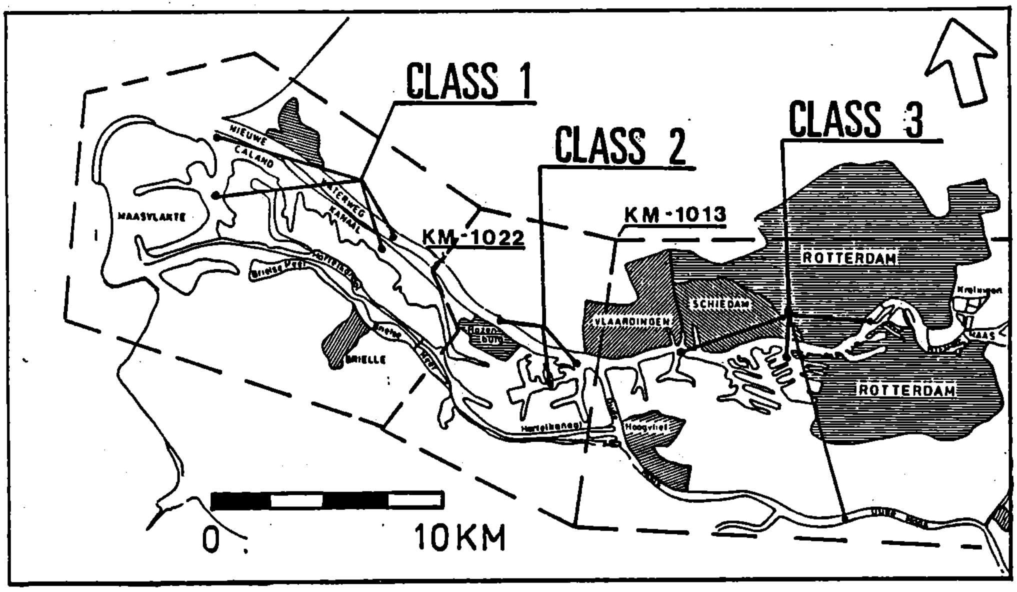

Figure 1: Classification of dredged sludge from the harbours and waterways in and around the Municipality of Rotterdam.

CLASSIFICATION OF DREDGED MATERIAL

Since the completion of the EIR in 1979$^{3)}$, the SGBB formulated its policy plan (1982) that can be characterised as a plan for short and middle/long terms in dealing with the handling of dredged material.
The plan introduced a geographically orientated classification of dredged material which took into account the estuarine mixing of river sediment with relative clean sediment from the sea. The classification was associated with the east to west decrease of contamination levels in sediment.
In figure 1 the classification of dredged material from the harbour of Rotterdam is given. According to the policy plan the dredged material of class 1 would be disposed in the sea, the dredged material defined as class 2 and 3 would be disposed in a large-scale site (later known as Slufter) and class 4 material in a specially designed disposal site (Papegaaiebek).
Heavily contaminated dredged material with some parameters having contamination levels exceding class 3 materials were placed in class 4. These heavily contaminated materials originate from local activities like industrial water effluent.
In table 1 the approximate annual quantities of dredged material are given. The policy plan of 1982$^{1)}$ stated that after 1985 the disposal of dredged material in the sea had to be restricted to dredged material from the Western harbour (approximate 14 million m^3 annually).
Also was stated that dredged material classified as 2 and 3 should be disposed in a large scale site with a size of 100-150 million m^3. Since such large scale sites were not available on land in the provence of South-Holland, realisation of new sites was sought on new land. The policy plan stated a preference for a "closed site" on or in front of the coast of the Netherlands. For heavily contaminated (class 4) dredged material the policy plan stated that storage on an industrial area where special

Table 1: Approximate quantities of dredged material divided over four contamination levels.

Classification	Approximate quantities (1988)$^{6)}$ of dredged harbour sludge
Class 1	14 million m^3 annually
Class 2	4 million m^3 annually
Class 3	4 million m^3 annually
Class 4	½ - 1 million m^3 annually

measures could be taken to prevent transfer of contaminants to groundwater, was preferable.

In 1988 introduction of new soil quality standards led to the establisment of reference values for heavy metals and organic micropollutants in soils by relating them to the lutum and organic matter content. In the same year an interim system for classification of sediments[4] was introduced. This system was based on conversion of the levels of contaminants to an extrapolated concentration level of a standard sediment with 10% organic matter and 25% lutum.
The converted concentration levels can be compared to standard concentration values and so an "overall" classification of the sediment can be made.

LARGE-SCALE DISPOSAL SITE (CLASS 2 AND 3)

In 1982, in accordance with the policy plan of the SGBB, the Municipality of Rotterdam, the Public Authority of Rotterdam and the Ministry of Transport and Public Works presented a plan for a large scale site. The Ministerial Council decided to apply the EIR-procedure for this large scale site for the disposal of dredged material.

The project-EIR published in 1984, gives information and consequences of environmental, financial and civil engineering aspects during construction, lay out, use and maintenance of four alternative disposal sites[5].

The following technical and environmental aspects were investigated and formed the basis of the project-EIR:

1. Dredged Material from Maintenance work. The amount and quality of the dredged material was determined.
2. Handling and Construction Use.
3. Transport of Dredged Material and Drainage Water.
4. Geotechnical Investigation.
5. Physical Processes.
6. Dispersion Processes.
7. Coastal Morphology.
8. Ecology.
9. Ecotoxicology.
10. Landscape, Use and Lay out.

So the project-EIR can be used to predict the environmental impact by using the best technical means available for each of the alternative disposal sites.
A permit by the Waste Material Act for the realisation of a large scale disposal site, the Slufterdam, capacity 150 million m^3 (10 million m^3 of dredged material class 2/3 annually) was granted in 1985.

DISPOSAL OF CLASS 4 MATERIAL

In 1986 a disposal site on the "Maasvlakte", known as Papegaaiebek was realized for the disposal of 1,5 million m^3 of heavily contaminated dredged material (class 4).
The disposal site is designed according to the ICM criteria (Isolate, Control and Monitor) because the law governing the disposal of waste matter (Waste Material Act) takes these criteria into account when granting permits.
The disposal site is contructed in a way that the dredged material is placed 0,5 m above the groundwater level.
The dredged material is packed in a liner. The efficiency of the isolation of the disposal site is monitored by a drainage system beneath the lines.

ENVIRONMENTAL STUDY OF FORMER DISPOSAL SITES

After completion of the Environmental Impact Report (EIR) environmental studies related to the problem of disposal of dredged material on land were carried out. In the Broekpolder a geochemical investigation on a geochemical calculation model was carried out to prognose the movements of the contaminants from dredged materials[7].
The Municipality of Rotterdam initiated investigations to determine what risks can occur during the lay out and use of former disposal sites for dredged material.
The study was completed in 1986[8].
The following aspects were studied:

1. Transport of contaminants in a sand cover; vertical transport of contaminants in clean soil on top of ripened dredged material.
2. Partitioning of contaminants; partitioning in mineral fractions and level of contamination on former disposal sites.
3. Quality of ground moisture and surface water modelling the behaviour of contaminants in de top layer.
4. Drinking water pipelines. Permeability of plastic drinkwater pipelines in contaminated dredged material.
5. Underfloor space; transport of organic contaminants in the gasphase to the underfloor space underneath buildings.
6. Building organisation.
7. The effect of ingestion of contaminants by children.
8. The effect on the fauna.
9. The effect on the flora.

The resulting recommendations[9] stated that former disposal sites may be layed out for residential use after covering the site with 1,2 m of sand. This is only valid for sites with a groundwaterlevel of 1,0 metre below the surface level of the ground.
For industrial and recreational sites, with the exception of playgrounds, a cover of sand was not recommended.
In the case of lay out of allotment-gardens a covering layer of 0,4 m of humus and 0,9 m of sand was recommended.

FORMER HARBOUR SLUDGE LANDFILLS

In 1985 the DCMR started an inventory, commissioned by the Soil Clean-up (interim) Act (1983) to locate the unknown harbour sludge landfills.
The inventory included the following data:

- data from historical investigations;
- the nature and quantity of the deposited harbour sludge;
- the present and future use of the landfill;
- soil formation and geohydrological situation;
- contamination levels of deposited sludge and groundwater;
- prognoses of the future movements of the contaminants by groundwater-transport and future risks to humans and the environment.

The inventory[10] located 150 sites in the province of South Holland which were levelled up with harbour sludge (DCMR 1987). This totals an area of 4000 ha. Some locations are in use for agricultural purpose. This totals an area of 500 ha. On several of these disposal sites a concentration of allotment-gardens was found.
The results of the inventory made it possible to distinguish the health risks assessed by exposure levels of contaminants to humans for different sludge disposal sites. The inventory includes a priority list of landfills which from an environmental and a human health point of view should lead to further investigations. High on this priority list stand the former landfills, the Broekpolder in Vlaardingen, because this site was used for agricultural purposes and the Steendijkpolder in Maassluis.
In the Steendijkpolder a housing estate was built directly on top of the layer of harbour sludge.

CONTAMINATION OF AGRICULTURAL PRODUCTS ON THE BROEKPOLDER SITE

Back in 1977 investigations of contaminants in Rhine sediment led to the insight that the level of heavy metals in recent sediments were higher than older sediments taken from forelands (which amounts to 40.000 hectares in the Netherlands). It appeared that the heavy metal contents in reed, grass and other crops were strongly raised especially for zinc, copper, cadmium, mercury, arsenic and antimony[13,14].
So a problem arose for the authorities how far these higher heavy metal concentrations formed a threat to the health of plants, animals and the public.
Evaluation of the first investigations led to the provisional conclusion that no risk of health was to be expected from ingestion of foodcrops coming from the forelands[15].
Approximately at the same time, a plan was put forward for establishing an area for allotment-gardens (vegetable-gardens) on a former disposal site, called the Broekpolder, in Vlaardingen, situated near Rotterdam.
Evaluation of the analytic results of contamination levels in crops (potatoes) grown in the Broekpolder led to the conclusion by the Municipality of Vlaardingen that regular eating of potatoes in combination with other crops grown in the Broekpolder could possibly effect the public health.
Comparison between the concentration levels of heavy metals found in potatoes from Broekpolder and the average concentration showed the following factors for the different heavy metals:

zinc	1,8	lead	3,4
copper	2,4	cadmium	2,2
chromium	2,7	mercury	2,7
nickel	3,4	arsenic	3,1

Based on the growing insight of the uptake of contaminants in foodstuffs grown on these disposal sites the Institute of Soil Fertility recommended that agricultural use of former sludge disposal sites in the surroundings of Rotterdam had to be limited to forestry, cattle breeding (with the exception of holding sheep), and agricultural use (but no production meant for human or animal consumption)[16,17].
The use for market-gardening and lay-out of allotment-gardens on harbour sludge disposal sites was explicit forbidden because of the risk of accumulation of contaminants in the green parts of vegetables and grains.

Table 2: The amounts of chlorinated hydrocarbons in the "le Petroleumhaven" and in the soil of the landfill, the Broekpolder (mg/kg d.w.).

	sludge le Petroleumhaven 1977	sludge in the Broekpolder maximum	median (n=25)
HCB	0,14 - 4,4	1,5	0,40
aldrin	0,31 - 6,0	15	6,8
dieldrin	0,14 - 5,0	40	18
endrin	< 0,01 - 3,6	23	12
isodrin	< 0,01 - 6,6	58	33
sum chlor. h.c. (EOCl)	11 - 1900	168	106

After recognition that contamination of chlorinated organic hydrocarbons in the dredged material could lead to raised levels of these organic components in milk produced by cattle grazing on these sites the ministrial authorities gave the advice to renounce the use of foodstuffs grown for feeding cattle in the Broekpolder[23].
In table 2 the amount of chlorinated organic hydrocarbons in the "le Petroleumhaven" (with contamination level of class 4) and in the soil of the landfill, the Broekpolder is given.

DISPOSAL SITE STEENDIJKPOLDER

This area of about 23 ha was raised during 1962-1964 with 1,3 million m^3 of harbour sludge. The sludge originated form around 20 harbour basins in Rotterdam and the industrial area around the Nieuwe Waterweg. In the soil organic solvents, PAH's, aldrin, dieldrin, isodrin, telodrin and several heavy metals were found as contaminants.
During 1965 and 1973 the area was in agricultural use until increased concentrations of Cd, Pb, Hg and As were found in several cultivated products (grains, maise etc.).
The investigating authorities advised against consumption of the products[2,11].
During 1975 and 1983 a housing estate of around 800 houses was built in the Steendijkpolder, situated directly on a 4 m thick layer of harbour sludge.
The investigations on behalf of the Soil Clean-up (interim) Act were started in 1983. The results gave a clear understanding on the soil quality and the characteristics of the specific problem of contaminants in a housing area. Investigations were carried out on soil, air, drinking water, surface water, groundwater and the quality of cultivated crops[12].
For a number of chemicals (arsenic, mineral oil, EOX, chloriated pesticides and polycyclic hydrocarbons) clear relationships could be established with the origin of the sludge and the sludge layer in which it was found. The analytical results of the sludge samples from the upper soil-layer (0 - 0,4 metre) were used to estimate the health risks for the people living on the site.
The specific trends between the analytical results and the origin of the sludge can result in a limitation of the parameter list.

The following parameters are recommended for soil-sample analyses on sludge sites:
- pH
- cadmium, lead, arsenic
- clay- and organic matter content
- screening and identification of organic contaminants (by advanced gaschromatography-mass spectrometric analysis).

Because deposited harbour sludge is not very permeable and chemicals are almost completely adsorbed on sludge or are precipitated, the groundwater quality within the sludge site is relatively normal as compared to the background quality of groundwater.
The following list of parameters are useful for analysis of groundwater:
- cadmium and arsenic;
- fenolic compounds;
- volatile aromatic hydrocarbons;
- mineral oil;
- chlorinated pesticides (drins);
- pH, chloride, sulfate and ammonium.

HOME-GROWN VEGETABLES FROM THE STEENDIJKPOLDER

Ten adresses in the Steendijkpolder were selected for the investigation of the safety of the comsuption of home-grown vegetables. The locations were selected on account of combinations of the highest concentrations of Cd, Pb, Hg and drins. Four vegetables were investigated: radishes, carrots, spinach and endives. All crops were sown and cultivated by the Public Gardens Department.

Table 3: Concentrations Cd and dieldrin in vegetables (min.-max.)

location	radishes		carrots		spinach		endives		soil	
	Cd	dieldrin	Cd	dieldrin	Cd	dieldrin	Cd	dieldrin	Cd	dieldrin
Controls (n=2)	4–5	n.d.	13–14	n.d.	46–56	n.d. < 10	17–19	n.d.	0,14–0,25	< 0,1
Steend. (n=10)	16–28	n.d.–10	n.d.–94	n.d.–40	82[a]–180	n.d.–40	80–600	n.d.	3–14	< 0,1–5

Concentrations in mg/kg d.w. (soil), in µg/kg d.w. (vegetables), dieldrin concentrations in µg/kg f.w.; n.d. = not detected (d.l. < 0,003 ppm, dieldrin < 0,001 ppm); [a] = one sample: n.d.

Table 3 shows the main results, the concentrations of Cd and dieldrin in the four crops. Increased Cd-concentrations were found in the four investigated crops cultivated in the ten gardens in the Steendijkpolder. In three out of ten samples of carrots the combined dieldrin and telodrin concentrations amounted to the residue tolerance of 50 µg/kg fresh weight. This was also the case for one sample of spinach.
This investigation resulted in an advice against the consumption of home-grown vegetables[12,18,19,20].

INTAKE OF CONTAMINANTS BY INGESTION

In the Steendijkpolder two environmental compartments, air and soil, are the prevailing routes of exposure to the contaminants in the harbour sludge[18].
The investigation of the composition of drinking water did not indicate any influence of the soil pollution.
Since the population consumated only occasionally home-grown vegetables, this route of exposure to contaminants was considered very small.

Air

The concentrations of drins and related compounds in the indoor air of the living rooms were used to calculate the intake by inhalation of contaminated air. The toxicity of drins was expressed in dieldrin equivalents.
The calculated daily intake was 4 µg dieldrin equivalent for an adult and 0,2 µg for a child.

Soil

One of the pathways to soil contaminants is the ingestion of contaminated soil, especially by infants (1-4 years) because of their typical hand-mouth behaviour.
A daily average of 200 mg was seen as a reasonable estimate. In table 4 the calculated intake of contaminants by soil ingestion is given[19].
Aldrin, dieldrin, isodrin and telodrin are insecticides with a similar molecular structure and the same effects on the central nervous system. The toxicity of the drins was expressed in dieldrin equivalents. The ADI of dieldrin amounts to 0,1 µg/kg bodyweight, this is at least 100 times lower than the no-effect level in laboratory animals. The calculated maximal daily intake of drins by soil ingestion and the maximal exposure by inhalation of contaminated indoor air together with the median intake by the daily diet exceeded the ADI by roughly three times[19].

Table 4: Calculated intake of contaminants by soil ingestion (in µg)
average dry weight of soil sample: 74,1%

Compound	daily intake med.[a] – max.[a]	compound	daily intake med. – max.
sum PAH	0,77 – 2,48	Cd	1,07 – 2,22
toluene	0,23 – 1,10	Hg	0,44 – 0,83
xylenes	<0,008 – 0,18	Pb	≦85
ethylbenzene	<0,008 – 0,05	Cr	≦45
alkenes	2,0 – 17,6	Ni	≦10
sum drins	0,18 – 2,89	As	≦30

[a] = based on the median and highest concentration found in 71 samples (0-40 cm below g.l.).

ESTIMATION OF CONTAMINATED SEDIMENTS

Results of an inventory by the governmental authorities in 1987 on the pollution of sediments in regional waters in the Netherlands led to the preleminary conclusion that the contamination-level of a great number of locations exceded the signal values for clearance[21].
Especially of concern were the relative high levels of PAH and heavy metals. The estimation stated that about 40% of the dredged material in regional waters exceded these signal values and this demonstrates the urgency for remedial action.
The provincial authorities and the Waterboards in the Province of South-Holland initiated in 1987 an exploratory examination to gain insight into the contamination levels of the sediments of fairways and channels in their province. The investigation concluded that yearly 1 million m^3 of dredged material needed to be handled.
While using the interim sediment quality criteria (1988)[22] it was estimated that only 20-25% of the dredged sludge could be classified in class 1[24].
Till the year 2000 approximately 8 to 9 million m^3 (wet) of contaminated sludge (class 2-4) will have to be deposited on controlled disposal sites.

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CONCLUSIONS

REFLECTIONS AT THE END OF THE THE FIRST CATS-CONGRESS

by G. Thues (Port of Antwerp)
President of the Scientific Committee

A cycle of CATS congresses is scheduled for the following years, covering subjects similar to those of the first edition.

Extensive research is being carried out nowadays, and new techniques are being applied on an industrial scale. Yet official standards and legislation in general do not effectively reflect these developments. Our CATS congress should serve as an aid to authorities in charge of bridging this gap between relevant legislation and scientific advances.

Lawmakers should also be aware of the lack of logic in trying to enforce financial punitive measures on those responsible for the transport and handling of so-called contaminated material, which simply involves moving sediments. They should not forget that the situation is the very result of adhering to legislation enacted in the recent past. If the principle of "the polluter pays" is accepted, then the same logic should be applied to those authorities who permitted these things to happen : they should also pay for the clean-up now that they have clearly changed their mind.

Meanwhile the Scientific Committee is looking forward to the new ideas and developments which will be brought forward during the next congress.

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CONCLUSIONS OF SESSION 1A

PROCESSING TECHNOLOGIES OF DREDGED MATERIALS

Chairman : P. Geuzens (Belgian Nuclear Research Centre)
Secretary : A. Faseur (Duphar nv)

The development of new cleaning techniques for contaminated dredged material (CDM) is still going on. It is mainly switching over from physical techniques (e.g. hydrocyclones) to chemical and biological techniques. The physical techniques remain certainly valuable but are not always applicable and/or adequate. This is certainly true when one is aiming to reconver polluting elements as much as possible instead of only reducing depositing volumes.

For the removal of organic micropollutants, valuable methods become available. Solvent extraction was practically demonstrated with good results.
Biological treatment techniques are very suitable for lighter organic components. Landfarming is the most simple technique. If a shorter residence time is required, or for more refractory components as PCA's or PCB's, aerated basins and bioreactors are promising treatment techniques.
Discussions remain w.r.t. stripping losses, toxic intermediates, the use of non natural micro organisms, rest concentrations of pollutants etc.

With respect to heavy metals developments are less clear and positive. The discussion about necessity of removing metals from CDM remains. Because of low leachability under anoxic conditions, the sense of an extraction treatment is not always evident. Therefore more extensive research about availability and environmental impact of heavy metals in deposited dredged sludge is necessary.
Chemical extraction techniques give poor results compared with terrestrial soils. Availability of heavy metals after extraction treatment could be a problem.
Interesting developments are bio-leaching and the use of high gradient magnets for removing heavy metals from contaminated sludges.

CONCLUSIONS OF SESSION 1B

PROCESSING TECHNOLOGIES OF DREDGED MATERIAL

Chairman : H. De Vlieger (Baggerwerken Decloedt)
Secretary : I. Goemaere (Silt nv)

In the first part, I will summarize and sometimes criticize the content of the papers presented, and in the second part, I will confront you with some essential conclusions, claims and viewpoints stated by the authors.

As opposed to the past, and with everybody's growing concern for environmental damage, the pre- and post dredging technologies become as important as the core technique of dredging itself.

The sessions on processing technologies of dredged materials in fact highlighted that the, at first sight enormously complex CDM-problem (CDM stands for contaminated dredged material) can be broken down into a number of intermediate steps, to each of which there is a scientifically and environmentally sound solution available, with adequate technical equipment to implement them.

1. As the composition, contamination level and environmental behaviour of dredged material varies a lot from place to place, even within the same dredging zone, a <u>profound</u> and <u>detailed</u> preliminary study of the CDM is an absolute necessity.

2. Before kicking off a project, with a reasonable expectation of success, one has to have insight in :
   -- the horizontal and vertical dispersion of contamination in a volume of dredged material,
   as well as,
   - the concentration and mobility of the contaminants in the various fractions of the CDM at hand.

3. The selection of the adequate processing technique needs furthermore an in depth knowledge of the physical characteristics of the dredged material, and I mention grain size, density, dry matter content, void ratio, Atterberg limits, compressibility, etc.

4. In the present dredging industry, having to cope with more stringent international legislations as LDC and OSPARCOM, a lot of research is concentrated on the improvement of existing plant and the development of new, mainly smaller and more sophisticated devices for <u>environmental- friendly</u> excavation of materials.

5. Classically orientated dredging engineers will have to develop an entirely new approach to a CDM dredging project : indeed, not just the <u>productivity</u> but also the <u>quality</u> of the dredging process becomes important.

   a. <u>Ecologically</u>, it is now necessary to dredge with no spillage nor resuspension;

b. Economically, it is of primordial importance to pay more attention than usal to accuracy and selectivity;

c. Technically, we will have to get used to work with smaller outputs per hour, and to dredge at in-situ density of the material.

6. The price to pay for CDM dredging operations will inevitably be a higher one, but thanks to the recent developments in dredging technology, like automatization, visualization for the dredge-master, monitoring of process parameters during the excavation, and dredging at in-situ density, the ultimate price-level can be kept within reasonable limits.

After these observations of a more general nature, I would like to come to the key issue in the decision process in preparing a CDM dredging project, which is THE CHOICE OF THE TREATMENT TECHNOLOGY.

In the key-note speeches and on the posters related to this session, the techniques commented upon were mainly sludge separation technology and dewatering or consolidation technologies.

Let us now compare the presented techniques with the 10 following evaluation criteria in mind :
a. Scientific background;
b. Modelling support;
c. State of the art;
d. Economical feasibility;
e. Compaction degree;
f. Simplicity of process;
g. Separation efficiency;
h. Flexibility;
i. Production capacity;
j. Field operation.

1. In areas where vast quantities of CDM from maintenance dredging projects have to be handled, LARGE SCALE SEPARATION and DEWATERING fields are by far the most indicated technique. Moreover, they are very attractive pricewise.

   The material consolidation and separation behaviour of all types of sludges is theoretically welle documented in literature.

   Computer models have recently been developed to give a support in estimating the dimension of separation fields or dewatering ponds to be used for a specific project.

   Crucial point in the use of models is the extrapolation to the real situation. A very sucessful example to this effect has been given by the DOLSO-project in Antwerp, which was supported by the CONSOL-model developed by SILT, IMDC and the VUB.

   Provided a good estimation of the dimensions, large scale natural separation can easily cope with production rates in the dredging process.

As disadvantages we mention :

the time and space needed for this technique and a lower separation efficiency compared to mechanical techniques.

2. Hydrocyclonage has been used as a sludge separation technique for several years and has has been tested in the field on a large scale. It is an easy and simple technique, and investment costs are relatively low.
   Provided a good design of the dimensions and shape, hydrocyclones have a good separation efficiency, be it based on granulometry or density of the processed materials.
   The capacity of hydrocyclones is quite high. Moreover, hydrocyclones can easily be combined on-line with other treatment processes.

3. The same advantages can be attributed to the FLOTATION-TECHNIQUE, although it hasn't yet been tested as widely as hydrocyclones.

4. Because the use of hydrocyclones & flotation techniques involves the use of large quantities of water, efficient dewatering methods for the upper discharge are important to reduce the fraction to ultimately dispose off.

5. In order to prevent contamination of the surface water by the process water used in separation methodologies, it should be recirculated as much as possible and eventually purified.

Finally, let us however not forget that separation in different flows is not always THE SOLUTION to the problem! This is only the case when the non-contaminated coarse particles form an important percentage of the total CDM-stream to be treated.

As appeared during session 1A, treatment technologies now available to the dredging industy are numerous, and can be grouped into 3 categories :

1. Mechanical treatment technologies like we just discussed.

2. Physico-chemical techniques like extraction and fixation or immobilization.

3. Microbiological treatment technologies for mainly organic contaminants.

It is precisely the job of the Authorities, research laboratories, consultants & contractors to combine these available means to provide a global solution for each specific CDM-problem at any specific location.

A first step towards a combination of methods has been highlighted by Prof. WATSON - I would call that method the FATAL ATTRACTION method - where bacteria fattened with silfides are attracted by powervul magnets. This method combines in this way mechanical and microbiological techniques.

CONCLUSIONS OF SESSION 2

CHARACTERISATION METHODS FOR DREDGED MATERIALS

Chairman : E. van den Eede (Minsitry of Public Works)
Secretary : J. Van Hoof (Ministry of Public Works)

1. As a major conclusion of this session, it can be stated that even though heavy metal cations show a preference for exchange reactions with the finest fractions of dredged material, not all pollutants are found in these fractions.

   In order to make an assessment of the relevancy of separation or other treatment methods, a correct definition of both the particle size distribution and the contamination content of each fraction is necessary.

   The laser diffraction method is a tool for the determination of the particle size distribution, even in the range of the smallest fractions, for which up until now sedimentation methods were the only operational alternatives.

   A complementary method consists of the so called "Fingerprint method", by which information about the distribution of the pollutants in relation to the particle size distribution is acquired. This is done by intensive hydrocyclone treatment, additional gravity separation techniques and subsequent analytical characterisation.

   The combination of the results of this methods allow to decide wether or not separation should be carried out and at what cutpoint. In any case, the provided information proved the whidespread assumption that all pollutants are concentrated in the fraction smaller than 63 micron to be wrong and emphasizes the necessity of a tailor made or case by case approach in the decision process for any treatment.

2. Normally the contamination load of marine sediments is much lower than this of the sediments coming from upstream? Consequently, this proves that for the assessment of the potential ecological impact of dredged material, it is very important to be able to make a distinction between marine and estuarian mud, as it is obvious that the frain size distribution does not allow any conclusion in this matter. The use of methods such as gammadensitymetry, radiography and scanning electron microscopy can be helpfull to make such a distinction.

3. It is generally agreed that total chemical analysis gives no valid basis for the determination of the environmental effects of dredged material as the amounts of heavy metals that are extracted, highly depend on the used decomposition technique and on the way samples are handled and stored. Sequential analysis methods were presented, which are intended to overcome the shortcomings of total analysis.

However, there exists doubt about this method being an improvement for the assessment of ecological impact. First of all, the results seem dependent of the used method.

Next the time factor is not taken into account. So, it is not possible to determine how long it will take the mobile fractions of the contamination to become mobile, although this seems necessary information for the assessment of treatment or disposal options in regard to the existing or planned locations.

4. Biological methods for the characterisation of dredged material and for the assessment of the effects on the environment are highly needed.

CONCLUSIONS OF SESSION 3

DREGDED MATERIALS AND ENVIRONMENTAL IMPACT

Chairman : H.L.F. Saeijs (Rijkswaterstaat, directorate Zeeland)
Secretary : H. Goossen (Betech nv)

RIVER-, LAKE- AND SEABEDS OBJECTS OF CONCERN

In this short report I will focus on two items. I will start with a short report dealing with the contributions today. Than I would like to make an appeal for more attention for the essential functions of river-, lake- and seabeds. Why are we worrying about polluted beds ?

So first the short report. In this session there were two main subjects :

1. The construction of disposal sites and
2. The effects of dumping on the ecosystem

So apparently suspended matter, mud, sediment, or how you will call it, has become a real problem to society. How come ?

Of course, through the ages man has used estuaries and tidal inlets as a transport way and harbour. Shipping channels can silt up and dredging throughout the year is necessary to maintain navigation routes at a sufficient depth. Mr. De Wolf in his lecture has given us a review of dredging and dumping activities used nowadays in the Belgian coastal area. But dredging and dumping as such is a problem we can handle.

The estuarine system has natural trapping characteristics for sediments and nutrients. These lead to a net surplus of imported organic matter, originating from the river, soil drainage and the sea. Innumerous marine and fresh water organisme live and die off in the transition zone between fresh and salt water. No other area has such a variety of life, not even a tropical rainforest.

Again Mr. De Wolf gave us a description of the sedimentology and ecology of the Belgian continental shelf. With our knowledge it must be possible to find a way to manage the sediments, like we did find a way to manage the water itself. Dredging sand and even silt gives opportunities for beneficial use.

The only real problem of course is the severe contamination of sediments with practically the whole range of chemical pollutants associated with the modern industrialised and agriculturally intensive hinterlands, as Mr. Taat stated in his introduction. Why is this a real problem ?
Because nature can not deal with an overflow of pollutants !
It is also a widespread problem because sediments are transported; not only by dredging, but also by tidal action and waves.

Mr. Turkstra in his lecture showed us how transportation and settling of suspended matter and the adsorbed contaminants gives rise to accumulation in bottom sediments in a wide area from the point of discharge. The spatial distribution of cadmium represents the distribution of a wide range of pollutants in the Nort Sea.
Mr. Burt presented a beautiful example with heavy metals as a tracer, how fine material from a disposal site at River Tees is sorted out and transported elsewhere.
Also very nearby we can observe the outcome of transport processes. Preliminary results of research on sediment cores from the "Land van Saefthinge" disclose the pollution history of the Scheldt with respect to PCB's and PAK's. Vertically one can scan the amount of adsorbed pollutants throughout the years. Present concentrations show up to be two to three times lower as in the early sixties. A pleasant message, but they are still much too high!

How to solve this problem ?
Terminate all discharges of pollutants is the one and only real solution of course.
But I am afraid that, at least temporarily, we will have to manage by accident. May be we can learn something from the mussel. Some of you will know that a mussel is a filter-feeder : he pumps water with suspended matter through his gills and sorts out the ingestible organic matter. Then he has to purge the rest of the particles. Therefore he clogs them together and secludes it as pseudo-faeces. Let us treat the contaminated sediment as if it was pseudo-faeces.

Five lectures in this session provided information about building disposal sites.
Mr. De Smedt demonstrated an impressive theoretical model which can be used as a basis for practical solutions and in fact has been used to evaluate the long term effects of the underwater disposal of dredged material under the Doeldok.
The Geuzenhoek project, presented by Mr. Taat, will add a lot of valuable information about performances of different types of barriers. Both authors emphasize the long time scales involved and the need for "fail-safe" design.
Mr. Claeys in his lecture showed us reliable technical solutions for dredging and dumping polluted sediments in an underwater site.
Mr. Tack more or less proves even after land disposal migration of metals to be minimal. In fact, because of similar findings in the Netherlands the authorities allow sediments only polluted with heavy metals to be stored in an open disposal site like the Slufter near Rotterdam.

But technical solutions always are only partial solutions.
Let us assume that Mr. de Haan is right when he says that from the point of view of environmental impact, polluted dredging spoil if preferably stored in deep pits underwater. Let us also assume that the techniques of underwater storage fulfil our ecological demands. Than still we have problems which are familiar to us from the discussions about stocking up nuclear waste. It really must give us bad feeling to solve a problem by burying it. I think we only can do it by doing it only once.

Three years ago the Brundtland Commission set out the goals for the future in their report "Our Common Future". From then on governments around the world stated that their future environmental policy would be based on the concept of sustainable development. That means satisfying the needs of the present generation may not interfere with the needs of future generations. Environmental problems can only be solved and prevented in a situation where the load on the environment is not higher than can be endured without damage in the long term.
As long as you are not sure of the environmental impact, in my opinion standards of lake-, river and sea beds have to be at the safe side. Let's use the precaution principle as it is used for the North Sea. The beds are worth to be protected.
Mr. Turkstra in his model REFEREE uses two submodels : REFOOD and REFECT. I really hope the latter will become unwarranted !

Why do river-, lake- and sea beds bare us concern ? Without healthy beds, no water system can function as it should. The issue is much more important than the prevention and cleaning-up of polluted beds.

It is becoming increasingly evident that polluted beds not only form a serious danger to public health, but also that they stand in the way of the exploitation of the possibilities of water systems.
Water systems with toxic beds are sick. You can compare a water system with a polluted bed, to someone who has been poisoned. No matter how smart or handy the person is, he'll be incapable of functioning correctly. All this functions are at stake. A water system in such a state reacts the same way.
It's a question of survival. After all, if we're willing to accept, that segments of our entire life-support system degenerate or die-off completeley, then we must face the fact that the basis for life is at stake. The question, as to why polluted beds have to be removed, is for me just as important as the question of how we go about it.

What does a healthy river bed imply ?
The first thing one notices is that the river bed is teeming with life, in it, and on it; water plants, bottom creatures, fish and birds. The bed shelters certain species and communities.
In Holland, my country, we don't pause each day to think about it, but a large part of our country we live on, consists of vegetable debries (let's say peat). It has also been for a long timespan the source of our energy, our foodstuff and is still our existence.

Let's take a brief look at the flats and shoals as we come across them in our tidal estuaries. The productivity of this kind of environment can easily surpass that of the best run farm.
This distinction is primarily due to the bottom fauna. And since they are completely free, bottom fauna are our cheapest laborers.

In a healthy functioning tidal system, they ensure that organic material and nutrients wich normally abound there, in an ecologically acceptable manner, are broken down.
Moreover, the billions of larves, which zoobenthos procedure, as plankton are of the utmost importance to the natural equilibrium in the water system above and in the neighboring coastal waters. In this way, they also contribute to the productivity in coastal seas.

In fresh water the processes are identical
Nowadays, in regulatory practice, experiments are being conducted with fresh water mussels, since these by nature are able to withstand copious amounts of nutriments. We call it "active biology"

Bottom fauna has thus an influence on our river beds. In this way they play an essential role in the exchange between bottom and water system.

But beds play also other key roles.
On and in the bottom, we find bacteria and fungi, which are of fundamental importance as reducing agents in the ecological life-cycle. To realize this capability, the other organisms such as worms and shellfish are necessary.

In Lake Grevelingen, in the Netherlands, a man made lake, for instance, in spite of an overabundance of phosphate, it turns out that the water is extremely clear, and highly productive, thanks to the combination of bottom fauna, bacteria and fungi.

Stop to consider what this means to our society ! There is little additional human labor required, only inventiveness. Attention is focussed mainly on a healthy bottom with oxygen-rich water above it.

If we could make use of this process on a large scale in fresh water lakes, the advantages for society would be incredible. A continued overdosis of phosphate which causes no problems in these lakes !

Aside from biological processes, there are also physical and chemical processes going on in river beds. An uninterrupted continuation of these processes is then also of essential importance for the metobolism of the system.

The role which the morphology of the bottom of a water system plays is generally underestimated according to me.

A number of problems in certain Dutch surface waters should, I believe, be able to be solved if the morphology of these systems is improved. And then such that relatively little wind energy causes a good mixing and thereby prevents anaerobic conditions.

The river bed is also the recipient of organic material and silt along with everything adhering to it. In this way, the bed consolidates the sediment and is capable of removing it from the life-cycle in the water column for a long time, and even forever.

Most "fossil fuels" originated on the sea floor when debris wasn't assimilated by bacteria. Our atmosphere, with an abundance of oxygen and relatively little carbon dioxide, came in part, into being due to this consolidation and isolation process. The present climate and biosphere of the earth are the results.

That the many pollutant emissions in surface waters haven't led to the total ruination of the water system, is due, for the most part, to this consolidation feature of the sea bed. It took quite some time before we realized this.

This consolidation feature of the sea bed is, for that matter, also the reason that we have a severe sea bed problem at the moment : polluted and overnourished sea beds. And so we come fill-circle.

I hope that I 've been able to inspire you with my sketch of the most important character traits of the sea bed. It is certainly worthwile to pay more attention to the subject of the sea bed and, especially, to do something about it.

I think you'll now believe me when I say that there's more than only pollution and toxicity involved when dealing with the sea bed.

CONCLUSIONS OF SESSION 4

PROJECT STUDIES AND MANAGEMENT

Chairman : T. Vellinga (Gemeentewerken Rotterdam)
Secretary : W. Rokosch (Rijkswaterstaat, Directorate Noordzee)

Project Studies

Evaluation of the project studies leads to the recommendation that in preparation and execution stages of clean-up and treatment operations it is very important that utmost attention is being paid to :

- Pre-contract survey
- Risc analysis
- Tailor made tendering
- Tailor made monitoring.

Management

Decision and actions should be based on a clear Management Strategy. The following structure is recommended :

Step 1 : Set long term goals for the environment. These should be site-specific and based upon the definition of allowable man-made disturbance.
Undistrubed sites can be used to determine local reference levels.

Step 2: Set up a prevention program. Based on the long environmental goals a plan should be made to reduce and control the sources for contamination.

Step 3 : Develop management plans for the "meantime", source control should eventually lead to a clean environment. Recommended plan features :

* The start should at least be a "stand still principle", meaning, no further increase in contamination.

* Decision making should primarily be based upon the availability of the contaminants for the environment, not simply on total load of contaminant.

* A structured case by case approach, based on environmental impact studies, is prefered above the development of supra-regional classification schemes. Some standardisation however is necessary, in order to obtain equivalent decesionmaking criteria for all cases. On this point it is necessary that the governmental policy is clear.

* Treatment solutions should be chosen in an intelligent matter. Emphasis should be placed on selective cleaning and re-usability instead of total cleaning.

"OSCAT" AWARD

The OSCAT is a distinction awarded by the Scientific Committee for the contribution that impresses most for its original and promising features.

The first OSCAT was presented to Mr. Watson of the University of Southampton at the end of the CATS-congress in Ghent in February 1991, for his paper on "The removal of heavy metals and organic compounds from anaerobic sludges".

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