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influence of civil engineering projects on water quality in deltaic regions

A. J. de Groot* and W. Salomons

* Institute for Soil Fertility, Haren (Gr.)

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Abstract The Dutch coastal region contains the mouths of a number of rivers (Rhine, Meuse, Scheldt) which are polluted to a considerable extent with heavy metals. The pollutants are largely associated with the suspended matter in the water. In the estuaries and lagoons these solids were formerly diluted with relatively uncontaminated marine material and subsequently mainly transported out to sea. Meanwhile, civil engineering projects have resulted in the enclosure of the river mouths (Delta plan) and a lagoon (former Zuyder Sea), as well as in the construction of large harbours (Rotterdam). The creation of fresh water lakes and deep harbours favours the sedimentation of polluted material and restricts discharge out to sea. Furthermore, the longer residence times of the river water in these reservoirs gives rise to an increase in pH and an enhanced adsorption of dissolved pollutants to the sediments. The above-mentioned processes were studied for many years in the relevant areas. The consequences of the enhanced retention of polluted sediments will be discussed with respect to environmental quality.

Influence des travaux de génie civil sur la qualité des eaux dans les régions deltaäques

Résumé. La région côtière des Pays-Bas comporte les estuaires d'un certain nombre de rivières (Rhin, Meuse, Escaut), qui sont le siège d'une pollution considérable par les métaux lourds. Les polluants sont en grande partie associés avec les matières en suspension. Dans le passé, ces suspensions étaient mélangées dans les estuaires et lagunes avec des sédiments marins relativement peu contaminés, puis la majeure partie émigrait dans la mer. Depuis, les gros travaux à la mer eurent pour conséquences la clôture d'eau du bras de mer (plan Delta) et d'une lagune (l'ancien Zuiderzee), ainsi que la construction du très grand port de Rotterdam. La création de lacs d'eau douce et de ports profonds favorise la sédimentation de matières polluantes et diminue leur migration vers la mer. D'autre part, la durée plus longue du séjour des eaux fluviales dans ces réservoirs conduit à une augmentation du pH et de l'adsorption par les sédiments des polluants solubles. Ces processus ont été étudiés durant de nombreuses années dans les régions intéressées. Les auteurs exposent les conséquences de cet accroissement de la rétention des sédiments pollués sur la qualité de l'environnement.

INTRODUCTION

The River Rhine and to a lesser extent the Rivers Meuse and Scheldt transport large quantities of heavy metals to the Dutch coastal area. The River Ems, on the contrary, can be regarded as relatively clean. Upstream in the rivers large proportions of heavy metals are bound to suspended matter. This especially holds for Cr, Pb and Cu. Elements like Zn and Ni, on the other hand, show a preferred occurrence in the dissolved state.

The heavy metal contents of sediments from the Rhine, representative of this river as it enters Dutch territory, are given in Table 1 for the period 1960–1975. From these data it is obvious that the contents of certain metals decreased during this period, while others increased by a considerable extent. The As content decreased considerably, and to a lesser extent this happened with Pb and Zn. The Hg content increased from 1960–1970 and even reached a level of 23 ppm in 1972. Afterwards it decreased to the level of 1960 as a consequence of measures in the relevant industries. There is great concern about the extremely high Cd content, which is steadily increasing.

The bond of the main part of the heavy metals to the suspended matter means that the distribution of these metals in the aquatic environment is largely determined by

TABLE 1. Heavy metal content of Rhine sediments, expressed in ppm at 50 per cent of the fraction less than 16 μm

	1960	1970	1975
Zinc	2420	1850	1910
Copper	290	320	330
Chromium	640	790	820
Lead	530	450	400
Cadmium	14	27	31
Nickel	54	62	81
Mercury	11	15	10
Arsenic	200	140	54

the hydrodynamic behaviour of the suspended matter. Civil engineering projects, such as the enclosure of river mouths and a lagoon, as well as the construction of large and deep harbours, highly influence the sedimentation pattern of this suspended matter and the admixture of this polluted material with less polluted marine sediments.

For a full understanding of the impact of civil engineering activities on water quality, however, investigations on the chemical behaviour of the heavy metals is necessary. Interactions between suspended matter, sediments and interstitial and surface water are important in this respect. The significance of the metals in both solid and dissolved forms for the biota in the aquatic environment is being intensively studied in cooperation with the Netherlands Organisation for Applied Scientific Research (TNO). The latter aspects, however, will only be mentioned aside in this short communication.

DISTRIBUTION OF HEAVY METALS IN SEDIMENTS IN THE DUTCH DELTA

The distribution of heavy metals as components of deposited mud in the Dutch delta is given in Fig.1. The heavy metal content of the deposited materials has been expressed as percentages of the content of the relevant metals in the suspended matter upstream in the Rhine. From this figure it is obvious that the main influence on the heavy metal composition in the delta is the Rhine (for geographical locations see Fig.2, for the relevant literature see de Groot, 1973; de Groot and Allersma, 1975; de Groot *et al.*, 1971, 1976).

The Rhine has a natural outlet to the North Sea via the Rotterdam harbour area (Waalhaven and Europoort), apart from the favoured sedimentation conditions as a consequence of the extension of the harbour areas. Within these areas mixing processes occur between heavily polluted Rhine sediments and less polluted material coming from the North Sea. The mixing processes could be described quantitively by means of the application of stable isotope geochemistry ($^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratios) on several components of the sediments (carbonates, clay minerals and organic matter) (Salomons, 1975; Salomons et al., 1975).

After leaving the Rhine outlets the sediments are mainly transported in a north-easterly direction along the Dutch coast. The Rhine material, mixed with a great deal of marine suspended matter, partly reaches the Dutch Wadden Sea.

The connections of the other Rhine outlets with the open sea are very restricted now, as a consequence of the construction of enclosure dikes. This happened first by enclosing the Zuyder Sea in 1932 so that the River IJssel, a tributary of the Rhine, became the sole source of sediments for Lake IJssel.

Another important mouth of the Rhine was originally the estuary via Hollands Diep and Haringvliet. The Haringvliet was enclosed in 1970 as part of the well-known Delta plan. The same happened with the Grevelingen which was enclosed in 1972.

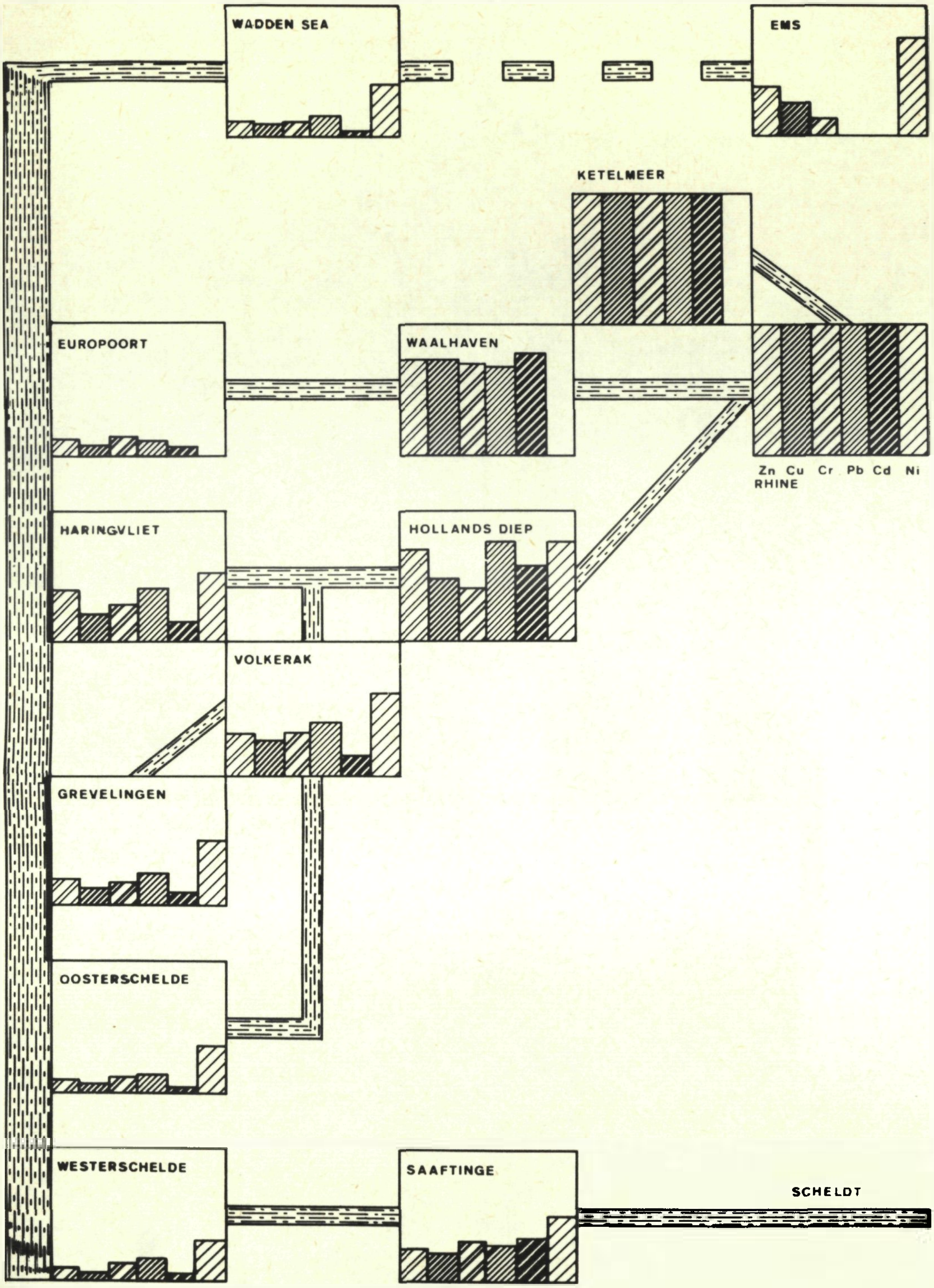

FIGURE 1. Heavy metals in deposits in the Dutch delta (Rhine = 100).

The impact of civil engineering projects on water quality with respect to heavy metals, can now mainly be divided into two categories: the favoured siltation of polluted sediments in harbour basins and the sedimentation of this material in fresh water basins which have been created by building enclosure dikes.

Harbours

Especially in those harbours in the Rotterdam area which are located some distance

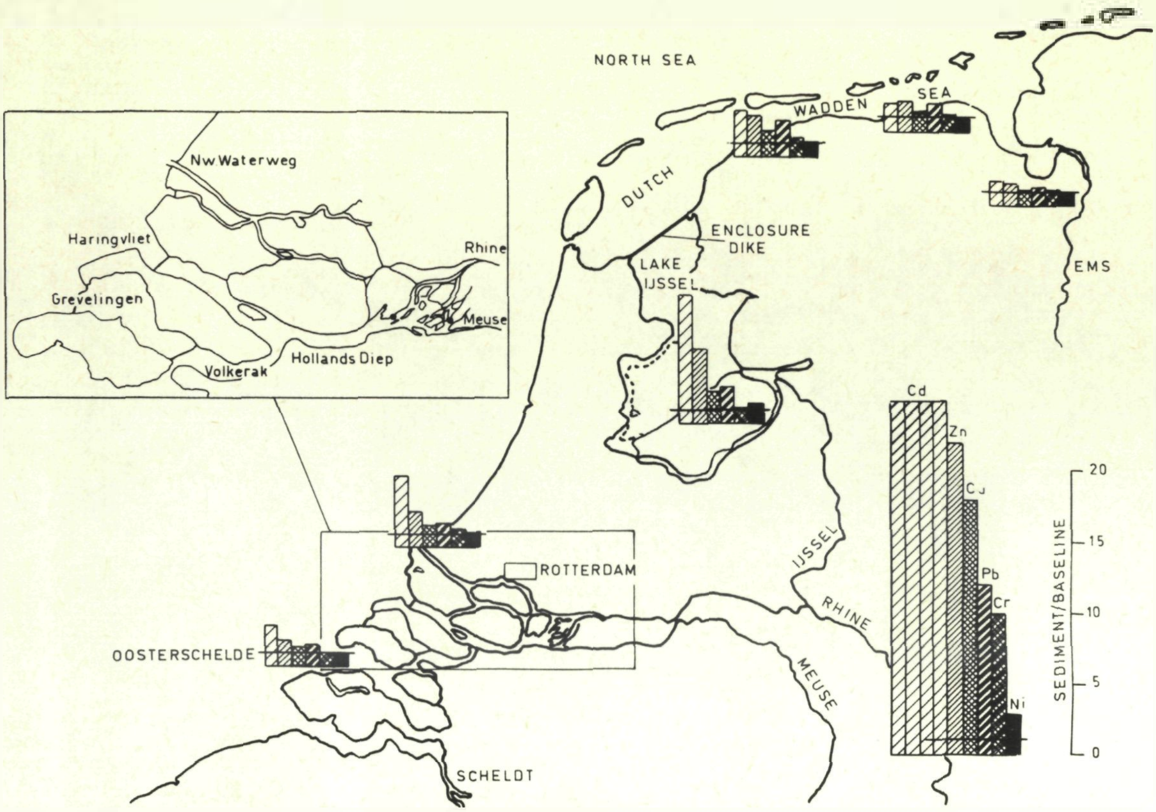

FIGURE 2. Heavy metals in deposits in the Dutch delta relative to base line levels.

upstream of the mouth (e.g. Waalhaven), large quantities of polluted material settle and have to be dredged. From Fig.1 it can be seen that these sediments contain about 70 per cent of the heavy metal content of the comparable upper Rhine deposits. The dredge spoils are either dumped at sea or used for landfilling.

The consequences of the dumping at sea on the local marine environment are being studied. An important point in this respect is the ratio between the velocity of solubilization of metals fixed to the dredge spoils and the velocity of diffusion of the material out of the dumping site.

The dredge spoils distributed on land are generally used for agricultural and horticultural purposes. Especially high amounts of Cd, which are easily taken up by crops, restrict the use of these soils for plant growth and subsequent human consumption of the agricultural products. In this connection research has to be carried out on alternative wet disposal destinations for dredge spoils.

Enclosure dikes

The consequences of enclosure of the Zuyder Sea and the Haringvliet can be seen from Fig.1. The main deposition area of the River IJssel (which carries 11 per cent of the water of the upper Rhine) is now the Ketelmeer (part of Lake IJssel). It is obvious from Fig.1 that the deposits from the Ketelmeer are the same as those of the upper Rhine from the viewpoint of heavy metal pollution. As far as sedimentation does not take place in the Ketelmeer, the suspended matter contributes to the pollution of the larger Lake IJssel.

The enclosure of the Hollands Diep–Haringvliet area has taken place more recently than that of the Zuyder Sea. Nevertheless, it can be seen from Fig.1 that the deposits in the Haringvliet area are now more contaminated than those of Europoort. We calculated that the average metal content of the Haringvliet deposits increased during the

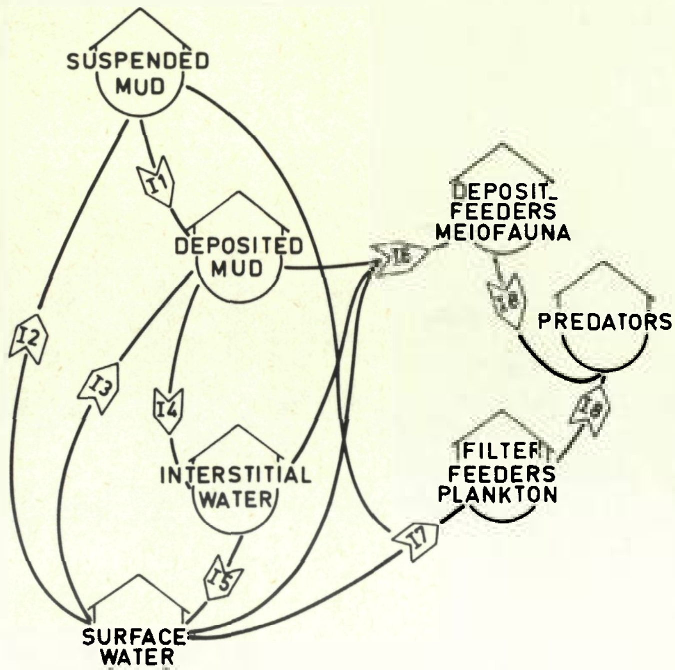

FIGURE 3. Review of the role of heavy metals in an aquatic ecosystem.

I1: Sedimentation, transport, erosion.
I2: Adsorption of metals by suspended matter. Precipitation of dissolved metals.
I3: Reactions between surface water and deposited mud.
I4: Provision of the interstitial water with heavy metals.
I5: Release of metals from the interstitial water to the surface water.
I6, I7: Uptake of metals by organisms.
I8: Accumulation in the food chain.

period 1970–1975 from 37 to 58 per cent, expressed as a percentage of the content of the upper Rhine. It can be expected that the enclosure of this area will give rise to the deposition of more and more contaminated sediments. In the more distant future a situation can be expected, which equals that of the Ketelmeer at present.

A similar effect can be seen in the Grevelingen area, which was enclosed in 1972. This area no longer has an open connection with the Rhine.

The Oosterschelde will only be partially enclosed in the near future. This will lead to an enhanced deposition of sediments. The degree of pollution of these sediments will mainly depend on the situation in the open sea.

Figure 1 clearly shows the influence of the Rhine on the various sedimentation areas. It may be expected that the heavy metal content in near-shore and lake sediments has increased as compared to their natural background values. We have been able to estimate this increase by analysing fluvial, marine and lagoon sediment samples actually collected about 50 years ago. In Fig.2 the composition of present-day sediments is related to a base line, based on these sediment samples. The large increases in the Cd contents are most striking.

DISCUSSION

In the preceding paragraphs much attention has been given to the deposited material. Heavy metals, however, are present in several reservoirs of an ecosystem. A survey of these reservoirs and their interactions has been given in Fig.3. In order to predict the impact of civil engineering projects on the aquatic environment, all these reservoirs together with their interactions must be taken into account. Much of our present work is focused on the study of this system.

As abiotic reservoirs the deposited mud, the interstitial water, the suspended material and the surface water can be distinguished. Under reduced conditions the deposited material can provide the interstitial water with rather high concentrations of heavy metals and nutrients. Especially high concentrations of Cu and Zn, P, ammonia and Si have been observed in the interstitial waters of marine and fluvial deposits. These high concentrations of heavy metals (and some nutrients) may influence the composition of surface waters. Through processes of diffusion, consolidation, erosion and bioturbation the heavy metals and nutrients present in the interstitial waters may be released to the overlying waters. The influence of erosion processes on the composition of surface waters has been demonstrated convincingly in the Wadden Sea (Duinker *et al.*, 1974). Apart from these physical processes biologically mediated reactions occur in the sediments, by which heavy metals are transformed into more toxic organometallic compounds (methylating processes).

In polluted rivers there is not always an equilibrium between the metals dissolved in the water and those bound to the suspended matter. The long residence time of the river water in a reservoir like Lake IJssel may favour the fixation of some metals to the suspended matter and subsequently give rise to more polluted sediments, as a consequence of sedimentation. We observed in this respect a drastic decrease in the concentrations of dissolved Zn and Cd from the IJssel mouth to the enclosure dike. Laboratory experiments showed that this increased adsorption is primarily caused by an increase of the pH. The pH of surface water is controlled by reactions occurring in the system $CO_2-HCO_3^--CO_3^{2-}$. Detailed laboratory and field studies are in progress to quantify these reactions (e.g. loss of carbon dioxide to the atmosphere, uptake of carbon dioxide by algal growth and carbonate precipitation).

The contributions of the four abiotic reservoirs to the heavy metal burden of organisms depend on their way of life. In Fig.3 some biotic reservoirs have been presented, as they are investigated by the Central Laboratory TNO (Hueck, 1975).

As a representative organism for the water phase (surface water and suspended matter) e.g. the mussel (*Mytilus edulis*) is used in both laboratory and field experiments. As deposit feeders certain worms (e.g. *Arenicola marina*) can be used. Under fresh water conditions similar organisms are available. These studies have proved that organisms which accumulate heavy metals are very useful for the characterization of the significance of heavy metals in the aquatic environment.

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p.o. box 177 delft the netherlands