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COMPOSITION, TRANSPORT AND ORIGIN OF SEDIMENTS IN THE SCHELDE ESTUARY[1)]

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ABSTRACT

Wartel, S. (1977). Composition, transport and origin of sediments in the Schelde estuary. Geol. Mijnbouw, 56, p. 219-233.

The grain-size characteristics (grain-size distribution, comparison of one percent value (C) of a given grain-size distribution with the median value (M) in so-called CM-patterns, silt/clay ratio's) of the Schelde estuary are distributed in relation to the existence of a turbidity maximum. Fine sand, silt and clay are deposited, while fluid mud occurs.

Towards the North Sea, as well as in an upstream direction, the sediments become much coarser. Silt, clay and part of the sand are derived from the river drainage basin. Sands are also brought into the estuary from the North Sea. Flocculation is important as a depositional agent. However, deflocculation in a seawards direction, favouring seawards transport of silt and clay particles, is assumed. Movement of fluid mud deposits in relation to river discharge has not been observed. This can be explained by narrowing of the channel and the corresponding increase in stream power, where the river crosses the Boom clay (Oligiocene).

INTRODUCTION

The estuary of the Schelde river (Fig. 1) is a well mixed to partially mixed coastal plain estuary (Pritchard, 1967) with a fluvio-marine equilibrium zone, which varies in position with river discharge (de Pauw & Peters, 1973; Wartel, 1973b). The upper edge of salt penetration reaches upstream to Temse during periods of low river discharge (20 m^3/s at Schelle) and only to Bath during periods of high river discharge (600 m^3/s at Schelle).

The bottom sediments of the main river channel between Temse and Bath consist of sand, mud (Bastin, 1974) and fluid mud (a very loose silt and clay rich (up to 90%) sediment with a bulk density lower than 1,2) (Wartel, 1974) as observed in other estuaries (e.g. Allen, 1973). Suspended sediment concentrations are also highest in this area indicating that it has the maximum turbidity of the estuary (Wartel, 1973a, 1974). The annual sediment supply, as calculated from hydrographical data of some tributaries of the Schelde, is approximately 1 million tons a year (Tison, 1958; Gilles & Lorent, 1966; Wirix & Lorent, 1966), although some authors (e.g. Wollast, 1972) give higher supply rates (2.2 million tons a year). However no data of the sediment supply from the North Sea or the behaviour of the equilibrium between both sources or the differences in sediment type between them are available.

This study aims to contribute some answers to these problems of sediment composition, origin and transport on the basis of a series of investigations made in the estuary between 1967 and 1971.

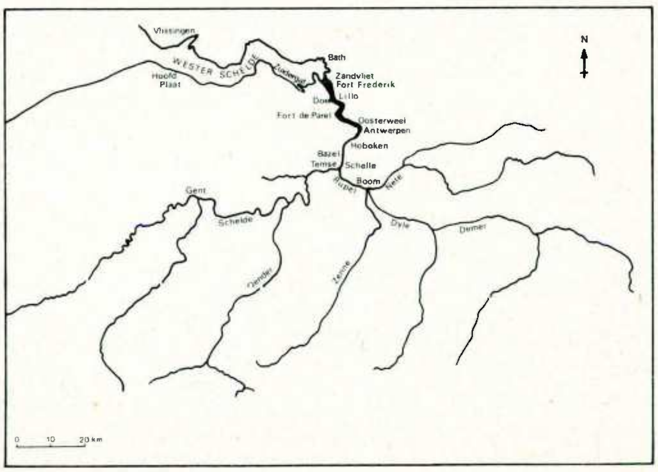

Fig. 1
The Schelde basin.

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METHODS

Field sampling

Bottom sediments from tidal flats were accurately sampled by scraping off the uppermost layer (a few millimeters thick) with a knife. Bottom sediments from the main river channel were sampled using a "SHIPEK"-bottom sampler. Suspended sediments from the tidal flats were collected using siphon samplers (Jakobsen, 1961). Suspended sediments from the main river channel were sampled by pumping water from a given depth and concentrating all the suspended particles with a continuous separator for a period of 15 to 30 minutes, depending on the depth and suspension concentration.

Analytical procedures

Grain size analyses were performed on 20 g of dry sample (dried at 105°C). Salts, organic compounds and carbonates were previously eliminated with a H_2O_2 solution (volume ratio technical H_2O_2 (100 vol.) : H_2O = 1 : 2) and HCl 1N. The sample was suspended by adding 500 ml of distilled water and 50 ml of a solution of 8.93 g of Na-oxalate and 1.33 g of Na-carbonate in 1000 ml of distilled water. The suspended sample was then poured on a 5 φ sieve. The finer particles (< 5 φ) were analysed for their grain-size composition using a sedimentation technique (Gullentops, 1966) and the coarser particles by dry sieving using A.S.T.M. sieves with a $\frac{1}{4}$ φ interval.

The main sediment parameters used in this study are given in table 1. They are based on formulae given by Inman (1952). The classes of sorting used in this study are given in Folk & Ward (1957).

The amount of carbonate was determined using a SCHEIBLER-DIETRICH calcimeter. The CO_2-volume, liberated by reaction of concentrated HCl on 2 g of sample, was gasometrically measured and converted to weight percent $CaCO_3$.

The amount of organic matter in 1 g of sample was determined. The organic matter was oxidized using 1 N potassium dichromate in the presence of concentrated H_2SO_4. The excess of potassium dichromate was titrated with ferrous sulfate in the presence of diphenylamine (Walkley & Black, 1934).

SUBSTRATUM

The geological substratum of the estuary consists essentially of Oligocene to Pliocene and Quaternary sands, clayey sands and clays, covered by a 2 m thick Holocene peat layer overlain by clays (Dunkerque transgressions).

One feature of major importance for this study is the presence of a very cohesive clay layer (Rupelian, Oligocene) crossed by the estuary between Schelle and Hoboken. During its formation (Quaternary) the Schelde valley was incised into this clay layer, forming a straight, rather narrow channel. On top of the clay a continuous Quaternary gravel deposit occurs (Paepe & van Hoorne, 1967; Beeckmans & Verbruggen, 1974).

HYDROGRAPHICAL CHARACTERISTICS

The estuary of the Schelde extends from Gent to Vlissingen (Flushing). The average tidal differences are 3.8 m at Vlissingen, 5 m at Antwerpen (Antwerp) and 2 m at Gent, where the tide is stopped by a sluice. The discharge from the river basin depends essentially on the rainfall (Wirix & Lorent, 1966; Gillis & Lorent, 1966; Peelen, 1967).

The average total fresh water discharge at Schelle is 88,70 m^3/s (Valcke *et al.*, 1966). Daily values vary from a few m^3/s to 600 m^3/s. These values are small compared to the flood discharge at the same place (2,590 m^3/s). During periods of high runoff the river discharge is twice as high for the Rupel branch as for the Schelde. This results from the fact that the Schelde waters are impounded in Gent to feed several artificial canals.

The salt water, which enters the estuary at Vlissingen, is mixed with fresh water further inland. Mixing increases in a downstream direction (de Pauw & Peeters, 1973). This can be explained by an increase in the complexity of the channel morphology and associated water flow pattern (Codde, 1958) and by the fact that an increase of water flow from the river basin produces a more pronounced salinity stratification. However, vertical salinity stratification is always very low (it never exceeds 0.25 g Cl^-/l/m) and only occurs over short periods of the tide (mostly during slack

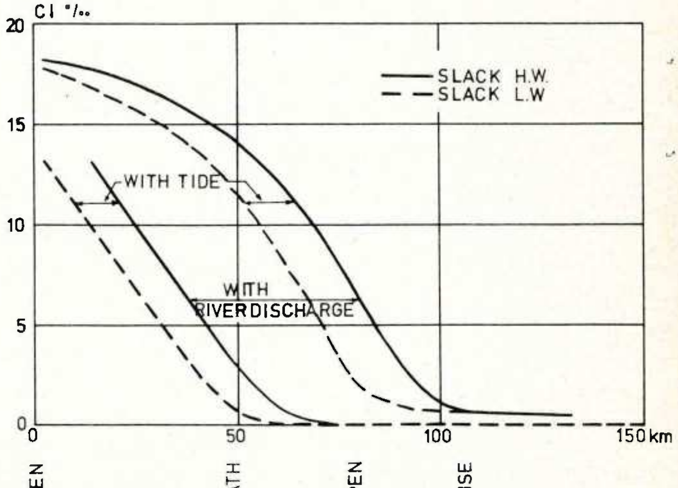


Fig. 2
Salinity variation in the estuary (after de Pauw & Peters, 1973).

high water). During periods of low river discharge (20 m^3/s) a measurable amount of sea salt (1 $^0/_{00}$ Cl^-/l) is present as far upstream as Temse (Fig. 2) and the partially mixed zone extends from Temse to Bath.

When river discharge increases to 250 m^3/s the partially mixed zone shifts in a downstream direction with a maximum downstream position between Bath and Vlissingen. In this case there is no measurable sea salt (less than 1 $^0/_{00}$ Cl^-/l) upstream of Zandvliet (W a r t e l, 1973b).

The average current velocities (V a l c k e *et al.*, 1966) are highest at Schelle (1.20 m/s during ebb and 1.40 m/s during flood) and diminish both upstream and downstream. Near Bath they are lowest (0.86 m/s during ebb and 0.73 m/s during flood) and increase again towards the North Sea.

Shear velocities (which can be defined as the velocity of the water close to the bottom) ranging from 3 to 12 cm/s have been calculated (W a r t e l, 1973a).

SUSPENDED SEDIMENT CONCENTRATIONS

During the period 1967 – 1969 a large number of suspended sediment concentration measurements were made in the area between Schelle and Bath (W a r t e l, 1972, 1973b). The concentration of suspended sediment attains its maximum between Antwerpen and Zandvliet. During ebb as well as during flood the maximum observed values attain several g/l (concentrations up to 5 g/l were measured) near the bottom and 250 mg/l near the water surface.

The lowest concentrations (less than 250 mg/l near the bottom) occur downstream of Zandvliet as far as the North Sea. Sediment concentration is lowest during high and low water stages at Antwerpen, with a minimum at the time of high water (500 mg/l near the bottom). This difference can be explained by tidal asymmetry (periods of low current velocity, during which the sediment settles out, are longer at high water than at low water), as seen from current velocity measurements in V a l c k e *et al.* (1966). The same phenomenon has also been observed by P o s t m a (1961) in the Dutch Wadden Sea.

The evolution of suspended sediment concentration with tide is shown for three stations: 1) near the upstream end of the turbidity maximum (Hoboken); 2) in the turbidity maximum (Oosterweel); and 3) near the downstream end (Zandvliet) (Fig. 3).

Within the turbidity maximum a pronounced turbidity gradient occurs over the whole water column. But, near the upstream and downstream boundaries of the turbidity maximum, turbidities are homogeneous and low in the upper parts of the water column and a pronounced gradient only occurs in the lowest 10% of it. This is believed to be due to high saltation and bottom transport in the outer areas and increased suspension transport due to resuspension of bottom sediments by tidal scour in the central part of the turbidity maximum. Scour and settling lag (v a n S t r a a t e n & K u e n e n, 1957; P o s t m a, 1961) play an important role, since a decrease in mean velocity exists towards the turbidity maximum.

MINERALOGICAL COMPOSITION

Silt and clay fractions

The mineralogical composition of the silt and clay fractions has been studied by d e l l a F a i l l e (1961) and W o l l a s t *et al.* (1967-1971). The major constituents are quartz, clay minerals and carbonates. The quartz content is lower in the clay fraction ($< 9\,\varphi$) (50%) than in the silt fraction ($9\,\varphi$ to $4\,\varphi$) (66 to 71%) and also lower in the bottom sediments than in the suspended sediments (d e l l a F a i l l e, 1961). The clay minerals consist essentially of illite, kaolinite (disoriented), montmorillonite and interlayered minerals. The carbonates consist of calcite, aragonite and dolomite (W o l l a s t *et al.* 1967 – 1971; L a u r e n t, 1969). Iron is present as sulphides, amorphous oxides and hydroxides (L a u r e n t, 1969) and as traces of siderite (W o l l a s t *et al.*, 1967 – 1971).

Sand fraction

The sand fraction ($4\,\varphi$ to $-1\,\varphi$) consists of quartz, feldspars, mica, glauconite, calcite, silex fragments and heavy minerals. Quarts is the main constituent (70 – 80%). The amount of glauconite depends on the erosion of underlying Tertiary deposits (W a r t e l, 1972). The heavy-mineral content only occasionally exceeds 2% of the total fraction. Zircon (15%), garnet (15 to 20%), epidote (26 to 29%) and amphiboles (16 to 17%) predominate.

Very coarse sands and gravels

The coarsest particles consist mainly of artifical waste products. 56% are brick-bats, coal fragments, iron slags... etc, 20% chalcedony, 7% quartz, 1% sandstones and 16% shell grit. With the exception of the shell grit (platey grains) most of these particles are angular to rounded. The chalcedony as well as the quartz gravels are derived from the gravel layer occurring on top of the Boom clay. Chalcedony only occurs downstream of Schelle, which is an indication for the resultant downstream transport of gravels in this area.

GRAIN-SIZE CHARACTERISTICS

Bottom sediments upstream of Schelle

Very little data were known concerning the bottom sediments upstream of Schelle (T i s o n, 1958). Data have now become available for many localities. The main channel sediments of the Schelde between Temse and Schelle consist of more or less homogeneous, well sorted medium to coarse

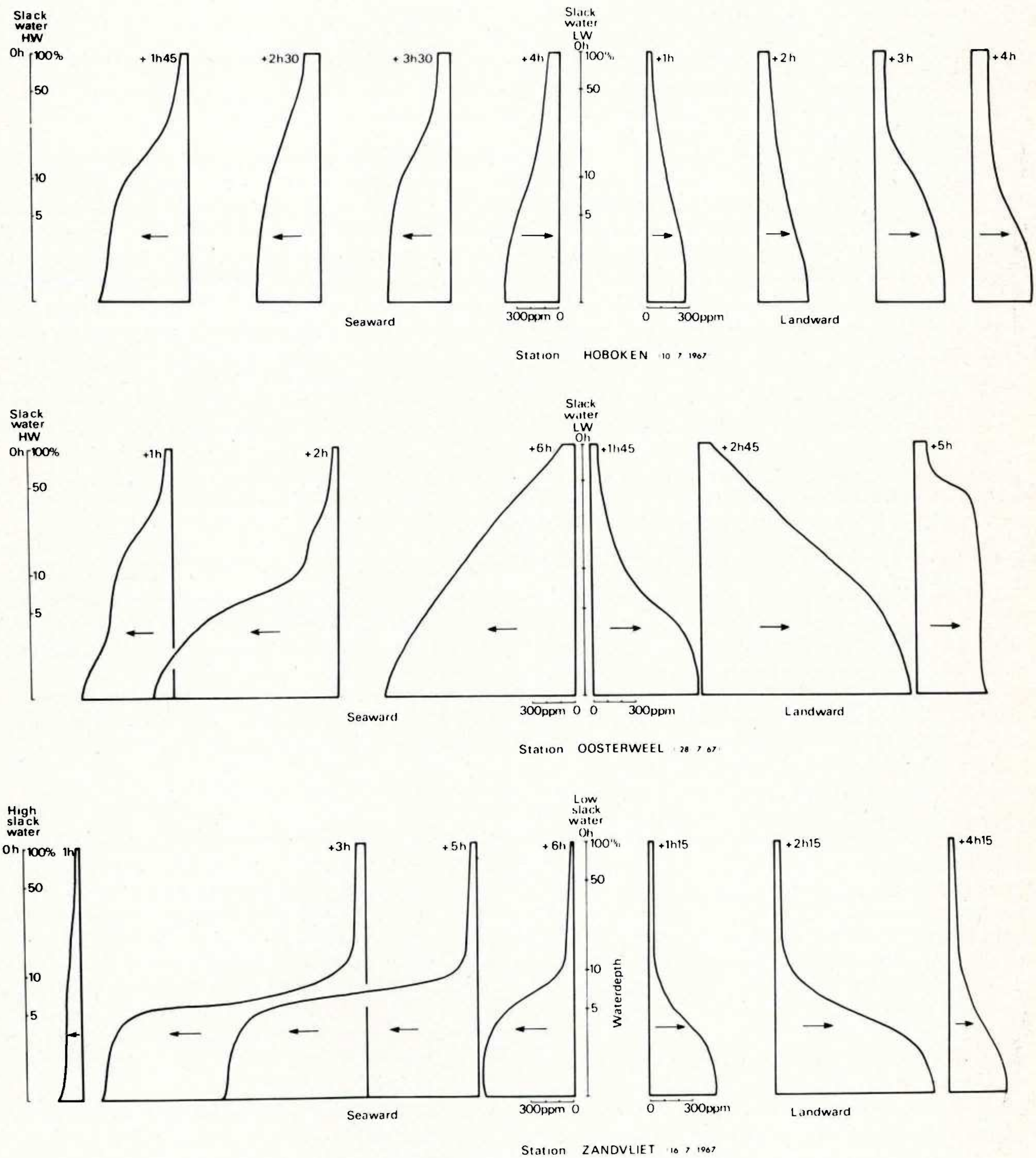


Fig. 3
Vertical variation of suspended sediment with tide for three stations:
a) upstream of the turbidity maximum (Hoboken),
b) in the turbidity maximum (Oosterweel)
c) downstream of the turbidity maximum (Zandvliet).

sands (Fig. 4). Median diameters range between 2.25 φ and 1.74 φ.

At the extremity of the coarse grain size a small tail occurs, which is separated from the better sorted middle part of the grain-size distribution by a break or truncation point near 1 φ. Since only a thin sediment layer was sampled one can accept that these tails represent particles transported by rolling along the bed (M o s s, 1962, 1963; V i s h e r, 1969). This rolling population never exceeds 4% of the total grain-size distribution for the sediments considered. A second truncation point occurs in the sieve fractions smaller than 3 φ. It separates the better sorted middle part of the grain-size distribution curve from a flat tail extending towards the clay sized fractions. The better sorted middle part of the grain-size distribution curve can be considered to represent a population of particles transported mainly by saltation. 87 to 90% of the sediment belongs to this population. The flat tail in the finest fractions represents a population of particles transported in suspension and, in the area considered here, never exceeds 10%.

The bottom sediments of the Rupel river reflect a different sedimentation pattern. The same homogeneous coarse sediment as in the Schelde occurs near the Rupel mouth (Fig. 4), but in addition finer silt and clay-rich sediments (median diameter between 4.64 φ and 3.32 φ) composed of 30 to 50% saltating grains (well sorted middle part of distribution curve) and up to 70% suspended particles (tail in the finer fractions of the distribution curve) occur.

This indicates that the sediment supply along the Schelde branch consists mainly of saltating and rolling sand particles, while finer suspended particles are, to a large degree, derived from the Rupel branch. One of the reasons for this observed difference in sedimentation is the higher discharge and hence a higher supply of suspended sediments during periods of high runoff along the Rupel branch. Another explanation must be sought for in an important sedimentation upstream of Gent (T i s o n, 1958), caused by the damming up of the entering tide.

Bottom sediments between Schelle and Antwerpen

The bottom sediments of the main channel between Schelle and Antwerpen consist mainly of medium and coarse sands and at some places of gravels. The coarsest sediments (gravels up to -6 φ) occur between Schelle and Bazel. They form a thin layer (from a few centimeters up to several decimeters in thickness) on top of the eroded Boom clay (Rupelian). At some places this clay has no sediment cover at all. Next to these gravels very coarse sands occur (Fig. 4). Rolling particles are very abundant in these deposits (X 23) and may even represent as much as 50% with 47% saltating and 3% suspended particles. The suspended particles are sometimes absent. The saltation population is here very coarse (0 to 1 φ). Downstream particles of this size are observed as rolling grains and they form only less than 5% (M8, Fig. 4), which indicates a decrease in transporting competency. Downstream of Bazel the rolling population disappears almost completely (M 11, Fig. 4). In this area the sediments are also finer (median diameters between 2.32 and 3.32 φ) than upstream of Schelle.

In summary all grain-size characteristics of bottom sediments from the main channel indicate clearly a maximum transport competency near Schelle and a decrease of it in upstream and downstream directions.

Bottom sediments between Antwerpen and Zandvliet

Grain-size data from bottom sediments from the main channel between Antwerpen and Zandvliet corroborate the already mentioned downstream decrease in transport competency.

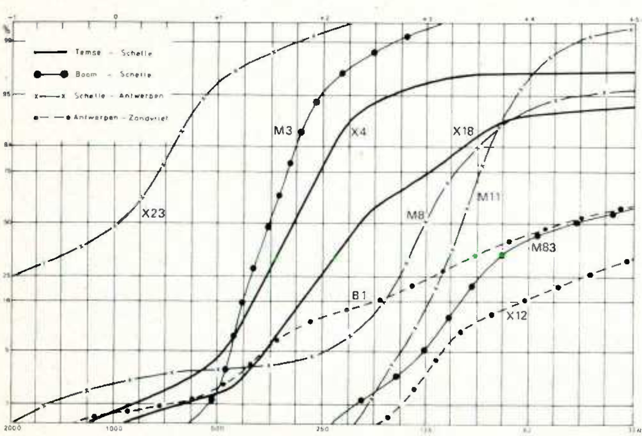


Fig. 4
Grain-size distribution of bottom sediments upstream of Zandvliet. Only the extreme grain-size distribution curves for each area considered are represented.

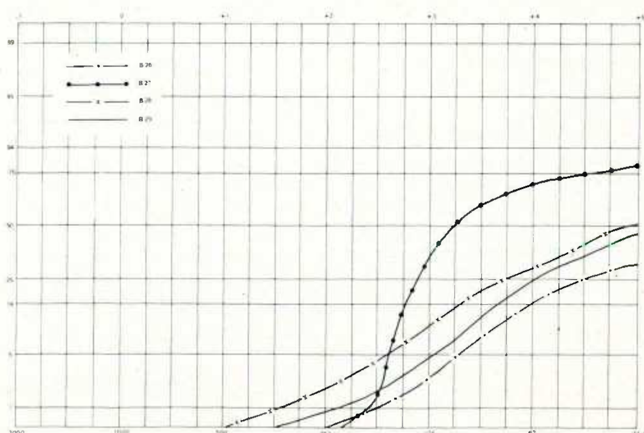


Fig. 5
Grain-size distribution of mud deposits between Antwerpen and Zandvliet.

The bottom sediments in this area consist of sands, sandy muds and muds. The sands are medium to fine with median diameters between 2.32 and 2.73 φ (Fig. 4 and B27 in Fig. 5). The rolling population, where present, seldom exceeds 1% and begins at 2.51 φ. The saltation population (mostly 30 to 50% of the grain size distribution) occurs between 2 and 3.48 φ. The suspension population (below 3.32 φ) occupies 50 to 60% of the grain size distribution.

An important part of the bottom of the main channel is occupied by silt and clay rich sediments (muds and fluid muds) with 60 to 85% particles smaller than 4φ (Fig. 5; see also Antwerpse Zeediensten, 1960; Bastin, 1974). The sediments are very poorly sorted, contain 20 to 30% clay and show no marked inflection or truncation points in the distribution curve.

At some places between Fort De Parel and Zandvliet fluid mud occurs (Migniot, 1968) in layers with thicknesses of 20 to 30 cm (Wartel, 1974).

Bottom sediments between Zandvliet and Vlissingen

Downstream of Zandvliet the N-S orientation of the Schelde changes abruptly to an E-W orientation and the width of the channel and the wetted section increase. The morphology of the channel changes into a complex system of sandbars and tidal gullies.

The bottom sediments consist mainly of medium to coarse sands (Fig. 6) with only exceptional mud deposits. The median diameters are always coarser than 3.84 φ and finer than 1.32 φ. A rolling population is often present and may even represent 30% of the grain size distribution. The saltation population represents 55% to 90% of the grain size distribution and the suspension population 10% or less.

Gravelly sediments consisting of bricks, sandstones, large shells and shell fragments occur at Zuidergat (Fig. 1).

Tidal flat sediments

Surface sediments from the tidal flat were sampled at 12 locations between Schelle and Bath. Grain size analyses of these samples showed no difference between the sampling locations. The sediments (Fig. 7) range from homogeneous well to very well sorted medium sand (median diameters between 3.32 and 2.74 φ) to heterogeneous extremely poorly sorted clayey silts (median diameter $< 4.06\ \varphi$). Particles coarser than 2 φ are generally lacking. There is an increase in silt and clay content from the low water level (less than 5% to 10% $< 4\ \varphi$) to the salt marshes (more than 50% $< 4\ \varphi$). The sand content generally increases near the salt-marsh cliff due to erosion. The coarser particles are concentrated at the foot of the cliff, while the finer ones are resuspended and transported laterally landwards or to the main channel (Verger, 1968). Erosion of the salt marsh cliff is mostly a consequence of wave action produced either by stormy winds or by boats. During stormy periods a considerably higher supply of sand is observed on the tidal flat and after longer periods of storms the whole tidal flat is covered with sand (Bw 68-1, Fig. 7). The grain-size-distribution curves show the absence of a rolling population (when present, it occurs near the low water level and is always less than 5%). The sandy sediments consist of a saltation population separated by a distinct bend (located in the 3.32 φ range for the more sandy sediments and moving towards the finer fractions for silt and clay rich sediments) from a suspension population. The change in this bend with increasing clay content is accompanied by a decrease in the value of the coarsest particles present in the sample.

The sedimentation pattern on the tidal flats shows a regular decrease in grain size towards the salt marsh. This can be explained by a winnowing of the finest particles on the lower tidal flat during rising water level and transport towards the higher tidal flats. When the whole tidal flat is submerged settling and scour lag phenomena also explain the increasing clay content towards the salt marsh.

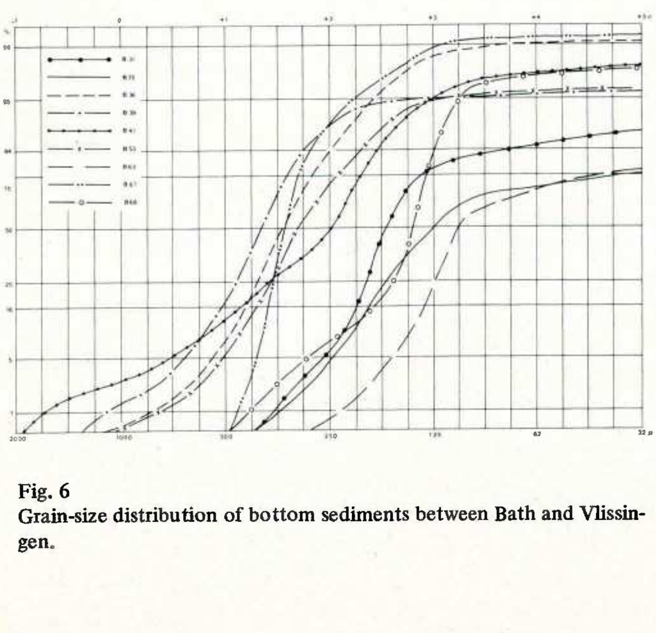


Fig. 6
Grain-size distribution of bottom sediments between Bath and Vlissingen.

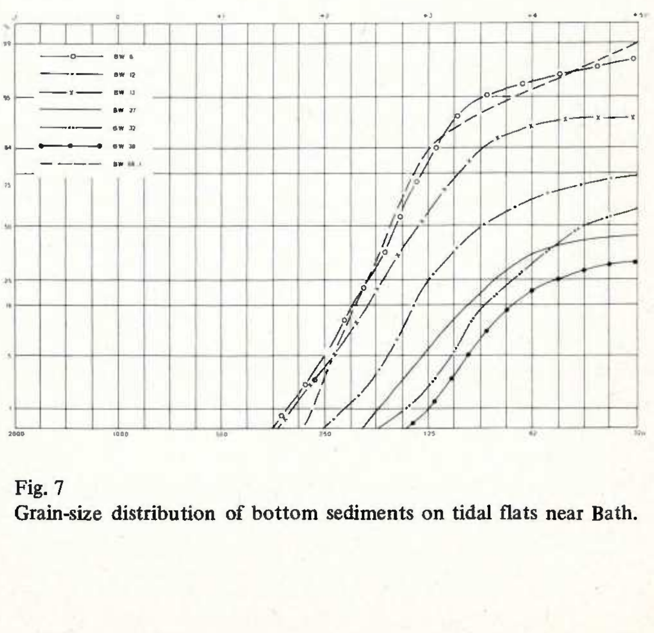


Fig. 7
Grain-size distribution of bottom sediments on tidal flats near Bath.

Suspended sediments

More than 100 samples from suspended sediments taken between Schelle and Bath have been analysed. 30 to 40% of the suspended matter consists of organic matter, carbonates and iron colloïds which will not be considered here.

Della Faille (1961) showed that the sand content upstream of Schelle (Fig. 8) varies with the total suspended matter concentration from less than 20% sand (for a concentration of 120 mg/l) to more than 40% (for a concentration of 220 mg/l). Also some tributaries of the Schelde (e.g. the Dender) have a systematically higher sand supply than others. The grain-size distribution of the suspended sediments between Schelle and Bath is represented in Fig. 9. The curves do not represent individual results but have been grouped according to the sampling localities and depth below water level. Only the extreme grain-size distributions are represented, whereas other samples from the same locality and depth lie within these extremes and have approximately the same shape. Comparison of Fig. 9 A to 9 D clearly demonstrates the differences between localities and depths. Suspended sediments in the lowest water layers (1 m off the bottom) have a well developed saltation population (as much as 70% of the total grain size distribution) upstream of Antwerpen (Fig. 9 B, samples analysed by D. I. A. H., 1965), between Fort Frederik and Zandvliet (Fig. 9 A) and between Zandvliet and Bath (Fig. 9 A). Between Antwerpen and Fort De Parel the saltation population is almost absent. In this area the truncation point, separating the saltation and suspension populations, does not move towards finer fractions with increasing silt and clay content, as observed on the tidal flats, but remains constantly in the 3.32 φ range.

For all localities the saltation population disappears gradually towards the water surface.

The data indicate that saltation transport occurs at both sides of the turbidity maximum, diminishing to the centre of

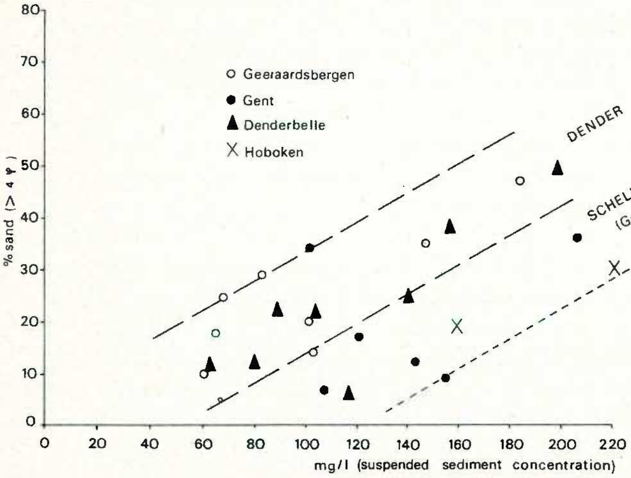


Fig. 8
Sand content of suspended sediments upstream of Schelle (della Faille, 1961).

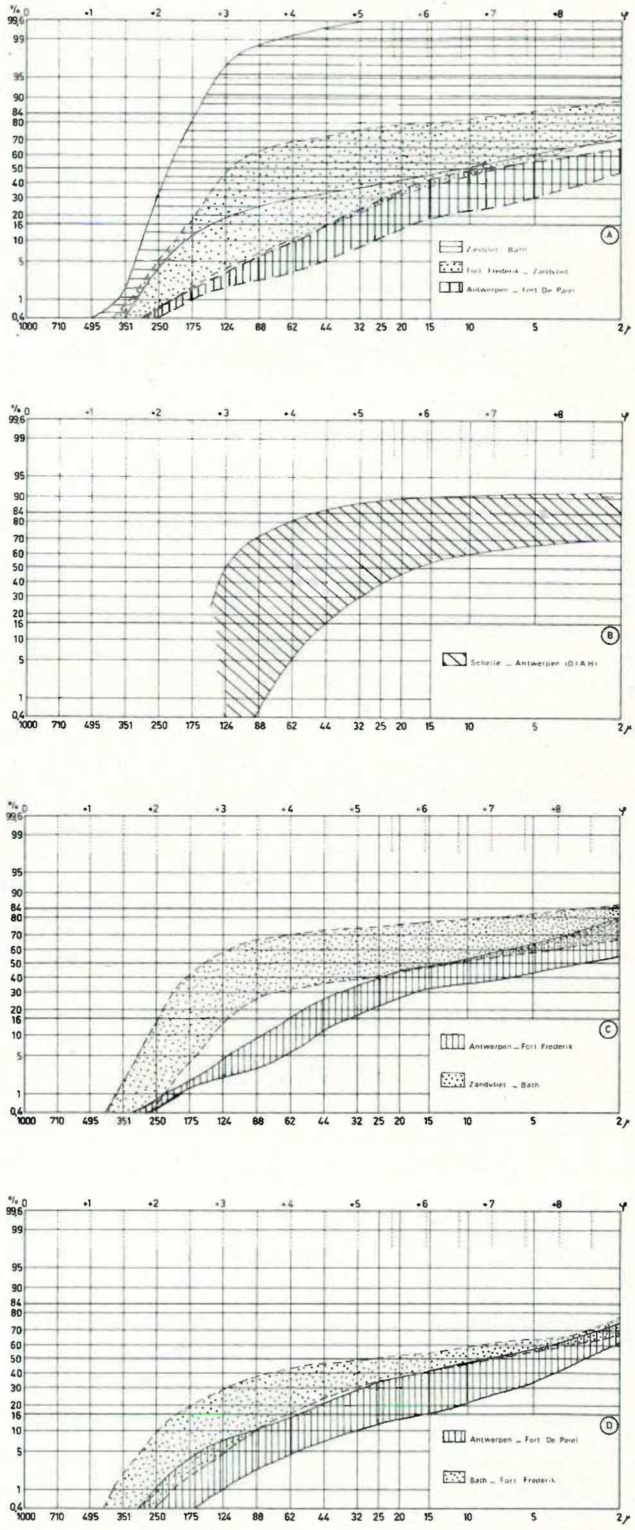


Fig. 9
Grain-size distribution of suspended sediments from the main channel.
Each field represents a group of curves belonging to the same depth below water surface and the same area.

the turbidity maximum where transport of suspended silt and clay predominates. It seems likely that saltating grains, which sink to the bottom at each turn of the tide, are trapped in the muddy bottom sediment and are removed only when fixed to smaller or larger flocules (with settling velocities corresponding to quartz grains with diameters between 7 and 7.5 φ (as shown by unpublished experiments made by the author) which form in this area (B e r t h o i s, 1961; W u n d e r l i c h, 1969).

Grain-size distributions of suspended sediments on the tidal flat (0.5 to 1.0 m off the bottom) correspond to those of suspended sediments from the surface waters in the main channel.

The samples (Fig. 10) taken with a siphon sampler at the tidal flat near Bath show good agreement with grain size data from suspended sediments taken near the surface in the main channel between Fort Frederik and Bath. Samples mk1 to mk14, taken near the low water level, contain much more sand (7 to 37%) than samples nk1 to nk8 (1 to 5%) taken at the midpoint of the tidal flat. The sand content also varies with the weather conditions. Samples taken during periods of prevailing strong winds (mk6 to mk11, sampled between October and February 1969) contain more sand (13-35%)

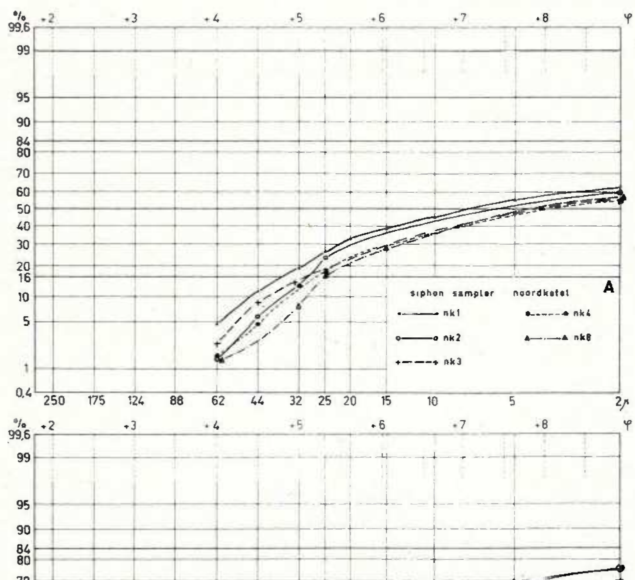


Fig. 10
Grain-size distribution of suspended sediments on tidal flats.
Samples "mk" where taken near the low water line and samples "nk" at midway between high and low water line.

than samples taken during periods of calm weather (mk1 and mk2 sampled in April and May 1968 and mk14 sampled in May 1969 with only 7 to 17% sand). During the sampling periods the sand content did not change very much at station nk. Nevertheless sampling after a long period of stormy weather indicated a high sand supply even near the salt marsh cliff (up to 60% particles $> 4\ \varphi$). The suspended sediment on the tidal flat never contains particles coarser than 2 φ, which is in perfect agreement with analysis of the bottom sediments.

Silt/clay ratios

Since the grain-size-distribution curves, plotted on log-probability paper, do not show much variation in silt and clay ranges (represented by nearly horizontal curves), another method (silt-ratios after F a v e j e e, 1960) was followed. For this purpose the ratio of each cumulative fraction below 4 φ (P_n) to the percentage of particles $< 9\ \varphi$ (P_2) was calculated and represented by curves as shown in Fig. 11.

Two different types of curves can be distinguished. The first type shows curves which are almost parallel with a small and regular increase in the silt ratios between 7.65 and 4 φ (Fig. 11 A). Fluid muds and suspended sediments from the main channel belong to this type. The second type (Fig. 11 B) shows a strong increase in the silt ratio for particles larger than 6.64 to 5.33 φ and a considerable variation for smaller particles. This type represents sediments from the tidal flat and muddy-sand sediments from the main channel. Both types are met in the suspended sediments from the lowermost water layers of the main channel at places where the bottom sediment consists of sand.

Two different silt-sized sediments can thus be recognized. The first has a uniform grain-size distribution throughout the whole silt range, with only minor differences between the samples. The second shows a large variation in the grain-size distribution of the coarser silt fractions and also important differences between the samples. The same phenomenon is shown in Fig. 12 where the fine silt fraction (6 to 9 φ) is compared to the coarse silt fraction (4 to 6 φ).

For tidal flat sediments the coarse silt fraction is up to 2,5 times larger than the fine silt fraction, whereas both fractions are almost equally represented in the main channel sediments (bottom and suspension).

F a v e j e e (1960) attributed these differences to the flocculation effect of sea water on particles smaller than 5.33 φ. Circumstances during sedimentation can not change the ratio between amounts of the fraction $< 5.33\ \varphi$ if flocculated and constant ratio's are obtained. Thus sediments from the turbidity maximum in the main channel clearly show a stronger flocculation effect than sediments from the adjacent tidal flats.

These differences in flocculation can be attributed to several causes. On the tidal flats the suspended sediment concentrations are almost less than 200 mg/l. E i n s t e i n & K r o n e (1962) and M i g n i o t (1968) showed that there is

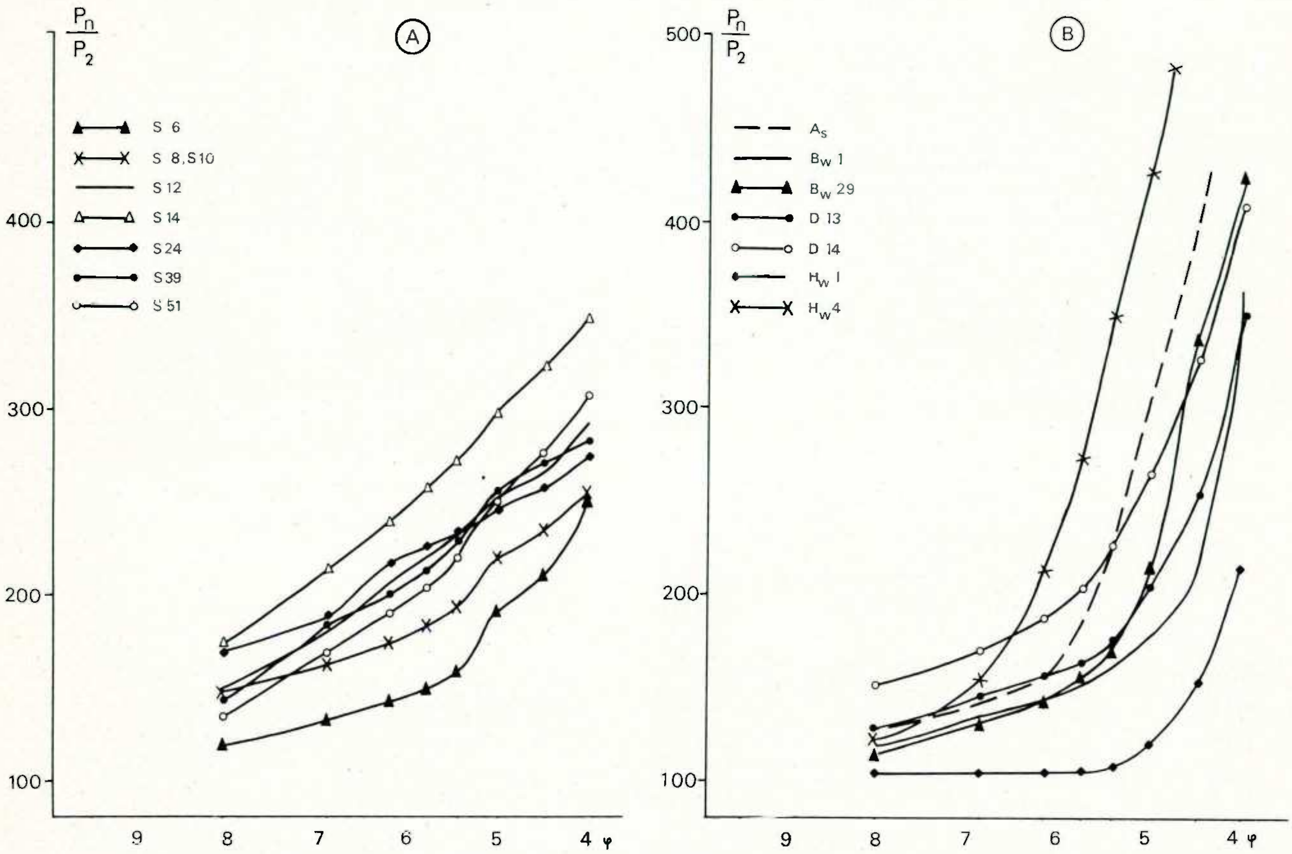


Fig. 11
Silt/clay ratio's (after Favejee, 1960).

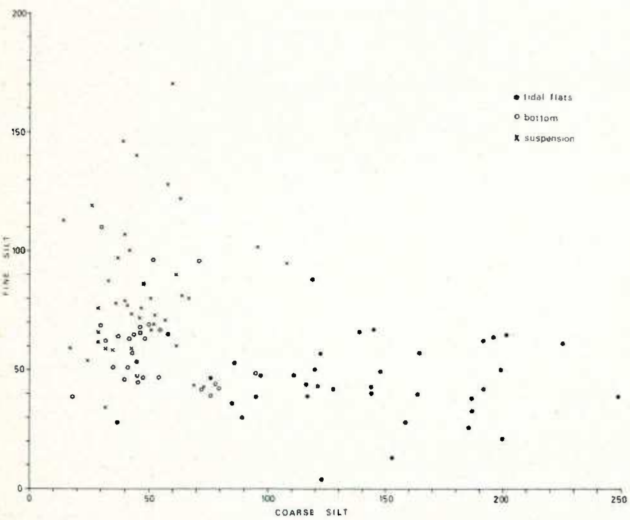
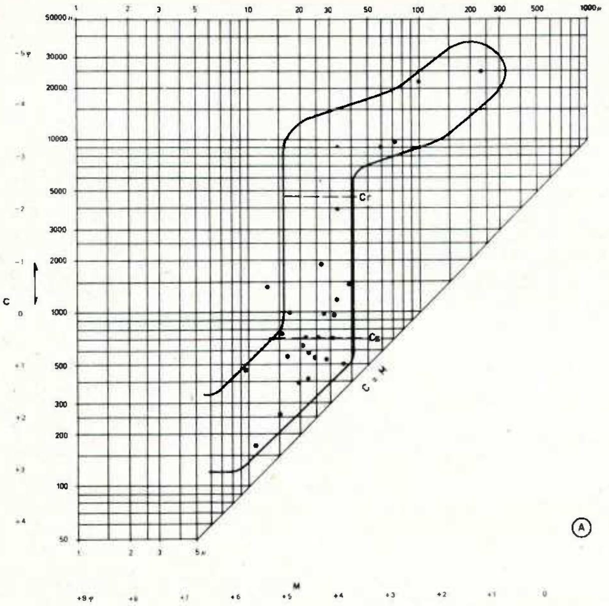


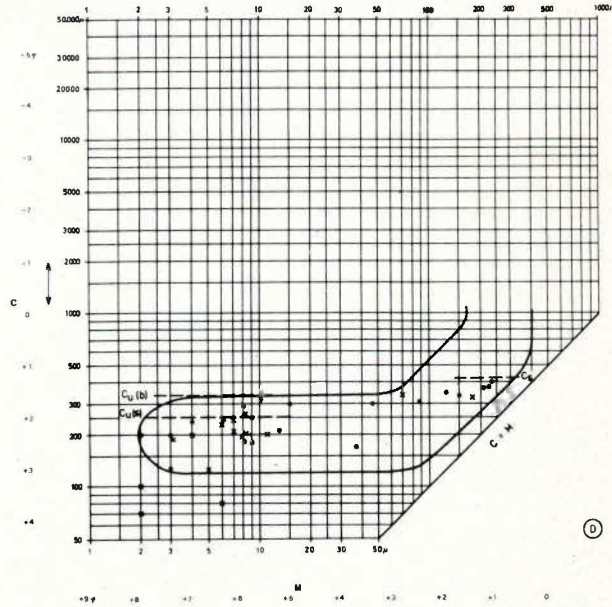
Fig. 12
Coarse silt $\left[\frac{6\varphi - 4\varphi}{6\varphi}\right]$ versus fine silt $\left[\frac{9\varphi - 6\varphi}{6\varphi}\right]$ fraction.

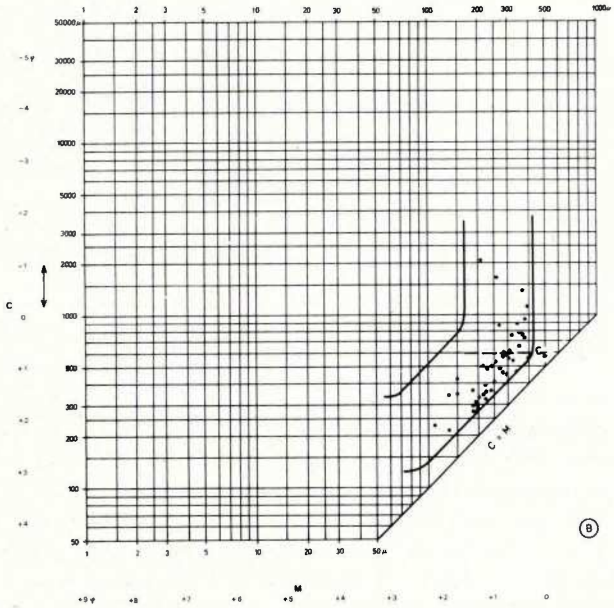
an increase in flocculation with increasing concentration of suspended sediment but a minimum concentration of 300 mg/l seems necessary. Rainfall also has to be considered as an important factor as 1) it reduces the salt content of the surface water on the tidal flat and decreases the flocculation rate (W u n d e r l i c h, 1969) and 2) it has a small erosional effect caused by the impact of rain drops on the surface of the tidal flat. Flocculated particles deposited on the sandy lower tidal flat surface will also be deflocculated by the abrasional effect of moving sand grains. This may explain why suspended sediments in sandy areas of the main channel show both types of silt ratio curves. The flocculation rate in this environment is less than in mud areas. On the other hand in the main channel suspended sediment concentrations are nearly always above 300 mg/l and hence flocculation will be intense.

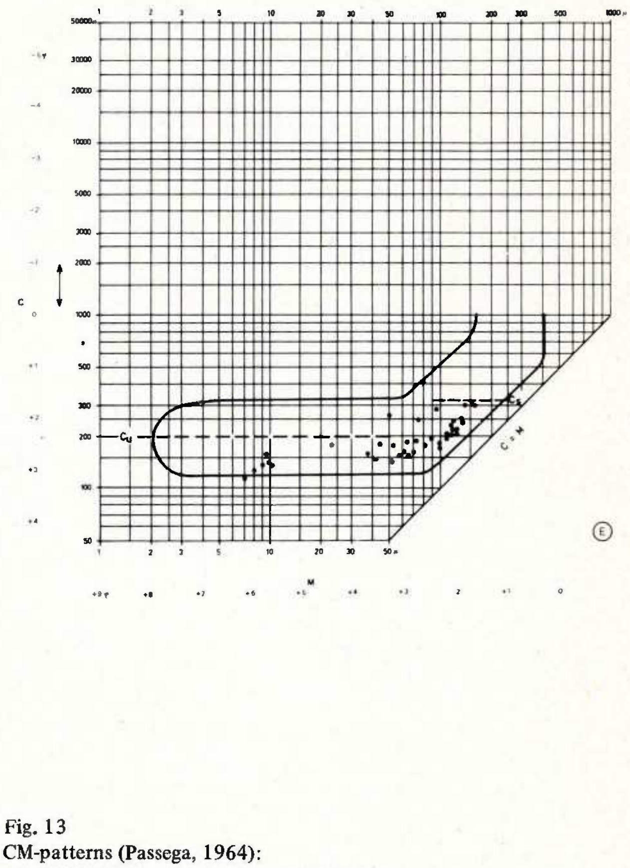
Discussion of CM-pattern

P a s s e g a (1964) showed that when the one-percent value (C) of a given grain-size distribution is compared to the median-value (M) on logarithmic paper, all points fall within certain limits (CM-pattern) which are a function of the circumstances prevailing during transport and deposition of the sediment considered.









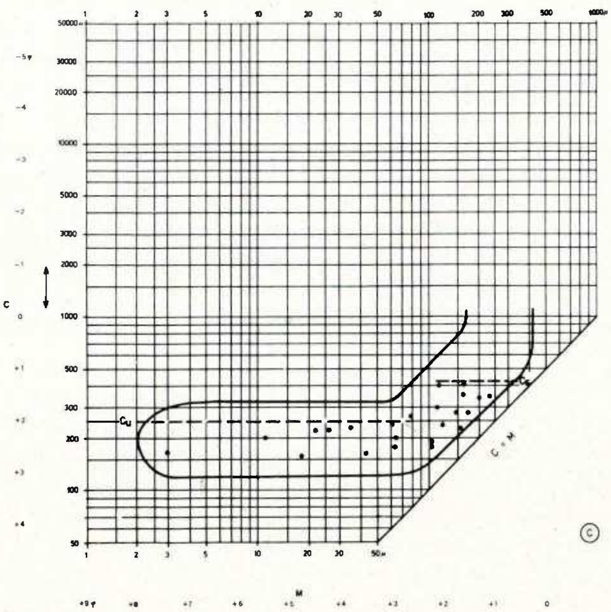


Fig. 13
CM-patterns (Passega, 1964):
A) bottom sediments upstream of Hoboken,
B) bottom sediments downstream of Zandvliet (Wester-Schelde)
C) bottom sediments between Antwerpen and Zandvliet,
D) suspended sediments between Antwerpen and Zandvliet
E) tidal flat sediments.

When tractive currents are considered, several segments can be recognized in the complete CM-pattern, each representing a certain mode of transportation and deposition. Several of these segments can clearly be recognized for the sediments of the estuary of the Schelde: sediments transported as a uniform suspension (RS, Fig. 13), as a graded suspension (QR) and as a combination of graded suspension and rolling (PQ). A fourth segment (PON), representing bottom suspension and rolling grains, is only represented by a few points.

Since a complete description and explanation of these pattern is given by Passega (1964 and Passega & Byramjee (1969), the following paragraphs only briefly review some of the principal characteristics. Passega recognized two modes of transport by tractive currents: rolling and suspension. Just above the bed a part of the suspension is graded, indicating that the maximum and median grain sizes as well as their concentration in the water decrease with height above the bed. Saltating populations belong to this type of sediment. The segment QR, representing the graded suspension, shows that an increase in M-value is coupled to a similar increase in C-value. The value Cs represents the largest grain size transported as a graded suspension and is a measure of the maximum bottom turbulence, provided grains of all sizes are available.

Above this graded suspension (which can have a thickness of several meters) grain sizes and sediment concentrations are uniformly distributed throughout the water column. This uniform suspension is represented by segment RS showing a large variation in M-value for a rather constant C-value. The value Cu is the largest grain size transported as a uniform suspension and is a measure of the water turbulence. The segment PQ represents graded suspension deposits to which a small amount of grains is added by rolling, affecting the value of C without changing M. It is assumed that the value Cr represents the grain size which is easiest to roll, under given conditions.

A last segment PON represents sediments transported essentially as rolling grains, with the addition of some graded suspension sediments in the segment PO.

Not every segment is represented in the estuary of the Schelde. Bottom sediments upstream of Hoboken and downstream of Zandvliet belong to the "graded suspension", "suspension with rolling" and "rolling" segments (Fig. 13 A and 13 B). The scattering of the M-value is greatest for the bottom sediments upstream of Hoboken (Fig. 13 A), which can be explained by mixing of sediments derived from the turbidity maximum and deposited farther upstream, thus decreasing the median diameter of the deposit slightly. This phenomenon is not observed downstream of Zandvliet (Fig. 13 B) where the sediments are grouped in a smaller range of QR and PQ segments. A few exceptional sediments of the same part of the estuary also belong to the PON segment. This typical rolling deposit occurs mostly between Schelle and Hoboken, and in the Zuidergat.

The upper limit of the graded suspension (Cs) occurs around 0,52 φ upstream of Hoboken and 0,74 φ downstream of Zandvliet. Measurement of U_*-values (shear velocity) (Wartel, 1973a) suggests that the upper value of saltating grains must be around 1 φ which is somewhat smaller than the values given above. This may be due to the fact that U_*-values were measured during a summer period (July-September) and much higher values may occur during periods of higher river discharge. The higher value for Cs upstream of Hoboken is in agreement with the narrowing of the channel and the greater competency (Wartel, 1974) observed in this part of the estuary.

Sediments from the region between Antwerpen and Zandvliet (Fig. 13 C) belong to segments QR (graded suspension) and, to a lesser degree, to RS (uniform suspension). The upper limit of the graded suspension (Cs) occurs at 7.25 φ while the upper limit of the uniform suspension occurs at 2 φ. Analyses of suspended sediments from the main channel (Fig. 13 D) are in good agreement with this.

Most suspended sediments analysed belong to the uniform suspension and graded suspension segments. The upper limit of the uniform suspension is somewhat higher near the bottom of the main channel (Cu(b)= 1.64 φ) than at mid depth or near the water surface (Cu(s)= 2 φ). Three samples of suspended sediments have a very low C-value (3.84 to 3.32 φ) and fall beneath the uniform suspension segment.

The CM-pattern for bottom sediments from the tidal flat (Fig. 13 E) is somewhat different. These sediments also belong to the uniform and graded suspension segments but with lower C-values (Cs= 4.64 φ and Cu= 5.65 φ) than sediments from the main channel. This can be explained by a lateral decrease in grain size from the main channel accross the tidal flat due to a decrease in water turbulence.

From this it is possible to state that the CM-pattern of Schelde sediments agrees with the interpretation of sediment distribution as deduced from the log-probability size curves. Although no essentially new conclusions can be drawn, it is possible to give some more accurate data on the limits of size of grains transported in suspension or by rolling for the different areas of the estuary.

Upstream of Hoboken and downstream of Zandvliet the sediment transport is dominated by a graded suspension and rolling transport. The upper grain-size limit of the graded suspension (3.84 φ) decreases towards the turbidity maximum (Antwerpen – Lillo, 4.57 φ) where a uniform suspension transport with maximum grain size between 1.97 and 2 φ dominates. The presence of sediments belonging to the graded suspension and rolling populations at both sides of the turbidity maximum further indicates that bottom currents are stronger in these areas and loose importance towards the turbidity maximum where a uniform suspension settles.

Sorting and skewness

Large variation exists in the sorting coefficient (Table I) of the Schelde sediments. The best sorted sediments have a sorting coefficient of 0.2 φ-units and the poorest sorted more than 3.0 φ-units. A negative correlation exists between the

Median	(M)	$\varphi 50$
Mean	$(\bar{X})$	$\frac{\varphi 16 + \varphi 84}{2}$
Sorting	$(\sigma\varphi)$	$\frac{\varphi 84 - \varphi 16}{2}$
Skewness	$(\alpha\varphi)$	$\frac{\bar{X} - M}{\sigma\varphi}$

Table I
Formulae for the calculation of the different grain size parameters ($\varphi 16$, $\varphi 50$, $\varphi 84$ are the intercepts of the 16^{th}, 50^{th} and 84^{th} percentile with the cumulative curve).

Size class	Sorting
sand	0.15 to 0.65
muddy sand	0.30 to 1.50
sandy mud	0.70 to 3.00
mud	1.40 to 3.00
clayey mud	2.20

Table II
Sorting limits for the different sediment classes of Sindowski (1961).

sorting coefficient and the amount of silt and clay present (Fig. 14). Also an increase in the spread of sorting values with increasing silt and clay content is observed.

There is no difference between sediments from the main channel and from the tidal flats or sediments in suspension. It is possible to give some more or less definite sorting limits to the sediment classes of Sindowski (1961) (Table II).

Friedman (1962), Shepard & Young (1961) and Beall (1970) showed a relationship between sorting and median diameter for dune and beach sediments (sorting coefficients ranging between 0.2 and 0.8 phi-unit) while the sorting coefficient increases for median diameters from 3 to 0φ.

Since all the sediments in Fig. 14 were taken from the area between Antwerpen and Bath it may be stated that they have a median diameter between 3 and 2φ. It follows from this that also for median diameters smaller than 3φ a decreasing sorting is observed and one can conclude that the optimal sorting occurs for sediments having median diameters around 3 φ at least for the environments considered here.

This relationship must be viewed with respect to the transport mode whereby sediments deposited from a saltation population (median diameter between 3.32 and 2φ) are clearly better sorted than those deposited from a rolling or a suspension population.

The nature of the depositional process also plays an important role. Rolling particles will practically always be mixed with saltating particles when deposited thus explaining the poor sorting of the coarser sediments. The suspended population in turn occupies a broad grain-size range (3 to 10φ) while the saltation population only varies between 1,5 to $3{,}5\varphi$. Thus the more suspended sediment is added to a saltating sediment the poorer the sorting will be.

The relation between skewness and the amount of silt and clay is less pronounced (Fig. 15). The differences between samples with the same amount of fines are always very large. The coarsest sediments (less than 10% silt and clay) may have negative skewness coefficients due to the combination of a rolling and saltation population in the same deposit. All other sediments have a positive skewness coefficient with

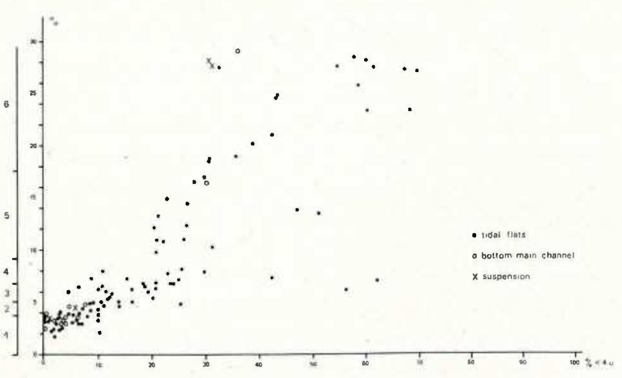


Fig. 14
Relation between sorting ($\sigma\varphi$) and silt-clay content.
1) very well sorted,
2) well sorted,
3) moderately well sorted,
4) moderately sorted,
5) poorly sorted,
6) very poorly sorted.

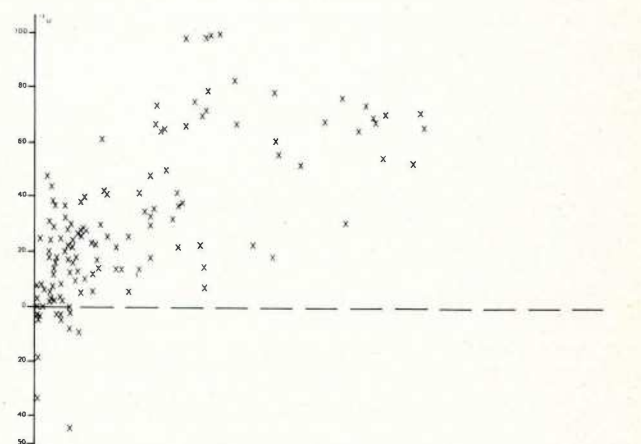


Fig. 15
Relation between skewness ($\alpha\varphi$) and silt-clay content.

increasing value when more silt and clay (derived from the suspension population) are added. In this respect there is no difference from the river or dune sands described by F r i e d m a n (1962).

SEDIMENT TRANSPORT AND DEPOSITION PATTERNS.

The grain size of the bottom sediments from the main channel of the estuary increases both upstream of Antwerpen and downstream of Zandvliet. Two peak values occur respectively at Schelle and Zuidergat (maximum diameters up to -6φ). Between them an area exists corresponding to the turbidity maximum- with much lower values (1 to 3φ) and outside them two areas with coarsest particles between 0 and -2φ.

In the above mentioned outside areas bottom transport by rolling and saltation (or graded suspension) are most important. T i s o n (1958) already mentioned that even coarse sand particles (up to 1φ) will be transported in a downstream direction in the upstream part of the estuary. In the Wester-Schelde, on the contrary, sands near the bottom are moved in an opwards direction, in agreement with upwards pointing residual currents in this area (P e t e r s 1972). Former studies (B a a k, 1936; C r o m m e l i n, 1949; d e G r o o t, 1964) also suggested that most sands in the Wester-Schelde are derived from the North Sea. The importance of this bottom transport diminishes towards the central area where rolling grains are absent while the upper limit of saltating grains diminishes from 0.74 to 3.32φ. All this indicates a decreasing transport competency from the outer areas towards the central area or turbidity maximum.

Suspended sediments are mainly derived from the river basin. They consist of silt and clay (60 to 80%) and fine to medium (up to 2 φ) sand (20 to 40%). The major part of silt and clay is most probably derived from the Rupel branch while more sand is derived from the Schelde branch. The supply of sand will also be highest during periods of high runoff (October-January) in agreement with a greater intensity of land erosion during the same period (see also Fig. 8). Most of these suspended sediments will settle out within the central area (Antwerpen – Lillo) partly as a consequence of the diminishing transport competency, partly also because of flocculation processes. K r o n e (1972) showed that flocculation will on the one hand increase with increasing sediment concentration and on the other hand decrease with increasing shearing motions in the water. Since sediment concentration decreases and the velocity gradient increases towards the surface (W a r t e l, 1972) a lowering of flocculation degree in the uppermost water layers can be anticipated, as is shown by the grain size parameters in the silt fractions.

Sediments transported downstream in the estuary will cross the area between Schelle and Hoboken where high shearing rates prevail (W a r t e l, 1973a) while further downstream shearing rates decrease. This, together with the increasing sediment concentration downstream of Antwerpen, indicates that flocculation will be more important in a downstream direction.

Muds, eroded in the turbidity maximum during the ebb stage, will be transported seawards. Deflocculation processes will now operate. In the first place the velocity gradient increases (W a r t e l, 1973a) and sediment concentration decreases from Doel towards Bath. In the second place the flocculated particles will, after a downstream transport towards the Wester-Schelde, settle on a sand bottom, where they will be easily reeroded. They will also break down by the abrasive effect of moving sand grains on the bottom. These deflocculating processes are in favour of a resultant seawards transport of these fine sediments. According to W o l l a s t (1972) this seawards transport is approximately 14% of the total sediment supply of the river.

One aspect of the general sediment distribution pattern however needs further explanation. If the observed maximum in sediment transport competency between Schelle and Bazel can be explained by a maximum in mean current velocities in this region, partly due to the confluence of Schelde and Rupel (V a l c k e *et al.,* 1966), geological circumstances are also important. Between Schelle and Hoboken the Schelde is incised in the Boom clay (Oligocene) forming a straight channel. This clay is very cohesive and difficult to erode and a rather narrow channel has developed, explaining the high competency, reflected in the complete erosion of bottom sediments at some spots (Schelle – Bazel) and the presence of 3 m high sand dunes further downstream (W a r t e l, 1974). Besides this however there is another even more important consequence which makes the estuary of the Schelde different from other estuaries such as the Loire or the Gironde (France). In the latter two estuaries a movement of the fluid mud deposits as a function of river runoff has been observed (A l l e n *et al.* 1974; G a l e n n e, 1974). During periods of low runoff fluid muds occur in front of the maximum salt intrusion. Thus for the Schelde estuary, during summer periods, fluid muds should occur upstream of Schelle. This however has never been observed. Fluid muds never reach further upstream than Oosterweel. It is possible that even during periods of low river discharge the erosional velocities in the incised valley between Schelle and Hoboken are still too large to allow a deposition of fluid mud, thus causing deposition of these sediments either further upstream in the Schelde or the Rupel or downstream of Oosterweel.

CONCLUSIONS

The sediments of the Schelde estuary range from gravels (up to –6 φ) to clayey sands and sandy clays. The comparative grain-size study of a large number of bottom samples enables us to distinguish three different areas : 1) the upstream area comprising the estuary upstream of Antwerpen; 2) the central area extending from Antwerpen unto Doel; and 3) the downstream area which comprises the Wester-Schelde, extending from Zandvliet to Vlissingen.

In the central area the finest bottom sediments (fine sands to clayey silts) occur. From the CM-pattern it is obvious that most of these sediments are transported either as a uniform or as a graded suspension. The maximum grain size which can be transported in this way is approximately 2 φ, which is also the maximum grain size of the tidal flats.

From this central area towards both the up- and downstream areas a marked increase in grain size of bottom sediments (gravels and medium to coarse sands) occurs. 10 to 30% of the sediment here is transported by rolling and the rest as a graded suspension, which is the most important, and as a uniform suspension.

The origin of these sediments is rather complex. The coarser sediments (medium sands to gravels) are derived from the land in the upstream part of the estuary and settle out with decreasing thickness towards Antwerpen. This is in accordance with the observed decrease in transport competency and downwards pointing residual bottom currents. At the other side, through the Wester-Schelde, coarse sands, derived partly from the North Sea and partly with a local origin, are transported by rolling and as a graded suspension in an upstream direction favoured by upstream pointing residual bottom currents. This sediment settles out towards Doel.

The bulk of the finer sediments (fine sand to clay) is derived from the land with a yearly average of at least 1 million tons. This supply is strongest during periods of high runoff. These finer sediments settle out in the area between Antwerpen and Lillo, from which it is supposed that flocculation is an important factor. A large part of these sediments are resuspended after deposition and contribute to the observed high suspended sediment concentrations in this central area, indicating that it is the turbidity maximum of the estuary.

Almost 14% of the sediment, deposited in this central area, is transported through the Wester-Schelde towards the North Sea. Deflocculation in the sand environment of the Wester-Schelde must be a contributing factor in this seawards transport.

An important feature in the estuary of the Schelde is the existence of a narrow channel between Schelle and Hoboken, caused by the incision of the river into the Boom clay. In this channel high transport competencies prevail as expressed by the gravelly bottom sediments. The narrowing of the channel also has an effect on the fluid mud deposition. Fluid muds do not follow the salt water intrusion as observed in other estuaries by lowering of the river runoff. It is assumed here that, because of the high transport competency and deflocculation processes as a consequence of high velocity gradients between Schelle and Hoboken, muds deposited during slack water will always be re-eroded and transported either upstream or downstream with a dominant downstream component.

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