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# CHANGES IN SUSPENDED-MATTER FLOC SIZE DURING THE TIDAL CYCLE IN THE DOLLARD ESTUARY

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## ABSTRACT

**Measurements of *in situ* particle size of suspended matter in a tidal channel in the Dollard (Dutch Wadden Sea) indicated systematic variations in floc size during the tidal cycle that can be explained by assuming settling during slack tide, resuspension during the early ebb and early flood, flocculation of fine particles into large ones during most of the tide, and deflocculation of large flocs into smaller particles during or after settling to the bottom. There was a characteristic difference in floc-size variation during ebb and during flood. During the ebb maximum floc size coincided with maximum suspended-matter concentration (maximum collision frequency); during the flood maximum floc size continued to increase towards high-water slack tide. The adjacent tidal flats had a marked influence on floc size: where the flats were small, the highest percentages of large flocs (>128 μm) occurred around slack tide when current velocities are low. Where the adjacent flats were broad and extensive, high percentages also occurred during intermediate periods. Flocs of maximum size are probably not in equilibrium with the bulk of the suspended matter: they are mainly formed during periods of high suspended-matter concentrations of short duration.**

## 1. INTRODUCTION

In tidal, partially mixed estuaries a considerable variation in floc size was found by EISMA *et al.* (1991a, b), which had little or no relation with salinity or with suspended-matter characteristics except particle concentration (EISMA *et al.*, 1991a, b). The sampling was done along transects through the estuaries from fresh water to high salinity but without reference to the tidal phase. As flocculation of suspended-matter affects the particle-settling velocity and the surface area of the suspended particulate matter, as well as creating micro-environments in and around the flocs (ALLDREDGE & SILVER, 1988), the variations in floc size during the tidal cycle are of importance in estuaries. Therefore a series of *in situ* floc-size measurements was carried out during several tidal cycles (13-h periods) in the Dollard estuary in January 1991. In this paper the results are presented and discussed and some conclusions are given regarding flocculation of suspended matter in tidal estuaries.

## 2. SAMPLING AREA AND SAMPLING METHODS

The Dollard is part of the Ems-Dollard estuary, situated on the German-Dutch border (Fig. 1) and consists of tidal flats and one main tidal channel with several smaller channels branching from it. The channel depth in the main channel at the entrance of the Dollard is approximately 6 m below Dutch Ordnance level (NAP) decreasing inward to about 4.5 m (at point B; Fig. 1) and approximately 2.8 m at point C. The tides are semidiurnal with a range of about 3 m. Current velocities in the main channel reach 70 to 90 $cm \cdot s^{-1}$ at the entrance at points A and B and 60 to 70 $cm \cdot s^{-1}$ at point C (RIJKSWATERSTAAT, 1990, and unpublished measurements NIOZ 1987-1988). Typical tidal velocity curves for the Dollard main channel are given in Fig. 2. Currents in the ebb direction are usually 10 to 30 $cm \cdot s^{-1}$ stronger than flood currents. The period of low current velocities (<15 $cm \cdot s^{-1}$) is about 1 h around high tide and 1.5 to 2 h around low tide.

At the points A, B and C (Fig. 1) *in situ* floc-size was measured with an *in situ* suspension camera system (EISMA *et al.*, 1990) at approximately mid-depth which varies between 3.7 and 2.7 m above the bottom around high tide and between 2.3 and 1.5 m around low tide. Measurements were made every hour, with some additional measurements at half-hour intervals around slack tide. At the same time and waterdepth, water samples were collected for determining total suspended-matter concentration by filtration over a pre-weighed 0.4-μm poresize Nuclepore filter. Organic content of the suspended matter was subsequently determined by ashing the filters at 500°C for 8 h. Floc-size distributions were determined by analysing 4 to 8 negatives with an image-analysis system (EISMA *et al.*, 1990). They were expressed in volume percentages per size fraction. Salinity was determined in the water samples by titration with silver nitrate or with an Autosal salinometer. Titration was only done for samples with low salinities (less than approximately 5‰) because at such salinities the composition of the fresh water influences the relation between the total salt content (or chlorinity) and the conductivity.

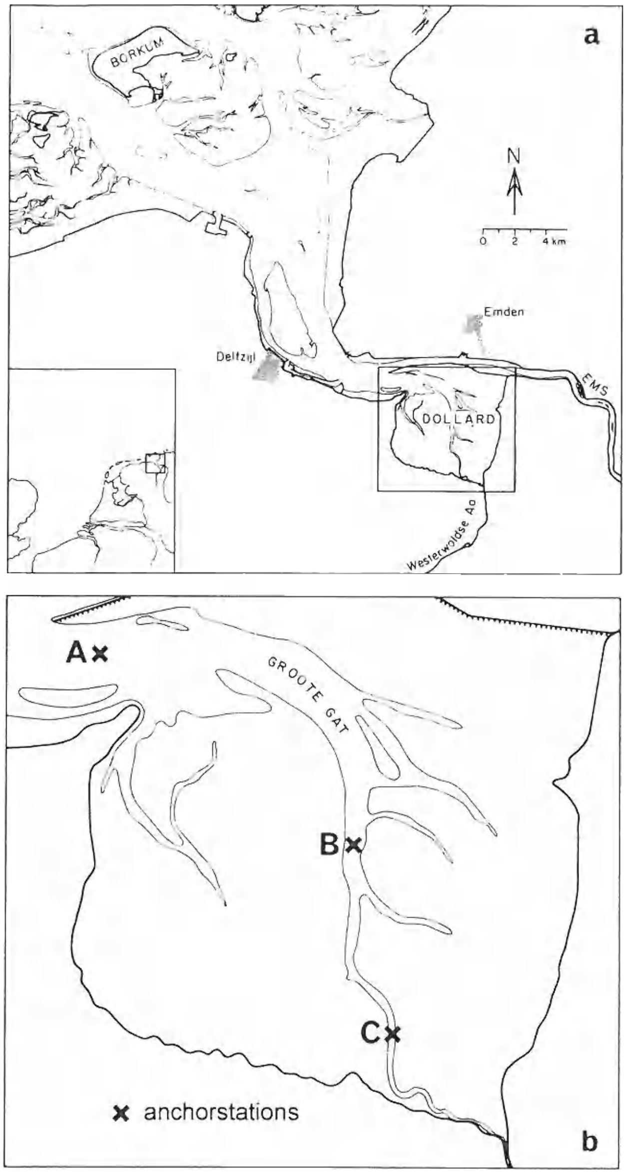



Fig. 1. General map of the Ems-Dollard estuary and location of stations in the Dollard.

### 3. RESULTS

#### 3.1. STATION A

Fig. 3 shows data collected on 17 January 1991, starting at 9.00 h and ending at 22.00 h. The numbers along the horizontal axis indicate the time; the numbers in brackets indicate the sequence of floc-size distributions shown in Fig. 10. Maximum concentra-

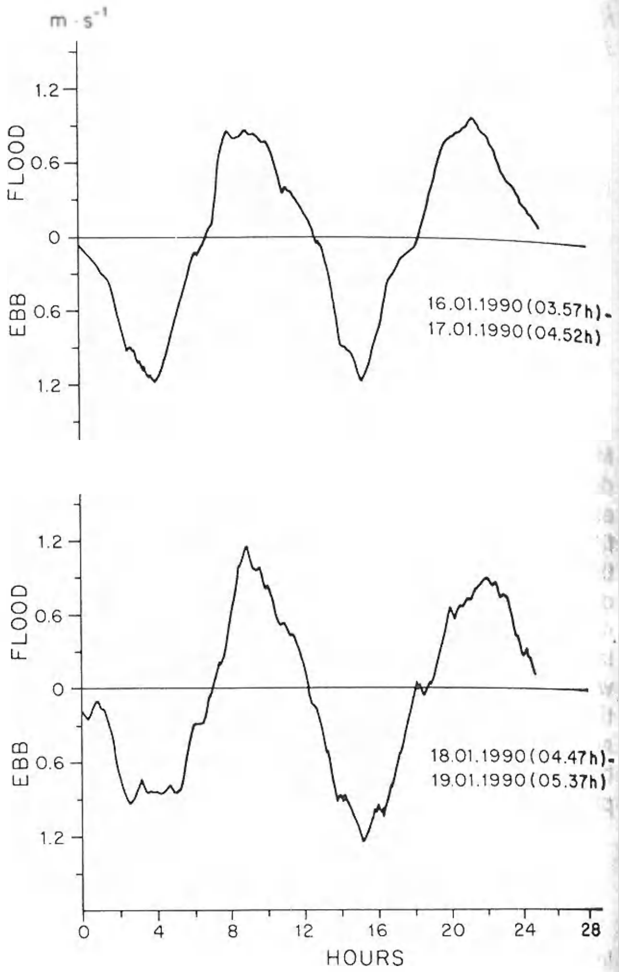



Fig. 2. Tidal-current velocities during two tidal cycles in the Dollard main channel in surface water at station B. Horizontal scale: hours after starting the measurements.

tions of suspended matter occurred during the flood at 11.00 h, which was about 4.5 h after low tide (at 06.40 h), and during the late ebb at 18.00 to 19.00 h, which was approximately 5 to 6 h after high tide. The *in situ* size distributions showed relatively high percentages of flocs >128 μm around high tide and low tide. Relatively high concentrations of small particles (<32 μm and <64 μm) occurred during the flood at 9.00 to 10.00 h (with possibly higher amounts before that time) and at 21.00 h, and during the ebb at 16.00 to 17.00 h. These peaks preceded the peaks of high concentration by approximately 1 to 3 h. The maximum floc size showed a different distribution with peaks at 12.00 to 13.00 h and at 18.00 to 19.00 h. The first peak was about 1 to 1.5 h later than the maximum concentration; the second peak coincided with the second maximum in concentration. Both peaks occurred half an hour before high tide and low tide, respectively, with a small decrease towards slack tide. Salinities (Fig. 6) were low around low tide but

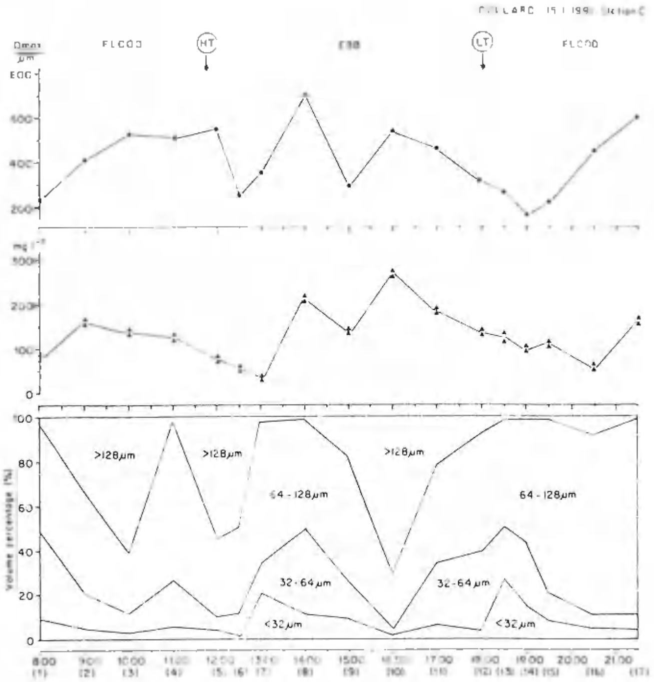



Fig. 5. Changes in maximum floc size ($D_{max}$), concentration ($mg{\cdot}dm^{-3}$) and *in situ* size distribution (in % volume) over approximately half a tidal cycle at station C, 15 January 1991. For further explanation see Fig. 3.

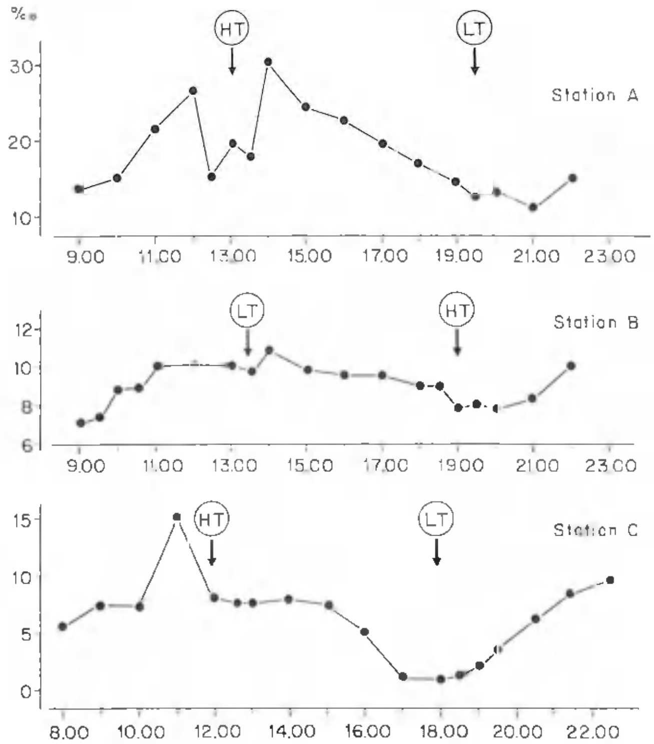
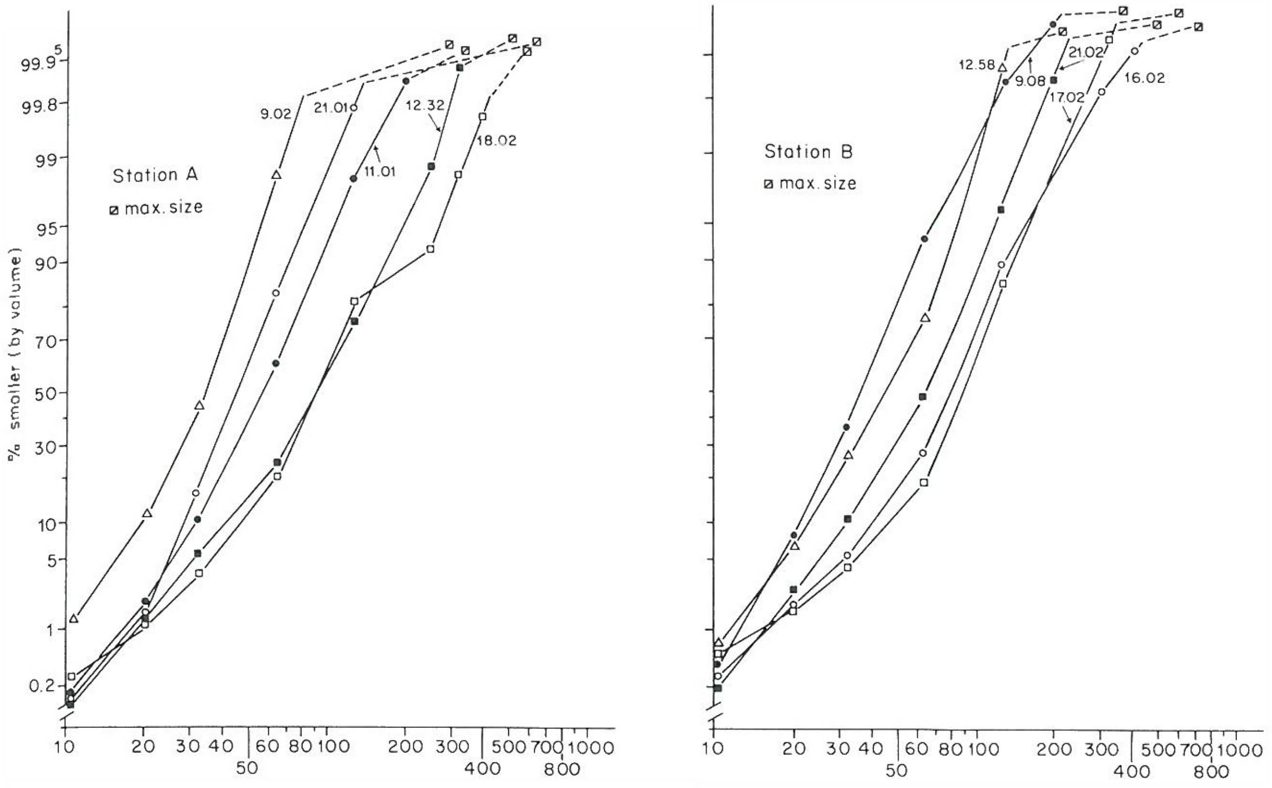



Fig. 6. Salinity (in ‰) during the measurements at station A, B and C, respectively. HT = high tide; LT = low tide.


Fig. 7. *In situ* photographs of flocs in the Dollard estuary. Those with 'stringers' were photographed around slack tide.

### 3.4. *IN SITU* FLOC SIZE DISTRIBUTION CURVES

All particles observed were found to be flocs (Fig. 7); the *in situ* floc-size distributions are given in Fig. 8 on log-probability paper with the log floc diameter on the horizontal scale and the cumulative percentage smaller-than-a-given-floc-size (by volume) on the vertical scale. Log-normal size distributions give straight lines on such paper: they follow a (Gauss) probability curve around a mean (DOEGLAS, 1946). Apart from some irregularities, the curves in Fig. 8 follow approximately straight lines, in particular those with smaller mean-size values, whereas those with coarser mean values are more curved. The curvature (skewness) is towards the fine sides, which indicates a constant admixture of fine flocs (or particles) that do not entirely settle out during slack tide, while the population of larger flocs varies in size. Using the relations found between floc diameter and differential density (RILEY, 1970; KAJIHARA, 1971; HAWLEY, 1982; McCAVE, 1984; GIBBS, 1985; summarized in VAN LEUSSEN, 1988 and EISMA, 1993) the *in situ* floc-size distributions



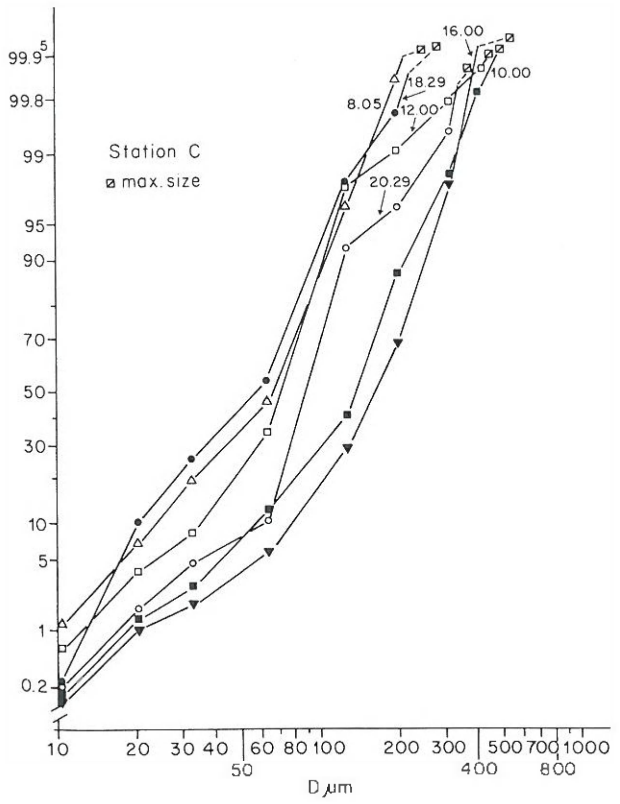




Fig. 8. *In situ* floc-size distributions (by volume). The numbers indicate time of sampling, corresponding to Figs 3, 4 and 5, respectively.

were calculated by weight and also plotted on log-probability paper (Fig. 9). Not much difference was found when either the relation given by McCAVE (1984) + KAJIHARA (1971) was used or the relation given by RILEY (1970) + HAWLEY (1982) + GIBBS (1985) with extrapolation towards the diameters larger than 200 µm. As the differential density is inversely related to the floc diameter, the skewness shows even stronger in the curves calculated by weight than in those given by volume. The most irregular curves were measured at station C, whereas those at stations A and B were more regular.

## 4. DISCUSSION

At all three stations A, B and C the maximum of fine particles during the flood came up to 2 h after slack tide (low tide) and during the ebb 0.5 to 3 h after slack tide (high tide). Also at all three stations the maximum suspended matter concentration occurred 0.5 to 3 h later than the peak of fine particles, both during the flood and during the ebb. The maximum floc size

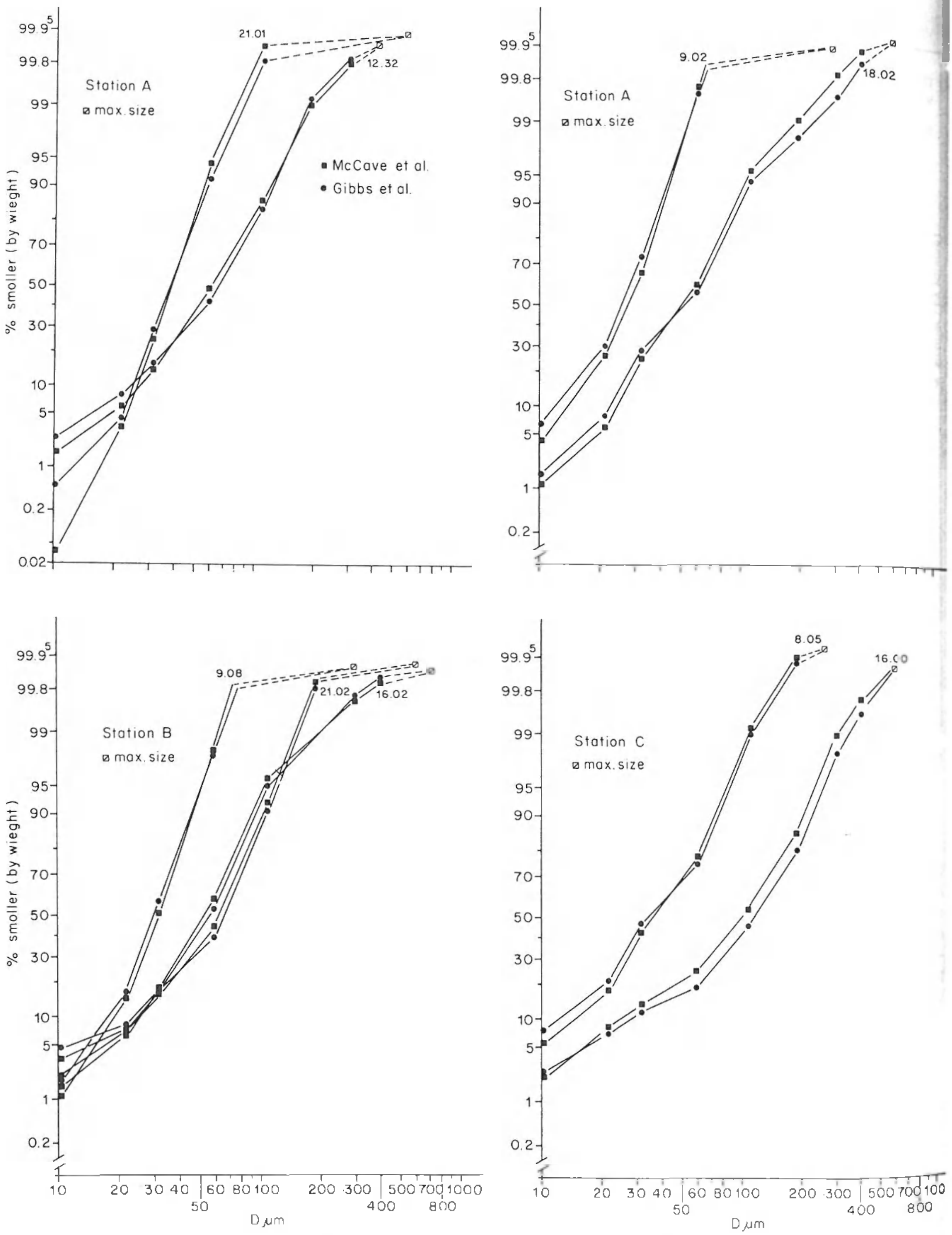



Fig. 9. *In situ* floc-size distributions (by weight). The numbers indicate time of sampling corresponding to Figs 3, 4 and 5 respectively.

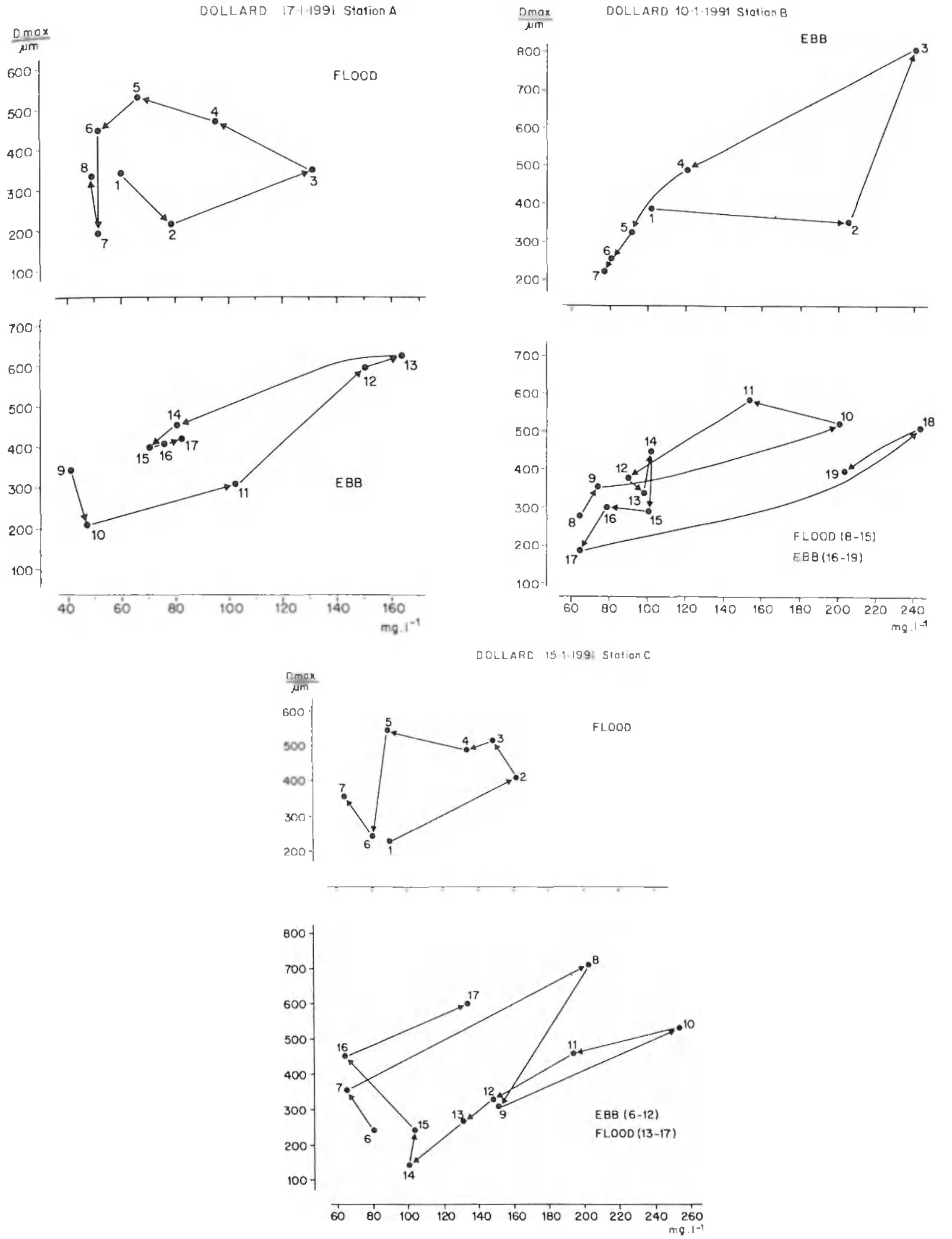



Fig. 10. Relation between $D_{max}$ (µm) and concentrations (mg·dm$^{-3}$) at: station A (during the flood and the following ebb), station B (during the ebb and the following flood and early ebb), and station C (during the flood and the following ebb and early flood).

($D_{max}$) occurred 0.5 to 1.5 h later than the concentration maximum during the flood but occurred almost simultaneously during the ebb. This characteristic difference is shown more clearly in Fig. 10. During the flood the floc size continued to increase for a few hours although the particle concentration decreased, whereas during the ebb floc size started to decrease when also the particle concentration decreased.

For flocculation of suspended matter there has to be a mechanism that brings the particles together as well as a mechanism that keeps the particles together after they have come into contact. We assume that sticky material is present in the form of organic matter adhering to the particles as surface coatings (LODER & LISS, 1985; EISMA, 1986, 1993). Mechanisms bringing particles together are turbulence, the Brownian motion (for very small particles) and organisms that actively aggregate particles (McCAVE, 1984; VAN LEUSSEN, 1988). Because of the shallow depth, differential settling is not considered an important process in this area except around slack tide when turbulence is reduced. It should be realized that flocs may have been formed under different conditions than existed during the measurements and may be 'relict', being still there because they were not broken apart.

We think that during the tidal cycle the following happens. With rising or falling tide, with current velocities increasing after slack tide, fine particles are resuspended from the bottom resulting in a peak concentration 0.5 to 3 h after slack tide. Such peaks can be seen not only in the relative percentages as given in Figs 3, 4 and 5, but also in the absolute particle concentrations (in $mm^3 \cdot dm^{-3}$) as shown in Fig. 11 for station C. Also in Fig. 11 it can be seen that at 9.00 and 10.00 h both small particles and large particles increased in number (the larger ones much more so than the small ones). An alternative explanation for the fine-particle peaks would be the breaking apart of larger flocs (deflocculation) because of increasing shear when the current velocity increases. This, however, is difficult to visualize because some hours later the fine particle peaks were followed by the presence of much larger flocs, which occurred when there had been a further increase in shear rather than a decrease. Therefore it is most likely that the peaks of fine particles are caused by resuspension from the bottom.

With increasing tidal velocities, the suspended matter concentration also increased: there was also a relative increase in the number of larger particles (flocs) while the fine particles showed a relative decrease. The increase in the number of larger particles can be caused by resuspension of larger particles from the bottom as well as by flocculation of the finer particles into large ones (or through scavenging by larger ones). The disappearance of so many fine particles can be explained only by flocculation or scavenging, but probably both processes - resuspension of large ones and flocculation of fine ones - play a role. Fig. 11 shows that most peaks of large particles (>64 µm) came about 2 h later than the peaks of fine particles (<64 µm), but already between 8.00 and 10.00 h both the amounts of fine and large particles increased (in absolute amounts). The amounts of large particles that came into suspension (not only between 8.00 and 10.00 h but also at the later maxima) were much larger than can be explained by flocculation of the amounts of fine particles that disappeared from suspension even if it is taken into account that the larger flocs may have a looser structure and enclose larger amounts of water. Therefore resuspension of large flocs has also to be an important process: directly from the bottom or as smaller particles (or flocs) that are quickly flocculated.

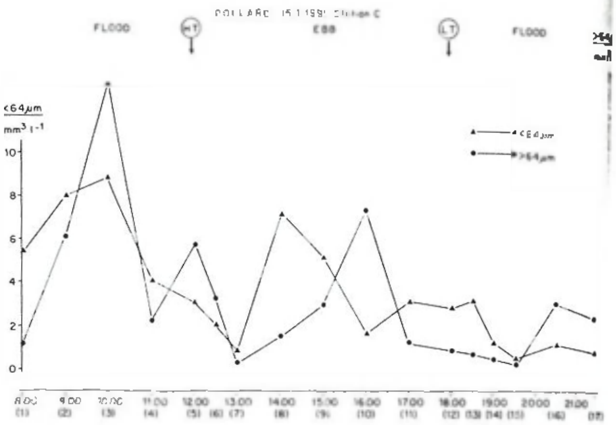



Fig. 11. Concentrations of particles >64 µm and <64 µm a
station C during the period of measuring (approximately ha
a tidal cycle). HT = high tide; LT = low tide.

After the disappearance of the fine particles, part
cle concentrations reach a maximum, which is high
during the ebb than during the flood. This can b
explained by the higher current velocities during th
ebb. High concentrations favour flocculation becaus
the collision frequency is enhanced. Maximum fl
size occurred during the ebb at or slightly later th
the maximum particle concentration, but during flo
several hours later when the particle concentrati
had already decreased considerably. This differen
in floc size during flood and during ebb may
explained by the different flow characteristics duri
flood and ebb. During the flood the water rises in t
channels and over the adjacent flats. The water dep
increases and when particle concentrations decrea

because current velocities decrease (while
water level continues to rise), turbulence is reduc
while particles settle out, large flocs can rem
intact, flocculation continues and larger flocs
formed. They can remain in suspension until they s
tle out shortly before or during slack tide; Fig. 10 in
cates that a large amount of large flocs settled
during slack tide.

During the ebb, however, and in particular during the late ebb, water flows off the flats through the gullies ('prielen' in Dutch) that are present along the borders of the flats. This flow is rapid (up to 80 $cm \cdot s^{-1}$; VAN STRAATEN, 1954) and increases at decreasing water depth. These conditions are not favourable for flocculation to continue and for existing larger flocs to remain intact. Particularly in the gullies there is considerable re-suspension which contributes to the concentration maxima in the channel during the late ebb. This implies that the floc sizes in the channel are much influenced by the conditions on and at the borders of the flats, which is particularly so during the late ebb when the flow from the flats to the channels through the gullies is strongest.

During slack tide particles settle out. Velocities lower than about 15 $cm \cdot s^{-1}$, which allow suspended particles to settle (EINSTEIN & KRONE, 1962), occur for 30 to 120 minutes around slack tide (unpublished data NIOZ). Because of the smaller water depth and the longer period of low current velocities, more suspended matter can settle out around low tide than around high tide, but this probably is not an important effect, as there was no consistently higher peak of resuspended fine particles after low tide. The material that settles out during slack tide is resuspended a short while later. Because of the large amounts of small particles that are usually present in suspension after slack tide, some deflocculation has probably taken place. Biological influence (organic-matter consumption) is considered negligible: Fig. 12 gives the total content of organic matter in the suspended matter as measured at the three stations. There was no consistently lower organic-matter content in the suspended material after slack tide, which suggests that the loss of organic matter because of animal or bacterial consumption was not large. The measurements were performed in January when biological activity is low, but EISMA *et al.* (1991) found that the total organic content does not influence floc-size: the presence of specific long-chained compounds such as polysaccharides is more important. It is therefore more likely that the shear during resuspension had caused floc break-up so that mostly fine particles came into suspension again, and then flocculated into larger flocs. It has been shown before that flocs of up to 1000 µm easily break apart into (micro)flocs smaller than 125 µm, which are difficult to reduce further in size (EISMA *et al.*, 1983; EISMA, 1986). The sequence of events as explained here implies that during a tidal cycle both considerable flocculation and deflocculation take place besides deposition and resuspension, not only during the flood and ebb tides, but also during or shortly after slack tide when flocs settle out that are resuspended a short while later.

A more detailed comparison of the results of the three stations shows a considerable variation. At station A, where the adjacent flats are small and the larger flats are at a much greater distance than at stations B and C, the high percentages of flocs >128 µm occurred around slack tide (both at high and low tide), when current velocities are very low. In between, smaller flocs dominated. Near to slack tide also the largest flocs were found which at slack tide may have settled already from mid-depth where the measurements were performed. This sequence is very similar to the sequences found in the Elbe estuary near Brunsbüttel in June 1991 (Chen & Eisma, in prep.), where the tidal flats bordering the channel are also small.

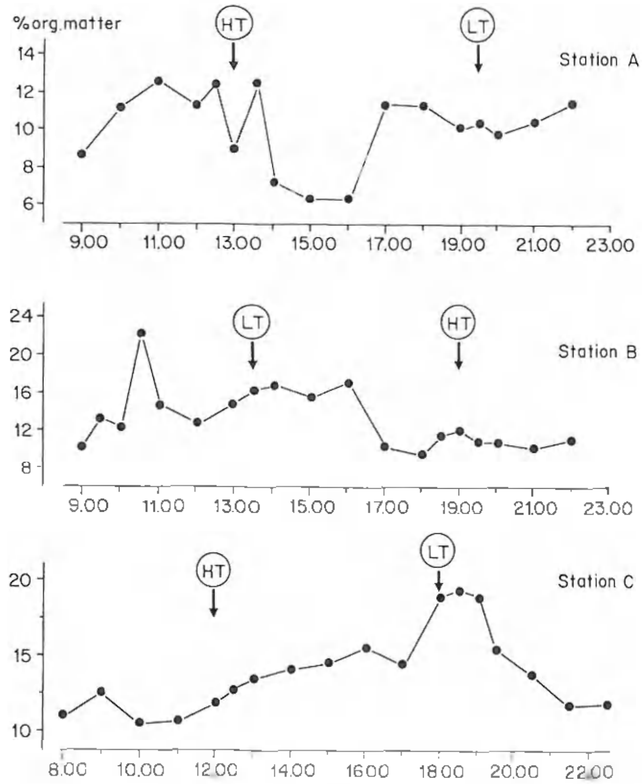



Fig. 12. Proportion (%) of organic matter in the suspended matter at the three measuring stations. HT = high tide; LT = low tide.

At station B the sequence was more irregular. Relatively large percentages of flocs >128 µm were present not only during slack tide, but during the entire flood, while the maximum floc size was large, also when the percentage of flocs >128 µm was low. Large tidal flats are present along the channel where station B is located so that the difference, as compared to station A, may be attributed to a stronger influence of the nearby flats, particularly during the ebb. This is even more so at station C, where the channel is small and the sequence was even more influenced by the nearby flats.

At stations B and C, but also at station A, the maximum floc size did not match very well with the relative percentages of flocs >128 µm: in the curves of Figs 8 and 9 the maximum floc size at the coarse end of the curves deviates sharply to the right, particularly at stations A and B, but less so at station C. There is a much better match with the total concentration of suspended matter (Figs 3, 4, 5): high concentrations favour the formation of large flocs because of a higher collision frequency. As the flocs of maximum size only constituted a small percentage of the total amount of material in suspension and their size in most cases did not seem to be related to the floc size of the bulk of the material, there was probably no equilibrium: the periods of high suspended-matter concentrations were of short duration (particularly at station B, where they lasted only about one hour) and it is possible that this was not long enough for more than only a few large flocs to be formed. The bulk of the flocs in suspension approximately followed normal (Gauss) distributions with an admixture of fine-sized flocs (or particles). Only at station C at the coarser size distributions (with a larger mean floc size; Fig. 8), did the maximum floc size approximately fit into the size distribution of the entire suspension. Also at station C high percentages of flocs >128 μm were found during the late flood and late ebb (Fig. 5). One can speculate that relatively large flocs of a less fragile nature are picked up from the tidal flats during these periods.

## 5. CONCLUSIONS

During the tidal cycle in a channel in the Dollard estuary the *in situ* suspended-matter (floc) size showed systematic variations, which can be explained by assuming settling during slack tide, resuspension during the early ebb and early flood, flocculation of fine particles into larger ones during most of the tide, and deflocculation of large flocs into smaller particles during settling to the bottom (because of increased shear near to the bottom) or after having settled.

The strong variations have a range similar to that observed in the *in situ* measurements along transects through the Ems, Rhine and Gironde, where measurements were performed regardless of the tidal phase (although in these measurements only the fraction >80 μm was measured; EISMA *et al.*, 1991). The variations along the transects therefore very likely were caused by the *in situ* size variations related to the tides.

In the Dollard in January 1991, floc size reached a maximum during each ebb and flood and then decreased again towards slack tide. During ebb tide the maximum floc size occurred during the maximum of suspended-matter concentration or shortly after. During flood tide the floc size continued to increase also after the concentration maximum was reached. This difference in flocculation during ebb and flood can be explained by the difference in flow characteristics during ebb an during flood. During the flood the water depth increases so that also during the second half of the flood flocculation can still continue, resulting in larger flocs, which is enhanced by the reduced turbulence. This can continue until the flocs settle out near, or during, slack tide.

During the ebb water depth decreases, and p larly during the second part of the ebb, wh water becomes concentrated in the channel, flows at rather high velocities from the adjace into the channel through shallow gullies. The bottom shear is not favourable for the forma large flocs, nor for existing flocs to remain intac

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