The settling of mud flocs in the Dollard estuary, The Netherlands

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The settling of mud flocs in the Dollard estuary, The Netherlands

Het bezinken van slibvlokken in het Dollard estuarium
(met een samenvatting in het Nederlands)

PROEFSCHRIFT

Ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de Rector Magnificus, Prof. Dr. H.O. Voorma, ingevolge het besluit van het College voor Promoties in het openbaar te verdedigen op vrijdag 8 september 2000 des middags te 14.30 uur

door

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Geboren op 17 oktober 1970, te Hengelo

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1 INTRODUCTION AND LITERATURE REVIEW

1.1 Problem definition, objectives and outline of the thesis

1.1.1 Problem definition

The morphodynamics of channels and mudflats along muddy coasts are of major interest for coastal protection, nature conservation and management of navigation channels. For understanding these morphodynamics, one needs to know when and where sediment is eroded, transported and deposited again. Knowledge about the sediment transport is the key to understanding morphodynamics. This thesis addresses only a small part of the sediment dynamics of muddy coasts. It concentrates on the settling velocity of muddy sediments in the Dollard estuary. This is a small but vital part of the whole sediment transport process. The settling velocity of the sediment determines, among other factors, when and where sediment is deposited.

Mud is defined as fine-grained sediment with a size smaller than 53 μm. Mud particles are cohesive. The surface to mass ratio of the particles is large so that they are not only affected by gravitational forces but by electro-static and VanderWaals forces as well. Because mud is cohesive it tends to form mud flocs. These flocs have a higher settling velocity than the constituent particles. This is very important for sediment deposition, as there would be little accumulation of fine-grained material, if the suspended fine sediment particles would not aggregate (Partheniades, 1984; Van Leussen, 1994).

Unlike the size and settling velocity of a sand grain which is static, the sizes and settling velocities of mud flocs are dynamic properties. Mud floc sizes and settling velocities vary in time and in all three spatial dimensions. Many physical, biological and chemical processes govern these variations. A better understanding of these variations and the processes that cause these variations is needed to improve the knowledge about fine-grained sediment transport and morphodynamics of mudflats and tidal channels.

1.1.2 Objectives

This thesis is mainly process oriented and tries to identify and quantify the flocculation processes in an estuary. This is based on a geographic approach where spatial and temporal floc settling velocity variations in the Dollard estuary are used to distinguish which flocculation processes are relevant and on what temporal and spatial scale.

Therefore, the general aim of this study is, *to assess the variations in the size and settling velocity of mud flocs in the Dollard estuary, The Netherlands, and to assess the processes that cause these variations.*

This leads to the following objectives of the study:

1. Identify which so called flocculation processes affect mud floc sizes and settling velocities
2. Quantify the impact of the separate flocculation processes on mud floc properties
3. Assess the temporal and spatial variation of mud floc properties based on its dependence on and interaction with the flocculation processes in the Dollard estuary.

1.1.3 Outline of the thesis

Flocculation processes were identified from the literature review that will be presented below. From this review was determined which flocculation parameters were potential key parameters. The validity of these parameters was tested in the field.

By means of researching on different time scales and spatial scales it was possible to partly separate the impact of different flocculation processes on mud floc properties. SSC and turbulent shear were mainly studied on the time scales of tides and across the estuary. Biopolymers and salinity were mainly studied on the time scales of seasons and along the estuary. Finally the temporal and spatial variation of floc settling velocities and some of the implications of this variation for fine-grained cohesive sediment dynamics in the Dollard estuary were assessed.

Note, however, that the presented research is merely based on field measurements. A large advantage of field measurements is that they are taken from the complex reality and not from simplified models, wherein important processes may not have been identified. Large disadvantages of field measurements are the limitations imposed by instruments, weather and measurement capacity.
Especially the instruments for measuring floc size and settling velocity had severe shortcomings. From three instruments, two could only measure relative differences in floc size or settling velocity. The third instruments, The Video *In Situ* (VIS), was capable of absolute floc size measurements and to a lesser extent absolute settling velocity measurements but only within a limited range. Floc size and settling velocity measurements in the near bed region, where increased turbulence may cause floc breakup, where even impossible, as no instrument is yet small and capable enough for measurements at a few centimeters above the bed without causing a lot of disturbance. Still the collected data enabled to reach a large part of the objectives of this thesis.

The remainder of this thesis is set up in the following order:
This chapter, **Chapter 1**, deals with the objectives of the thesis and a literature review on flocculation processes. **Chapter 2** deals with the fieldwork, the used methodologies and their limitations. **Chapter 3** deals with the effect of SSC and turbulence intensity on floc size. It focuses mainly on the tidal variation in floc sizes and settling velocities above the tidal flat and the tidal channel. **Chapter 4** deals with the seasonal variation in floc sizes. It focuses on biological effects, especially the effect of the 1996 spring phytoplankton bloom

on floc sizes in the Dollard estuary. **Chapter 5** deals with the differences between floc size and settling velocity variations on the tidal as well as the seasonal time scale. It shows the importance of floc density decreases as flocs grow and it shows that variations in floc settling velocities depend on erosion, resuspension and deposition of the flocs. That means that the "transport capacity" of the currents for a large part determines the floc settling velocities. **Chapter 6** provides a synthesis of all the previous chapters. In this chapter the objectives of the thesis are evaluated and the conclusions are summarized.

1.2 Flocculation processes

This study will start with a literature review on flocculation processes, their impact on mud floc properties and their expected temporal and spatial variation. The aim of this review is to identify the key parameters that determine the mud floc size and settling velocity in an estuary.

Aggregation of particles occurs when two particles collide and stick together. The amount of aggregation depends therefore on the frequency of collisions and the efficiency of the collisions in sticking together. First the collision mechanisms will be dealt with, followed by a review of the processes that determine the collision efficiency.

1.2.1 Particle collisions

There are four different collision mechanisms:

1. Brownian motion of the particles.
2. Velocity gradients within the suspending liquid.
3. Differential settling of the suspended particles.
4. Turbulent inertia of the suspended particles.

(Eisma, 1993; Partheniades, 1993; Van Leussen, 1994)

The collision frequency depends on the above mechanisms and on the particle number concentrations. It can be written as follows:

$$N_{ij} = K(d_i, d_j) \cdot n_i \cdot n_j \tag{1.1}$$

Where:

N_{ij} = Number of collisions per unit time and per unit volume.
$K(d_i,d_j)$ = Collision frequency function depending on collision mechanism, particle sizes and properties like temperature and pressure.
d_i = Diameter of particle class i (m).
d_j = Diameter of particle class j (m).
n_i = Number concentration (volume^{-1}) of i-particles of diameter d_i.
n_j = Number concentration (volume^{-1}) of j-particles of diameter d_j.
(Van Leussen, 1994)

The collision frequency function for Brownian motion K_{BM} depends on particle diameter, temperature and the dynamic viscosity of the liquid. When particle collisions are caused by Brownian motion and the particles stick together this process is called perikinetic flocculation. The collision frequency function for the effect of velocity gradients K_{SH} depends on the particle diameters and the amount of shear. Particle collisions caused by shear resulting in flocculation are called orthokinetic flocculation. The collision frequency function for differential settling K_{DS} depends on differences between particle settling velocities in the suspension. The collision frequency function for turbulent inertia K_{TI} depends on the difference in mass between particles, since turbulent accelerations in turbulent flow produce relative particle velocities for particles of unequal mass (Pruppacher & Klett, 1978 in: McCave, 1984).

Van Leussen (1994) made comparisons of the number of collisions caused by Brownian motion and the number of collisions caused by shear using standard collision frequency functions. He showed that under normal estuarine conditions orthokinetic flocculation is much more important than perikinetic flocculation. Only for particles smaller than 2 µm Brownian motion is more important than the velocity gradients, therefore in some situations perikinetic flocculation will be of importance in the beginning of the flocculation process (Van Leussen, 1994). McCave (1984) also found that Brownian motion dominates below 1.5 to 8 µm, but if large particles are present at realistic concentrations, they become important in the removal of fine particles by shear-controlled coagulation.

According to McCave (1984), turbulent inertial coagulation is only important when particles extremely differ in diameter. For most particles its effect is orders of magnitude less than the effect of turbulent shear. Therefore the effect of turbulent inertia of suspended flocs is not likely to be an important flocculation mechanism in the Dollard estuary. Stolzenbach & Elimelech (1994) showed that the likelihood of collision between a small particle and a faster settling, but less dense, larger particle is very small. Small particles overtaken by the large settling particle are deflected around the larger particle and collisions are impossible. Only collisions between flocs with a size difference of a factor 10 or more are still able to collide. The density of larger estuarine flocs is generally lower than the density of smaller estuarine flocs (Dyer, 1989). Therefore, the findings of Stolzenbach & Elimelech (1994) suggest that differential settling is probably hardly important in an estuary. A complicating factor is however the porosity of the flocs, throughflow typical of large marine aggregates increases the collision probability by an order of magnitude (Stolzenbach, 1993 in: Stolzenbach & Elimelech, 1994). The porosity may partly suppress the deflection of small particles around large particles and still make some collisions, due to differential settling, possible. However, Stolzenbach and Elimelech conclude that aggregation by differential settling is only significant between very small and very large particles.

Suspended sediment concentration (SSC)

As can be seen in equation 1.1 the particle number concentrations govern the collision frequency of the particles. Therefore, it is to be expected that the sizes and settling velocities of the suspended flocs depend strongly on the SSC. Several field studies in estuaries have shown that the median floc settling velocity increases with sediment concentration raised to a power (Burt, 1984; Pejrup, 1988; Van Leussen & Cornelisse, 1993a). This relation has a limited range, when the sediment concentration exceeds about 2 g/l hindered settling occurs. The settling sediment then has to displace so much water that the upflowing water hampers the settling of the sediment. When the sediment concentration exceeds about 5 g/l the settling velocity even starts to decrease with increasing SSC (Eisma, 1993).

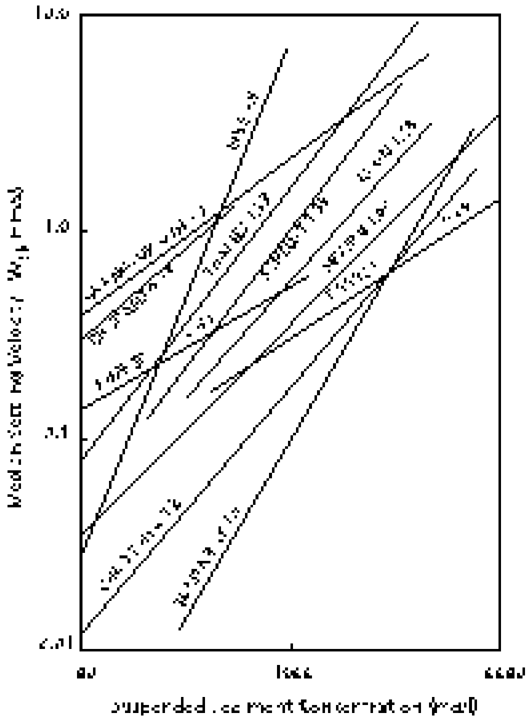

Figure 1.1 The relationship between median settling velocity and concentration for muds of various estuaries. The numbers are the value of n in the formula $W_s = aC^n$. W_s = settling velocity, C = suspended sediment concentration, a and n are constants (Dyer, 1989)

Despite the generally occurring exponential relationship between settling velocity and sediment concentration there are considerable differences in this exponential relationship between estuaries (Dyer, 1989) as is shown in figure 1.1. Van Leussen & Cornelisse (1993a) showed that there are even considerable differences in the median settling velocity/concentration relationship between two locations in the same estuary (figure 1.2). Dyer, 1989 ascribes these differences to floc density variations, organic content variations and different tidal states.

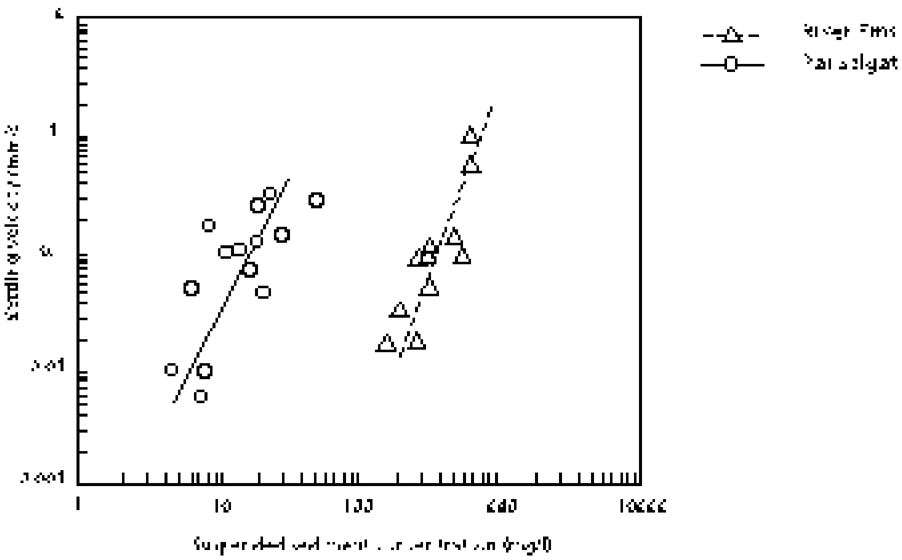

Figure 1.2 Median settling velocity obtained from field settling tube measurements as a function of the suspended sediment concentration at two locations in the Ems estuary (Van Leussen, 1994)

1.2.2 Collision efficiency

When two particles collide they do not always stick together. Therefore the collision efficiency or stickiness is also an important factor in particle flocculation. A collision efficiency factor can be added to equation 1.1:

$$N_{ij} = a \cdot K(d_i, d_j) \cdot n_i \cdot n_j \qquad (1.2)$$

Where:
a = Collision efficiency factor.

The collision efficiency factor depends on the cohesivity of the particles. The following processes mainly determine the collision efficiency or stickiness of the particles.
1. Particle charge and ion concentration in the water.
2. Biopolymers and organic coatings on the particles.

Particle charge and ion concentration in the water.

In the neutral pH range, suspended solids typically encountered in natural water are negatively charged (Stumm & Morgan, 1970; Loder & Liss, 1985). A cloud of positive ions that compensate this negative charge surrounds these particles. A concentration gradient of positive ions develops around the particles. This gradient is the result of an equilibrium between the electrostatic attraction of positive ions towards the negatively

charged particles and a thermal diffusion that causes positive ions to move towards areas of lower positive ion concentration, away from the particles. On the other hand negative ions in the solution are repulsed by the negatively charged particles and a gradient of negative ions is also formed with the lowest concentration near the particles.
These gradients of ion concentrations (in particular of the cations) are called the “diffuse double layer”. The extent of the diffuse double layer corresponds to the width of the zone where the ionic concentrations differ significantly from the concentration in the bulk (equilibrium) solution (Bolt & Bruggenwert, 1978). When the salt concentration of the solution increases, the concentration gradient of the ions decreases. That reduces the diffusion of the ions and decreases the extent of the diffusive double layer as is shown in figure 1.3 (Bolt en Bruggenwert, 1978)

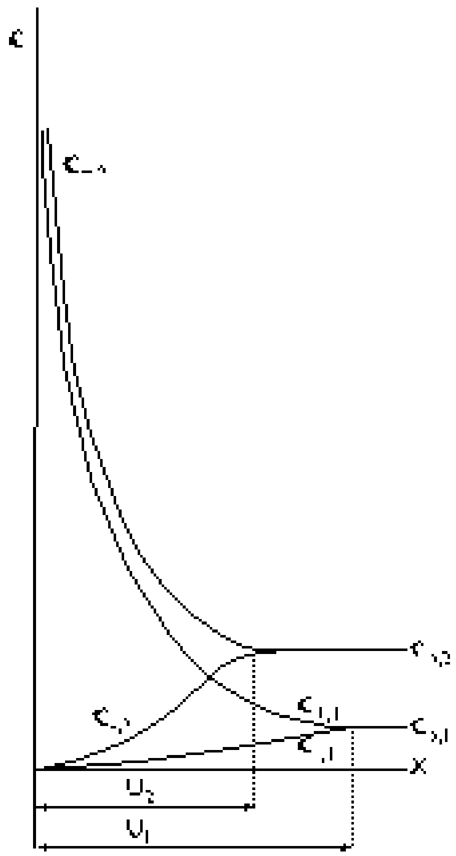

Figure 1.3 Concentration of counter and co-ions in a diffuse double layer on a negatively charged surface for two values of the equilibrium concentration, $c_{0,1}$ and $c_{0,2}$. u = extent of diffuse double layer (after: Bolt & Bruggenwert, 1978)

When two charged particles approach each other, there will be a repulsive force between the particles because the positive ions in the double layers around the particles repulse each other. There will also be an attractive Van der Waals force between the particles. The attractive Van der Waals force decreases very rapidly with increasing distance from the particle. The repulsive electrostatic force decreases exponentially with increasing distance from the particle and depends on the double layer thickness. Figure 1.4 shows an idealized model of the diffuse electrical double layer and the repulsive and attractive energies of the particles under different salt concentrations.

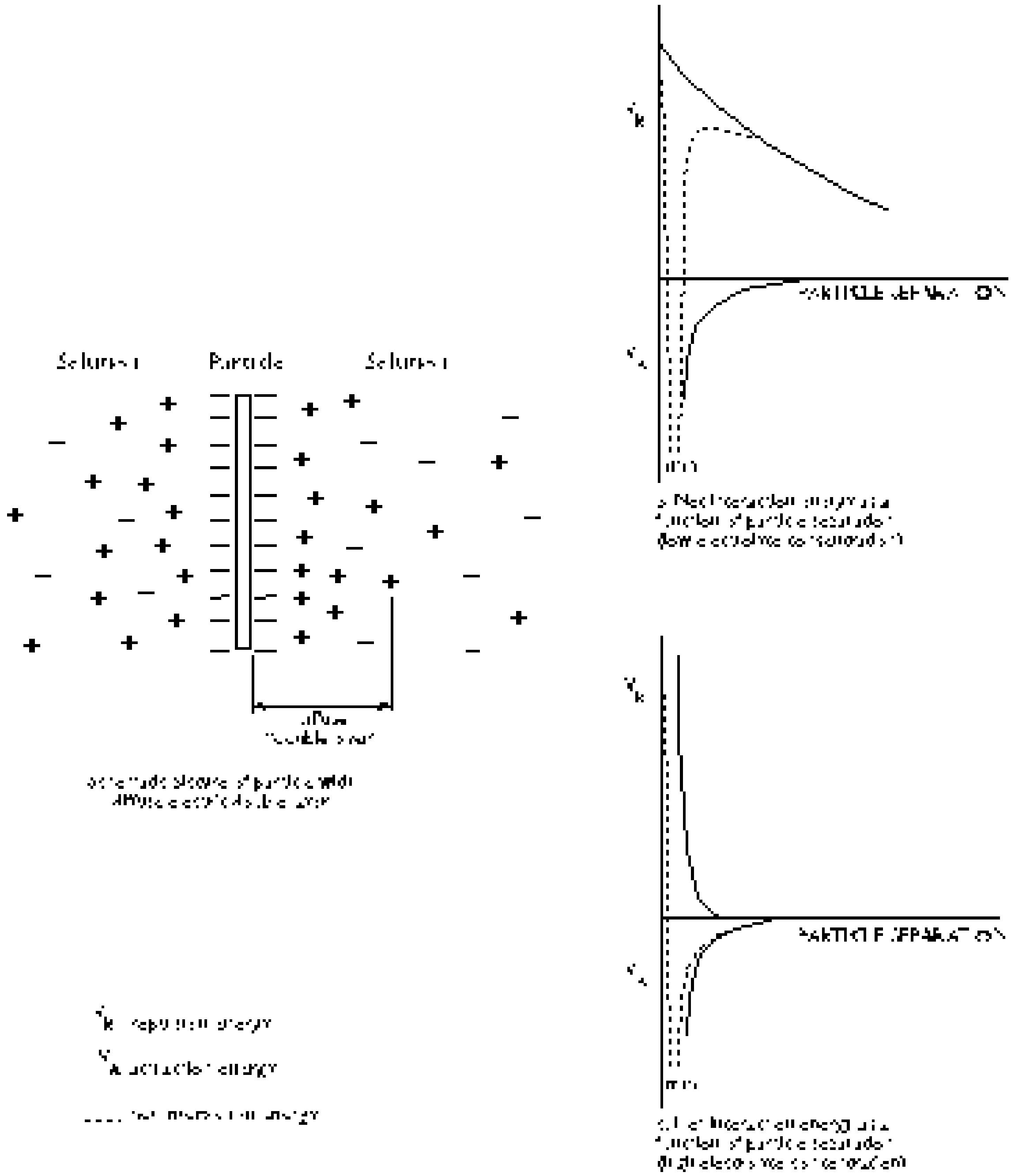

Figure 1.4 Idealized model of particle diffuse electric double layer and interaction energies. Reprinted by permission of John Wiley & Sons, Inc. from: Van Olphen, An introduction to clay colloid chemistry. For clay technologists, geologists and soil scientists, Copyright (1977)

The broken line shows the net interaction energies of the particles. With low electrolyte concentration (fig 1.4b) there is a thick diffusive double layer. Therefore the repulsive force extends so far away from the particle that the net force (electrical repulsion minus VanderWaals attraction) will cause repulsion between particles when they approach each other. With high electrolyte concentration (fig. 1.4c) the diffusive double layer is much thinner. Therefore electrical repulsion occurs only close to the particle, but there the VanderWaals attraction is already higher than the repulsive force. When two particles approach each other this VanderWaals attraction will lead to coagulation.

It is clear that particle interaction is prevented by the net repulsive force with low electrolyte (salt) concentration. With a high electrolyte concentration however, the diffuse double layer is thinner, therefore the particles can approach each other closer where the attractive Van der Waals force is higher than the repulsive electrostatic force what results in particle flocculation. This mechanism is called salt flocculation.
Not only is the concentration of ions an important factor for salt flocculation, but the valency of the ions in the solution is also an important factor. Divalent cations (Ca) are attracted more than monovalent cations by a negatively charged particle (Stumm & Morgan, 1970; Bolt & Bruggenwert, 1978). Fewer divalent cations than monovalent cations are needed to compensate the negative charge of the particle, therefore the diffuse double layer thickness will decrease with increasing valency of the counterions.

Origin of surface charge

The importance of particle charge for particle flocculation was shown above, now the origin of surface charge will be looked at. The surface charge of particles may originate in three ways:

A. Chemical reactions at the particle surface of groups like: -OH, -COOH, $-OPO_3H_2$. The charge of these particles becomes dependent on the degree of ionization (proton transfer) and consequently on the pH of the medium (Stumm & Morgan, 1970). Most oxides and hydroxides show this acid-base behaviour just as organic surfaces. Organic materials in water are often charged as a result of protolysis reactions of functional amino and carboxyl groups. for example,

$$R\begin{matrix} \diagup COOH \\ \diagdown NH_3^+ \end{matrix} \rightleftarrows R\begin{matrix} \diagup COO^- \\ \diagdown NH_3^+ \end{matrix} \rightleftarrows R\begin{matrix} \diagup COO^- \\ \diagdown NH_2 \end{matrix}$$

At low pH a positively charged surface prevails; at high pH, a negatively charged surface.

B. Surface charge at the phase boundary may be caused by lattice imperfections at the solid surface and by isomorphous replacements within the lattice (Stumm & Morgan, 1970). Clay minerals are negatively charged due to substitution of Si^{4+} and Al^{3+} ions by other cations of lower valence (Bolt & Bruggenwert, 1978). The lattices of clay minerals are terminated at the edges. Thus the edges of clay minerals contain ‘broken bonds’ of the Si-O-Si structure where acid-base reactions can take place. So in addition to the constant ‘substitution’ charge, clay minerals will posses a pH-dependent charge along the edges (Bolt & Bruggenwert, 1978). Some clay minerals will exhibit positively charged edges in the neutral pH range others will exhibit negatively charged edges in the neutral pH range. Thus, clays may carry different double layer structures on the same particle. Therefore, when clay minerals aggregate, different modes of particle association may occur: face to face, edge to face, and edge to edge (Van Olphen, 1963 in: Stumm & Morgan, 1970). These contacts between plate-shaped minerals can form a firm flocculated structure. Starting with particles of 1 µm or smaller, units of 10-20 µm can be formed, that can flocculate further into flocs of up to 200 µm size (McDowell & O’Connor, 1977)

C. Ion adsorption may also cause a surface charge. Ion adsorption can arise from VanderWaals interactions and from hydrogen bonding. The adsorption of polymers is an example. Even adsorption of anionic polymers on negative surfaces is common (Stumm & Morgan, 1970). The effect of biopolymers and organic coatings on the flocculation of particles will be dealt with in the next section.

Salinity

Increasing salinity should cause increasing flocculation because of compression of the diffuse double layer. A thinner diffuse double layer diminishes the repulsive forces between particles. In the past it was considered that flocculation was controlled entirely by salinity. It is clear right now that many other factors are also essential for flocculation (Dyer, 1989). Eisma (1986) even states that salt flocculation plays a minor role, if any. He even observed decreasing floc sizes at the salt water contact. From measurements in five Northwest-European estuaries Eisma et al. (1991a,1991b) concluded that the in situ particle size is not related to changes in salinity. Particle sizes measured by Coulter counter and pipette analysis became finer at the saltwater contact. The latter particle sizes are floc fragments formed during sampling and analysis. Van Leussen (1994) however observes an increase of macrofloc sizes in the seaward direction in the Ems estuary. He suggests that this increase of the sizes of macroflocs in the seaward direction corresponds with higher flocculation abilities in the direction of higher salinities. The effects of salinity on flocculation are more extensively dealt with in Chapter 4.

Biopolymers and organic coatings on the particles.

Organic coatings on suspended particles can have a major influence on the particle surface charge as was shown by Loder & Liss (1985). They have shown that uptake of organic material from natural water onto the particle surface can substantially alter the charge of even strongly positively charged particles. These results strongly support the idea that organic coatings control the negative surface charge of suspended particles in natural water containing its natural organic material. This shows the importance of the above described ion adsorption onto particles. Organic coatings are expected to be present on suspended particles in almost all estuaries (Van Leussen, 1994). Hunter & Liss (1982) show that suspended matter in estuarine waters possesses a high degree of surface uniformity with respect to electrical properties. They suggest that this results from the formation of metallic and/or organic surface coatings on suspended particles.

Biopolymers can significantly alter the collision efficiency of particles that have polymers attached to them. The polymer chains extend into the surrounding fluid and can become attached to another particle on the free side of the polymer chain. Causing a bridge between the two particles. This is called the interparticle bridging model (Ruehrwein and Ward, 1952; La Mer and Healy, 1963). The polymer bridges can extend over the repulsive energy barrier caused by the diffusive double layer and can cause flocculation in spite of the repulsive electrical forces. See figure 1.5.

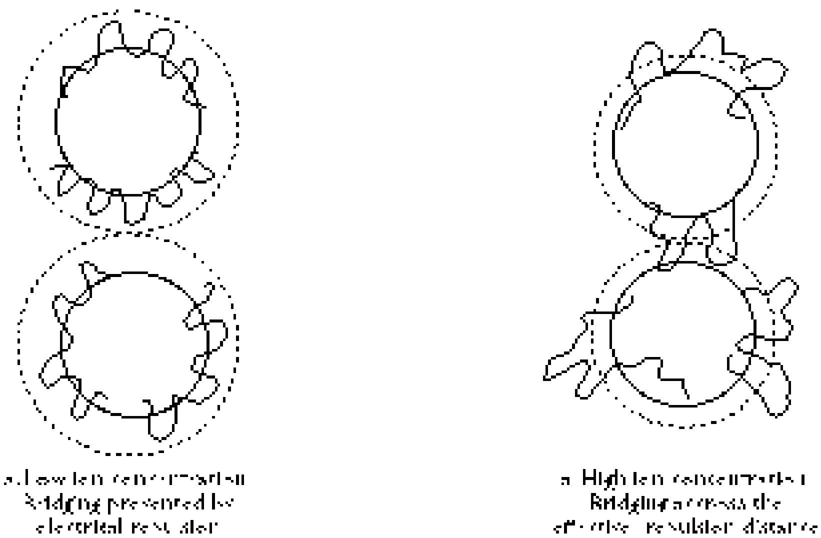

Figure 1.5 Schematic picture of polymer bridging and the repulsive energy barrier at the particle surface (Gregory, 1978; reprinted with kind permission from Kluwer Academic Publishers)

The polymer chains can form bridges between particles, but they can also become attached with all segments to the same particle. When many polymers are present all available sites for attachment may already be in use by polymers that are not attached to other particles. Therefore too many polymers may prevent interparticle bridging. This is illustrated in figure 1.6.

This implies that there is an optimal polymer concentration for optimum flocculation. When polymer concentration is low, there are few interparticle bridges and flocs are easily broken by fluid shear. When polymer concentration is high, there are too few sites available for interparticle bridging and aggregation is hindered (Van Leussen, 1994).

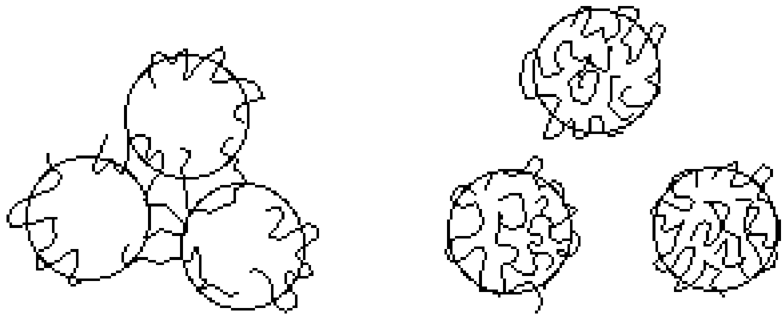

Figure 1.6 Flocculation and restabilization by adsorbed polymers (Gregory, 1978; reprinted with kind permission from Kluwer Academic Publishers)

Polymers that cause increasing collision efficiency or stickiness are humic acid, fulvic acid, RNA, DNA, proteins and polysaccharides (Van Leussen, 1994) or Extracellular Polymeric Substances (EPS). Many sticky organic polymers are released by algae as extracellular mucus that mainly consists of polysaccharides (Harris and Mitchell, 1973). Bacteria are also important producers of EPS especially during the decline of a phytoplankton bloom due to a rapid increase of bacterial biomass (Pavoni et al., 1972; Harris and Mitchell, 1973; Biddanda, 1986). The possible effects of biopolymers on flocculation of particles are more extensively dealt with in chapter 4.

1.2.3 Floc Breakup

Previously it was shown that the collision frequency of particles caused by shear is one of the most important flocculation mechanisms. Therefore floc formation depends largely on the fluid shear in the suspension. On the other hand shear can also break flocs. Floc break-up as a result of fluid shear on the particle is considered the most important floc size limiting factor (Dyer, 1989; Eisma, 1986; Hunt, 1986; Luettich et al., 1993; Van Leussen, 1994). Floc sizes can also decrease due to surface erosion of the flocs by fluid shear (Argaman & Kaufman, 1970; Parker et al., 1972) or flocs can break as a result of collisions instead of flocculate (Eisma, 1993).
Eisma (1986) found that the maximum floc size (3-4 mm) in the Ems estuary was of the same order as the Kolmogorov microscale of turbulence (λ = 3.5 mm). Van Leussen (1994) also found maximum floc sizes in the same size range as the Kolmogorov microscale of turbulence. They suggest that macroflocs are formed under viscous flow conditions, and that macro flocs will break as soon as they experience turbulent shear.

1.2.4 Water temperature

The water temperature does not seem to directly affect the flocculation process. It does however affect the viscosity and density of the water. A particle with a fixed size and density settles faster in warm water than in cold water. At a water temperature of 24ºC, a spherical quartz particle with a diameter of 93 µm has a settling velocity of about 7 mm/s.

At a temperature of 4ºC, the same settling velocity is reached by a particle with a diameter of 116 µm (Krögel & Flemming, 1998). Assuming constant energy conditions, the position at which a given particle is in depositional equilibrium will be different in summer than in winter (Krögel & Flemming, 1998). Such temperature effects may also cause differences in the average floc size or settling velocity of the sediment in the Dollard estuary in summer and winter.

1.3 Potential flocculation key parameters

In the previous sections the main flocculation mechanisms were identified. It could be seen that there is a clear distinction between the physical processes that mainly determine the collision frequency and the chemical and biological processes that mainly determine the collision efficiency or stickiness. Dyer (1989) proposed a conceptual flocculation model that relates floc size with the SSC and fluid shear (fig. 1.7).

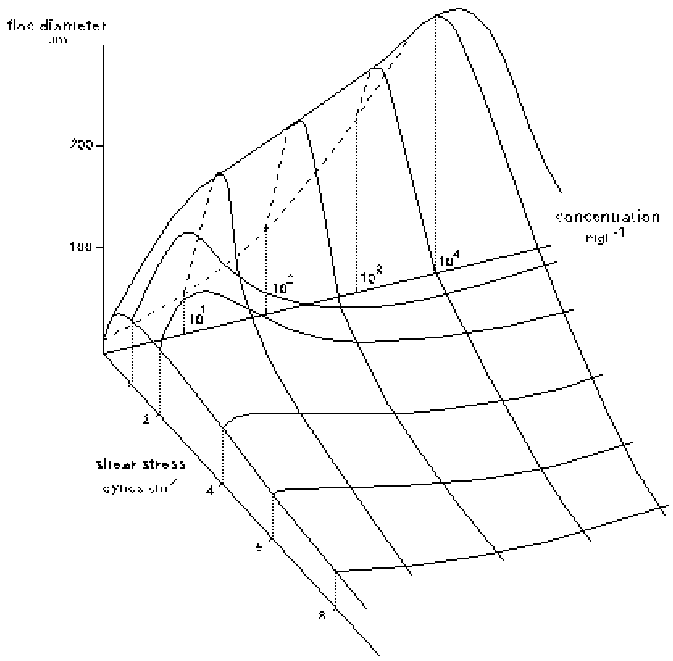

Figure 1.7 A conceptual flocculation model. (Dyer, 1989)

The model shows an increase in floc sizes with increasing SSC until hindered settling occurs. According to Dyer (1989), increasing shear stresses initially cause increasing floc sizes until floc breakup due to fluid shear becomes more important and floc sizes decrease again. In Dyers model, perikinetic flocculation (flocculation due to Brownian motion) and differential settling are not taken into account. This can be justified by Van Leussen (1994), who showed that perikinetic flocculation is unimportant for flocs in the size range normally occurring in estuaries. And also by Stolzenbach and Elimelech (1994), who showed that differential settling is hardly important for flocculation. The trajectory of smaller particles settling slower than a larger, but less dense, particle will often deflect around the larger particle instead of being scavenged by it. Only flocs that are very porous, so that water flows through them, may be able to scavenge smaller flocs.

Processes that affect the collision efficiency are also not taken into account in Dyers model. Therefore, he states that further studies of the surface characteristics of particles are required since flocculation is caused by, or strongly modified by the polysaccharide mucal films associated with bacterial or other biological activity. The conceptual model of Dyer is therefore a good starting point in modeling flocculation but it should be extended with formulations about the collision efficiency, which depends on salinity and biopolymers.

Another very important issue is the floc history. There are two aspects about this floc history:

1. The initial size of flocs after resuspension.
   The sediment may erode as constituent particles that flocculate in the water column or it may erode as flocs. These latter flocs may exhibit properties (e.g. a large density) that are the result of consolidation processes on the bed. These properties may also affect floc sizes and settling velocities in the water column independent of the processes in the water column.

2. Residence time of the flocs.
   The residence time of the flocs determines whether they reach some sort of equilibrium floc size. Van Leussen (1994) distinguished a number of turbulent zones over the water column. The flocs are moving through these zones, which results in floc growth in zones of low turbulence, and floc breakup in zones of high turbulence. The ultimate floc size is then some sort of dynamic equilibrium on the condition that the flocs do not settle before even reaching this dynamic equilibrium.
   Mehta and Partheniades (1975) stated that the strong shear and lift forces near the bed control the size distribution of the flocs in suspension.
   Winterwerp (1998; 1999) claimed, based on a flocculation model, that the ascending branch at small shear stress in the conceptual model of Dyer (fig. 1.7) is the result of a limited residence time. Flocs are unable to grow larger since they will have settled to the bed before reaching the equilibrium floc size. If the residence time was unlimited, the floc size would further increase with decreasing turbulent shear. According to Winterwerp it is not true that in the ascending branch flocculation effects dominate, and in the descending branch floc breakup processes, as is often suggested in literature.

After reviewing many possible flocculation processes it can be concluded that the size and settling velocity of mud flocs mainly depend on: the floc history, the turbulent shear, the SSC, the salinity, the biopolymer concentration and the water temperature. The floc history determines what type of flocs where eroded from the bed. The residence time of the flocs is also very important. The flocculation behaviour of flocs that reached equilibrium floc size (i.e. their size is limited by turbulent shear), will be significantly different from the flocculation behaviour of flocs that settle before they can reach an equilibrium. The turbulent shear is responsible for floc breakup. It will limit the floc size especially in the near bed zone, where turbulent shear is at it's maximum. The SSC may affect floc size, since an increasing SSC leads to increasing floc collisions, which leads to faster floc growth. Salinity and Biopolymer concentration may affect the floc collision efficiency and the water temperature affects the viscosity and density of the water, which changes the settling velocity of the sediment.

1.4 The relation between floc size and floc settling velocity: variations in density.

Floc settling velocities determine the ultimate sedimentation rate and are therefore the most interesting property of mud flocs when one is interested in sedimentation. The floc size however is much easier to measure. Therefore it is important to determine the relation between floc size and floc settling velocity.

1.4.1 Stokes law

The settling velocity of a small spherical particle with a small Reynolds number ($Re = W_s d/\upsilon$) in water is given by Stokes law:

$$W_s = \frac{1}{18}\frac{(r_s - r)}{r}\frac{gd^2}{u} \qquad (1.3)$$

Where:

W_s	=	particle fall velocity (mm/s)
ρ_s	=	particle density (kg/m^3)
ρ	=	fluid density (kg/m^3)
ρ_s-ρ	=	effective density (kg/m^3)
g	=	gravitational acceleration (9.81 m/s^2)
d	=	particle diameter (m)
υ	=	kinematic viscosity of the fluid (m^2/s)

From Stokes law, it can be seen that the settling velocity of particles depends on particle size as well as the effective density, (ρ_s-ρ), of the particles. Settling flocs however are not spherical and sometimes the Reynolds number of large and fast settling flocs exceed the applicable range ($Re < 1$) for Stokes law. Furthermore the average density of the flocs is generally unknown. Normally floc density decreases with floc size. In addition, the flow field around flocs is modified due to flow through the floc as well as around the floc. As the floc density is generally unknown, the settling speeds of flocs can not be predicted through the use of Stokes law and must be measured directly. According to Stokes law an increase in particle size should result in a quadratic increase in settling velocity. But since the floc density decreases with floc size, this increase in settling velocity is partly diminished. Floc density calculations from measured floc sizes and settling velocity will be extensively dealt with in chapter 5. The effects of porosity, non-sphericity and Reynolds numbers larger than 1 will also be discussed in chapter 5.

1.4.2 Orders of aggregation

It has been established that several orders of aggregation may exist (Krone, 1978 in: Partheniades, 1993; Partheniades, 1965). The first order is the commonly known “floc” consisting of primary particles. A floc, or second order aggregate, is a conglomerate composed of first order flocs. A third order floc is an agglomeration of second- and lower-order flocs and so on. Michaels and Bolger (1962), Firth and Hunter (1976) and Van de Ven and Hunter (1977) proposed a four level floc structure: primary particles - flocculi - flocs - aggregates. Figure 1.8 is a schematic picture of this floc structure (François, 1985).

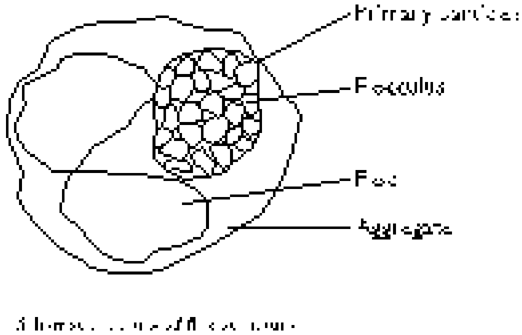

Figure 1.8 Schematic picture of floc structure (François, 1985)

Eisma, 1993 distinguishes macroflocs that can be broken into microflocs by turbulent shear. Microflocs can be seen as flocs in the floc structure and macroflocs can be seen as aggregates. He does not use the terms flocculi, flocs and aggregates to give a size definition because he distinguishes many different floc types with different sizes, organic matter contents, shapes, and structures that cannot be described with a four order floc structure. In this thesis aggregates and flocs are defined as clusters of fine particles and organic constituents without a size definition.

1.4.3 The fractal dimension of flocs

According to Stokes law of settling velocity (eq. 1.3), the settling velocity of a floc depends on the floc diameter and its density. This floc density and floc diameter can be related to each other by using a fractal aggregate model. This model assumes that the structure of mud flocs is a self-similar fractal (Mandelbrot, 1982 in: Kranenburg, 1994). That means that the smaller building blocks of a larger particle have the same structure and geometry, on all size scales. So when such larger particles form an even larger particle or aggregate this aggregate has the same structure and geometry but now on a larger size scale, and it contains the same number of building blocks as on the smaller size scale. So the aggregate is build from for example 15 larger particles and the larger particles are build from 15 smaller building blocks and so on until the building blocks consist of the primary particles e.g. clay minerals. As a result, the Total number N of primary particles in a fractal aggregate or floc of size d scales as (Kranenburg, 1994):

$$N \sim \left(\frac{d}{d_p} \right)^{nf} \tag{1.4}$$

Where, d_p (m) is the size of the primary particles, and nf is the fractal dimension. The fractal dimension may be any number between 1 and 3. When nf = 3 the density of a large particle equals the density of a small particle, since the volume of the larger particle is totally filled with smaller particles. When nf = 1 the volume of a large particle is only very partially filled with smaller particles and therefore the density of particles decreases with increasing size. This results in a very loose floc structure and very low densities of larger flocs. The differential density of a mud floc in water is (Winterwerp, 1998):

$$\Delta \rho_f = \rho_f - \rho_w \propto (\rho_s - \rho_w) \left[\frac{d_p}{d} \right]^{3-nf} \tag{1.5}$$

Where ρ_f (kg/m^3) is the floc density, ρ_w (kg/m^3) is the density of water, and ρ_s (kg/m^3) is the density of the primary particles. If we consider that the density of the primary particles (ρ_s), the density of water (ρ_w) and the size of the primary particles (d_p) are all independent of the floc size (d), equation 1.5 reduces to:

$$\Delta \rho_f \propto d^{nf-3} \text{ or } \rho_f \propto d^{nf-3} \tag{1.6}$$

And since the gravitational acceleration g and the kinematic viscosity ν are also independent of the floc diameter the combination of Stokes Law of settling velocity (equation 1.3) and equation 1.6 results in:

$$W_s \propto d^{nf-1} \tag{1.7}$$

The fractal dimension can therefore be determined from a log-log plot of size versus settling velocities as well as a log-log plot of size versus floc density.

According to Kranenburg (1994) the fractal dimension may serve as a unifying parameter that relates various properties of cohesive sediment, like size and settling velocity, density, strength, permeability, bed structure etc. He however also states that it would be naive to expect that mud would form aggregates that are exactly self-similar, because of the large variability in mud properties. Fractal theory assumes homogeneous primary particles, while in nature these primary particles may vary as well in size as in material origin (organic matter, clay minerals). This may weaken the concept of self-similarity.

The use of the fractal dimension seems however justified since a power-law relationship between differential density and floc size (as in equation 1.6) or floc settling velocity and floc size (as in equation 1.7) is commonly observed, by several authors (e.g. Gibbs, 1985; Hawley, 1982; Kajihara, 1971; Tambo & Watanabe, 1979; Ten Brinke, 1993). These authors all found a decreasing density with increasing floc size.
Several authors used, instead of Stokes law, an empirical power-law relation between floc settling velocity and floc size: $w_s = ad^m$, which is equivalent to equation 1.7. Both a and m are variables that are dependent on flocculation parameters like fluid shear, sediment concentration and salinity (Lick & Huang, 1993). Ten Brinke (1993) found $m = 0.92$ ($nf = 1.92$) for the Eastern Scheldt tidal basin. Alldredge and Gottschalk (1988) found $m = 0.26$ ($nf = 1.26$) for marine snow. Burban et al. (1990) found values for m varying between 0 and 2.1 (nf between 1 and 3.1) for tests in a settling column with fresh water and seawater. In general m is almost always less than two and generally less than one. This demonstrates the decrease in the effective density of a floc as the diameter of a floc increases (Lick & Huang, 1993). According to equation 1.7 the corresponding fractal dimensions (nf) are in the range 1-3. These values confirm that the full spectrum of aggregate structures, from tenuous to compact, occurs in nature as well as in the laboratory (Kranenburg, 1994).

Summary

The settling speed of flocs is a function of floc diameter and floc density. The non-spherical shape of flocs and the open internal structure of flocs, which can modify the flow around and through the floc, also affect the settling speed but are generally minor factors compared to the changes in floc size and density (Lick & Huang, 1993). Therefore an approximation of the actual average density of a floc can be determined from Stokes law (eq. 1.3), when the floc settling velocities and floc size are known, and their Reynolds number does not exceed the applicable range for Stokes law. Furthermore, the fractal dimension may serve as a unifying parameter that relates various properties of cohesive sediment, like size and settling velocity, density, strength, permeability, bed structure etc. (Kranenburg, 1994).

1.5 The temporal and spatial variation of mud floc sizes and settling velocities in an estuary.

In an estuary, mud floc properties are changing constantly over time and in all three spatial dimensions. In the previous section the parameters that steer these changing properties were identified. For understanding these variations in mud floc properties we therefore need to know how the parameters that steer these properties vary. There is a clear distinction between the physical processes that determine the collision frequency of the flocs and the biological and chemical processes that determine the collision efficiency of the flocs. The physical processes vary mainly within the tide whereas the biological and chemical processes vary mainly on a seasonal time scale. There is also a clear distinction between the spatial variation along the estuary, the variation across the estuary and the variation with depth. Therefore the variation in flocculation processes will be studied on two time scales, the scale of the tide and the scale of the seasons and in three spatial directions, along the estuary, across the estuary and relative to the bed of the estuary.

1.5.1 Tidal variations

The current velocity that varies within the tide determines the variations in SSC and turbulence intensity. With higher current velocities the SSC will increase which may result in an increase in floc sizes. Simultaneously however the turbulence intensity also increases. When turbulence intensities are high, this could result in floc breakup. Towards the bed the turbulence intensity increases. That could even enhance floc breakup (Van Leussen, 1994). When the tide passes a fixed point in the estuary, changing properties of water and suspended sediment can occur due to gradients in these properties along the estuary. These variations can be excluded by observing the tidal variation in a Lagrangean way. That means that variations are observed floating with the current, following approximately the same water column. While following this water column, the salinity will remain constant and the biochemical properties of the suspended mud will probably not change on a tidal time scale. However, the erosion of bed sediment with different properties than the suspended sediment may change the overall suspended sediment properties. The biopolymer concentration may also change during the day due to a fast production of EPS by plankton when there is enough light for photosynthesis.

1.5.2 Seasonal variation

On the seasonal time scale many flocculation parameters can vary. The SSC may vary due to displacements of the turbidity gradient in the estuary as a result of changes in river discharge. This will also affect the salinity. Especially in spring, plankton blooms may occur that result in large amounts of biopolymers in the water, which could increase the stickiness of the mud. Phytobenthos blooms on the tidal flats may also contribute to the biopolymer content in the water and in an increased erosion resistance of the tidal flats. Kornman & de Deckere (1998) observed a lower SSC in the Dollard estuary, which was presumably caused by an increased erosion resistance of the tidal flats due to a phytobenthos bloom in the spring of 1996. Both the biopolymers, excreted by the phytobenthos, as well as the lower SSC may have affected floc sizes and settling velocities.

1.5.3 Variations along the estuary

Estuaries are characterized by a salinity gradient from the river to the sea. Most estuaries also have a SSC gradient with a turbidity maximum in the upper estuary. This also results in an increase in mud content of the bed sediments. In the upper estuary the tidal flats are often better protected against storm waves which also results in a higher availability of fine-grained sediments on the bed. Going from the turbidity maximum towards the sea the SSC decreases and floc sizes should also decrease. Van Leussen, 1994 however observed an increase in maximum floc size towards the sea. He ascribes this floc size increase to the increased salinity, which should have increased the flocculation ability of the suspended mud.

1.5.4 Variations across the estuary.

Along the estuarine channels are the tidal flats. When they are immersed the water above them is shallow and waves can easily increase erosion. This increase in suspended sediment could result in larger flocs, but the increase in turbulence intensities due to waves and the close proximity of the bed may also result in floc breakup.

1.5.5 Variations with depth

Near the bed turbulence intensities are higher due to current shear along the bed. Near the bed therefore floc breakup is more likely to occur. Due to the balance between vertical diffusion and settling velocity of the sediment, a vertical concentration gradient develops with higher SSC near the bed. This leads to a higher collision frequency of the flocs near the bed, which may promote flocculation.

1.5.6 Separation of flocculation processes.

It is clear that assessing mud floc properties from flocculation parameters requires knowing the impact of the separate flocculation processes on these mud floc properties. Many flocculation parameters vary simultaneously and therefore it is difficult to extract the impact of one single parameter on mud floc properties. How do we identify and quantify the separate impact of the flocculation parameters on mud floc sizes and settling velocities?

Flocculation parameters like salinity, SSC etc. all vary on different time scales and spatial scales. They can rather easily be determined by measurements. A limited data series on mud floc sizes and settling velocities on different temporal and spatial scales can also be measured. These measurements are however much more laborious and less reliable as will be discussed in chapter 2.
Data on flocculation parameters and floc sizes / settling velocities can be combined and will be used in this thesis to separate some of the different processes that determine floc sizes and settling velocities. Simultaneously, these processes will be quantified empirically for so far that is possible.

2 FIELDWORK AND METHODOLOGIES

2.1 Introduction

The present research was undertaken in the Dollard estuary. Three different instruments were used for measuring floc sizes and/or settling velocities. Furthermore other parameters that were important for studying flocculation processes were collected with numerous other instruments. This chapter will give a description of the Dollard estuary, the instruments used to collect data and the measurement strategy. The instruments used for collecting data will also be evaluated.

2.2 Research area: The Dollard estuary

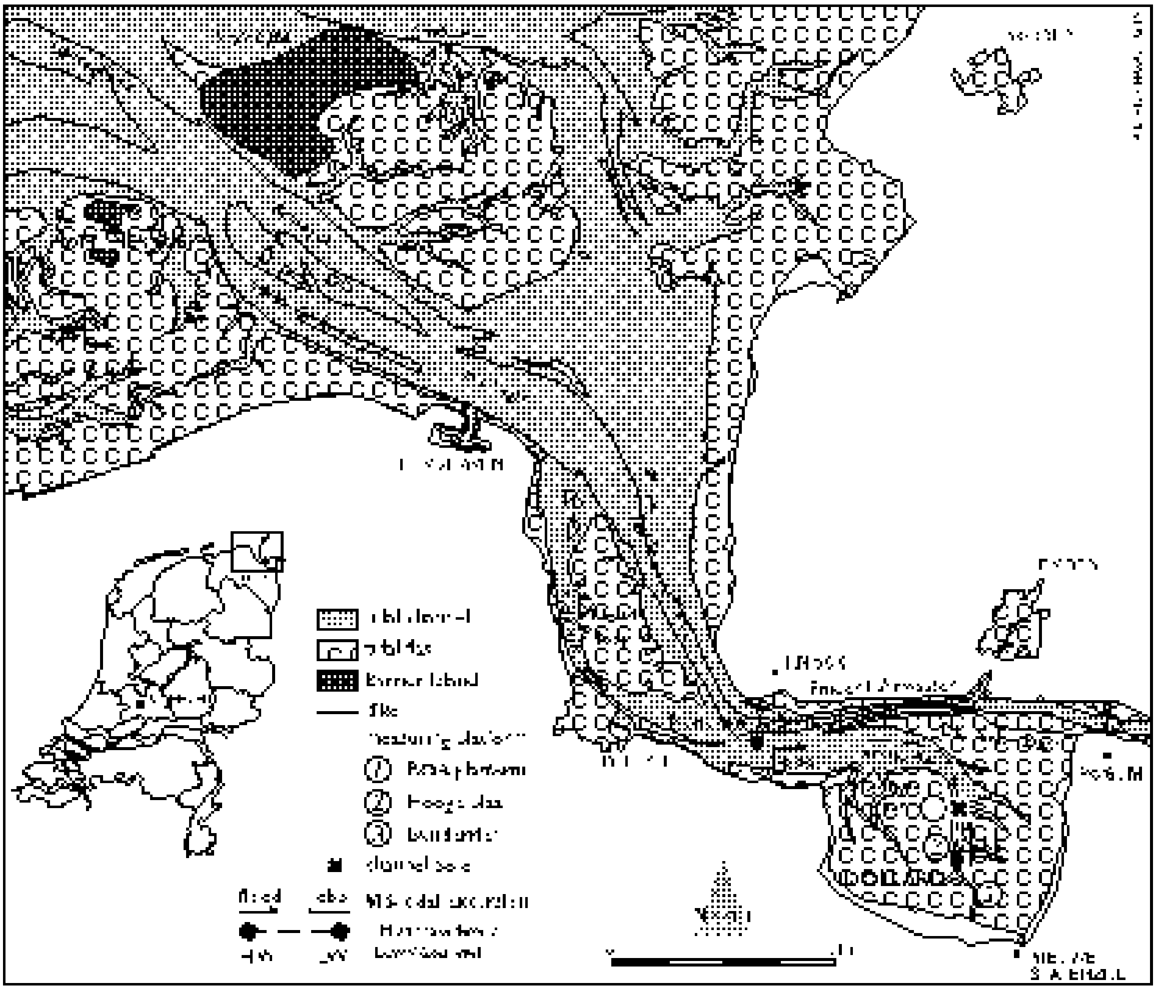

Figure 2.1 The Dollard estuary

The research was carried out in the Dollard, which is located near the head of the Ems-Dollard estuary (fig. 2.1). This meso-tidal estuary may be classified as well mixed, even at high discharges (Van Leussen, 1994). The estuary is 75 km long between the mouth and the fluvial tidal boundary at the town of Leer in Germany, and covers 500 km^2 in area, the outer delta excluded. The tidal range varies from 2.25 m in the mouth to over 3.0 m near Emden and in the south-eastern part of the Dollard. Fresh water inputs into the estuary are from the Ems river (100 m^3/s on average) and from the Westerwoldse Aa (12.5 m^3/s on average)(De Jonge, 1992). As the Dollard is part of the larger Ems-Dollard system salinity gradients and suspended sediment concentrations in the Dollard are affected by the Ems estuary. In the mouth of the Dollard near Delfzijl (fig. 2.1) Ems and Dollard waters are mixed during ebb and flow into the Dollard again during flood.

The tidal prism of the Dollard is about $115x10^6$ m^3 and the tidal excursion is about 12 km (De Jonge, 1992). On the lower reaches of the Ems, the intertidal flats comprise about 40% of the estuary, but about 85% of the Dollard consists of muddy tidal flats. These flats are situated along the main tidal channel 'Het Groote Gat'. On about 70% of the Dollard tidal flats, the mud content exceeds 50%. The surface of the tidal flats is quite smooth and uniform. Sometimes wave ripples occur when and where the surface material contains sand. Small dewatering channels are present on the lower flats along the main channel. An extensive physical system description of the Ems/Dollard estuary is given in Van der Ham (1999). The Dollard was chosen for the present research for its relatively simple geometry (one tidal channel bordered by tidal flats), its muddy character and the availability of much data from previous research.

2.3 Instrumentation for measuring floc size and settling velocities

For measuring floc sizes and/or settling velocities three different instruments were used. The Video *In Situ* (VIS), a Braystoke SK110 Owen tube and the Cilas925 Laser particle sizer. These instruments will be described and evaluated below.

2.3.1 The Video *In Situ* (VIS)

Floc size and settling velocity measurements took place with an underwater video camera, the Video *In Situ* (VIS) (Van Leussen & Cornelisse 1993b).
The VIS was deployed from a research vessel floating with the current, in a quasi-Lagrangian approach. The VIS consists of an underwater housing that contains a settling tube. When the VIS is immersed in the water, flocs can settle from above into the settling tube. In the settling tube the flocs are illuminated by a light sheet, filmed by a CCD camera and recorded by a superVHS video camera (fig. 2.2;2.3). During a VIS operation the section of the VIS, where floc sizes were measured, was about 2.9 m below the water surface. The VIS floated some 30 meters away from the research vessel, and was connected to the research vessel by power and video cables. Floating with the current minimised the effect of turbulence around the VIS, which could cause floc break-up. It

also minimised the effect of horizontal advection. The variation in suspended sediment concentration or floc sizes were therefore supposed to be the result of local erosion/sedimentation or flocculation/break-up and not of horizontal advection.

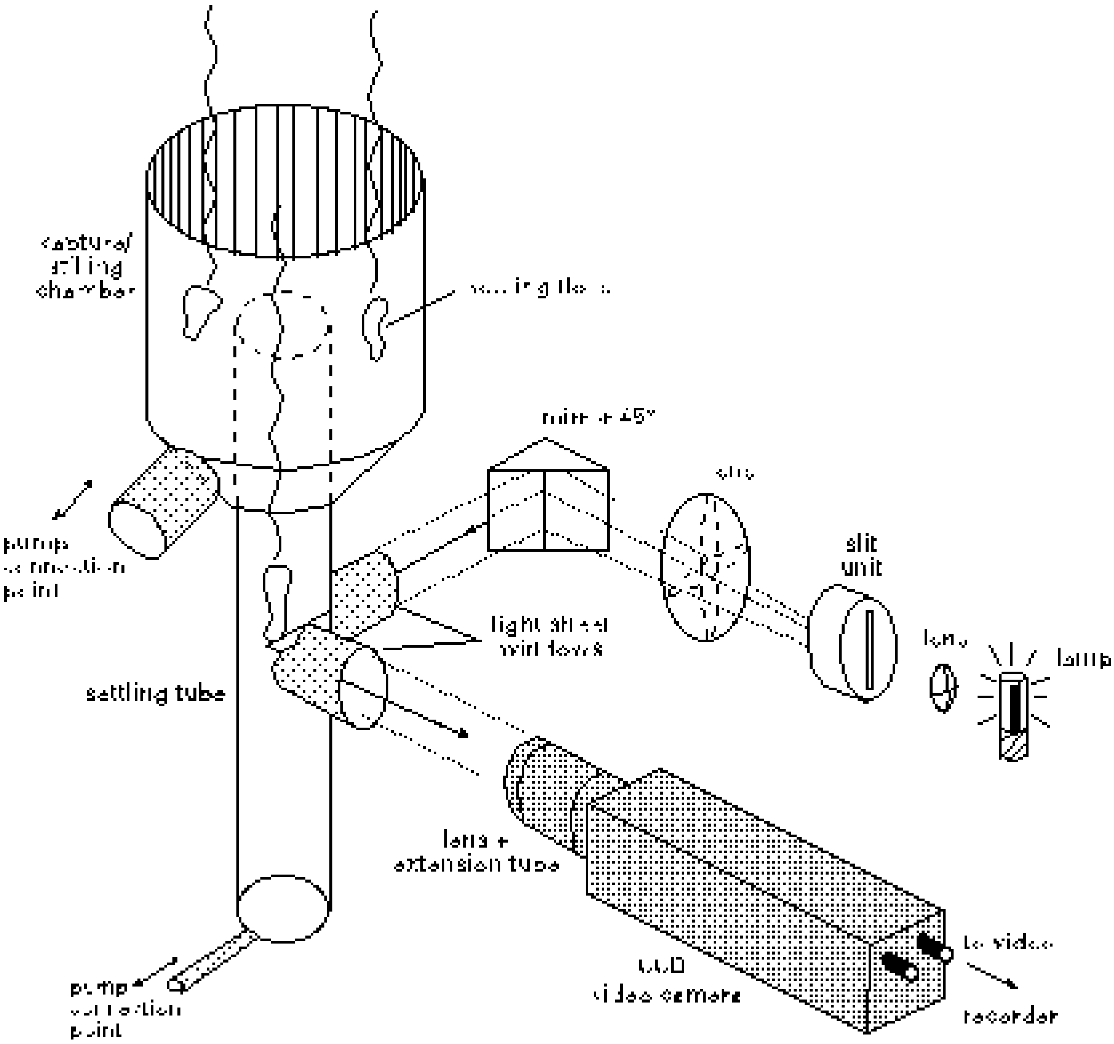

Figure 2.2 The Video *In Situ* (VIS) (Van Leussen & Cornelisse 1993b)

Video *In Situ* data processing

Video images of the Video *In Situ* system cover an area of 6.5 mm (vertical) x 10 mm (horizontal). The images were digitised and processed to obtain size and settling velocity of the observed mud flocs. This was done with an IBAS image analysis system at the faculty of Biology at Utrecht University. The floc size was defined as the equivalent diameter of a circle with the same surface area as the surface area of the floc measured with the VIS. Settling velocities were determined for flocs that appeared in consecutive images. The time interval between consecutive images depended on the settling speed of the flocs, their size and the water movement in the VIS. Mostly a time interval of 0.08 s between consecutive images was used. Often the settling velocity of the same floc was determined several times in consecutive images. Each of these floc settling velocity determinations were used for the calculation of average floc settling velocities, so flocs that appeared longer in the consecutive images contributed more often to the average. Floc settling velocities were not determined for each VIS measurement. They were obtained for only two VIS measurements on each measurement day, since the data processing to obtain floc settling velocities was very laborious and much more time consuming than measuring floc sizes.

Figure 2.3 The Video *In Situ* (VIS)

The following errors may occur due to video image quality, data processing limitations and water movement within the settling tube of the VIS:

1. Floc diameters were determined from the surface area of the flocs on the video images. The floc diameter was calculated from the floc surface area as if this surface area was a circle. A lower detection limit with a surface of 35 pixels per floc was chosen, to avoid noise in the video-images being interpreted as flocs. This surface of 35 pixels represents a floc diameter of about 85 µm, that means that flocs smaller than 85 remain undetected. A second camera in the VIS took enlarged images. With this camera smaller flocs could also be detected. Since this camera observed a very limited measurement section it did not detect enough flocs for a statistical determination of the floc size distribution. However, it was used to estimate the volume percentage of flocs that remained below the detection limit of the main camera. It appears that on average about 8% and a maximum of 15% of the suspended sediment volume remained undetected by the larger camera. That means there is a certain overestimation of the size of flocs determined with the large camera of the Video *In Situ*.
2. Flocs that are only partially illuminated by the light sheet in the VIS appear to be smaller than their actual size. Flocs that are out of focus may be digitised too large or too small when the fuzzy edges are converted to sharp boundaries. Sometimes overexposure of the flocs leads to oversaturation of the videcon, so that flocs on the screen appear larger than their actual size. The effects of partial illumination, fuzzy flocs and overexposure on the calculated floc sizes can be established by comparing the consecutive calculated sizes of one and the same floc in different images. In a randomly chosen VIS measurement, the average standard deviation of the calculated sizes of one floc was 13 µm, with an average floc size of 130
standard deviation observed in the size of one floc was 21 µm (floc diameter = 155 µm, N = 15).
3. Floc settling velocity in the VIS was complicated by water movements in the settling tube of the VIS. Only those parts of a VIS measurement were selected for determination of settling velocities, that showed no visible water movement or that showed an equal downward water movement throughout the measurement section. The water movement was determined by assuming that the average velocity of the 5% slowest settling flocs was equal to the water movement. This water movement was then subtracted from all measured floc settling velocities. As the smallest flocs observed by the VIS are already as large as 85 µm this method leads to an overestimation of the water movement and therefore to an underestimation of the floc settling velocities.
4. Small scale turbulence can also affect the observed settling velocities in the Video *In Situ*. The effect of this can be assessed by looking at the settling velocities of one and the same floc in consecutive images of the VIS. This resulted in an average standard deviation of the settling velocity of about 0.37 mm/s, with an average settling velocity of about 3 mm/s. The maximum standard deviation observed in the settling velocity of one floc was 0.66 mm/s (floc settling velocity = 3.9 mm/s, N = 14).

Summarizing, there is approximately a 10-20% error in floc sizes and settling velocities. That means that the Video *In Situ* results still provide a reasonable reliability, despite all possible measurement errors. The VIS does distinguish the absolute sizes of the larger flocs. This is generally acceptable since these largest flocs dominate the vertical mass flux towards the bed (Van Leussen & Cornelisse, 1993a).
Disadvantages of the VIS are the large size and weight of the instrument and the fact that instantaneous measurements are impossible due to the complicated and labour-intensive post processing. Deployment above the tidal flat is therefore impossible as well as measurements of vertical size distribution profiles.
Therefore the VIS was only used for measurements throughout the tidal cycle in the Dollard tidal channel "Het Groote Gat".

Presentation and averaging of VIS data

Throughout this thesis floc sizes are presented as size distributions subdivided in size classes. These size classes are based on the equivalent spherical volume of the flocs and not on the number of flocs. For example: a few large flocs may contain 20% of the total volume of flocs in a sample, but only 2% of the number of flocs in that sample. It is apparent that a small number of flocs may constitute a large part of the total volume and mass of suspended matter in a sample. A volume based average is more representative for the larger flocs that are most important for the suspended sediment flux. Therefore the floc size distributions throughout this thesis present the percentage of flocs by volume and not the number percentage of the flocs. The percentage of flocs by mass would even be a better measure, but this requires knowledge about the densities of the measured flocs. Since these densities can not be determined most of the times, the percentage by volume is used as the best substitute.

When average floc sizes are calculated, also the volume based average is used. That is, all equivalent spherical volumes of the flocs are calculated. Then the average volume is calculated and transformed back into a floc size. In a formula:

$$\left(\sum_{i=1}^{N} d_i^3 \Big/ N \right)^{1/3} \tag{2.1}$$

Where d = floc diameter and N = number of measurements.

When an average settling velocity of the flocs is calculated, the mass weighed average is used, since it is the mass of the suspended flocs that determines the sediment flux, and not the number of flocs. The mass is calculated from the flocs equivalent spherical volume and it's Stokes density. The Stokes density is calculated from the measured floc sizes and settling velocities. Chapter 5 will deal more extensively with the use of Stokes law for floc density calculations. The calculation of the mass weighed average settling velocity in a formula reads as:

$$\frac{\sum_{i=1}^{N} m_i \cdot w_i}{\sum_{i=1}^{N} m_i} \qquad (2.2)$$

Where w = floc settling velocity, m = floc mass and N = number of measurements.

2.3.2 Owen tube (Braystoke SK110)

Figure 2.4 The Owen tube (Valeport Braystoke SK110)

A commercially available Owen tube, the Braystoke SK110 from Valeport was used for the experiments. The instrument combines a water sampler and settling tube in one (fig. 2.4; 2.5).

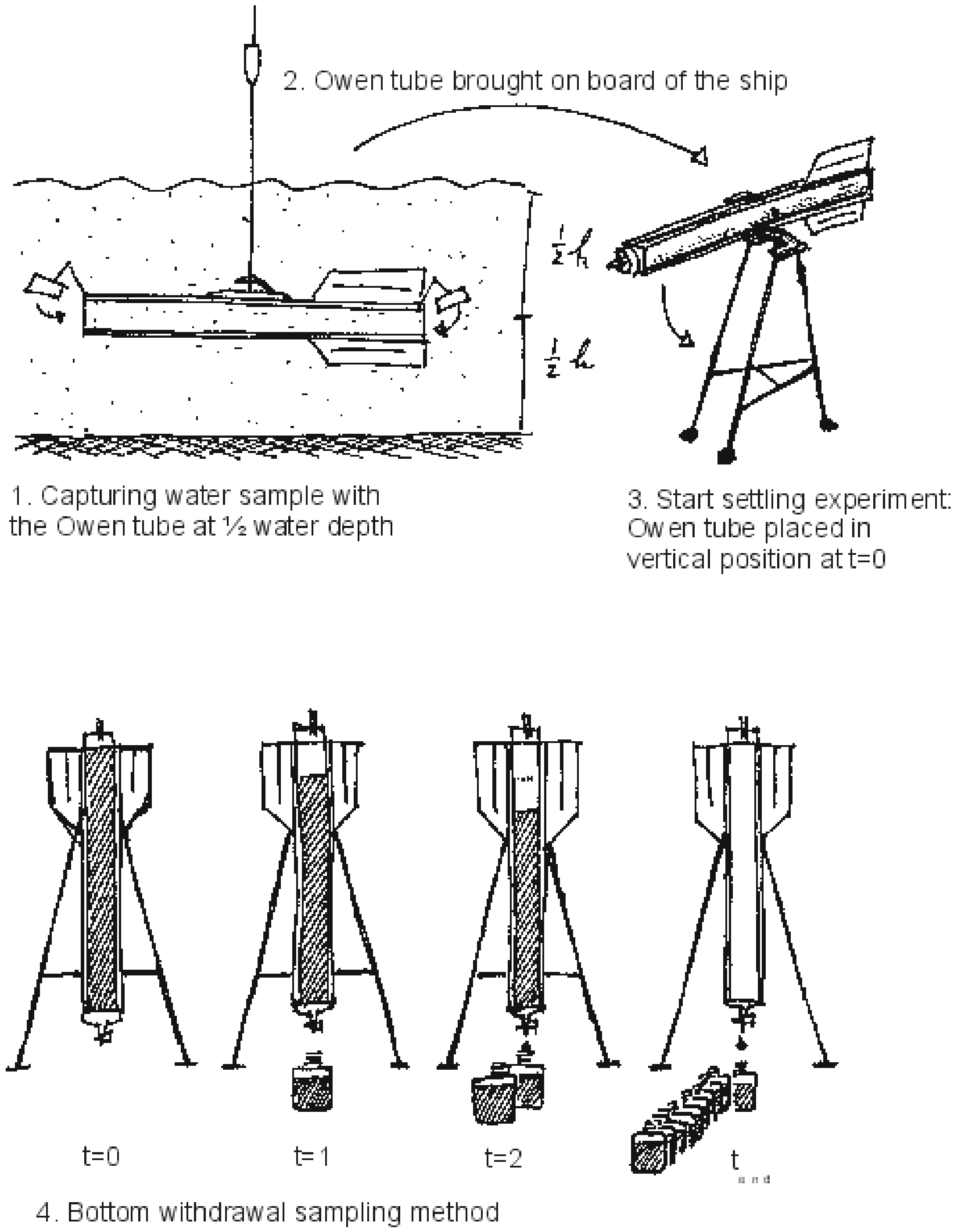

Figure 2.5 Operation of the Owen tube Braystoke SK110 (drawing: P. van der Wal)

The Owen tube consists of a 1 m long Perspex tube of diameter 50 mm and a volume of 2 dm^3. A tail fin is mounted on the back of the tube causing it to line up in the flow direction when lowered into the water. The tube is sealed at both ends by a release messenger from the surface when the tube is at the desired depth (generally half the water depth). After closure, the tube, remaining in a horizontal orientation, is taken out of the water as quickly as possible and placed in a vertical position in a tripod stand (Dyer et al., 1996). At that instant the stopwatch is started, and ten sub samples are withdrawn from the bottom of the tube at t = 30 s, t = 1, 2, 5, 9, 15, 25, 40 and 60 minutes. The remaining tenth sample contains the sediment that settles slower than 10 cm in 60 minutes. The sediment concentration of the sub samples is determined by filtration over glassfiber filters and from this data a settling velocity distribution is obtained according to the method described by Owen (1988).

During an intercomparison experiment in a tidal channel in the Elbe estuary with different in situ techniques for floc settling velocity measurements, Dyer et al., 1996 found that Owen tubes (i.e. field settling tubes) generally give settling velocities an order of magnitude smaller than direct video measurements. They suggest that the tubes may disrupt flocs on sampling. Dearnaley (1996) filmed the settling flocs in an Owen tube and compared their settling velocities with those from gravimetric analysis of the same tube. His analysis indicated floc breakup, reflocculation and the development of significant circulations within the settling column during the withdrawal of samples for the gravimetric analysis. Most strikingly he found that the settling velocities determined with the video camera inside the tube, were an order of magnitude higher than the settling velocities determined from gravimetric analysis from the same tube.

This shows that at least not all fast settling flocs were broken during sampling since they were observed with the video camera after sampling. In an inter-comparison of floc size measuring instruments, the camera that filmed inside the Owen tube measured floc sizes that were comparable to the floc sizes measured with other instruments, like in situ cameras, during the Elbe experiment (Eisma et al., 1996). Dyer et al. (1996) also showed that the settling velocities measured by Dearnaley (1996) in the Owen tube were comparable to the settling velocities measured with the underwater cameras VIS and INSSEV during the Elbe experiment.

According to Dearnaley (1996), the Owen tube samples provide information concerning the net settling of material within a column of water, taking into account the associated processes of floc breakup, reflocculation, hindered settling, circulations set up in the column and the effects of the withdrawal of material from the column. However, these processes in the Owen tube are not representative for the natural processes. Therefore the absolute settling velocities obtained from Owen tube measurements are not representative for natural conditions.

Dyer et al. (1996) concluded from the Elbe intercomparison experiment that a well-controlled sampling protocol with the settling tubes gave consistent results. Therefore changes in settling velocities measured from consecutive Owen tube measurements through time may still provide useful information about relative settling velocity variations.

The Owen tube was used for relative settling velocity measurements above the Dollard tidal flats where the VIS could not be used.

2.3.3 Laser particle sizer (CILAS925)

The commercially available CILAS 925 laser particle sizer was used for measurements of floc sizes (fig. 2.6). It consists of a 75 cm long tube with a diameter of 25 cm. The tube contains a laserdiode and a detector array, with a sensor unit with a measurement section of 30 mm on top of the tube. The output of the Cilas particle sizer is a particle size distribution for spherical particles. Since mud flocs are generally not spherical, this leads to inaccuracies in the measured size distributions. The values produced by the CILAS need therefore be considered as uncalibrated results. The two largest size classes of the Cilas generally showed unrealistic results. These were very likely to be measurement errors as they were also present when the instrument was measuring in air. Therefore the two largest size classes were ignored and as a result, the Cilas distinguished only particles smaller than 320 µm. Video *In Situ* data from the Dollard estuary show that flocs larger than 300 µm generally occur (Van Leussen, 1994; Van der Lee, 1998). This is a major limitation of the Cilas instrument, as it does not distinguish the largest flocs that are most important for the sediment mass flux.

Figure 2.6 The Cilas 925 laser particle sizer

2.3.4 Comparison between the Video *In Situ* and the Cilas laser particle sizer

On 18 April 1996 an intercomparison was made between the Cilas and the VIS in the tidal channel “Het Groote gat” in the Dollard estuary throughout a tidal cycle. The VIS and Cilas were deployed from the vessel, floating with the current in a quasi-Lagrangean way, minimizing the effect of horizontal advection and current shear on the measurements. The results from these measurements are presented in figure 2.7 and 2.8.

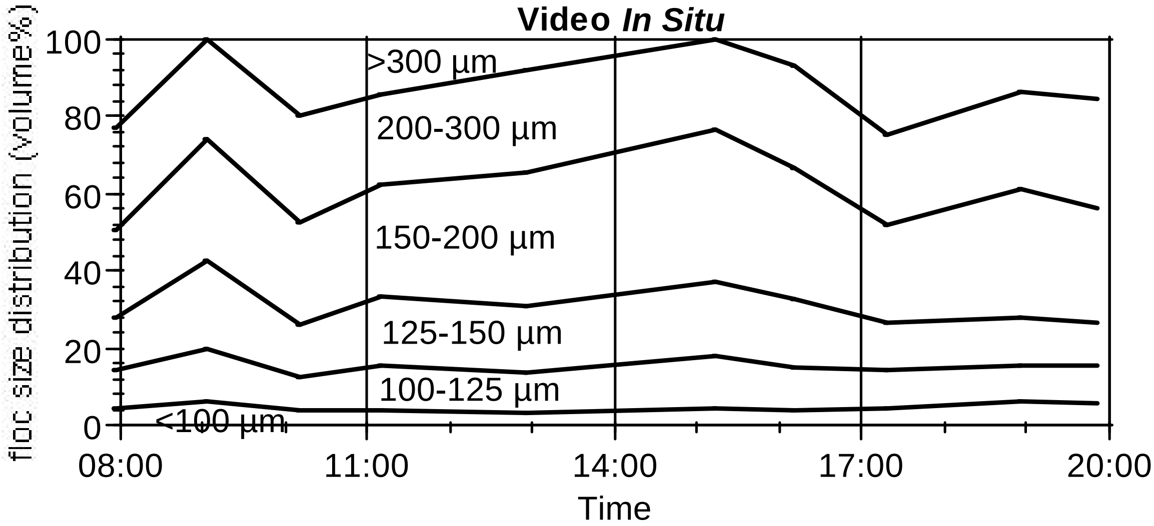

Figure 2.7 Floc size distribution determined with the Video *In Situ* in the tidal Channel "Groote Gat" throughout the tide on 18 April 1996

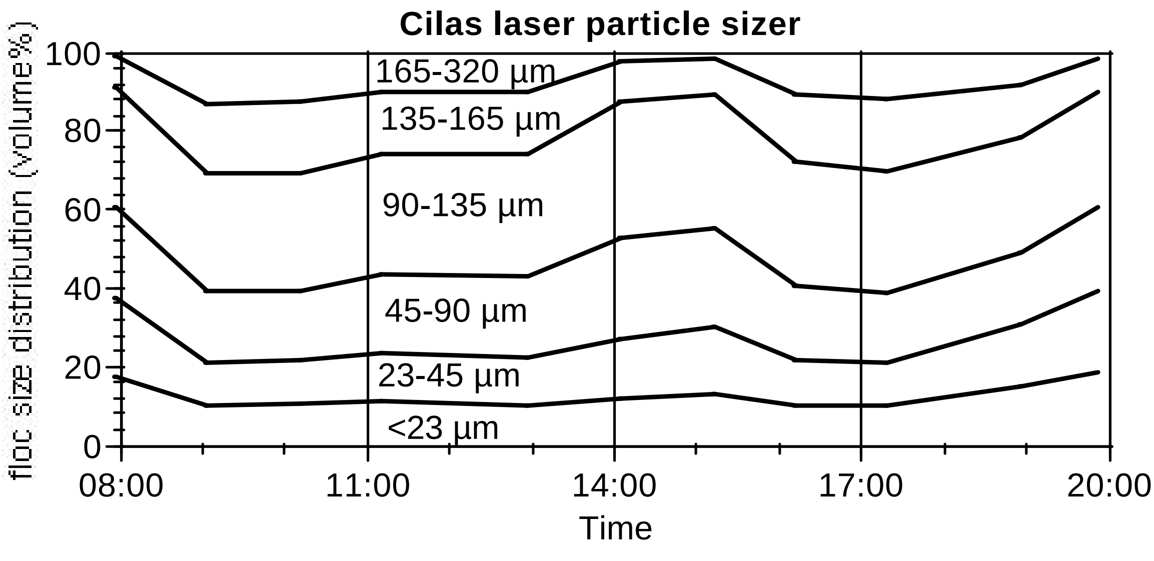

Figure 2.8 Floc size distribution determined with the Cilas laser particle sizer in the tidal Channel "Groote Gat" throughout the tide on 18 April 1996

Note that figure 2.7 and 2.8 show the percentage of flocs in a certain size class. That means that when the lines in figure 2.7 and 2.8 trend downwards, the floc sizes are actually increasing and vice versa. Water level, current velocity and SSC were simultaneously measured on 18 April and are presented in figure 2.9.

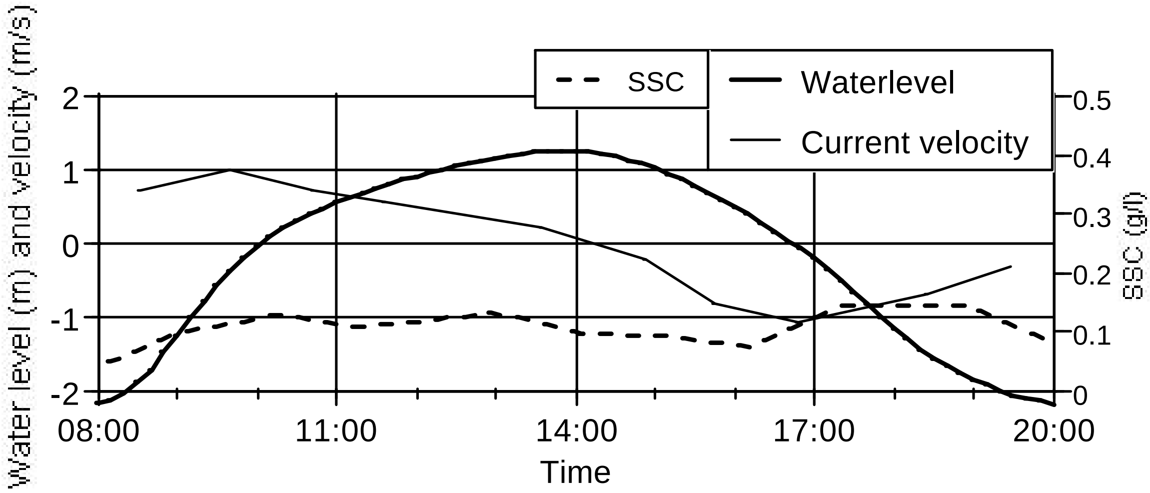

Figure 2.9 Water level and current velocity on 18 April 1996

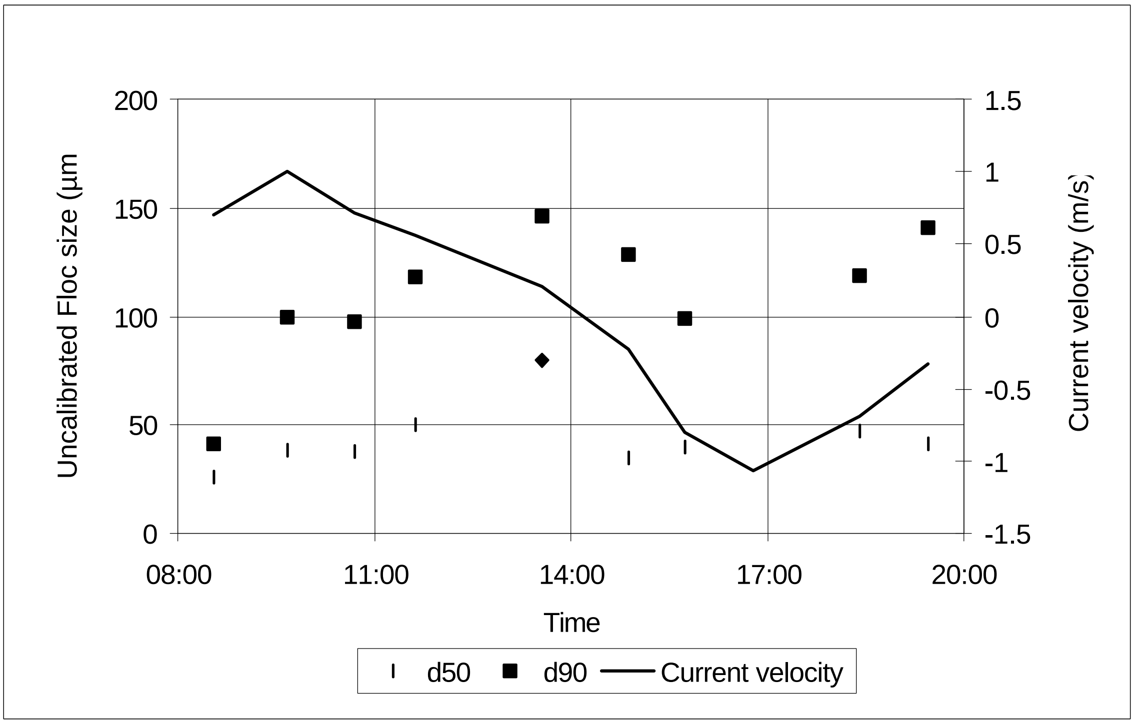

Figure 2.10 Cilas floc sizes at about half the water depth from anchored measurements

There is little variation throughout the tide on 18 April 1996, presumably because of the low suspended sediment concentrations in the Dollard during that period. But there is a reasonable relation between the VIS and Cilas measurements. Unfortunately the resolution of both instruments do not cover the whole size range of mud flocs suspended in the water. The Cilas is incapable of observing particles larger than about 320 µm and the VIS is incapable of observing flocs smaller than 85 µm. This leaves only a small overlap in the resolution of VIS and Cilas and makes a calibration of the Cilas impossible. The trend observed by the Cilas corresponds to the trend observed by the VIS measurements. So the Cilas does give a good representation of increasing or decreasing floc sizes. The Cilas data does not represent absolute floc sizes and must be considered as uncalibrated results.
Between floating measurements, the ship anchored and vertical profiles were measured with the Cilas in an Eulerian way. This introduces current shear around the instrument, which may disrupt the suspended mud flocs. Figure 2.10 shows the median and d90 floc sizes observed by the Cilas at approximately three meter below the water surface. This is the same depth as during the floating measurements that were presented in figure 2.8. Figure 2.10 shows that minimum floc sizes occur around 9:00 h at maximum flood velocity, and around 17:00 h at maximum ebb velocity. In contrast figure 2.8 showed maximum floc sizes around those periods. This suggests that current shear around the Cilas caused floc breakup, which explains why smaller flocs were observed during high current velocities.

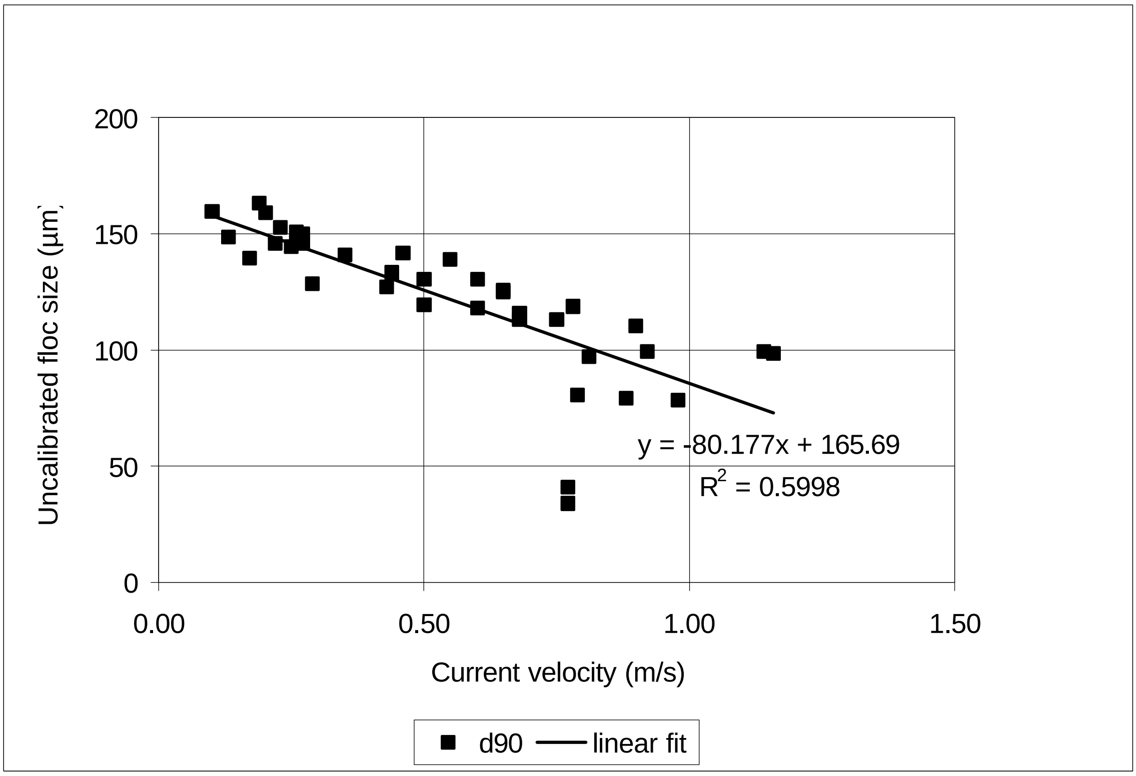

Figure 2.11 Floc breakup around the Cilas due to current shear

This is corroborated by figure 2.11 that shows the decrease in d90 floc size as a function of current velocity. The fitted linear trendline shows that a 1m/s current velocity causes a decrease of about 80 microns in d90 floc size. This shows that instrument induced floc breakup has a significant effect on the Cilas measurements. The Cilas can therefore only be used in Eulerian measurements when the current velocity is very low.

Summarising, one can conclude that the Cilas has as advantage that it provides an instantaneous particle size distribution. It is also possible to use the instrument above the tidal flats placed on the bed in a measurement frame, providing that the current velocities are sufficiently low to prevent instrument induced floc breakup.
A disadvantage is the limited resolution of the instrument, which does not allow for measuring floc sizes larger than 320 µm. It was also impossible to calibrate the instrument so the uncalibrated results indicate only relative floc size variations.

2.4 Instrumentation and methods for the determination of flocculation parameters

Several parameters may impact flocculation processes. Many parameters were determined during the field measurements, but only those used in this thesis will be dealt with. Measurements took place at the following locations:

- The BOA platform on the “Heringsplaat” tidal flat (fig. 2.1).
- A channel pole provided by Rijkswaterstaat in the tidal channel “Het Groote Gat” next to the Heringsplaat (fig. 2.1).
- At the tidal flats “Hooge plaat” and “Bunderriet” (fig. 2.1) with the INTRMUD measurement frame.
- From the research vessels “Regulus” and “Dr. Ir. Joh. Van Veen” in the tidal channel of the Dollard estuary (see VIS tidal excursion in fig. 2.1).

The instruments and methods used for the measurements will be described below.

2.4.1 Current velocity

Current velocities were generally measured with Electromagnetic Flow Meters (EMF) from Delft Hydraulics. An EMF generates a magnetic field. When an electrolyte (e.g. sea water) moves within this magnetic field a potential gradient develops which is measured by platinum electrodes at the sensor. The potential gradient is a measure for the current velocity. In total 12 EMF sensors were used. 3 disc shaped sensors (E232, E233, E234) and 3 spherical sensors (S252, S253, S254) at the BOA platform, 3 spherical sensors (S146, S200,S201) at the channel pole and 3 disc shaped sensors (D292, D293, D294) at the INTRMUD frame. They were operated on a 2Hz frequency. On the channel pole 10 minute averages of the EMF output were recorded and transmitted by packet radio to the “Rijkswaterstaat” building in Delfzijl where the data was stored and later calibrated. On the BOA platform the 2 Hz data was stored on harddisks. This data was first checked

for errors (e.g. spikes) and then calibrated. From the 2 Hz current velocity data 10 minute averages were calculated.
All EMFs were calibrated April 1994 and February 1996. The INTRMUD frame EMFs were calibrated in May and November 1996. The linear responses (≈ 1.0 V/(m/s)) of the instruments were comparable between calibrations. Offsets of the instruments were determined in the laboratory and for some EMFs also in the field. The inaccuracy of the instruments is 3% of the output value of the instrument with a maximum accuracy of 1 cm/s.
On the research vessels current velocities were measured with an OTT-type current meter, that was calibrated by "Rijkswaterstaat".

2.4.2 Suspended sediment concentration

Suspended sediment concentrations were generally measured by MEX turbidity sensors (BTG type RD 20/10). These sensors measure the light attenuation through the water. It consists of two infrared emitting diodes (LED) and two silicon photodetectors. The electronics transmitter alternates the LED's on and off, while continuously measuring the amplitudes of light transmitted through the water to the detectors. The alternating light principle (using two lightbeams of different length) automatically compensates for limited fouling and component aging (Van Rijn, 1993).
The measured turbidity is used as a measure of suspended sediment concentration although the turbidity also depends on the size of the suspended particles. The MEX sensors were calibrated several times throughout the year by taking water samples. The suspended sediment concentration is obtained from the water samples by filtration through 1 µm glassfiber filters. Concentration is defined as dry sediment weight per water volume. There were hardly any differences between calibrations taken at different times of the year. Calibration curves fitted to all collected data on the BOA platform throughout 1996 and 1997 showed explained variances of more than 98% ($R^2 > 0.98$). On the channel pole there were a lot of problems with extreme fouling on the MEX sensors. Calibration curves from individual calibrations of MEX sensors on the channel pole generally showed explained variances larger than 90%.

Water samples for the determination of SSC were taken with a pump that pumped the water next to the MEX sensor through 4 mm tubes up to the platform. The intake nozzle was perpendicular to the local flow direction. The current velocity in the intake tubes had to be sufficiently fast, to avoid sedimentation in the tubes. The current velocity was at least sufficient for particles with a size up to 250 µm. Since more than 90% of the suspended sediment had a size smaller than 50 µm, it was assumed that sedimentation in the tubes did not occur. Secondly, the intake velocity in the tube must be equal and parallel to the local flow direction (iso-kinetic sampling) to avoid sampling errors due to the inertia of large suspended sediment particles. This effect is however negligible with small suspended sediment particles, as was shown by Nelson and Benedict (1950 in: Van Rijn, 1993). The suspended sediment size in the Dollard is generally smaller than 50 µm therefore this pumping method was sufficiently accurate.

On board of the research vessels SSC was not determined with MEX sensors, but directly by pump sampling and consecutive filtration.

2.4.3 Water level and wave height

Water level was determined by a tide gauge from Rijkswaterstaat in the mouth of the “Groote Gat” tidal channel. It was also determined with capacitance wires (Endress & Hauser) from the BOA platform on the Heringsplaat. These capacitance-wires work like a capacitor. A steel wire within a coating is one ‘plate’ of a capacitor, the surrounding water is the other ‘plate’. A change in water level changes the capacitance of the capacitor. The measured capacitance is therefore a measure of water level. The capacitance wires were sampled with a frequency of 2Hz, which also allows calculation of the significant wave height above the tidal flats. The resolution of the Capacitance wires was about 2.5 mm. Calibration was done against a levelled tide gauge in June and October 1996 with an explained variance of 99% ($R^2 = 0.99$).

2.4.4 Meteorological data

Wind speed, wind direction, temperature, solar radiation, humidity and precipitation, were all measured by a Campbell weather station on top of the BOA-platform on the Heringsplaat. It was equipped with:

- 1 x Cup-anemometer (Vector Instruments)
- 1 x Wind direction vane (Vectron Instruments)
- 1 x Combined air temperature/relative humidity (Vaisala)
- 1 x Pyranometer (Skye Instruments)
- 1 x Tipping Bucket Raingauge (Campbell Scientific Ltd.)

2.4.5 Other parameters (Water temperature, Salinity, Chorophyll-a, Loss on ignition and Carbohydrates)

Water temperature and salinity were measured with a combined temperature and electrical conductivity sensor that was calibrated at the Laboratory of Physical Geography in March 1996. Chlorophyll a was determined from water samples by colorimetric measurements as part of the regular monitoring program of the National Institute for Coastal and Marine Management. Loss on ignition was measured to determine the organic content of the suspended sediment. Therefore pumped sediment samples on glassfiber filters were stored in an oven for 3 hours at 550 ºC according to NEN 5754:1992. Blanks were also used to ascertain that the glassfiber filters would not lose weight at these temperatures. The amount of biopolymers present in the suspended sediment could not be determined directly. As a measure of these biopolymers, the EDTA extracted carbohydrates content of the suspended sediment was used. EDTA or EthyleneDiamineTetraAcetic acid, is a ligand that captures metal ions. Therefore EDTA extracts sugars which have bonds to the sediment by metal-ion interactions. These sugars are for a large part responsible for the glue effect of the biopolymers. Filtered suspended sediment samples were frozen on board of the research vessel immediately after sampling. Later, the colloidal carbohydrates attached to the sediment on the filters were extracted with EDTA. The carbohydrates were hydrolysed with concentrated sulphuric acid and phenol was added as an organic colour developer. The carbohydrate concentration was subsequently determined by colorimetric measurements (Dubois et al., 1956).

2.5 Measurement strategy

An important objective of this study is the assessment of temporal and spatial variation in mud floc properties based on its dependence on and interaction with the flocculation processes in the Dollard estuary. Temporal and spatial data about floc size, floc settling velocity and flocculation parameters is needed to reach this objective. This section describes the sampling strategy that was used to collect the required data. First the hydrodynamic data collection on the BOA platform, the channel pole and the INTRMUD frame is described followed by the procedure used for collecting floc size and settling velocity data with the VIS, Owen tube and Cilas.

2.5.1 Measurements from The BOA platform

The BOA platform (Fig. 2.12) was located at 7º09’28”E - 53º17’06”N at the Heringsplaat tidal flat at about 300 m from the edge of the tidal channel (see also fig. 2.1). It consists of two 17 m poles drilled 11 m into the tidal flat 25 m apart. A horizontal pole between the two standing poles supported the platform and a 10 feet and a 20 feet container. The containers were used for storage and shelter. In this way the platform provided a base of operation for measurements on the tidal flat.
In the middle of the platform was an instrument pole that ended 10 cm above the bed (Fig. 2.13), thus preventing scouring effects. The instrument pole was equipped with 6 EMF sensors and measured current velocities at 0.03, 0.09, 0.42, 0.60, 0.78, 1.0 m above the bed. Three MEX sensors measured the suspended sediment concentration at 0.06, 0.11, 0.48 m above the bed. Also mounted on the platform were two capacitance wires, which measured water level and wave height. A salinity meter at 0.20 m above the bed was used to measure salinity and water temperature. Meteorological data were collected with a weather station on top of the platform at about 8 m above the tidal flat. The level of the tidal flat at the BOA platform was 0.18 m above Dutch ordnance datum (N.A.P.).
The BOA platform was operated continuously from spring 1995 until autumn 1997. During winter the platform was not operational to avoid damage to the instruments by floating ice in the estuary. More technical information about the BOA-platform can be found on http://www.geog.uu.nl/fg/boa.html provided by Bas van Dam, electronics engineer at the laboratory for physical geography.

Figure 2.12 The BOA measurement platform

Figure 2.13 The instrument pole on the BOA platform

2.5.2 Measurements with the channel pole

A channel pole of Rijkswaterstaat was positioned at 7º09’44”E - 53º17’19”N, about 500 m Northeast of the BOA platform in the tidal channel near the edge of the tidal flat (see also fig. 2.1). It was equipped with 3 EMF sensors that measured current velocities, and 3 MEX sensors that measured SSC. The EMF and MEX sensors were at 0.35, 0.7 and 1.0 m above the bed. All sensors were mounted on a frame that could be hoisted out of the water to enable cleaning of the instruments. Especially in summer, fouling of the instruments occurred so rapidly that a large part of the collected data could not be used.

The channel pole was operated from spring 1995 until autumn 1996. It was removed during the winter from 1995/1996 to avoid destruction of the pole by floating ice.

2.5.3 Measurements with the INTRMUD frame

The INTRMUD frame was named after the EC-MAST INTRMUD project, since it was built especially for this project. It was used at the Hooge plaat and Bunderriet locations (fig. 2.1) in 1997 for the collection of hydrodynamic data at these sites. It measured current velocities with three EMF sensors at about 0.04, 0.1 and 0.23 m above the bed. A turbidity sensor at about 0.17 m provided data about the SSC and a pressure sensor was used for the determination of wave heights and water level. Unfortunately calibration of the turbidity sensor failed so there are no continuous data available about the SSC on the Heringsplaat and Bunderriet locations. The INTRMUD frame was operated alternately on Hooge plaat and Bunderriet during summer and autumn of 1997.

2.5.4 Floc size and settling velocity measurements with the Video *In Situ* (VIS)

Measurements with the VIS took place throughout a full tidal cycle in the tidal channel “Groote Gat” in the Dollard estuary. The VIS was deployed from a research vessel floating with the current, in a quasi-Lagrangean approach. The average tidal excursion of the VIS and research vessel is shown in figure 2.1.

Besides floc size measurements with the VIS, water level, velocity profiles and concentration profiles were also measured. Water level was determined with a tide gauge operated by the “Rijkswaterstaat” at a fixed location in the tidal channel North of the Heringsplaat. The profile measurements required the ship to anchor. Velocities were measured with an OTT-type propeller current meter at about 8 positions over the water depth. Concentrations were measured by pump sampling at 4 positions over the water depth, near the bed, 50 cm above the bed, at half the water depth and 70 cm below the water surface. Per sample this took between 30 seconds and 2 minutes. The sample volumes were varied between 200 and 800 ml depending on the sediment concentrations. The samples were immediately filtered over pre-weighed glassfiber filters. After anchoring the ship sailed downstream to the position where the VIS would have been without anchoring of the ship. This position was calculated from the measured current velocity at 2.9 m below the water surface. At this position the drifting VIS measurements were resumed. During such a VIS measurement the SSC was also determined by pump sampling near the VIS.

A series of a VIS measurement followed by velocity and concentration profile measurements, lasted about 1 hour and 15 minutes. These measurement series were continued throughout the tidal cycle, which resulted in a sequence of drifting VIS measurements followed by anchored profiles, followed by more VIS measurements etc. These 13-hour tidal measurements took place on 11 and 19 October 1995, 11 and 18 April 1996, 29 May 1996, 1 and 8 August 1996, 14 and 21 October 1996 and 12 December 1996. Mostly two 13 hour measurements were conducted per season. One at or near neap tide and one at or near spring tide.

2.5.5 Floc settling velocity measurements with the Braystoke SK110 Owen tube.

Owen tube measurements were conducted almost monthly from May 1997 until September 1997 on three locations in the Dollard estuary: Heringsplaat, Hooge plaat and Bunderriet (fig. 2.1). Heringsplaat was the least sheltered location with the lowest mud content of the bed (about 30% < 53 µm) and Bunderriet was the most sheltered location with the highest mud content of the bed (about 80% < 53 µm). Sampling with the Owen tube took place at half the water depth as was described above and in figure 2.5. These Owen tube measurements were undertaken as part of a larger measurement program that included measurements on the emerged tidal flat during low water. The Owen tube measurements started therefore during falling tide as soon as the ship arrived above the tidal flat. The measurements were stopped just before the flat emerged. After immersion on the flood the measurements were resumed until high water. In this way it was still possible to sample the whole immersion period of a tide above the flat.
Additional hydrodynamic data to support the Owen tube measurements was provided by the BOA-platform for the Heringsplaat measurements and by the INTRMUD frame for the Hooge plaat and Bunderriet measurements.

2.5.6 Floc size measurements with the Cilas laser particle sizer.

Measurements with the Cilas laser particle sizer took place from 21 September 1995 until 21 October 1995 next to the BOA platform as part of a test program from the National Institute for Coastal and Marine management. The Cilas was placed on the tidal flat in a frame with the sensor unit at 30 cm above the bed. It continuously collected uncalibrated floc size distributions with intervals of a few seconds. Cilas measurements were also conducted by the author on the same location from 14 until 31 May 1996. Only the data from 11 October 1995 will be used in this thesis, as the data collected on this day are representative for the other measurements and were collected simultaneously with a VIS-measurement in the tidal channel. For additional Cilas results the reader is referred to Van Beuzekom (1996).

The Cilas was also used during an intercomparison experiment with the Video *In Situ* on 18 April 1996. During the floating measurements the Cilas was suspended into the water from a winch next to the research vessel at the same depth as the VIS.

2.5.7 The Data set

The described measurement strategy provided data about floc properties and flocculation parameters on temporal as well as spatial scales in the Dollard estuary. Temporal data about floc properties on the time scale of the tidal cycle were provided by the VIS in the tidal channel and the Owen tube and Cilas on the tidal flat. Variations on a seasonal time scale could be studied from the seasonal VIS measurements in the tidal channel and the monthly Owen tube measurements on the tidal flat.

Spatial differences in floc size and settling velocity variation between the tidal flat and the tidal channel could be studied by comparing VIS and Cilas/Owen tube measurements.
Spatial differences in floc settling velocity variation along the estuary could be studied by comparing the Owen tube measurements on the Heringsplaat, Hooge plaat and Bunderriet in order of increasing shelter from waves and accompanying mud content. There were no floc size and settling velocity measurements in the tidal channel along the estuary from head to mouth. However, Van Leussen (1994) did conduct such experiments along the Ems estuary. As Van Leussen already studied spatial floc size and settling velocity variations along the estuary, this thesis will mainly concentrate on temporal variations in floc size and settling velocity.

2.6 Conclusions

The Dollard was chosen for the present research for its relatively simple geometry (one tidal channel bordered by tidal flats), its muddy character and because previous research about the estuary already provided a lot of data.
Only the Video *In Situ* provides absolute floc size and settling velocity measurements with a reasonable accuracy. It can, however, not be used above the tidal flats, nor near the sediment bed. The Cilas and Owen tube only provide information about relative increases or decreases of floc size and settling velocity respectively.
There is currently no instrument available that can accurately measure floc size and settling velocity a few centimeters above the sediment bed without disturbing the measurements.
The described measurement strategy provided data about floc properties and flocculation parameters on temporal as well as spatial scales in the Dollard estuary. These data could be used for the assessment of the temporal and spatial variation of mud floc properties based on its dependence on and interaction with the flocculation processes in the Dollard estuary.

3 TIDAL VARIATIONS IN MUD FLOC SIZE AND SETTLING VELOCITY. THE IMPACT OF FLUID SHEAR AND THE SUSPENDED SEDIMENT CONCENTRATION ON FLOCCULATION AND BREAKUP

This chapter is partly based on: Van der Lee, W.T.B., 1998. The impact of fluid shear and the suspended sediment concentration on the mud floc size variation in the Dollard estuary, The Netherlands. In: Black, K.S., Paterson, D.M. & Cramp, A. (eds). Sedimentary processes in the intertidal zone, Geological Society, London, Special publications 139 pp. 187-198

3.1 Introduction

Mud particles tend to clog together and form flocs that have a much larger settling velocity than the constituent particles. A downward vertical flux of sediment in the water is only possible when the settling velocity of the sediment particles is larger than the upward transport by turbulence. Flocculation therefore enables sedimentation. There would be little accumulation of fine-grained material, if the suspended fine sediment particles did not aggregate (Partheniades 1984; Van Leussen 1994). Floc sizes and settling velocities are determined by many physical factors like differential settling, fluid shear and the suspended sediment concentration (SSC). They are also determined by physico-chemical or biological factors like the presence of sticky biopolymers on the flocs, surface charge, salinity, etc. The presented research focuses on the relative contributions of especially fluid shear and SSC to floc size and settling velocity in the Dollard estuary within a tidal cycle. Floc size and settling velocity variations in two environments, the tidal channel and the tidal flat, were studied to obtain more insight in the contribution of fluid shear and SSC to the flocculation/breakup process.

3.2 Theory

Flocculation is determined by the number of floc collisions (collision frequency) and the efficiency of these collisions in aggregation (collision efficiency). The collision frequency is determined by:

1. Differential settling, that is falling flocs scavenging smaller flocs on their way down. This is especially important in deeper water.
2. Fluid shear or turbulence intensity. Increased turbulence causes an increased collision frequency and thereby flocculation. However, it is also considered to be the most important limiting factor of floc size (Dyer 1989; Eisma 1986; Luettich *et al.* 1993; Van Leussen 1994). Larger flocs are more fragile and will break easier due to turbulent shear (Dyer 1989).
3. The number of flocs in suspension or the SSC. The more flocs there are in suspension the higher the collision frequency. Several field studies in estuaries have shown that the median floc settling velocity increases with SSC raised to a power (Burt 1984; Dyer 1989; Pejrup 1988; Van Leussen & Cornelisse 1993a).

Both turbulence and SSC show the largest variation on the time scale of a tidal cycle. This paper focuses on the floc size and settling velocity variations within the tidal cycle as a function of both mentioned parameters. The collision efficiency is determined by physico-chemical or biological factors (biopolymers, surface charge, salinity) that mainly vary on larger time scales than the tidal cycle (e.g., seasonal variation in biopolymer concentrations). The collision efficiency is therefore assumed to be constant throughout the tidal cycle.
Dyer (1989) described the effects of fluid shear and SSC on floc size in his conceptual diagram (fig. 1.7). An increase of SSC increases floc sizes, while an increase of shear stress only initially increases floc size due to an increased collision frequency of the suspended particles. Further increase of shear stress however causes flocs to break and decreases floc diameter.

A measure of turbulence intensity in the water column is the root mean square velocity gradient G, defined as the square root of the energy dissipation ε divided by the kinematic viscosity ν of the fluid (Van Leussen 1994):

$$G = \sqrt{\frac{e}{n}} \tag{3.1}$$

It’s reasonable to assume that the turbulent energy dissipation ε equals the turbulent energy production P (Van Leussen 1994):

$$e = P = \frac{t}{r}\frac{dU}{dz} \tag{3.2}$$

In case of a logarithmic velocity profile :

$$\frac{dU}{dz} = \frac{u_*}{kz} \tag{3.3}$$

and assuming that the maximum shear τ at the bed decreases linearly to zero at the surface:

$$\frac{t(z)}{r} = u_*^2\left[1-\frac{z}{h}\right] \tag{3.4}$$

Then:

$$G(z) = \sqrt{\frac{u_*^3\left[1-\frac{z}{h}\right]}{nkz}} \tag{3.5}$$

Where:
G(z) = root mean square velocity gradient at level z (s^{-1}).
z = level above the bed (m).
ε = turbulent energy dissipation (m^2/s^3).
P = turbulent energy production (m^2/s^3).
υ = kinematic viscosity (m^2/s).
$\tau(z)$ = shear stress at level z (N/m^2).
ρ = water density (kg/m^3).
U = current velocity (m/s).
u_* = friction velocity (m/s).
κ = Von Karman constant ($\approx$0.4).
h = water depth (m).

For the determination of G(z), u_* needs to be determined from velocity measurements. In case of a logarithmic velocity profile:

$$U(z) = \frac{u_*}{k} \ln\left(\frac{z}{0.033k_s}\right) \tag{3.6}$$

Where:
k_s = bed roughness (m).

3.3 Field experiment

The research was carried out in the Dollard estuary, which was described in chapter 2. This chapter will describe the results of floc size and settling velocity measurements throughout several tides in the tidal channel ‘Het Groote Gat’ and the tidal flat ‘Heringsplaat’ in the Dollard estuary (fig 2.1) with the VIS, Cilas and Owen tube as described in Chapter 2. The channel measurements with the VIS were conducted from a drifting vessel, which prevented floc breakup by current shear around the instrument. It also minimised the effect of horizontal advection on the measurement. Changes in suspended sediment concentration or floc sizes were therefore the result of local erosion/sedimentation or flocculation/break-up and not due to horizontal advection. The tidal excursion of the VIS measurements is shown in figure 2.1. Note that the presented Cilas and Owen tube measurements only provide a relative measure of floc size or settling velocity, as was explained in chapter 2. Besides floc measurements, current velocities and suspended sediment concentrations were also measured as was described in chapter 2.

3.4 Measurements of fluid shear

Fluid shear or G experienced by the mud flocs needed to be calculated from the friction velocity u_* with equation 3.5. In case of a stationary, uniform current and very accurate measurements of velocity at well defined levels above the bed, the friction velocity u_* and bed roughness k_s can be derived from a logarithmic fit on the velocity data (equation 3.6). In an estuary, however, the current is not uniform and not stationary which limits the logarithmic velocity profile to the near bed region. In practice the measured velocities and especially the measured levels above the bed in the Dollard were not accurate enough to calculate both u_* and k_s from the data. This was mainly caused by the movement of the research vessel on the waves in the channel and the low current velocities on the tidal flat. Bed roughness in the channel varied between $7*10^{-7}$ m and 5.3 m which are totally unrealistic. The median bed roughness k_s however was 0.03 m which is a more realistic value. For realistic calculations of u_* and G, a bed roughness k_s had to be estimated and u_* was calculated from the current velocity at one level above the bed assuming a near bed logarithmic velocity profile and zero velocity at $z=z_0=0.033k_s$.

The bed roughness can also be expressed as a drag coefficient C_d where:

$$C_d = \left(\frac{k}{\ln(\frac{z}{0.033 k_s})} \right) \tag{3.7}$$

Drag coefficients were deduced from measurements in several estuaries by different authors. Lewis & Lewis (1987) found drag coefficients ranging from 0.0019 to 0.0131 on an ebb tide and C_d lying between 0.002 and 0.0053 on the flood in the Tees estuary. A drag coefficient of $C_d = 0.003$ at z = 1 m seems to be a reasonable estimate for estuarine studies according to Van Leussen (1994) and Sternberg (1968). This corresponds to a k_s of 0.02 m, which agrees quite well with the median k_s of 0.03 m found from the logarithmic fits. Therefore, $k_s = 0.02$ m was used for the calculation of current related friction velocities in the channel as well as on the tidal flat. Current velocities were measured at 1.1m above the bed in the channel and at 0.079 m above the bed on the tidal flat. From $k_s = 0.02$ m and the measured current velocities, u_* was calculated with equation 3.6 and G was calculated with equation 3.5. While the uncertainties in estimating k_s are large, the impact of a 100% increase in k_s results in only 16% increase in G in the channel and a 26% increase in G above the tidal flat. The percentages differ because the velocity was measured at 1.1m above the bed in the channel and at 0.079 m above the bed on the tidal flat.

On the tidal flat waves also needed to be taken into account. Outside the wave boundary layer, the velocity profile under waves is different from a velocity profile without waves. This can be expressed by using an apparent roughness k_a due to waves instead of a k_s in equation 3.6. Based on analysis of experimental data from flumes with rippled beds, Van Rijn (1993) found:

$$\frac{k_a}{k_s} = e^{g \frac{\hat{U}_d}{U}} \tag{3.8}$$

Where:

k_a = apparent roughness due to waves (m).

k_s = current related bed roughness (m).
$\hat{U}_d$ = peak orbital velocity near bed (m/s).
U = mean current velocity (m/s).
γ = $0.8 + \phi - 0.3\,\phi^2$.
ϕ = angle between current and wave direction (in radians between 0 and π).
$\hat{U}_d$ and U were measured with an electromagnetic current meter that sampled at a 2Hz frequency at 0.079 m above the bed on the tidal flat.

3.5 Results

First the data collected with the VIS in the tidal channel will be presented. The VIS measurements of 11 October 1995, during spring tide, will be presented in detail as this measurement is representative for the general trend of floc size variations throughout the tide in the “Groote Gat”. The measurement of 19 October 1995, one week later and during neap tide, showed similar results. Other VIS measurements conducted throughout 1996 showed the same general trend as on 11 October 1995. This proves that the presented findings are not only valid for one day.

3.5.1 Tidal Channel data: results of the Video *In Situ* system.

Floc sizes

The results of the floc size measurements in the tidal channel are shown in figure 3.1abc. Figure 3.1a shows the tidal elevation and the bed level referenced to Dutch ordnance datum (N.A.P.). The bed level varies along the track of the VIS. The measurements started at low water at a deeper part of the estuary towards Delfzijl (fig. 2.1). Then the VIS floated into the estuary until high water slack where it reached shallower water. After HW the VIS floated back to approximately its original position at low tide in deeper water again. Figure 3.1b is an area chart that shows the measured floc size distributions. (Note that descending lines between the size classes mean increasing floc sizes and vice-versa). Figure 3.1c presents the depth-averaged velocity and the suspended sediment concentration in the settling tube of the VIS during the measurements. Measured floc sizes ranged from 85 µm (detection limit) to 660 µm. Peaks in floc size appeared at about one hour after maximum flood velocity and at maximum ebb velocity. At these moments approximately 20% volume percentage of the flocs was larger than 300 µm. The peaks in floc sizes correlate well with the peaks in SSC. This corresponds with the conceptual model of Dyer (1989). There is no evidence of shear stresses disrupting the larger flocs. While this does not mean that floc break-up does not occur, it implies that SSC seems to dominate the flocculation process.

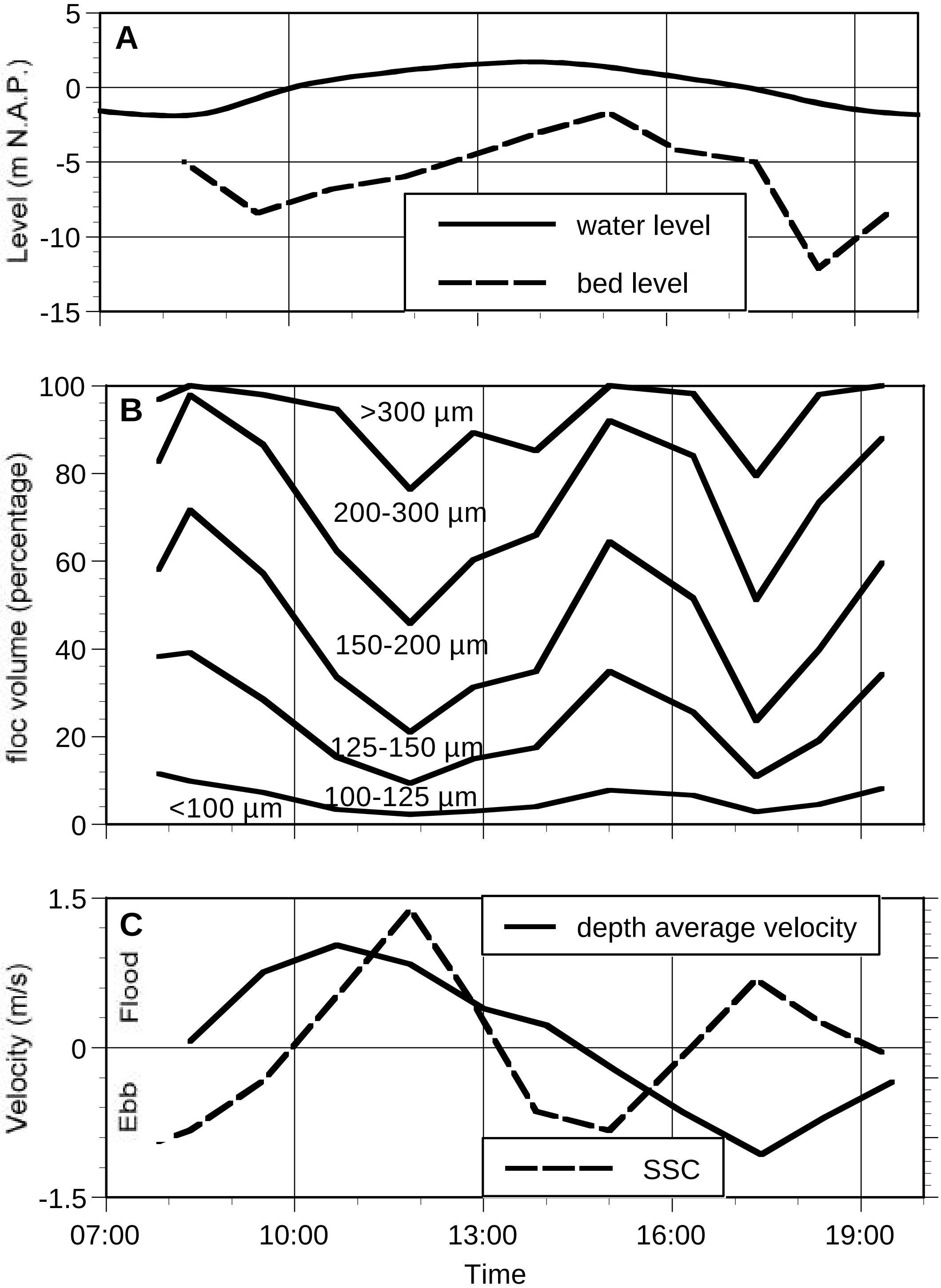

Figure 3.1 VIS measurements, Dollard, 11 October 1995. a) Water level and bed level against time b) Floc size distribution against time c) Depth averaged velocity and Suspended sediment concentration in the VIS against time

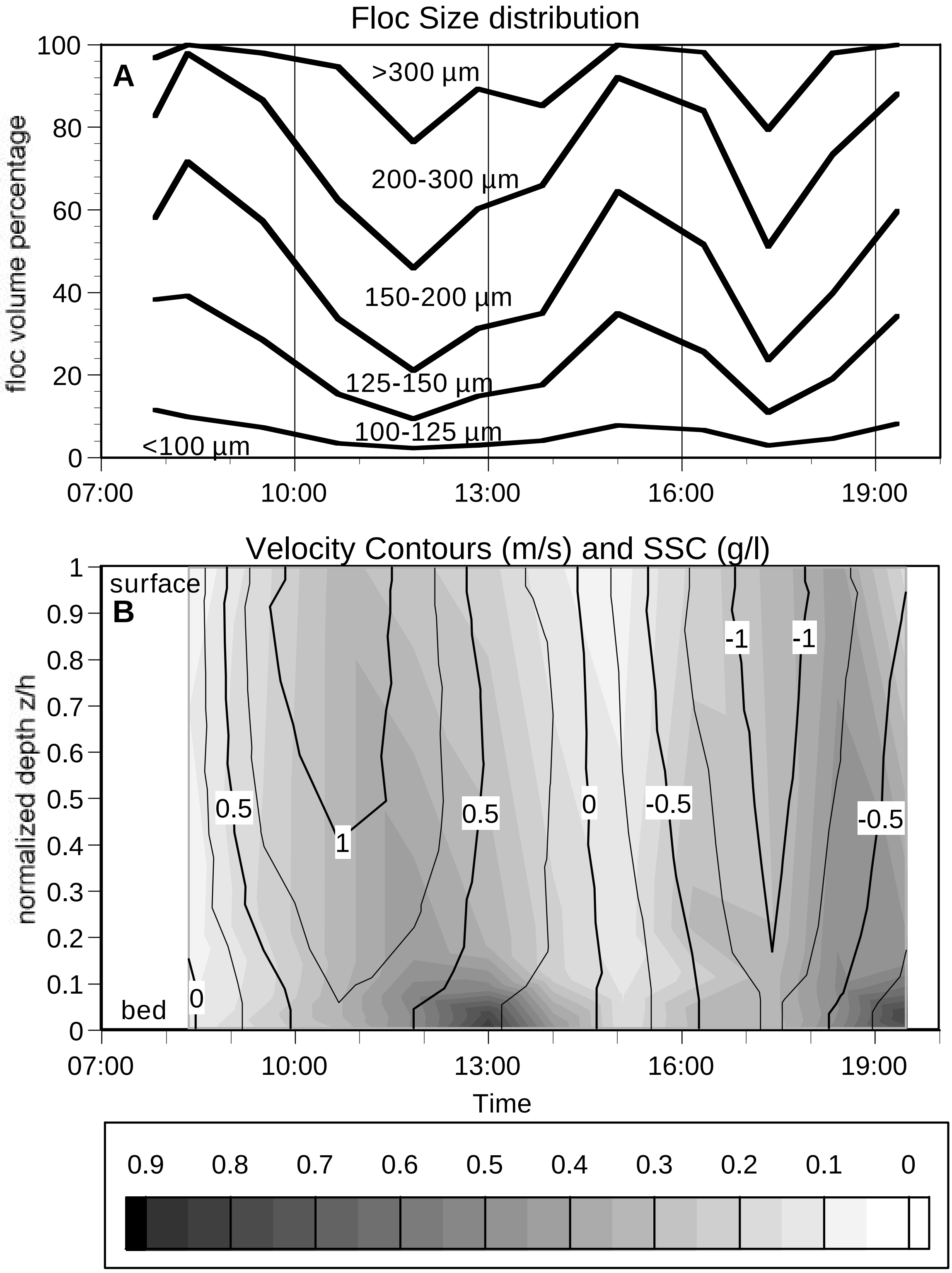

Figure 3.2 VIS measurements, Dollard, 11 October 1995. a) Floc size distribution against time b) Normalized velocity profiles (contours) and SSC profiles (gray-scales) against time

As the VIS is suspended at 2.9 m below the water surface and floating with the current, its relative position to the bed changes throughout the tide. In figure 3.1 it seems that the smallest flocs occur in the shallowest water. This is however coï ncidental, as correlation between bed level and floc size was not observed in other VIS measurements. For example, in the measurements of 19 October 1995 (fig 4.3; chapter 4) relatively small flocs also occurred in deep water in the mouth of the Dollard near Delfzijl at low water. Some of the measured floc size variation may be due to the proximity of the VIS to the bed. But such an effect was not observed in the measurements and it does not dominate the floc size variation. The floc size variation is related to the SSC.

In figure 3.2ab the floc size distribution and the velocity and concentration profiles are plotted. At the start of the measurements, after slack water, increasing current velocities resuspended mud into the water column. This mud was quickly mixed through the water column, so no vertical concentration gradient developed. As the SSC increased the floc size also increased. This may be caused by, either flocculation of smaller flocs, or resuspension of larger flocs or both. This mixing process continued towards maximum flood velocity. When the flood current velocity started to decrease, immediately a vertical concentration gradient developed. The current was no longer capable of keeping the larger flocs into suspension and therefore settling started. The maximum floc sizes appeared about one hour after maximum flood velocity, when the larger flocs were already settling and the SSC at the surface was decreasing. However, the SSC at the level of the VIS peaked at this moment (fig. 3.1bc). Differential settling may also have enhanced floc size at this time. With further decreasing current velocities the larger flocs kept settling, a lutocline developed and the floc sizes at the level of the VIS decreased again because the larger flocs had already passed towards the bed. At high water slack the settling sediment near the bed was deposited on the bed and the vertical concentration gradient disappeared. After high water slack a similar process occurred but now due to the ebb current. During ebb the maximum floc sizes appeared simultaneously with the maximum ebb current velocity (fig. 3.2bc), when the SSC in the VIS also reached its maximum value.

Eisma and Li (1993) also measured floc sizes in the Dollard estuary, at three fixed stations (Eulerian measurements). They also found a correlation between maximum floc size and SSC comparable with the present measurements. On the flood however they found increasing floc sizes also after the SSC maximum had occurred. They attributed this to the decreasing turbulence during flood as a result of the increasing water depth. In the present Lagrangean (floating with the current) measurements such increasing floc sizes after maximum SSC during flood were not observed. Maybe the increasing floc sizes towards high water as observed by Eisma and Li (1993) were caused by horizontal advection of flocs from upstream areas. In these areas, towards the mouth of the estuary, the current velocities are larger and could have resuspended more large flocs. The present measurements were floating measurements that were not affected by horizontal advection, and they do not show increasing floc sizes after maximum SSC.

Floc settling velocities

Floc settling velocities were not determined for each VIS measurement. They were obtained for only two VIS measurements on each measurement day. For that reason all settling velocity data collected from October 1995 until December 1996 was normalized relative to high water time and is plotted in figure 3.3. In this way it was possible to show the average tidal variation of floc settling velocities. Since the data was taken throughout a year, some of the floc size variation could also result from seasonal floc size variations. In chapter 5 (fig. 5.4) will however be shown that there is hardly any seasonal variation in the floc settling velocities in the Dollard. The floc size variations shown in figure 3.3 are therefore mainly tidal variations.

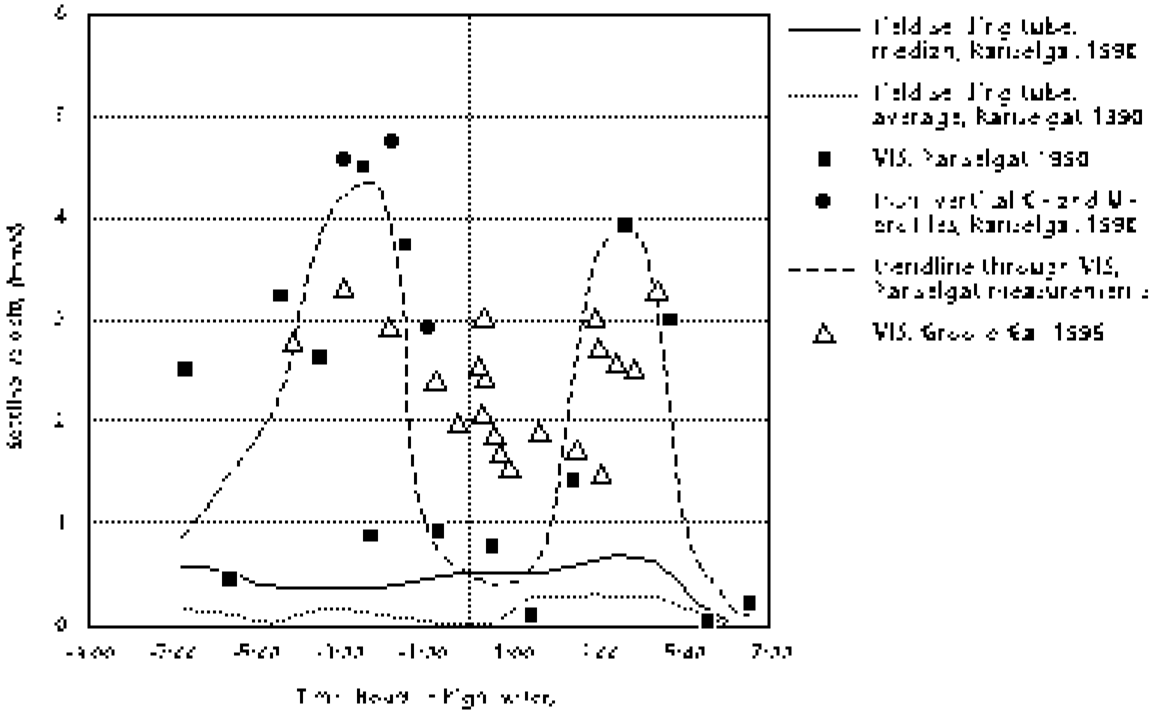

Figure 3.3 Settling velocities measured by Van Leussen (1994) in the "Ranselgat" tidal channel and settling velocities measured in the "Groote Gat" tidal channel. Video *In Situ* (VIS) data and field settling tube data

Each presented settling velocity is a mass weighted average settling velocity calculated from the data of a VIS measurement. A more extensive description of these settling velocity calculations will be given in Chapter 5. Figure 3.3 also shows the settling velocities of mud flocs in the "Ranselgat, EMS-Dollard" (fig 2.1) obtained by Van Leussen (1994) with the VIS and with a field settling tube. It is clear that the VIS measurements, as well as in the Ranselgat in 1990 as in the Groote Gat in 1996 show a strong increase in the floc settling velocity around or shortly after maximum current velocities. In both the Ranselgat and the Groote Gat maximum current velocities occur about 3.5 hours before and after high water. Slack tide occurs around high water.

The Ranselgat measurements by Van Leussen, 1994 show the settling velocities of the largest flocs that were observed. The Groote Gat measurements show mass weighted average settling velocities of all flocs. Obviously the settling velocities measured in the Groote Gat are therefore smaller than the settling velocities measured in the Ranselgat. Minumum settling velocities were observed around slack tide in the Ranselgat and about 1.5 hours after slack tide in the Groote Gat. This is probably also a result of the different measurement method, since in the Ranselgat only the largest fastest settling flocs were measured whereas in the Groote Gat the average settling velocity was obtained. It is logical that the fast flocs settle earlier after slack water than the average flocs.

Around and right after slack tide flocs generally fell slower, just as the smallest flocs were observed around and just after slack water in figure 3.1. Figure 3.3 and 3.1 show that the tidal variation in settling velocity is comparable to the tidal variation in floc size. The tidal variation observed from the "Groote Gat" results also agrees with the tidal variation observed by Van Leussen (1994) in the "Ranselgat", except for the 1.5 hour time lag which presumably resulted from the measurement method, as was explained above. Van Leussen also conducted measurements with a field settling tube in the Ranselgat (fig. 3.3). Due to the different methodologies, the settling tube results and the VIS results cannot be compared quantitatively. Qualitatively however, the results suggest that the strong increase of floc settling velocities is not observed by the field settling tube. Van Leussen (1994) suggested that flocs are broken by the field settling tube, which is conceivable when the fragile nature of the flocs is taken into account.

3.5.2 Tidal flat data: results of the Cilas laser particle sizer and the Owen tube.

Floc sizes (Cilas laser particle sizer)

Floc sizes on the tidal flat were measured with the Cilas laser particle sizer. As already stated above, the floc sizes measured by the Cilas are uncalibrated. Note that the Cilas was deployed at a fixed location so horizontal advection may have influenced the measurements. The floc size distribution, the water level and wave height and the current velocity and SSC are presented in fig. 3.4abc respectively. Only the high water period is shown since during low water the flat is emerged.
About half an hour after immersion, the flocs were relatively small and the flood velocity and SSC reached their maximum value. The second peak in SSC at about 11:45h coincided with the concentration peak in the channel (fig. 3.1c) and may be due to advection of sediment from the channel but may also be a coincidental event. Towards high water the current velocity and SSC decreased, but the floc sizes increased. During ebb the current increased to a maximum velocity of 0.36 m/s together with a small increase in SSC. The peak of SSC however occurred just before emersion when the water was very shallow and waves (fig 3.4b) stirred up the bed. The floc sizes decreased again towards the end of the ebb tide.

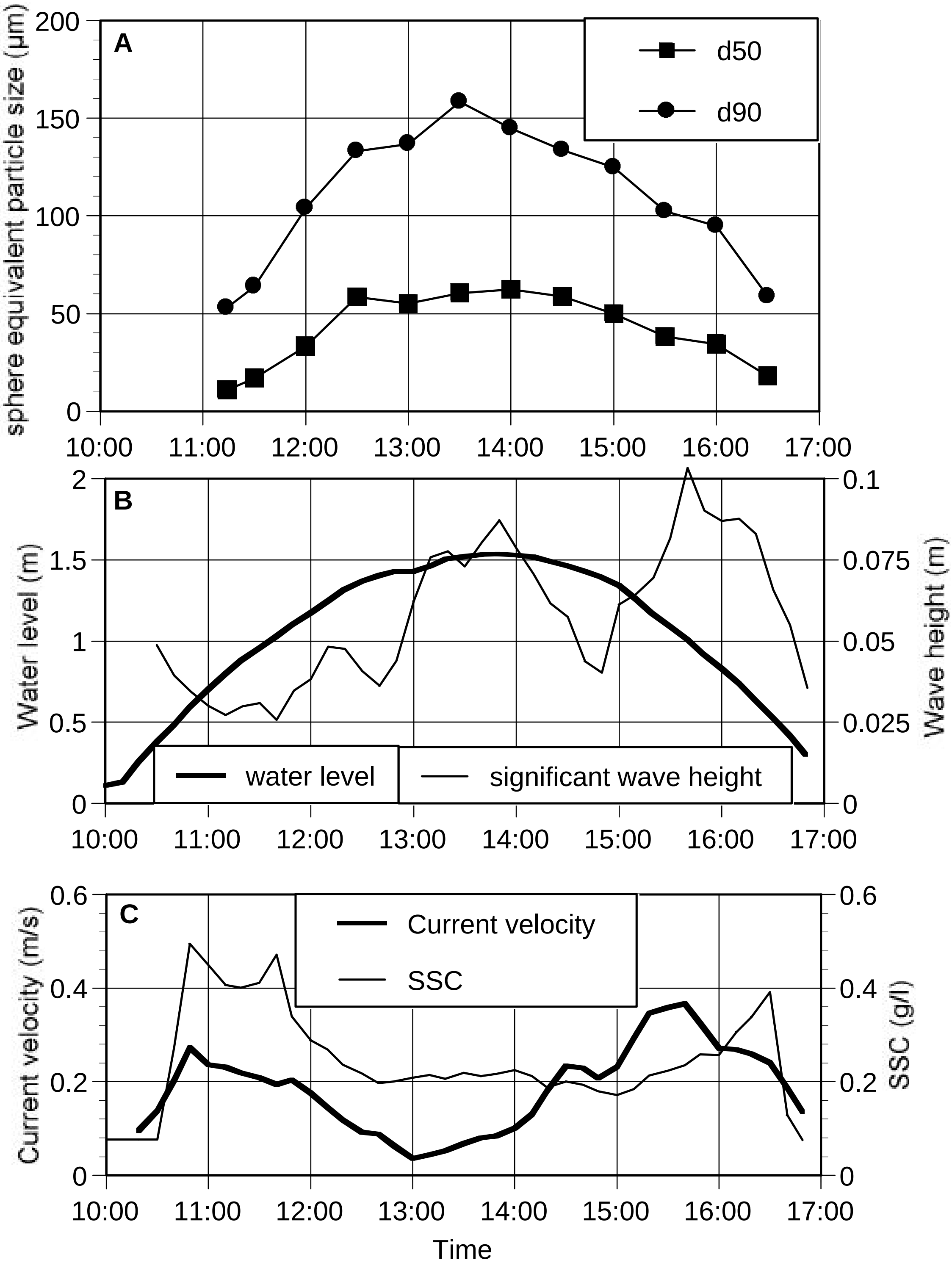

Figure 3.4 Cilas measurements, Dollard, 11 October 1995. a) Floc size distribution against time (data from: M. Ebben, RIKZ) b) Water level and significant wave height against time c) Current velocity and SSC against time

Floc settling velocities (Owen tube)

In 1997 a large number of Owen tube measurements were conducted at three locations above the Dollard tidal flats. Figure 3.5 shows a sequence of 4 Owen tube measurements throughout the immersion period of the Heringsplaat on 12 June 1997.

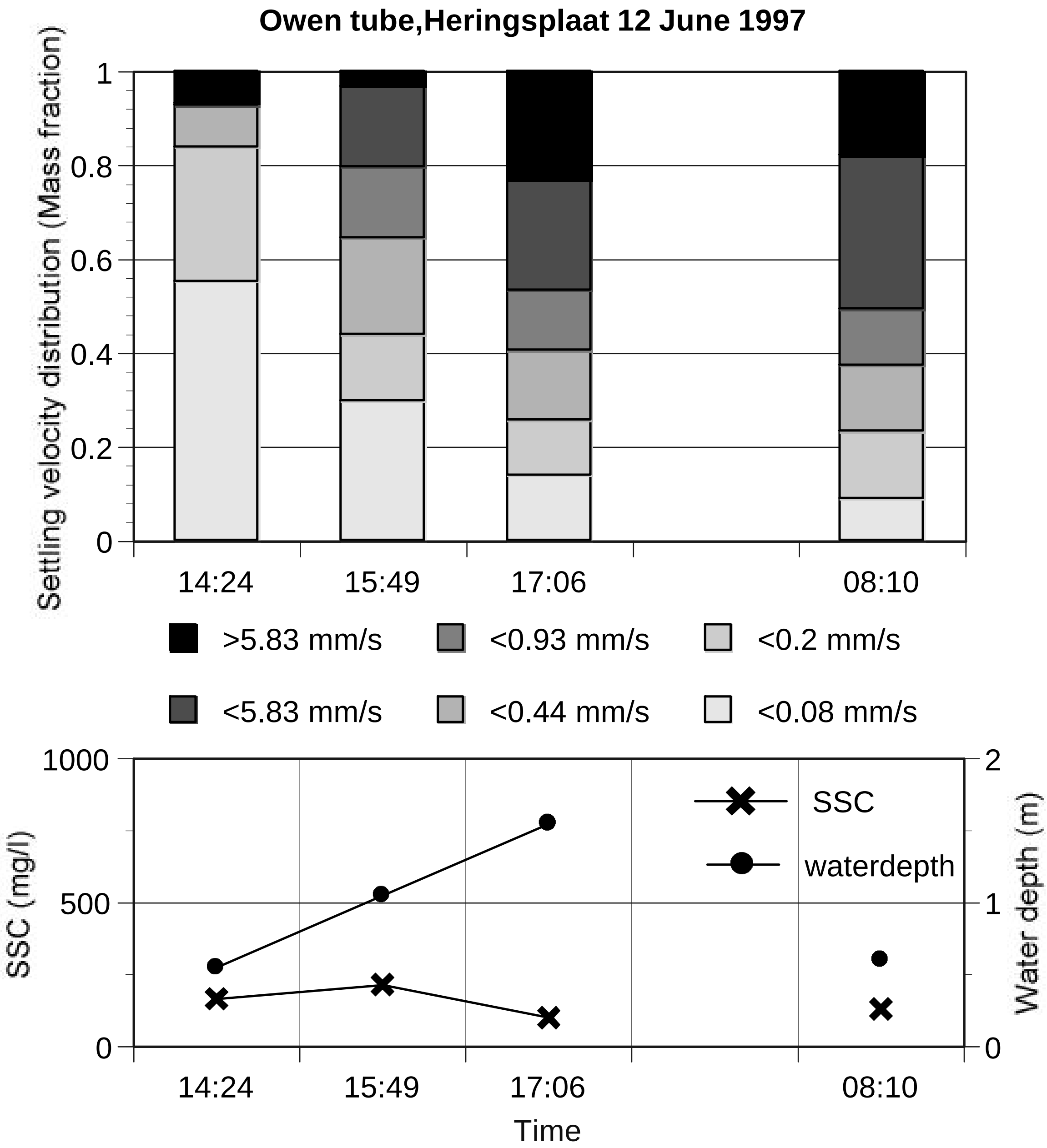

Figure 3.5 Tidal sequence of the floc settling velocity distribution above the Heringsplaat on 12 June 1997

The first three measurements describe the rising tide in the afternoon and the fourth measurement was taken during ebb of the preceding tide in the morning. The measurements were placed in this order to give an indication of the successive events occurring throughout the immersion period of the tidal flat. Note that the settling velocities in figure 3.5 are not the settling velocities as they would occur in situ, because of the shortcomings of the Owen tube described in chapter 2.

In figure 3.5, the settling velocity of the suspended sediment increases towards high water. This is in accordance with the observations from the Cilas (fig. 3.4), that showed the same behaviour for the floc sizes above the tidal flat. The results presented in figure 3.5 are however not consistent. Other measurements showed decreasing settling velocities towards high water, and positive relations between SSC and settling velocity as will be shown in figure 3.6.

For all Owen tube measurement that were taken in the Dollard during 1997, the median settling velocity was calculated. The accompanying times were normalised relative to the time of high water. These results are plotted in figure 3.6. It shows a very large scatter throughout the data. No consistent tidal variation can be observed. The data was also analysed for a seasonal variation but a relation between seasons and settling velocity variations could not be found.
Even though the Owen tube measurements were all conducted with the same sampling protocol, the results are inconsistent. Because of the inconsistency of the data it is difficult to draw conclusions from this data. Only a few indications can be derived from figure 3.6:

- The observed median settling velocities are between 0 and 1 mm/s, which is comparable to field settling tube data from other authors.
- During the flood, settling velocities are generally higher than during the ebb. During the flood, water from the tidal channel is also advected onto the tidal flat. Since maximum floc settling velocities in the tidal channel occur around maximum current velocities (fig 3.3), fast settling flocs may have advected from the tidal channel onto the tidal flat. This occurrence of larger settling velocities above the tidal flats during the flood than during the ebb may promote a residual sediment flux onto the tidal flats.
- Towards the end of the immersion period when the ebb current increases, the settling velocities increase again. Probably the ebb current resuspends some of the faster settling material. But Cilas measurements do not show a simultaneous increase in floc sizes towards the emergence of the flat. Possibly the ebb current resuspends some sand. This sand is detected as fast settling material by the Owen tube, but does not lead to the observation of larger particles by the Cilas.

Floc settling velocity measurements with the Owen tube were inconsistent. Therefore they cannot be trusted to be correct. The observations from the Owen tube may be instrument induced errors, due to floc breakup, reflocculation, hindered settling, water circulations inside the tube etc.

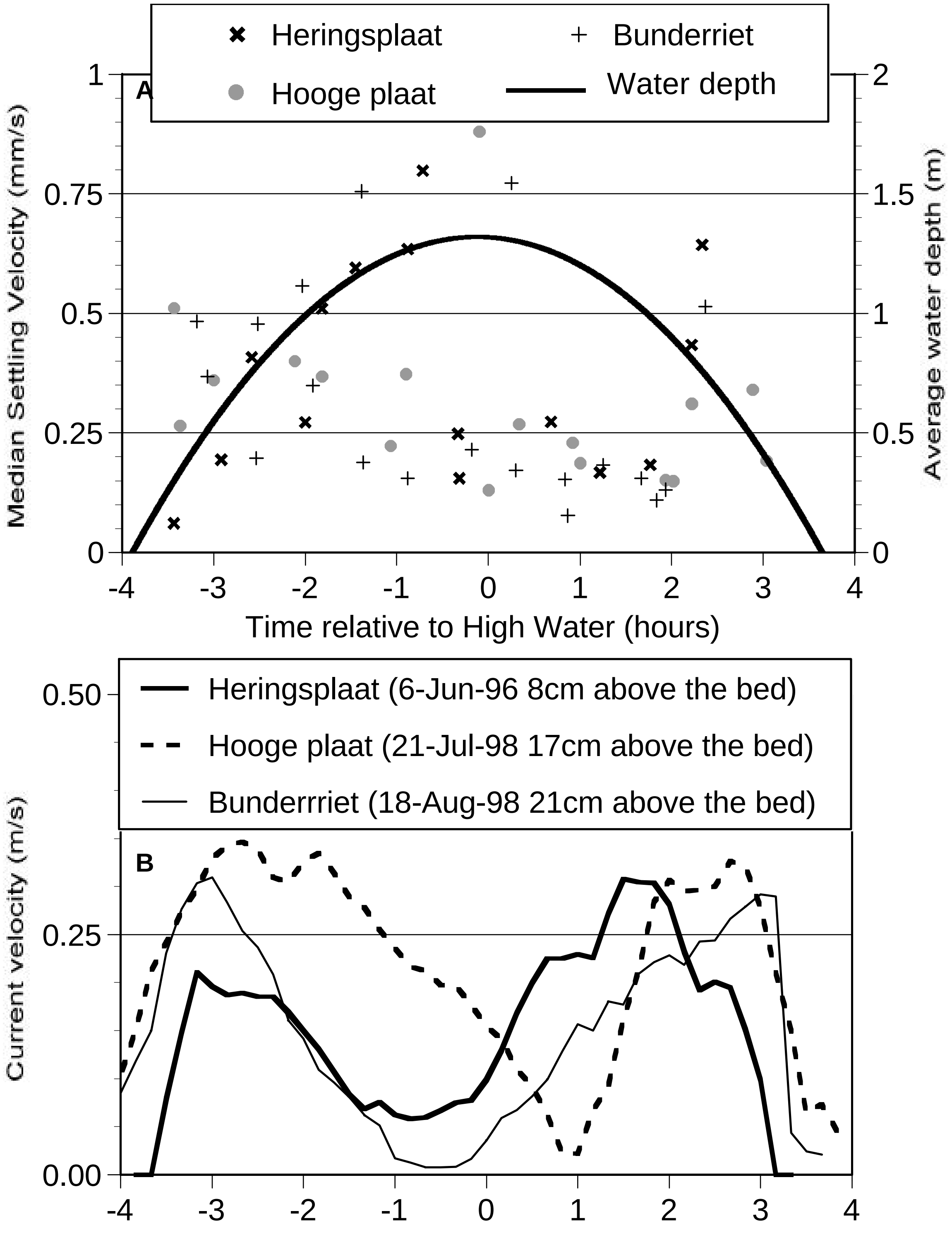

Figure 3.6 a) Median settling velocities of the suspended sediment throughout the tidal cycle. Based on Owen tube measurements taken throughout 1997 on three tidal flats in the Dollard estuary b) Representative current velocities above the tidal flats

In contrast with the Owen tube results, floc size variations measured above the tidal flat with the Cilas laser particle sizer did show consistent results. Floc sizes increase towards high water, and decrease again through the ebb. As the Cilas data seems much more reliable than the Owen tube data, the Cilas results will be mainly used in the discussion.

3.6 Discussion

In the tidal channel, both the floc size and floc settling velocity data showed a positive relation between SSC and floc size/settling velocity. Above the tidal flat there is a negative relation between SSC and floc size. The floc settling velocity data collected above the flat is inconsistent and will not be used. Above the tidal flat, large turbulence intensity due to currents and waves seems to inhibit the development of large flocs during flood and ebb tide. Larger flocs occurred only around high water slack, with low current velocities, larger water depth and therefore low relative wave height. This may have been caused by a decrease in turbulence intensity. Differential settling may also have played a role but this is unlikely. Firstly because of the shallow water (maximum 1.5 m) above the tidal flat. And secondly because Stolzenbach and Elimelech (1994) inferred that the effect of differential settling on aggregation in marine environments is small, since smaller particles that are overtaken by larger ones are deflected around the large particle instead of being scavenged by it. In the tidal channel floc sizes are affected by the SSC whereas above the tidal flat floc sizes seem to be dominated by the shear stresses.

In figure 3.7a the current velocity in the channel and the gradient G at the level of the VIS are plotted. In the channel obviously G depends on the current velocity. G ranged from 0.9 s^{-1} at slack tide to 11.2 s^{-1} at 17.25 h during maximum ebb current when the water was quite shallow (about 5 m depth) and the VIS was relatively close to, but still 2.1 m above, the bed. In figure 3.7b current velocity, wave height and G above the tidal flat are plotted. A distinction was made for G due to the current and G due to current and waves combined. G due to current and waves was calculated with equation 3.5 and 3.6 but instead of the bed roughness k_s, an apparent roughness k_a (equation 3.8) was used that corrects for the changes in the velocity profile due to waves. For the data on 11 October 1996 k_a varied between 0.022 m and 0.075 m. G was calculated at the level of the Cilas at 30 cm above the bed. Since there were only small waves, the waves do not contribute very much to the gradient. Only at 13:50h a peak in wave generated shear appears but this is probably due to a measurement error in the orbital velocities because the peak does not appear in the wave height data.
Above the tidal flat G ranged from 1 s^{-1} to 14.8 s^{-1} this is about the same range as measured in the tidal channel. The ranges of SSC are also comparable in both tidal channel and above the tidal flat. The Cilas data above the flat (fig. 3.4a) however suggests that the decrease in floc size at maximum current velocity is caused by floc break-up due to large shear (G). Since G at the Cilas is not significantly larger than G near the VIS another explanation needs to be found.

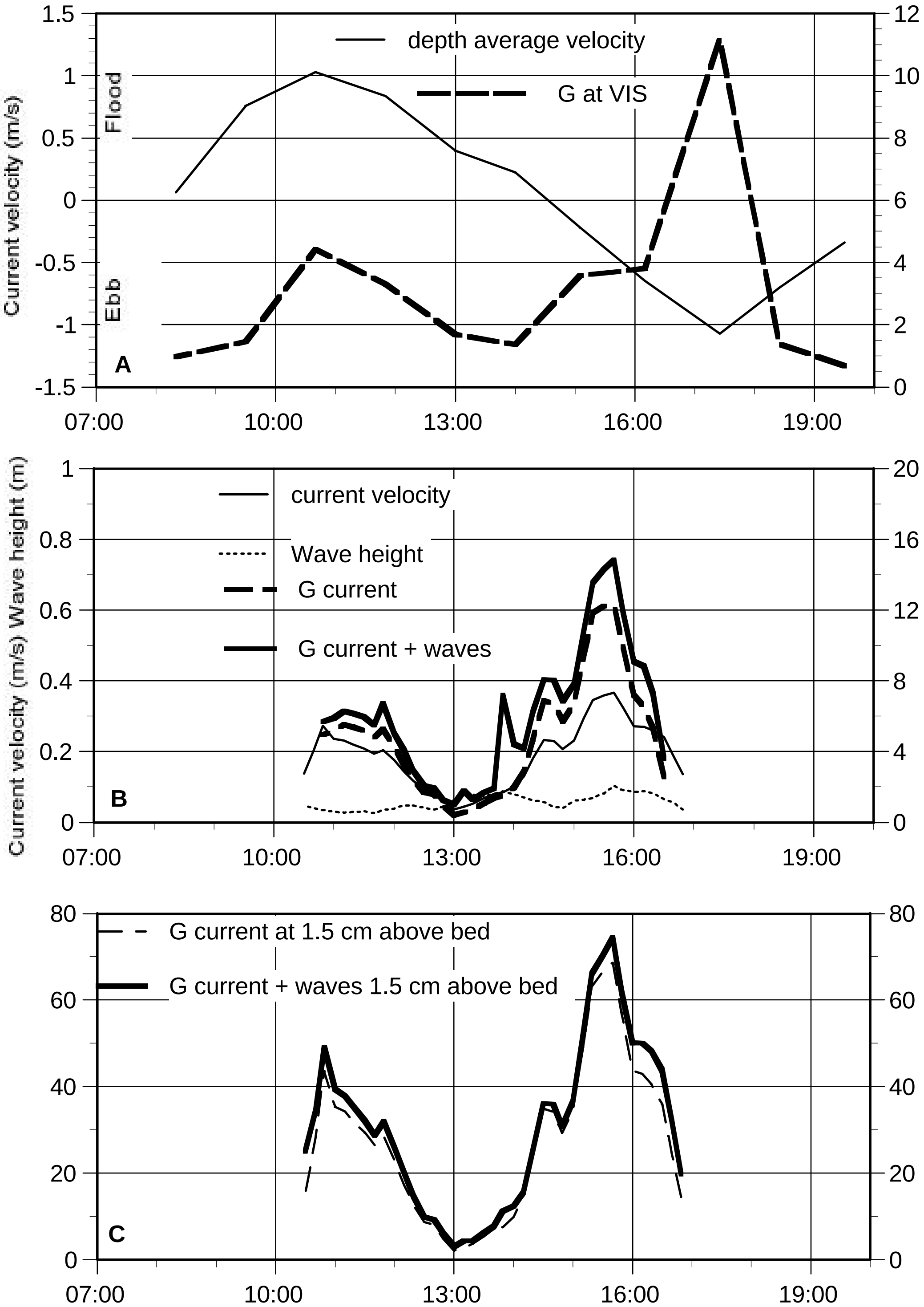

Figure 3.7 G in the tidal channel and above the tidal flat, Dollard, 11 October 1995. a) Depth averaged velocity and G in the tidal channel b) Current velocity, Wave height and G at 30 cm above the tidal flat c) G at 1.5 cm above the tidal flat

There are three hypotheses for the differences in floc size behaviour between the tidal flat and the tidal channel:

1. Advection.
   Horizontal advection of flocs may cause changes in floc size distribution. On the flood tide the water comes from the tidal channel. Since the tidal variation of floc sizes in the tidal channel do not correlate with the tidal variation of floc sizes above the tidal flat, it is not likely that the floc size variation above the tidal flat can be explained by advection of flocs from the tidal channel onto the tidal flats.
2. Instrument induced turbulence.
   The Cilas instrument is quite large in quite a large frame. Therefore the instrument itself generates turbulence that causes floc break-up during higher current intensity. In chapter 2 was shown that a current velocity increase of 1 m/s causes an average decrease in d90 floc size of 80µm. The maximum difference in current velocity above the Heringsplaat is 0.3 m/s. This could results in a 24µm decrease of the d90 floc size above the Heringsplaat due to instrument induced shear. But the observed changes in d90 amount to 100µm. So although instrument induced shear contributes to the observed decrease in floc size at larger current velocities it cannot explain the full amount of floc size variation.
3. Near bed shear.
   Near the bed the gradient G can be very large. As an example the gradient G at 1.5 cm above the tidal flat is plotted in fig. 3.7c. G ranges from 3 s^{-1} at slack tide to 74 s^{-1} at maximum ebb velocity. This very high near bed shear is almost certainly capable of floc break-up. Mehta and Partheniades (1975) stated that the strong shear and lift forces near the bed control the size distribution of the flocs in suspension. Van Leussen (1994) distinguished a number of turbulent zones in the water column. The flocs are continuously moving through these zones in a continuous process of flocculation and break-up resulting in the ultimate floc size. In the tidal channel the near bed shear is also very high, however the water is much deeper and therefore the frequency by which flocs move through the near bed region is lower. This might explain why shear seems to dominate floc sizes above the tidal flat and SSC seems to dominate floc sizes in the tidal channel.

The floc sizes measured with the Cilas may have been influenced by instrument induced turbulence as well as near bed shear. Floc breakup due to instrument induced turbulence explains about 25% of the observed floc size variation. The other 75% is likely to result from floc breakup by near bed shear. These percentages are only estimates, but they indicate that floc breakup due to near bed shear causes most of the observed floc size variations above the tidal flat. Above the tidal flat the water is shallower than in the tidal channel, so the average proximity to the bed is much closer above the flat than in the channel. Therefore, the impact of near bed shear on the floc sizes throughout the water column on the tidal flat will be higher than in the channel.

In Summary: gradients G at the level of VIS and Cilas were comparable. Near the bed G is much higher. Above the tidal flat the frequency by which flocs approach the bed is much higher than in the channel. Furthermore the measurements above the tidal flat were taken much closer to the bed. So probably breakup of flocs near the bed and resuspension into

the water column has a large influence on floc sizes above the tidal flat and causes smaller flocs at high current velocities. Floc breakup near the bed is also likely to occur in the tidal channel but with much less impact on the whole water column because the water in the tidal channel is much deeper. So the residence time of the flocs in water with relatively low turbulent shear is much longer in the tidal channel than above the tidal flat. This allows for the development of large flocs in the tidal channel, during ebb and flood.
It seems that SSC dominates the floc size as long as turbulence and the floc size itself are below a certain limit. The channel measurements show that SSC dominates floc sizes when $G < 12\ s^{-1}$. Very large flocs may however be so fragile that they will break under this fluid shear intensity. Near the bed the shear is so high that it may also cause break-up of smaller flocs. This is very important for the sedimentation of mud in estuaries because flocculation could produce large flocs that settle to the region near the bed. These flocs may break and may be resuspended in the water column, which inhibits deposition. This may cause large SSC near the bed as can be seen in figure 3.2b. Only at slack tide, when the near bed shear is much lower, actual sedimentation occurs.
Van der Ham (1999) conducted measurements of the turbulent diffusive sediment flux in the near bed zone of the Groote Gat. From these experiments he estimated settling velocities of approximately 0.5 mm/s in the near bed zone. Figure 3.3 showed settling velocities measured by the VIS in the Groote Gat ranging from 1.5 to 3.5 mm/s measured at about half the water depth. Even though the methodologies used to determine the settling velocities differ, this data indicates a smaller floc settling velocity in the near bed zone than higher in the water column. This also indicates that floc breakup in the near bed zone is likely to occur.

3.7 Conclusions

In October 1995 strong variations of floc sizes in the Dollard occurred within the tidal cycle. In the channel these variations correlated directly with the SSC and indirectly with the current velocity. Increasing current velocities caused increasing SSC, increasing floc sizes and good vertical mixing. Decreasing current velocities coincided with settling of larger flocs and the development of a vertical concentration gradient. It is possible that the high shear near the bed disrupted the large flocs and inhibited sedimentation. Deposition of mud to the bed was only observed with further decreasing current velocities.
Above the tidal flat the fluid shear instead of SSC seemed to dominate the floc sizes. Only at high water slack, fluid shear did not inhibit floc growth. The measured fluid shear and SSC above the tidal flat were however comparable to SSC and fluid shear in the tidal channel. The close proximity of the bed above the tidal flat, with high fluid shear along this boundary, may have caused floc breakup and resuspension of the broken flocs during ebb and flood tides, which explains the smaller flocs above the tidal flat during high current velocities. This is in contrast with the tidal channel where the water is deeper and the frequency by which flocs approach the bed is much lower, which explains why SSC is able to dominate floc sizes in the tidal channel.

4 MUD FLOC SIZE VARIATIONS ON A SEASONAL TIME SCALE. THE IMPACT OF A PHYTOPLANKTON BLOOM IN THE DOLLARD ESTUARY, THE NETHERLANDS

Reprinted from: Van der Lee, W.T.B., 2000. Parameters affecting mud floc size variation on a seasonal time scale: the impact of a phytoplankton bloom in the Dollard estuary, The Netherlands. In: McAnally, W.H. & Mehta, A.J. (eds), Coastal and estuarine fine sediment transport processes (in press), Copyright (2000), with permission from Elsevier Science.

4.1 Introduction

Aggregation of mud particles into flocs is essential for the sedimentation of mud. Mud flocs exhibit a larger settling velocity than the individual particles, which increases sedimentation or even creates the possibility of mud sedimentation. Floc size and settling velocity are determined by the balance between flocculation and breakup. Breakup is primarily caused by turbulent shear (Dyer, 1989; Eisma, 1986; Hunt, 1986; Luettich et al., 1993; Van Leussen, 1994). Flocculation depends on the floc collision frequency and the floc collision efficiency. The collision frequency is mainly determined by the suspended sediment concentration (SSC) and the turbulence intensity. The collision efficiency mainly depends on mud and water properties like salinity, organic coatings and the presence of biopolymers that may ‘glue’ flocs together. Dyer (1989) used the SSC and turbulence intensity in his conceptual model describing the floc diameter, presented as figure 1.7 in chapter 1. Both factors show a strong variation on the time scale of a semi-diurnal tide. On this time scale Dyer’s conceptual model can be reasonably applied since the factors that determine the collision efficiency remain relatively constant on this tidal time scale. On a seasonal time scale however, the collision efficiency may play an important role.

On a seasonal time scale mud and water properties may show a larger variation which affects the collision efficiency of flocs and therefore also floc sizes and settling velocities. The collision efficiency of flocs is determined by the physico-chemical properties of the floc surface. An electrical charge causes repulsion of flocs thereby preventing floc collisions. When however flocs are close enough to each other, Van der Waals or hydrogen bonds will bind the flocs together. These bindings can be intensified by polymeric substances on the floc surface or by separate organic flocs that act as glue.
The biological production of polymeric substances mainly varies on a larger time scale than the 13 hours of a semidiurnal tide. The impact of biological processes on floc sizes and settling velocities can therefore only be studied on a larger time scale. Therefore floc sizes were measured every season from fall 1995 until December 1996. This chapter will show the seasonal floc size variations that occurred in the Dollard estuary during that period. A few of these measurements were taken during a plankton bloom. Especially at the end of this bloom there was a significant biological impact on the floc sizes in the Dollard. The frequency of these measurements was too limited for an extensive assessment of the flocculation processes occurring during the bloom. Still the few measurements that

were taken, do give an indication of the impact plankton blooms may have on the flocculation dynamics in an estuary.

4.2 Theory

Changes of floc sizes and settling velocities on a seasonal time scale are largely determined by changes in the collision efficiency. The binding processes that take place between particles determine this efficiency. The two main binding processes, salt flocculation and biological cohesion of mud flocs, and their possible impact on floc size will be dealt with.

4.2.1 Salt flocculation

Most fine-grained suspended particles in natural waters exhibit a negative surface charge (Neihof & Loeb, 1972; Loder & Liss, 1985). This negative charge of the suspended particles is balanced by a cloud of positively charged ions around it. Together they form the so-called electrical double-layer. When two particles approach each other and the positive ion clouds overlap, electrostatic repulsion between the particles prevents a particle collision. Increasing salinity, however, decreases the thickness of the double layer, due to the lesser gradient between the positive ion concentration around the particle and the ion concentration in the surrounding water. Particles may then approach so close to each other that the Van der Waals forces are stronger than the electrostatic repulsion, and this leads to flocculation.
In the past this classical concept of salt flocculation was thought to cause flocculation of suspended matter in estuaries at the interface between fresh and salt water. The floc sizes and settling velocities should then increase at the transition from fresh to saline water. This concept of salt flocculation at the limnic-brackish boundary is however disputed by several authors:

> Puls & Kuehl (1986) found decreasing settling velocities at the transition from fresh to saline water in the Elbe estuary. They state that physico-chemical flocculation (salt flocculation) can not become effective due to organic coatings around the particles.
>
> Eisma et al. (1991a) measured particle sizes in five Northwest European estuaries in situ and by Coulter Counter and pipette analysis. Sizes measured by Coulter Counter or pipette analysis became finer at the saltwater contact. The *in situ* floc sizes measured with the camera, however, did not become finer but remained the same. There was however no relation between the changes in salinity and the *in situ* floc size. Therefore Eisma et al. (1991a) concluded that the particle sizes measured by the Coulter Counter and pipette analysis were the fragments of flocs broken during sampling and size analysis. The decrease in these sizes with increasing salinity indicated an increase in fragility of the suspended flocs, possibly

due to mobilization of organic matter in the saline water which weakened the floc structure.

Neihof & Loeb (1972); Hunter & Liss (1979); Hunter & Liss (1982); Loder & Liss (1985) all showed that particles in natural waters have a highly uniform negative surface charge due to organic and/or metallic coatings. The surface charge is therefore independent of the type of suspended material (e.g. clay minerals). Hence, organic coatings can have a considerable effect on the degree of salt flocculation in natural waters. Hunter & Liss (1982) also showed that the surface charge decreases with salinity.

Gibbs (1983) measured the effect of organic coatings on the collision efficiency factor of flocs. Figure 4.1 shows the collision efficiency factor plotted against the salinity. It demonstrates that increasing salinity causes increasing collision efficiency due to the decrease in double layer thickness and maybe also due to the decrease in surface charge. Besides that, the collision efficiency of coated particles is much less than that of uncoated particles. Coatings therefore slow down the flocculation process. Since particles in natural waters are coated, this may explain why several authors do not observe flocculation at the limnic-brackish boundary.

Eisma et al. (1991b) state that flocculation does not take place primarily by Van der Waals forces but by organic matter, whereby long-chain organic molecules, such as natural polymers, play an important role. These molecules extend through the water mantle around the particle and stick together when particles approach each other. Salinity has little effect on this.

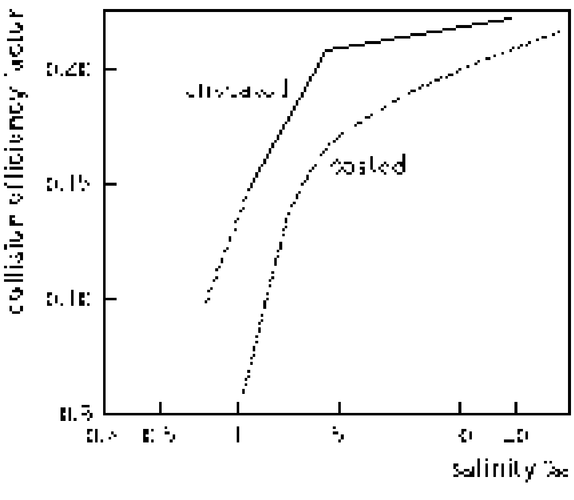

Figure 4.1 Effect of organic coatings on the flocculation process of natural sediment particles in blade type reactor tests (Gibbs, 1983). Reprinted with permission from Environmental Science & Technology 1983, 17,237-240. Copyright 1983 American Chemical Society

The classical concept of salt flocculation at the limnic-brackish boundary is therefore superseded. Van Leussen (1994) however measured the largest macroflocs at the seaward end of the estuary. This indicates an increase in flocculation ability (i.e. collision efficiency) with increasing salinity. Therefore, he states that salinity remains an important parameter in the flocculation of estuarine sediments, but not at the upper estuary with a few ‰ salinity. There organic coatings may retard the flocculation rate. At higher salinities however the double layer thickness may be sufficiently reduced for bridging between particles by polymers to become effective (Van Leussen, 1994).

It seems that the impact of salinity may differ along the estuary with its salinity gradient. Salinity changes may also occur on a specific location due to the tidal excursion and due to seasonal changes in freshwater input. It remains uncertain whether salinity will have an effect on the flocculation of the suspended sediments.

4.2.2 Biological cohesion of mud flocs

Wilkinson et al. (1997) studied the role of natural organic matter (NOM) for the coagulation of colloidal material in freshwater. They found that the chemical nature and structure of NOM is very important for the flocculation behaviour. NOM mainly produced in soils tended to form coatings around particles whose negative charge diminishes coagulation. NOM of aquatic origin appeared to accelerate the rate of coagulation by a polymer bridging process. Therefore the organic matter content alone is not likely to be a good parameter for defining biological cohesion of flocs. A more specific parameter like the biopolymer concentration in the suspended mud seems a better parameter, especially for defining the amount of sticky polymers present that may glue flocs together.

As was already stated above, natural polymeric substances can increase the collision efficiency which causes increased aggregation and therefore increased floc sizes (Decho, 1990; Eisma, 1986; Ten Brinke, 1993). These polymeric substances are mainly polysaccharides produced by plankton, benthos and bacteria (Harris & Mitchell, 1973; Avnimelech et al., 1982). Polymer bridging is thought to be an important biological flocculation mechanism. Polymer chains that are on one side attached to a particle and with the other side extending into the surrounding water can become attached to another particle (La Mer & Healy, 1963 in: Harris & Mitchell, 1973).

Another form of biological flocculation could be the flocculation by transparent exopolymeric particles (TEP). TEP are discrete transparent particles, rather than cell surface coatings (Alldredge et al., 1993). Discrete particles (TEP) are probably generated abiotically from the extracellular polysaccharides produced by diatoms (Passow et al. 1994). Passow & Alldredge (1995) observed that TEP are an important factor for the flocculation of diatoms during a bloom in a mesocosm. It seems that phytoplankton aggregation and the occurrence of organic flocs may be highly influenced by TEP. Whether TEP will be produced and how large the stickiness of it will be, depends on phytoplankton species composition, abundance and physiological state. In a natural environment as the Dollard estuary TEP are of course not only capable of flocculating diatoms but also other organic or inorganic particles may be captured by TEP. In this way TEP could very well be responsible for the formation of large mud flocs.

It seems that biological cohesion of flocs is strongly related with phytoplankton (e.g. diatoms) and possibly also with bacteria. The growth of these organisms obviously depends on seasonal variations, which explains why changes in biological cohesion of flocs mainly take place on a seasonal time scale.

4.3 Field experiment and methodology

The research was carried out in the ‘Groote Gat’ tidal channel with the Video *In Situ* (VIS) as described in chapter 2 and figure 2.1. Simultaneously current velocities and suspended sediment concentrations over the vertical were also measured. Other collected parameters were the water level, wave height, water temperature, salinity and chlorophyll a. The amount of biopolymers present in the suspended sediment could not be directly determined. As a measure of these biopolymers, the EDTA extracted carbohydrates content of the suspended sediment was used. A more extensive description of the measurements and methodologies is given in chapter 2.

4.4 Results

The results of the first VIS measurement are shown in figure 4.2. (This figure was already shown in chapter 3 as figure 3.1, but is repeated here for an easy comparison with figure 4.3) Figure 4.2a shows an example of the water level variation throughout the tidal cycle with the corresponding bed level referenced to Dutch ordnance datum (N.A.P.) on 11 October 1995. This bed level changes in time because the measurement ship was floating with the current. During flood tide the ship was floating up to the estuary head where the channel is shallower. During ebb tide, the ship was floating back towards the estuary mouth where the channel is deeper again. The tidal excursion along which the measurements took place is shown in figure 2.1. Figure 4.2b shows the measured floc size distribution expressed as a volume percentage. That means that at about 12:00 h 76% of the volume of suspended sediment consists of flocs smaller than 300 µm and 24% of the suspended sediment volume consists of flocs larger than 300 µm. When the lines in figure 4.2b go down the floc sizes are actually increasing and vice versa. Figure 4.2b shows that the floc sizes vary quite strong during the tidal cycle. Figure 4.2c shows the depth averaged current velocity and the suspended sediment concentration (SSC) at the depth of the size measurements, at 2.9 m below the water surface. The SSC strongly correlates with the floc sizes, which may be explained by the increased floc collision frequency due to a larger abundance of flocs at higher SSC. Another factor that could influence the floc sizes on this tidal time scale is the turbulence intensity that causes increasing collision frequency with increasing current velocity. This may results in larger flocs, but it may also cause floc breakup when the turbulence level is too high. Floc sizes may also increase due to resuspension of larger flocs from the bed.

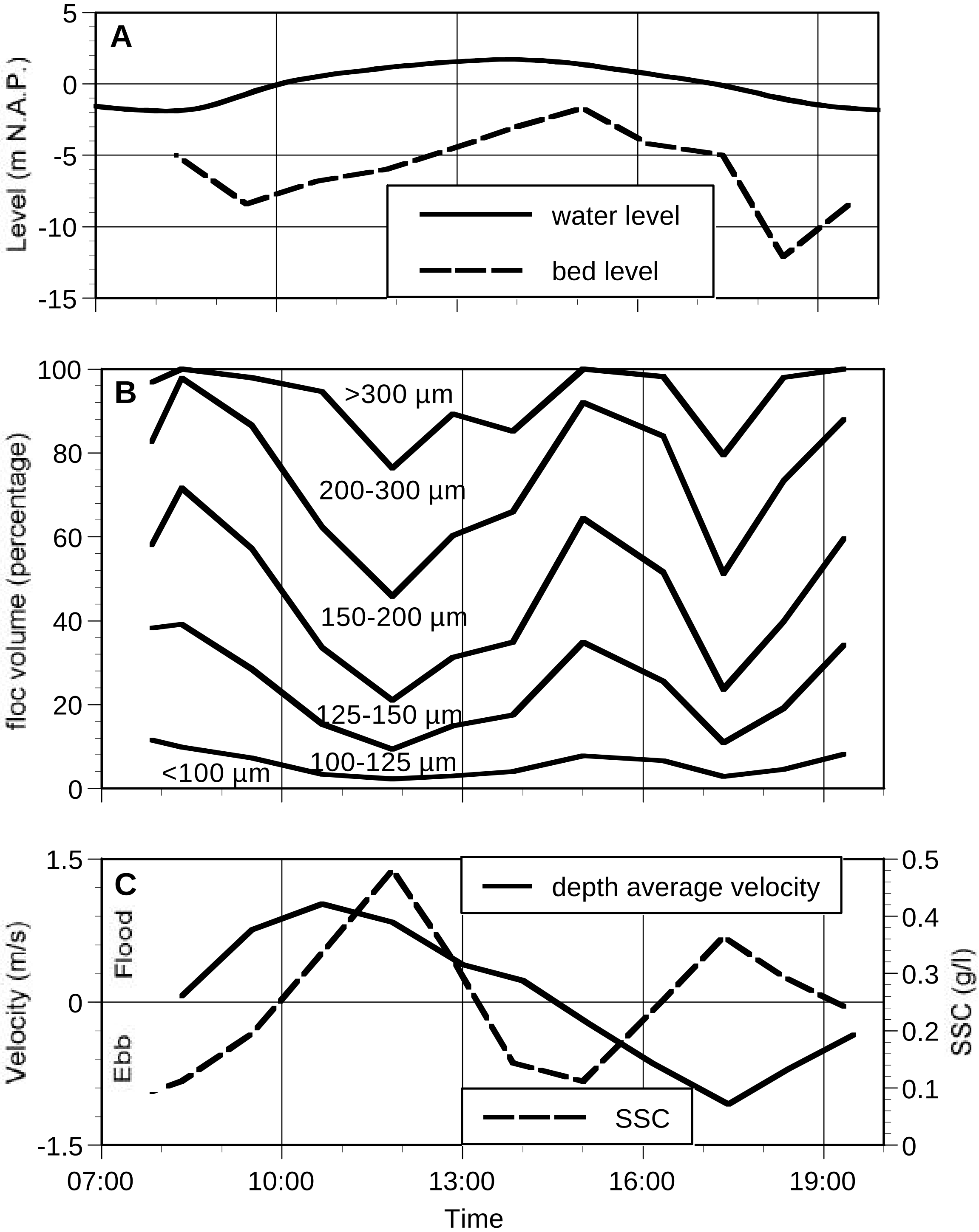

Figure 4.2 VIS measurements 11 October 1995

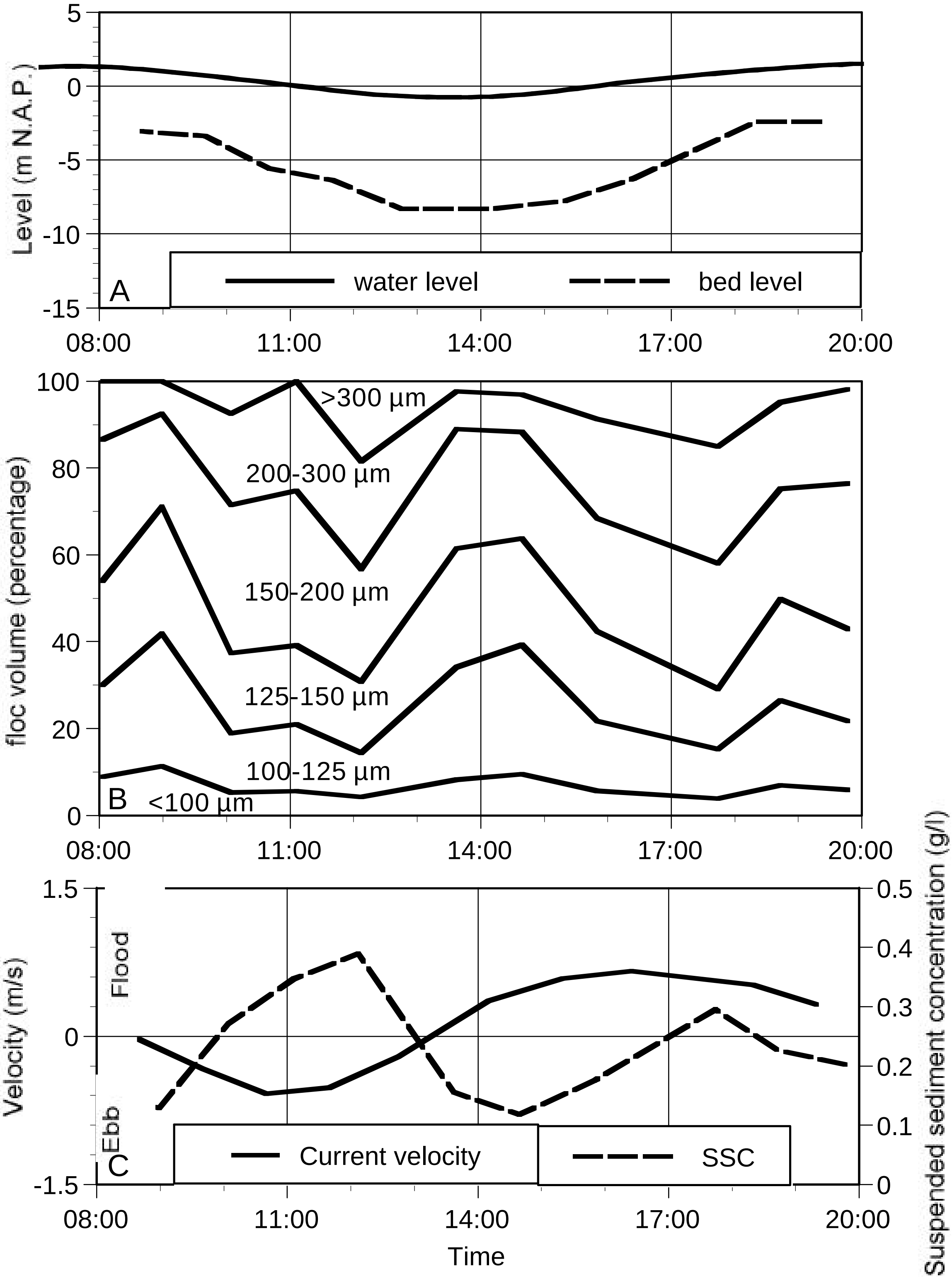

Figure 4.3 VIS measurements 19 October 1995

There are two possible origins of the large flocs observed at high SSC. They are either formed by aggregation in the water column, or the large flocs were eroded from the bed. Observations on 29 May 1996 (discussed later in fig. 4.5) showed increasing floc sizes while sediment was settling out of the water column due to a decelerating current velocity. This suggests that at that time flocs were formed by aggregation in the water column, since it is very unlikely that large flocs were eroded from the bed and dispersed into the water column during a period of sediment settling.

The measurements of 11 October 1995 took place about two days after spring tide. Figure 4.3 shows the measurements on 19 October 1995, which was about two days after neap tide. These neap tide measurements are quite comparable to the spring tide measurements. There is still quite a large tidal variation of the floc size and a good correlation with the SSC. There are some differences. The range of current velocity, SSC as well as the range of the floc size distribution is a bit smaller during neap tide. The smaller range of the floc size distribution during neap tide seems coincidental since this was not observed in all measurements.

Not all measurements are shown in detail here, but the daily averaged floc size, the daily averaged range of the floc size and the SSC of all measurements are shown in figure 4.4. The presented averages are based on the floc volumes. That means that the average floc volume was calculated and then the equivalent diameter for a sphere of this volume was determined, as was explained in chapter 2. It is a volume based average diameter. In this way, the calculated floc sizes are representative of the larger flocs. It is these larger flocs that make up most of the suspended volume and therefore they are the most important for mud transport and sedimentation.
However, the use of a mass weighted average floc diameter would represent the suspended sediment mass. For mud transport and sedimentation the mass fluxes are important, not the volume fluxes. Therefore floc sizes and settling velocities were determined from a limited number of Video *In Situ* measurements. The Stokes density of the flocs was calculated and subsequently the mass weighted average diameter was determined. A comparison between this mass based diameter and the volume based diameter showed that the volume based diameter is only about 3% larger than the mass based diameter. This difference is small enough to justify the use of the volume based floc diameter as representative for most of the suspended sediment volume and mass.

Figure 4.4a shows that the average floc size is approximately the same for all measurements. There is one measurement however on 29 May 1996, where the average floc size as well as the range of floc sizes is significantly larger than during the rest of the year. Figure 4.5 shows this measurement.

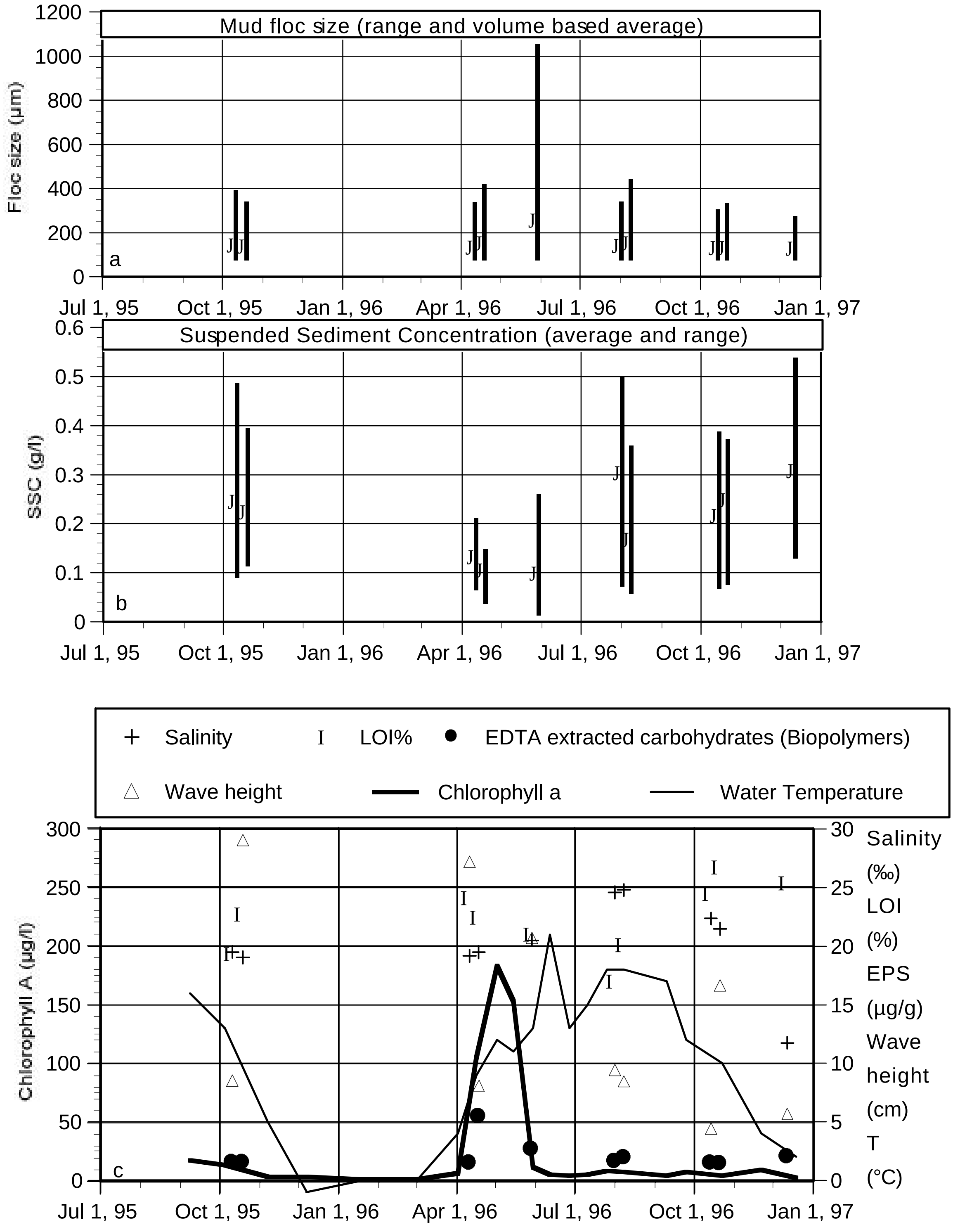

Figure 4.4 a) Seasonal variation of mud floc size b) Seasonal variation of suspended sediment concentration c) Wave height, EPS, LOI, Chlorophyll-a* and water temperature* (* data from the National Institute for Coastal and Marine Management (RIKZ), The Netherlands)

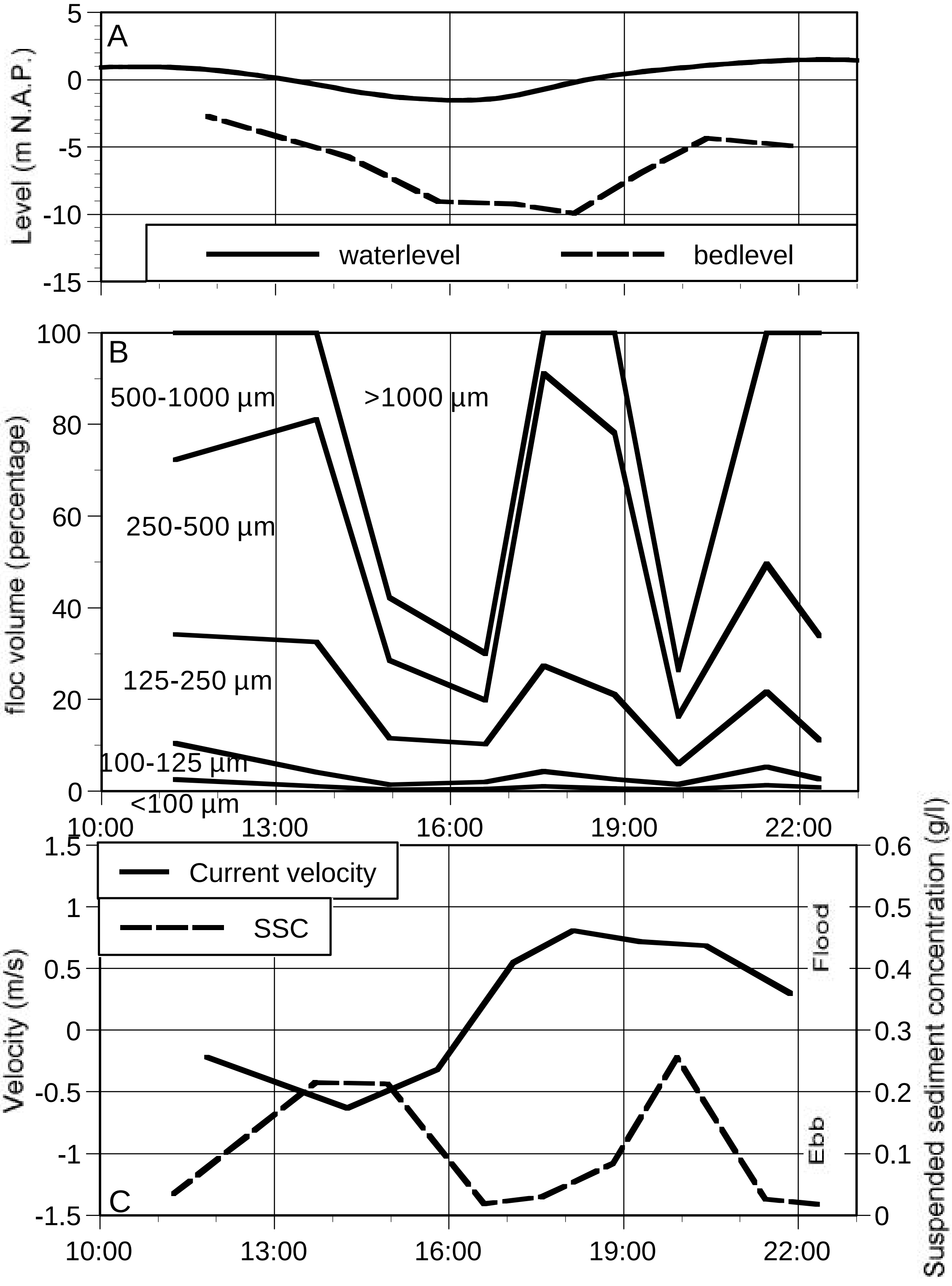

Figure 4.5 VIS measurements 29 May 1996

The following can be concluded from figure 4.4 and 4.5:

1. *Tidal variation in floc size and SSC.*
   Figure 4.5b shows an abundance of flocs larger than 1000 µm during this day. As in the other VIS measurements the floc sizes show a tidal variation. Figure 4.5c shows that there is a correspondence with the SSC. The increase in floc size during ebb and flood corresponds with increases in SSC. However, during the ebb tide, floc sizes kept increasing until slack tide, while the SSC was already decreasing. Only after slack tide, when the flood current increased the floc size decreased again.

2. *Flocculation occurs in the water column.*
   The measurement of 29 May 1996 also shows that flocculation in the water column at least partly determines the floc size and that floc size is not entirely dependent on erosion of large flocs from the bed. This can be seen from the observed floc sizes during the ebb tide. At that time maximum floc sizes did not coincide with the maximum SSC. Maximum floc size occurred about two hours after maximum SSC while the current was decelerating and sediment was settling. Lower turbulence levels may have decreased floc breakup at that time, which allowed the growth of large flocs. This suggests that flocs were formed by aggregation in the water column, either by settling induced collisions or by collisions due to the remaining turbulence. An increase of the floc size due to erosion of large flocs from the bed and dispersion into the water column is very unlikely during this period of sediment settling.

3. *Large flocs are not caused by a large SSC.*
   When the measurement of 29 May 1996 is compared to the other measurements, the SSC on 29 May is too low to explain the observed large floc sizes. This can also be seen in figure 4.4b that shows the seasonal variation of the SSC. From figure 4.4a and 4.4b, it is clear that the SSC did not determine the floc size variations on this yearly time scale as it did on the tidal time scale. There can still be an influence of the SSC, but clearly also some other factors must have determined these floc size variations throughout the year. There may be a relation with a plankton bloom in April and May of 1996 that will be dealt with in the discussion.

4.5 Discussion

There are several other factors than SSC that may influence the seasonal variation of floc size. Changes in the collision efficiency seem to play an important role. This may depend on salinity and biological cohesion of flocs, but water temperature, organic content and turbulence in the water due to wind waves may also play a role in the seasonal variation of floc sizes.

These factors are plotted in figure 4.4c. The possible impact of biological cohesion of flocs is expressed in the chlorophyll-a content and the amount of EDTA extracted carbohydrates from the suspended sediment.

Figure 4.4c shows the following typical results:

- The wave height does not seem to have a large influence on the floc sizes in the tidal channel. On 11 and 19 October 1995, 11 and 18 April 1996 and on 14 and 21 October 1996 the wave height varied considerable between the measurements in the same week. However there was hardly any variation in average floc size (figure 4.4a). The range of floc sizes was lower on 19 October 1995 and 11 April 1996 when the waves were high, but the range was also lower on 14 October 1996 when the waves were low. There is no correlation between the range of floc sizes and wave height. There is also no clear relation between range of floc size and neap/spring tide.
- In April and May 1996 there was a large phytoplankton bloom in the Dollard estuary as can be seen from the Chlorophyll-a content of the water. At the end of this bloom the much larger floc sizes of 29 May 1996 were measured. Earlier in the bloom however on 11 and 18 April the floc sizes were still in the same range as in the other measurements. So there could be a relation between the large flocs and the bloom termination.
- The effect of the plankton bloom is not visible in the organic content of the suspended sediment. The organic content is expressed by the loss on ignition (LOI%), which is the percentage of combustible organic material. The percentage of organic material in the suspended sediment varies between 17% and 27%, with the highest values in autumn. During the bloom the suspended flocs were still mainly composed of inorganic material. There is no relation visible between LOI% and floc size.
- The water temperature does not seem to have a direct influence on the floc sizes. The large average floc size on 29 May 1996 coincided with a high water temperature, but on 1 and 8 August 1996 water temperatures were also high but no large flocs were observed. In addition, the low water temperature on 12 December 1996 is not associated with smaller flocs. The increase in water temperature in spring however may have been a starting factor for the plankton bloom in May and June.
- A low salinity occurred on 12 December 1996 and a high salinity on 1 August 1996. On these days the average SSC was quite high and comparable. The floc sizes were of the same order. This indicates that salinity is not a steering parameter for the floc size. That corresponds with the findings of Eisma et al. (1991a) who also found no relation between salinity and *in situ* floc size. The lower salinity in winter however is consistent with winter run-off and nutrient fluxes necessary for the onset of the spring plankton bloom.

Summarising, waves, water temperature, organic content and salinity do not seem to explain the seasonal variation in floc sizes. But there may be a relation between the plankton bloom in April and May 1996 and the large flocs at the end of this bloom on 29 May 1996.

Diatom blooms are often terminated by mass sedimentation of the diatoms. Flocculation of the phytoplankton cells into large flocs (marine snow) enhances the settling velocity of the diatoms (Smetacek, 1985). Diatoms are also known to form more sticky flocs during later

stages of a bloom (Decho, 1990; Kiørboe et al., 1990). Decho (1990) suggests that exopolymeric substances excreted by diatoms cause this aggregation. These biopolymers may act as some sort of glue and increase floc sizes.
Mass flocculation of diatoms into macroflocs (marine snow) has regularly been observed by several authors in the field (Alldredge & Silver, 1988; Kranck & Milligan, 1988; Alldredge & Gottschalk, 1989; Riebesell, 1991) and in mesocosms (Riebesell, 1989; Passow & Alldredge, 1995). The occurrence of large flocs only at the end of the phytoplankton bloom in the Dollard is therefore consistent with the observations of mass flocculation at the end of blooms found in literature. The large flocs observed on 29 May 1996 are suggested to be caused by biopolymers excreted by phytoplankton or bacteria. Ten Brinke (1993; 1994) also found significantly larger floc sizes during a period with high algal biomass in the Eastern Scheldt and suggested that these larger flocs were caused by sticky biopolymers.

As a measure for biopolymers, the EDTA-extracted carbohydrates content of the suspended sediment was used. During the plankton bloom this carbohydrate content was higher than during the rest of the year, but the highest amount of biopolymers was measured on 18 April. This is not at the end but more at about one-third of the plankton bloom duration. Large flocs occurred only at the end of the bloom. Therefore the quantitative amount of EDTA-extracted carbohydrate is probably not a good parameter to describe the stickiness of the suspended particles. The plankton bloom and accompanying biopolymers also do not cause an absolute increase in the amount of organic material in the suspended flocs, as can be seen from the LOI% in figure 4.4c.

Figure 4.6 shows the plankton species composition in the tidal channel Groote Gat in the Dollard estuary. In the beginning of the bloom the diatom *Skeletonema costatum* dominated. Then the diatoms almost disappeared and dinoflagellates, mainly *Heterocapsa rotundata*, and micro-flagellates dominated. Subsequently in May the diatom *Thalassiosira nordenskioeldii* was most abundant. Kiørboe & Hansen (1993) investigated the production of particulate mucus or transparent exopolymeric particles (TEP) by phytoplankton cells and its role in aggregate formation. They found that *Skeletonema costatum* cells are sticky in themselves, and coagulation depends on cell-cell sticking and does not involve mucus. This suggests that *Skeletonema costatum* will not contribute to mud floc aggregation. Kiørboe & Hansen (1993) even found that *Skeletonema costatum* at times excretes a solute substance that reduces enhanced flocculation. This seems in accordance with the observed “normal” floc sizes on 11 and 18 April 1996 during the *Skeletonema costatum* bloom (fig. 4.6).

Other investigated diatoms, however, produced TEP and coagulation depended on TEP-cell, rather than cell-cell sticking. *Thalassiosira nordenskioeldii* was not investigated by Kiørboe and Hansen (1993) but *Thalassiosira pseudonana* was among the investigated diatoms and it produced TEP. Such production of TEP may have contributed to the growth of the mud flocs at the end of the plankton bloom in the Dollard estuary. Bacterial activity may also favour the formation of large aggregates during the decline of a bloom

(Riebesell, 1991). Ten Brinke (1993) found strong indications of a high bacterial biomass at the end of a bloom in the Eastern Scheldt estuary. Bacteria may greatly influence the process of flocculation by competing with phytoplankton for nutrients and by secreting sticky biopolymers (Ten Brinke, 1993).

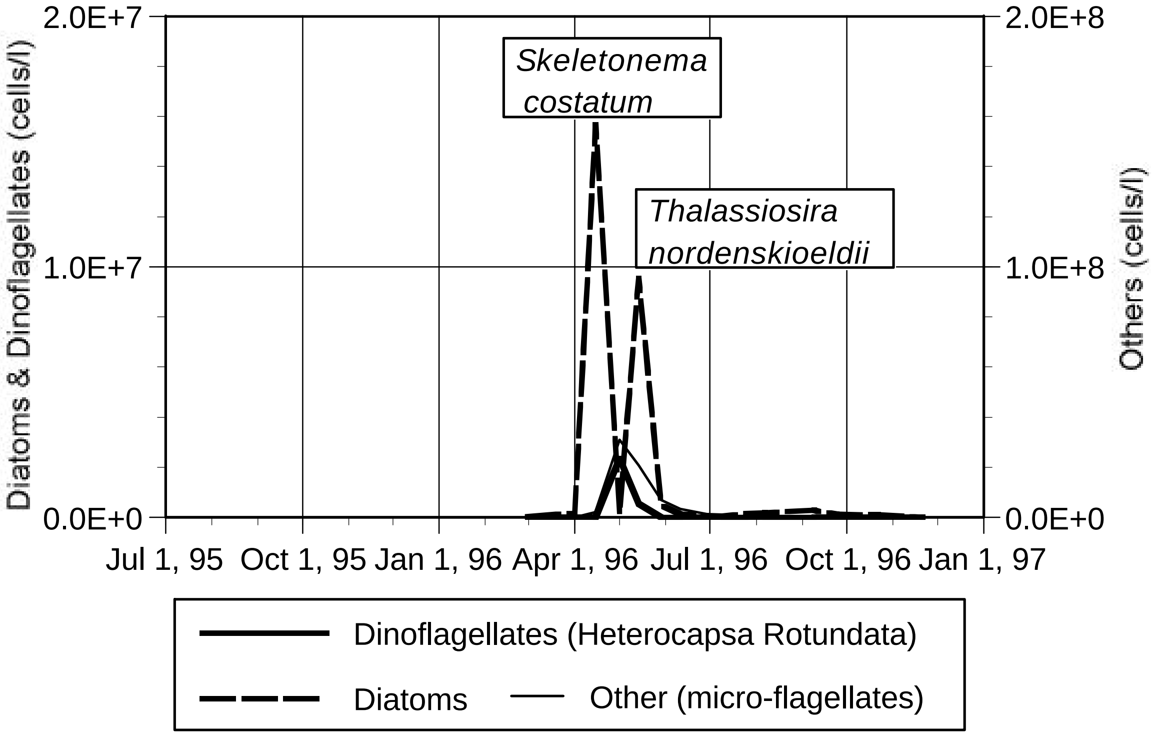

Figure 4.6 Observed Phytoplankton in the Dollard estuary. (Source: National Institute for Coastal and Marine Management (RIKZ), The Netherlands)

It seems clear that the quantity of biopolymers present in the mud flocs is not a good measure for the stickiness of these mud flocs. The particulate mucus produced by different species of diatoms differs in chemical composition (Decho, 1990) and appears also to differ in its surface properties (Kiørboe & Hansen, 1993). That means that the 'glue' quality of biopolymers present in the water is more important than the absolute quantity. Therefore biological cohesion of flocs may depend on phytoplankton composition, phytoplankton concentration, the physiological state of phytoplankton and bacterial production or degradation of biopolymers during cell lysis at the decline of a bloom.

It is still not clear how the large flocs observed on 29 May 1996 were formed. The absolute quantity of EDTA-extracted carbohydrates could not explain it. The large floc sizes did however occur during the decline of the bloom, which is a commonly observed phenomenon in the ocean and coastal seas. Probably the biopolymers present on 29 May 1996 had a large impact on the overall stickiness of the suspended sediment, even though the absolute quantity was less than on 18 April 1996 when large flocs did not appear. Although the exact cause of the intensive flocculation on 29 May 1996 can not be determined, it is likely that there is a relation with the plankton bloom. It seems that the mortality associated with the end of the bloom enhances the average size of the visualized flocs.

4.6 Conclusions

Many parameters that could affect mud floc size in the Dollard estuary were measured on 10 measurement days throughout the period of one year. This is a relatively short observation period for establishing seasonal fluctuations in floc sizes. Furthermore it is difficult to establish cause and effect relationships from correlations between observations. Despite these flaws the following conclusions can be drawn:

On a tidal time scale, floc sizes in the Dollard estuary were correlated with the SSC. The average floc size was about 140 µm.

On a seasonal time scale the observations of floc size and phytoplankton showed that during the decline of a spring plankton bloom floc sizes in the Dollard substantially increased. An average floc size of about 250 µm was observed. Factors like salinity, water temperature and wave height did not seem to have a direct influence on the seasonal fluctuation of floc sizes.

Large flocs can form in the water column from smaller aggregates or they are eroded from the bed. The observation of growing flocs while the SSC was already decreasing on 29 May 1996 shows that at least part of the suspended flocs were formed from smaller flocs or particles in the water column.

Biological cohesion of flocs is probably more dependent on the ‘glue’ quality of the biopolymers than on the absolute quantity. The quantity as well as the quality of the biopolymers may depend on the species composition, concentration and physiological state of phytoplankton and bacteria.

Biological processes seem more important than physical processes for the flocculation of fine sediment during the decline of a plankton bloom. This may have impact on the seasonal variation in fine-grained sediment dynamics.

5 TEMPORAL VARIATION OF FLOC SIZE AND SETTLING VELOCITY IN THE DOLLARD ESTUARY

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5.1 Introduction

This chapter presents measurements with the Video *In Situ* (VIS), that were executed from October 1995 until December 1996 in a tidal channel in the Dollard estuary. This instrument and the VIS measurement methodology were already described in chapter 2. The measurements were used to determine both the tidal and seasonal variation in floc sizes and settling velocity. Furthermore, They were used to elucidate the processes that cause these variations. This chapter also deals with the relation between floc sizes and floc settling velocities in the Dollard estuary.

5.2 Theory: size, settling velocity and density

The relation between size and settling velocity is complex. Under creeping flow conditions, that is with particle Reynolds numbers below 1, this relation can be described with the Stokes Law:

$$W_s = \frac{1}{18}\frac{(r_s - r)}{r}\frac{gd^2}{u} \tag{5.1}$$

Where:

W_s	=	particle fall velocity (mm/s)
ρ_s	=	particle density (kg/m^3)
ρ	=	fluid density (kg/m^3)
ρ_s-ρ	=	effective density (kg/m^3)
g	=	gravitational acceleration (9.81 m/s^2)
d	=	particle diameter (m)
υ	=	kinematic viscosity of the fluid (m^2/s^1)

Here the Stokes law will be applied to calculate effective densities from floc size and settling velocities measured in the Dollard estuary. The floc size is defined as the equivalent diameter of a circle with the same surface area as the surface area of the floc measured with the underwater camera. Most flocs are so small and settle so slowly that their Reynolds numbers do not exceed 1, but the larger and faster settling flocs may have Reynolds numbers up to 3.

Sometimes the Stokes law still holds for flocs with a Reynolds number larger than 1. For highly porous flocs Wu & Lee (1998) found that a Stokes law like relation can be valid for

Reynolds numbers up to 11. Lee et al. (1996) suggested that porous flocs under higher Reynolds numbers endure less boundary layer separation and a lesser wake than non-porous flocs, due to the flow through the floc interior. Thus the Stokes law may be used to obtain a floc density versus size relationship for porous flocs with a Reynolds number larger than 1. This will give a good estimate of the slope of this relation (Wu & Lee, 1998). The absolute value of the calculated densities may however be more erroneous as the Reynolds number increases (Wu & Lee, 1998). Furthermore the Stokes law does not take the effect of floc shape and roughness into account. This may also adversely affect density calculations obtained with the Stokes law. The calculated effective density may therefore not be considered as the real floc density, but as an apparent floc density which includes floc porosity and floc shape. According to Lick & Huang (1993) floc porosity and floc shape may affect the settling speed of flocs but are generally minor factors compared to a change in floc density.

For a floc with a diameter of 350 µm and a settling speed of 6 mm/s (Re = 2.1, representative for large and fast settling flocs in the Dollard), the density was calculated with Stokes law and with the Oseen modification of Stokes law, which is valid for flocs with Reynolds numbers up to 5 (Ten Brinke, 1993). There was a 3% difference between the calculated floc densities. Therefore a reasonable approximation of the actual density of the flocs measured in the Dollard estuary can still be determined from the Stokes law. However, Stokes densities should not be used for settling velocity calculations when only the floc diameter and density is known, as larger errors may arise when the Reynolds number exceeds unity.

5.3 Results

The seasonal as well as the tidal fluctuations in floc sizes and settling velocities in the Dollard estuary were assessed from the VIS measurements that took place from October 1995 until December 1996. The tidal and seasonal fluctuations in floc size will be shown first, followed by an evaluation of the relation between floc size and settling velocity, which is very dependent on the floc density. Finally the tidal and seasonal fluctuations in floc settling velocity will be shown.

5.3.1 Floc size during the tidal cycle

The VIS measurement on 11 October 1995 was already shown in figure 3.1 and 4.2. It showed the tidal variation in mud floc size. In this figure, the SSC strongly correlated with the floc sizes, which may be explained by the increased floc collision frequency due to a larger abundance of flocs at higher SSC. Another possible origin of the large flocs observed at high SSC is erosion of large flocs from the bed.
In brief, figure 3.1 and 4.2 showed that there is a strong tidal variation in floc sizes, that floc sizes larger than 300 µm occur and that the floc sizes are governed by the SSC.

5.3.2 Floc size throughout the seasons

Figure 5.1a shows the seasonal fluctuations in floc size in the tidal channel of the Dollard estuary. The dots represent the daily averaged floc size. This averaged floc size is a volume based average. This results in a larger average floc size than a number based average. A volume based average is more representative for the larger flocs that are most important for the suspended sediment flux. The vertical lines represent the range of floc sizes during the measurements throughout the tide. The minimum of the range is always 85 μm as the VIS is not capable of measuring smaller flocs. The maximum is the tidal average of the maximum floc size in each individual VIS measurement. In this way the tidal variation is averaged out of the data.

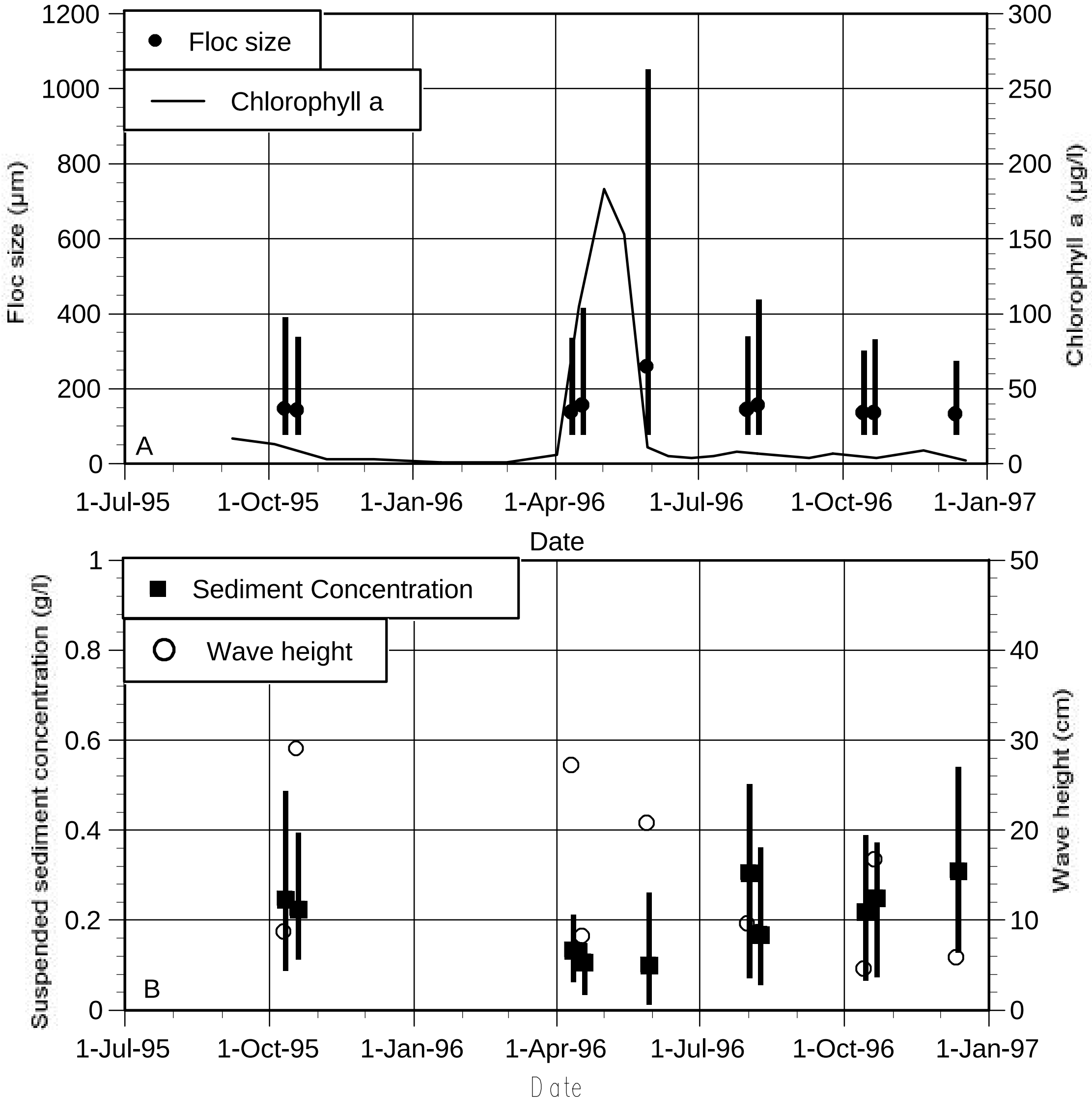

Figure 5.1 a) Floc size measurements and chlorophyll-a throughout the seasons b) Suspended sediment concentration and wave height throughout the seasons

The average floc size is rather constant throughout the year, except on 29 May 1996 when flocs up to 1000 µm occurred. Chapter 4 showed that these large flocs where associated with the decline of a plankton bloom as can be seen from the Chlorophyll-a concentrations plotted in figure 5.1a.
Figure 5.1b shows the average and range of the suspended sediment concentrations during the measurement days. The figures show no relation between SSC and floc size. It seems that SSC no longer dominates the size of suspended mud flocs on a seasonal time scale. Differences in weather conditions and therefore differences in floc breakup by turbulence also do not explain this lack in relation. There is no relation between the measured floc sizes and wave heights as can also be seen in figure 5.1b.
In brief, figure 5.1 showed that floc sizes are not dominated by the SSC on a seasonal time scale. Possible causes for this lack in relation will be discussed later. The figure further showed that at the end of a plankton bloom flocs up to 1000 µm can occur, presumably due to biological flocculation.

5.3.3 The relation between floc size and settling velocity

The settling velocity of flocs depends on the size and density of the flocs (eq. 5.1). Figure 5.2a shows a plot of floc settling velocity versus floc size and 5.2b shows a plot of floc density versus floc size. These measurements were taken during one survey of about 20 minutes on 8 August 1996. Note that the densities in figure 5.2b, are apparent densities, which means that they are calculated from floc sizes and settling velocities with the Stokes law. Each data point in the figures represents the size and settling velocity of a floc observed from two consecutive images. As the same floc may be observed again in the next image, it is possible that the same floc is represented by several data points in figure 5.2.

Figure 5.2a shows that there is no clear relationship between floc size and settling velocity. There is a certain increase of settling velocity with size, but due to the large scatter, it is not possible to infer a relationship with a fitted curve. Figure 5.2b also shows a lot of scatter but it is clear that in the smaller size ranges flocs with all possible densities occur, from highly organic or porous flocs to almost sand grains. With increasing floc size the densities decrease and the range of densities also converges. Larger flocs are more porous, and maybe they contain more light organic material, which explains their low density. There is a clear upper limit to the densities, and this limit decreases with floc size. However, it is not possible to establish a relationship between floc densities and floc size with a fitted curve. The figure shows that the flocs are very heterogeneous, and that floc size and floc density both determine the floc settling velocity.
The observed settling velocities are high. In this example the mass weighted average settling velocity is about 3.2 mm/s, which is equivalent to that of a sand grain of about 65 µm. The average of all measurements is 2.75 mm/s. In most sediment transport models the assumed floc settling velocity seldom exceeds 1 mm/s. Note, however, that these 1 mm/s represents an average settling velocity for the whole estuary, whereas the VIS measurements took place rather high in the water column of the tidal channel were floc

breakup does not so easily occur as near the sediment bed, where turbulence intensities are much higher.

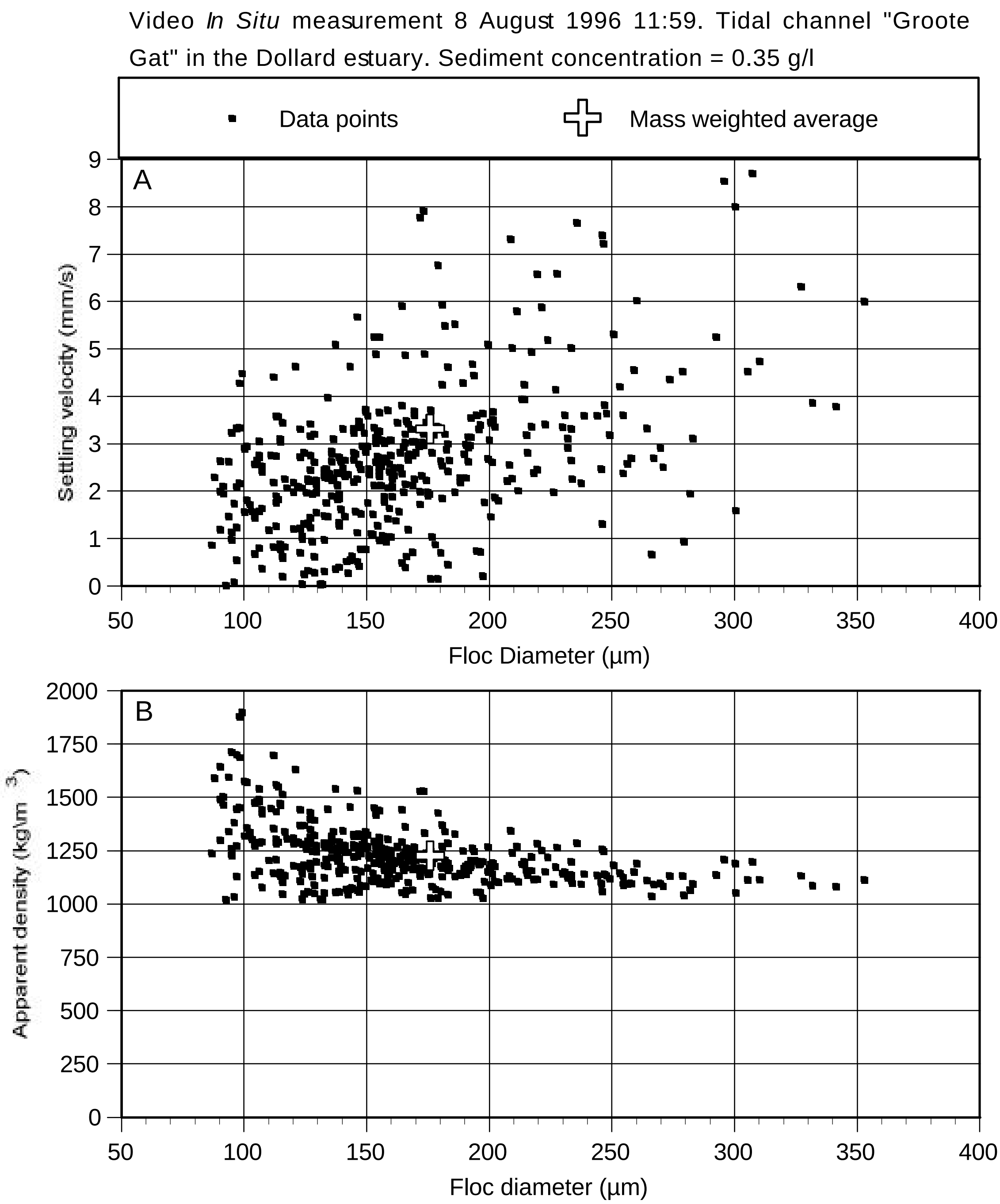

Figure 5.2 a) Size versus settling velocity of mud flocs b) Size versus density of mud flocs (VIS measurement of 8 August 1996 11:59 h)

5.3.4 Floc settling velocity throughout the tide

Figure 3.1 and 4.2 showed an example of the floc size variation throughout the tide. Floc sizes were obtained from all VIS measurements. Floc settling velocities were obtained from only two VIS measurements on each measurement day. For that reason all settling velocity data collected from October 1995 until December 1996 was normalised relative to high water time and is plotted in figure 5.3. In this way it was possible to show the average tidal variation of floc settling velocities. For comparison the measured suspended sediment concentrations were also normalised to high water and were plotted in the same way as the floc settling velocity. A sinusoidal fit was computed through the data to show the general trend. Since the presented data was taken throughout a year, some of the floc size variation could also result from seasonal floc size variations. In the next section (fig. 5.4) will be shown that there is hardly any seasonal variation in the floc settling velocities in the Dollard. The floc size variations shown in figure 5.3 are therefore mainly tidal variations.

Figure 5.3 shows that the tidal variation in settling velocity is comparable to the tidal variation in floc size (fig. 3.1). Floc size and settling velocity show similar trends with the SSC as can be seen in figure 3.1 and 5.3. The average settling velocity is about 2.75 mm/s.

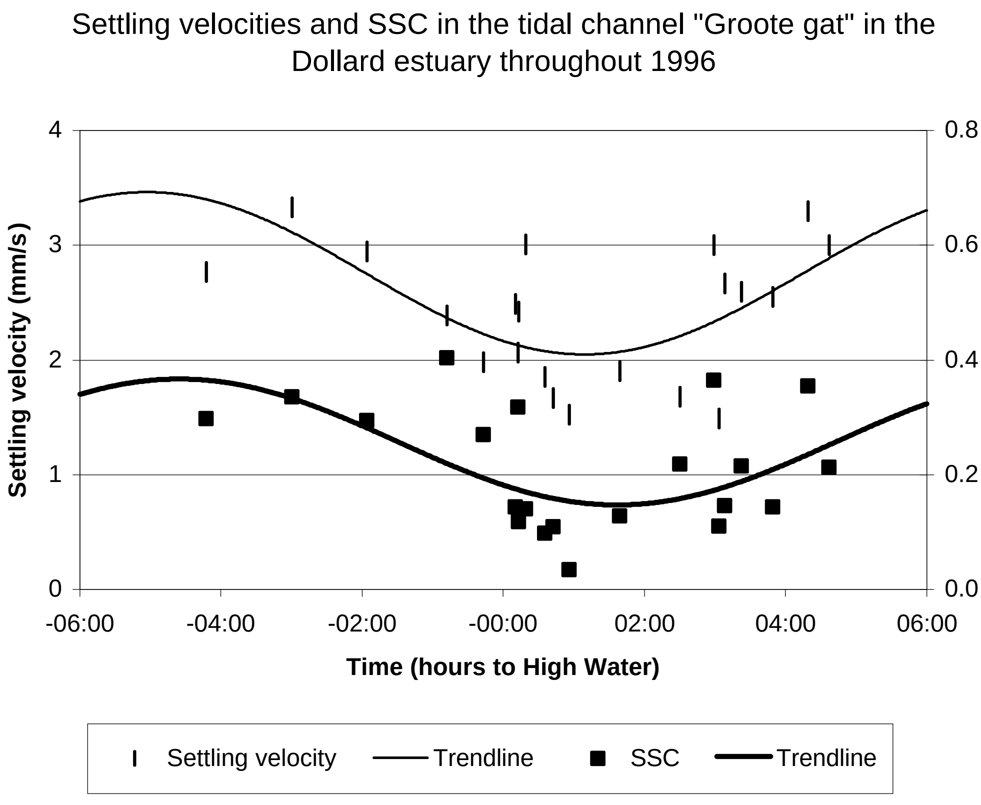

Figure 5.3 Settling velocity and suspended sediment concentration throughout the tidal cycle (Time is normalised to high water)

5.3.5 Floc settling velocity throughout the seasons

Figure 5.4 shows the mass weighted average floc sizes and settling velocity from October 1995 to December 1996. On 29 May 1996 the peak in floc sizes at the end of a plankton bloom is clearly visible as was also shown in figure 5.1a. There was, however, no peak in floc settling velocity on that day. It is likely that the effect of the large floc size on the floc settling velocity was totally counterbalanced by the very low density of these large flocs. The organic content of these flocs was 21% (measured by loss on ignition, see also fig. 4.4). This is comparable to the organic content of the flocs during the rest of the year. Therefore the low density of the flocs on 29 May must be the result of a very high porosity of the flocs. Figure 5.4 also shows that the average floc settling velocity in the Dollard was about 2.75 mm/s plus or minus 1 mm/s. There is little variation throughout the year. The large range of settling velocities can be explained by tidal variation as was shown above.

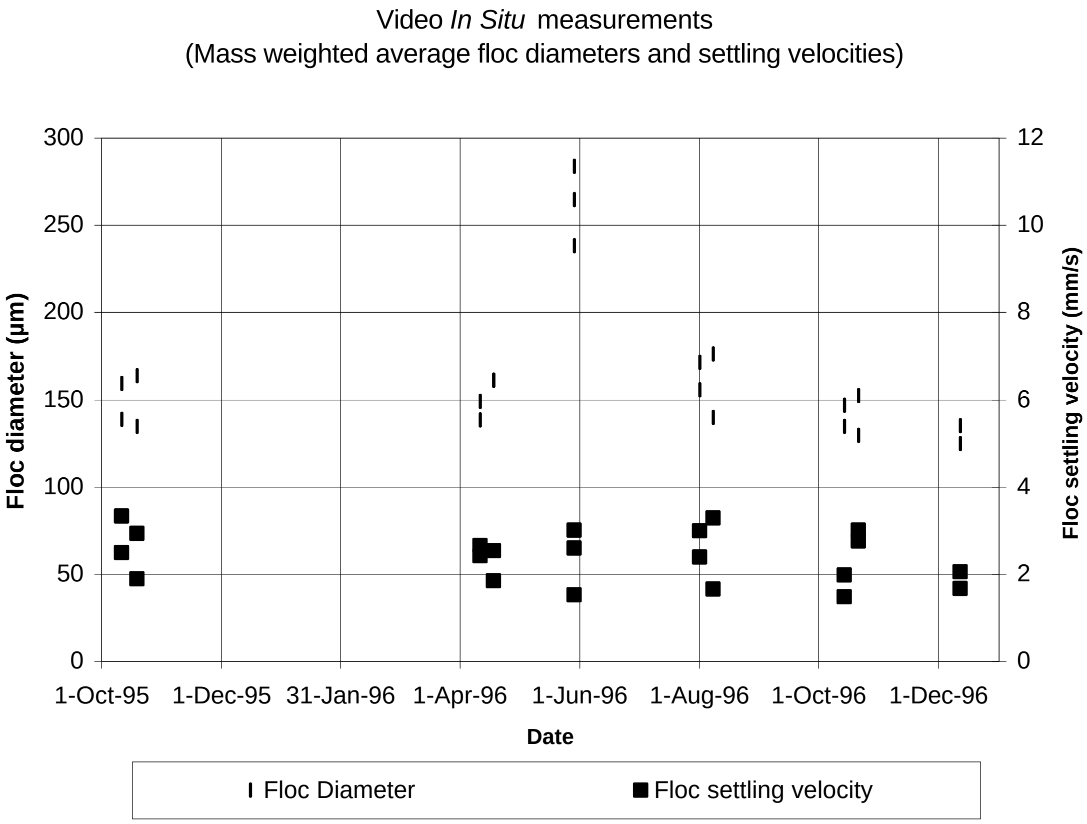

Figure 5.4 Seasonal variation of floc size and settling velocity

5.4 Discussion

5.4.1 Apparent floc density

The results in figure 5.2 show that there is no clear relation between floc size and settling velocity. Figure 5.4 shows that on 29 May 1996 the density of the flocs was so low that their settling velocity was comparable to the settling velocity on other measurement days, despite the very large size of the flocs. In general, the results show that the flocs in the Dollard estuary are very heterogeneous, and that floc size and floc density both determine the floc settling velocity.

5.4.2 Floc settling velocity and floc breakup

The observed average floc settling velocities were large, around 2.75 mm/s. Note that these settling velocities were measured in the upper part of the water column.
When there is little vertical diffusion around high water slack such a large settling velocity would mean that flocs can settle almost 10 m per hour. With a channel depth at high water of about 5.5 m this would mean that almost all sediment would settle in a little more than half an hour. However, minimum SSC, floc size and settling velocity occur only about 1.5 hours after high water slack. Since the flocs need about 1.5 hours to settle to the bed, this means that the vertically averaged settling velocity is in fact lower than 2.75 mm/s. In the upper water column a settling velocity may be measured as high as 2.75 mm/s, but closer to the bed the settling velocities are probably much lower. Near the bed, floc breakup due to high turbulence intensity probably occurs, as was also suggested in chapter 3 from measurements just above the bed of the Heringsplaat tidal flat.

5.4.3 The effect of the SSC on floc size/settling velocity and processes that may cause floc growth

There is a similar trend in the floc size/settling velocity and the SSC during the tidal cycle. An increase in SSC causes an increasing floc collision frequency in the water column. This enhances floc growth. Another possibility is that larger flocs are resuspended from the bed as erosion occurs. This may also explain an increase in floc size with increasing SSC. On the seasonal time scale there is no relation between floc size/settling velocity and SSC. There are two possible causes for this:

1. If floc growth occurs as a result of flocculation in the water column, a SSC increase should result in faster floc growth and therefore larger flocs, but this does not happen on a seasonal time scale. This can be explained if the binding properties of the flocs change strongly throughout the seasons whereby the collision efficiency of the flocs becomes more important in controlling the floc size than the collision frequency. Such changes in floc properties depend on changes in organic content, density, biopolymers etc.

2. If floc growth is caused by erosion of larger flocs from the bed, the tidal variation in floc size/settling velocity should be caused by local erosion/deposition. In that case floc size/settling velocity changes do not result from the collision frequency increase due to a higher SSC. Floc size increases are caused by resuspension of larger flocs from the bed or near bed zone, and floc size decreases by settling of the larger flocs towards the bed.

   On a seasonal time scale changes in SSC are not directly caused by erosion or deposition but more likely by a shift in the turbidity maximum in the Ems/Dollard system. This may explain why there is no relation between SSC and size/settling velocity on a seasonal time scale. If floc size/settling velocity would depend on the collision frequency of the flocs, governed by the SSC, there would also be a relation between SSC and floc size/settling velocity on the seasonal time scale.

   The above implies that the floc settling velocity depends on the erosion, turbulent mixing and deposition that occurs throughout the tidal cycle. This leads to a relation between floc size/settling velocity and SSC on the tidal time scale, but this relation results mainly from the process of erosion and deposition of the flocs and much less from an increased collision frequency of the flocs.

However, neither of these causes can solely explain the lack in relation between SSC and floc size/settling velocity, for the following reasons:

1. If floc growth occurs due to flocculation in the water column, it is implausible that the effect of SSC on floc size and settling velocity would totally disappear due to seasonal changes in floc properties. Furthermore, large changes in the organic content of the flocs were not observed.
2. If floc growth occurs due to erosion from the bed, it is unlikely that large flocs would survive the strong turbulent shear near the bed. There are many indications that floc breakup near the bed occurs (Mehta & Partheniades, 1975; Van Leussen, 1994; Van der Lee, 1998). If flocs with an average settling velocity of 2.75 mm/s as measured by the VIS, are present throughout the water column, the sediment would settle much faster during slack water than was observed.

Video observations from a sediment bed have shown the erosion of flocs and not of constituent particles (A. Oost, personal communication). But some VIS measurements showed the growth of very large flocs while the SSC was decreasing and erosion was obviously not taking place. This latter observations shows that flocculation in the water column also occurs, either as the result of differential settling or as the result of lesser floc breakup by turbulence.

Therefore flocculation in the water column as well as resuspension from the bed probably occur. Possibly microflocs are eroded from the bed under high current velocities, and macroflocs grow from these microflocs higher in the water column. These macroflocs are kept in suspension by the turbulent mixing. When current velocities and turbulent mixing decreases the larger macroflocs settle towards the bed and the floc size/settling velocity decreases again.

Microflocs are strongly bonded and rather tightly packed flocs, whereas macroflocs are loosely bonded fragile flocs (Eisma, 1986). In that case, flocculation is responsible for the development of macroflocs, but erosion from the bed determines the availability of the microflocs.
For a better knowledge of flocculation processes further research is needed to determine floc sizes throughout the water column and near the bed. Especially knowledge about the state in which sediment is eroded from the bed is very important.

Even though we do not know whether large flocs originate from flocculation in the water column, from the bed or both, it is clear that changes in floc size throughout the seasons are a result of changes in the binding properties of the flocs. This must be either by a different flocculation ability in the water column, or by better binding of the mud in the bed causing larger or stronger (micro)flocs.

5.4.4 Modelling settling velocity variations throughout the tide

It was shown that on a tidal time scale the variations in floc size and settling velocity show a similar trend as the SSC. This has been found by many authors and it is the reason why the settling velocity is often expressed as an exponential function of the SSC:

$$W_s = aC^n \tag{5.2}$$

Where W_s is the settling velocity, C is the suspended sediment concentration and a and n are constants. Dyer (1989) showed data from several authors who calculated the constants a and n in various estuaries. The constant n varied from 0.61 in the Humber estuary to 2.6 in the Elbe estuary. Van Leussen (1994) measured settling velocity and sediment concentration and found relations of the form of equation 5.2 for each location, but not for the entire estuary. Each location had a different a and n constant in equation 5.2. Van Leussen (1994) states that it is inappropriate to apply one relation in the calculations of fine sediment transport in the Ems estuary. The present data were all obtained in one tidal channel but at different times. In each tidal cycle there is a relation with the SSC (fig 3.1 and 5.3) but on a seasonal time scale this relation disappears (fig. 5.1.). Table 5.1 shows the a and n constants for the measurements in the 'Groote Gat' tidal channel.

Table 5.1 Constants a and n in equation 5.2 as was calculated from the VIS data

Date	a	n	R^2	Significant
October 1995	5.4	0.46	0.85	yes
April 1996	13.0	0.82	0.91	yes
May 1996	4.7	0.33	0.96	yes
August 1996	4.3	0.42	0.73	no
October 1996	3.4	0.26	0.15	no

Note that settling velocities were only determined from two VIS measurements on each day. The constants in table 1 were therefore calculated from only 4 settling velocity determinations, two around neap tide and two around spring tide in each season. Therefore, the accuracy of the numbers in table 1 is questionable, but it still shows that the relation between settling velocity and SSC varies throughout the seasons.

So even in one tidal channel there is no unique relation between settling velocity and SSC. This is consistent with the observations of Dyer and Van Leussen. It seems that a unique relation between settling velocity and SSC only occurs on a specific location in an estuary during a short period of time. At different moments and/or locations the relation changes. Unfortunately, that makes equation 5.2 questionable for modelling purposes. Figure 5.3, however, does show a relation between settling velocity and tidal phase (i.e. erosion and deposition), even with measurements that were taken throughout a whole year. For modelling purposes a simple model with settling velocity as a function of tidal phase could be more useful than assuming a constant settling velocity. For example:

$$W_s = a + b\cos(\tfrac{2p}{T}(t+c)) \qquad (5.3)$$

Where W_s is the floc average settling velocity, T is the tidal period (T = 12.4 h), t is the time in hours to high water, and a, b and c are constants. This model was fitted to the data in figure 5.3 by the least squares method and is shown as the trendline through the data. The constants were a = 2.75 mm/s, which is the average settling velocity, b = -0.71 mm/s, which determines the range of settling velocities and c = -1.15 hour, which means that there is a phase lag of the minimum settling velocity of 1 hour and 9 minutes after high water. The fit was tested significant and explains 42% of the variance. This explained variance is not high but it is better than assuming a constant floc settling velocity throughout the tide.

5.5 Conclusions

There is no clear relation between floc size and floc settling velocities as the floc settling velocity depends on size as well as density. Due to a large density decrease when flocs grow larger the positive effect of a floc size increase on the floc settling velocity is highly moderated.

On 29 May 1996 very large mud flocs up to 1000 µm were measured in the decline of a plankton bloom. Their settling velocity, however, was not larger than usual compared to other measurements due to the very low density of these flocs.

Measured settling velocities were large (average = 2.75 mm/s), but it is likely that these high settling velocities only occurred higher in the water column as floc breakup near the bed probably occurs.

The lack of relation between SSC and size/settling velocity on a seasonal time scale can be caused by large seasonal changes in floc properties like organic content and density. Another possibility is that the size and settling velocity is determined by the erosion and deposition of microflocs from and to the bed throughout the tidal cycle. Higher in the water column these microflocs aggregate into macroflocs and are kept in suspension until the current decreases. This means that floc size and settling velocity mainly depend on the tidal phase, and not directly on the SSC, which explains why a seasonal relation between SSC and floc size/settling velocity does not exist.

It is clear that changes in floc size throughout the seasons are a result of changes in the binding properties of the sediment. This may be due to either a different flocculation ability in the water column, or a better binding of the mud in the bed which causes larger or stronger (micro)flocs.

Floc size and settling velocity both vary throughout the tide. They show a positive relation with the SSC on a tidal time scale, but not on a seasonal time scale. The settling velocity cannot be expressed as a function of SSC, but it can be expressed as a function of tidal phase. At least in the Dollard estuary, the relation between settling velocity and tidal phase may be more useful for modelling purposes than assuming a constant floc settling velocity.

6 THE SIZE AND SETTLING VELOCITY OF FINE-GRAINED SUSPENDED SEDIMENT IN THE DOLLARD ESTUARY. A SYNTHESIS

6.1 Introduction

The general aim of this study was *to assess the variations in the size and settling velocity of mud flocs in the Dollard estuary, The Netherlands, and to assess the processes that cause these variations.* This led to the following objectives of the study:

1. Identify which processes affect mud floc properties (e.g size, settling velocity and density)
2. Assess the temporal and spatial variation of mud floc properties based on their dependence on and interaction with the flocculation processes in the Dollard estuary.
3. Quantify the temporal and spatial variation in mud floc properties as a function of flocculation parameters.

Identification of flocculation processes was mainly based on the literature review in chapter1. From this review potential key flocculation parameters were determined.

The impact of these key parameters on mud floc properties was investigated on different time scales and spatial scales. In the tidal channel of the Dollard estuary and on 3 locations above the Dollard tidal flats size and/or settling velocity were measured with 3 types of instruments, The Video *In Situ*, a Cilas laser particle sizer and an Owen tube. Only the Video *In Situ* was capable of measuring absolute floc sizes and settling velocities but still with some shortcomings as were discussed in chapter 2. The Cilas laser particle sizer and the Owen tube could only be used to derive relative differences in floc sizes or floc settling velocities. At the present time there is no instrument available that can be considered fully reliable in determining floc sizes and settling velocities. This is clearly illustrated by the results from intercomparison experiments in the Elbe estuary with several techniques for floc size or settling velocity measurements by Eisma et al. (1996) and Dyer et al. (1996). These authors concluded that results obtained with different instruments could be compared but were very variable as a result of the characteristics of the instruments and of the methods used.
Therefore, the floc size and settling velocity measurements presented in this thesis are not fully reliable. Despite this uncertainty, it was possible to use this data for a partial assessment of the relative importance of the different processes that affect floc size and settling velocity and for the assessment of the temporal and spatial variation of floc size and settling velocity in the Dollard estuary. The results from these assessments will be presented in this chapter.
The dynamics of fine-grained cohesive sediment in the Dollard estuary depend largely on the variations in the floc settling velocity. Therefore especially these variations were

quantified in a simple empirical model, that can possibly assist by modelling of fine-grained sediment transport in the Dollard estuary.

6.2 Relevant flocculation processes and their impact in the Dollard estuary

In chapter1 the following potential key flocculation parameters were determined:

- Residence time of the flocs
- Turbulent shear
- Suspended sediment concentration
- Salinity
- Biopolymer concentration
- Water temperature

Based on the various floc size and settling velocity measurements in the Dollard throughout 1995, 1996 and 1997 the relative importance of the above flocculation parameters and their associated flocculation processes was (partly) assessed. They will first be dealt with in the above order. Then a discussion of the tidal and seasonal variation in floc size and settling velocity as a result of the mentioned flocculation processes will follow.

6.2.1 Residence time of the flocs

Flocs in suspension are not necessarily in a dynamic equilibrium with their surroundings. If a floc is not in equilibrium, its properties will also depend on its history. In that case the residence time of the floc in its present surrounding conditions plays an important role. The role of this residence time is especially important in relation to the effect of turbulent shear on the floc size, which will be discussed in the next section.

6.2.2 Turbulent shear

The turbulent shear firstly determines for a large part the collision frequency of the suspended mud flocs. More collisions result in faster floc growth and the turbulent shear is therefore an important flocculation parameter. Secondly, turbulence is also considered to be the most important limiting factor of floc size (Dyer, 1989; Eisma, 1986; Luettich et al., 1993; Van Leussen, 1994). Larger flocs are more fragile and will break more easily due to turbulent shear (Dyer, 1998; chapter 4).

According to Winterwerp (1999) floc size is inversely proportional to turbulent shear when the residence time of the flocs in the turbulent field is unlimited. Under low turbulent shear, however, flocs often do not reach an equilibrium floc size as they settle to the bed, or the turbulent conditions change before flocs are so large that their size is limited by floc breakup. So long as flocs are not in equilibrium with floc breakup, increasing turbulent shear will lead to increasing floc growth. The effect of turbulence on floc size and or settling velocity is expressed in the conceptual flocculation diagram of Dyer (1989) which was shown in chapter 1 as fig 1.7. This diagram infers that the floc diameter first increases with increasing turbulent shear and later decreases. Winterwerp (1998; 1999) claims, based on a flocculation model in which the aggregates are treated as self-similar fractal entities, that the ascending branch at small shear stress in the conceptual model of Dyer is the result of a limited residence time. The descending branch results from floc breakup by turbulent shear. A conceptual diagram of Winterwerps model results is shown in figure 6.1.

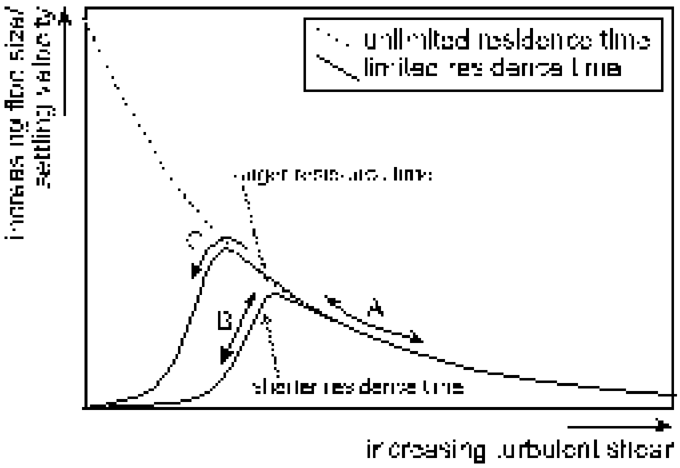

Figure 6.1 Floc size and settling velocity as a function of turbulent shear (After Winterwerp, 1999)

The solid lines in figure 6.1 show an increasing floc size/settling velocity with turbulent shear at small turbulent shear, and a decrease at large turbulent shear. This resembles the conceptual model of Dyer as presented in chapter 1. The ascending branches of these curves depend on the available residence time. The dashed line shows the equilibrium floc size/settling velocity with unlimited residence time. According to Winterwerp (1998;1999) it is not true that in the ascending branch flocculation effects dominate, and in the descending branch floc breakup processes, as is often suggested in literature.

The measurements presented in this thesis showed decreasing floc sizes with increasing turbulent shear in the near bed zone above the ‘Heringsplaat’ tidal flat (chapter 3). This chapter showed the fragility of mud flocs and their sensitivity for breakup by turbulent shear. If placed in the conceptual diagram of Dyer (1989) these measurements would pertain to the descending branch of floc size when turbulent shear increases. In figure 6.1 this is illustrated by arrow A. That infers a dynamic equilibrium between floc growth and floc breakup.

Floc size measurements in the tidal channel took place at approximately half the water depth. They showed an increase of floc size with increasing turbulent shear (chapter 3). This is likely to be related to the simultaneous increase in SSC but increasing turbulent shear will also enhance floc growth by an increased floc collision frequency. Since no decrease in floc size with increasing turbulent shear was observed, these measurements would pertain to the ascending branch in the conceptual diagram of Dyer (1989). In figure

6.1 this is illustrated by Arrow B. That infers that floc breakup did not yet limit the floc size as the flocs were not large enough yet to be affected by floc breakup. So at about half the water depth in the tidal channel the residence time of the flocs was probably not large enough for equilibrium between floc growth and breakup to develop. Near the bed the turbulent shear is larger and floc size limitation by floc breakup is more likely to occur.

On 29 may 1996 floc sizes in the tidal channel were much larger (chapter 4). This was related to a plankton bloom, which will be discussed later. During decelerating current velocities and decreasing SSC after the maximum ebb velocity the floc size showed a further increase. This could well have been the result of the decreasing turbulent shear hence decreasing floc breakup, which allowed the formation of larger flocs.
This implies that at maximum ebb current velocity, the floc size was already limited by floc breakup. This floc size increase with decreasing turbulent shear is illustrated by arrow C in figure 6.1. The range of turbulent shear is the same as in the other tidal channel measurements, but due to the larger flocs, floc size limitation by floc breakup probably occurred. As the SSC was decreasing, the sediment was settling. This means that the flocs must have grown in the water column and that they were not resuspended as already large flocs from the bed. Eventually, at low water slack, the large flocs settled, and floc sizes in the water column decreased again. This is illustrated by the descending part of arrow C.

The large flocs on 29 May 1996 may possibly have been the result of differential settling, but this is not very likely. The effect of differential settling on aggregation in marine environments is very small according to Stolzenbach & Elimelech (1994). They showed that smaller and denser particles are likely to move around a larger faster settling, but less dense, particle that overtakes them. The small particles are therefore not scavenged by these large particles, unless these large particles are very porous and water also flows through them. Differential settling is therefore unlikely to have occurred, but it can not be excluded.

Note that above the tidal flats the measurements took place at 30 cm above the bed. Here the turbulent shear was comparable to the shear at half the water depth in the tidal channel (see also chapter 3). The close proximity of the bed above the tidal flat, with high fluid shear along this boundary, may have caused floc breakup and resuspension of the broken flocs during ebb and flood tides, which explains the smaller flocs above the tidal flat during high current velocities. This is in contrast with the tidal channel where the largest flocs appeared during high current velocities. In the tidal channel the water is deeper and the frequency by which flocs approach the bed is much lower, which explains why floc breakup in the channel only seems to have occurred on 29 May 1996 when the flocs were extremely large.

The conceptual diagrams of Dyer (1989; fig. 1.7) and Winterwerp (1999; fig. 6.1) both give a good description of the effects of turbulent shear on floc size and settling velocity. Winterwerp (1999) ascribes the ascending branch of the curve to a limited residence time, where flocs settle to the bed before their growth is limited by floc breakup. Near the bed

these flocs are either deposited, or broken by near bed turbulence and resuspended. This agrees with the findings of Mehta & Partheniades (1975), who stated that the strong shear and lift forces near the bed control the size distribution of the flocs in suspension.
In Chapter 3 was shown that floc breakup most likely occurs in the near bed zone. Chapter 5 showed a strong relation between floc size/settling velocity and erosion/deposition of sediment. Chapter 5 also showed that there is a much lesser relation between floc size/settling velocity and collision frequency as a result of higher suspended sediment concentrations. The results from these chapters seem to support the hypothesis of Winterwerp that the ascending branch in figure 6.1 is caused by a limited residence time.

6.2.3 Suspended sediment concentration

When the SSC increases, the number of suspended particles or flocs also increases, which causes an increase in the collision frequency. This results in a faster floc growth and in a larger equilibrium floc size, since the faster floc growth is a better counterbalance for the floc breakup by turbulent shear.

In the tidal channel there is a relation between SSC and floc size (chapter 3). This can be the result of a larger collision frequency and therefore larger flocs, but it is also possible that larger flocs were eroded from the bed when the current velocities increased. Chapter 3 showed that flocs are fragile and that the odds of breakup near the bed are high. It is therefore unlikely that macroflocs could resuspend from the bed without being broken in the process. It is, however, possible that increasing current velocities eroded larger microflocs, which enhanced the floc growth.
Chapter 5 showed that on a seasonal time scale there is no relation between SSC and floc size/settling velocity. There are two possible causes for this:

1. There are such large seasonal changes in the binding properties of flocs that this effect fully overshadows the effect of SSC on the floc size/settling velocity.
2. The relation between SSC and floc size on a tidal time scale is an indirect relation, so there must be another factor that determines both SSC and floc size in the same way throughout the tide.

The first reason is not very likely because throughout the seasons floc sizes were very comparable and there were substantial changes in average SSC. Only on 29 may 1996 flocs were much larger, which was probably related to a plankton bloom. Almost all effects of SSC on the floc size should have been counterbalanced by a change in binding properties of the flocs to explain the lack of relation between SSC and floc size on a seasonal time scale. This is not very plausible.

On a tidal time scale changes in SSC are related to erosion of mud from the bed and deposition of mud to the bed. On a seasonal time scale changes in SSC are more likely related to a shift in the turbidity maximum. Since there is only a relation between SSC and floc size on the time scale of the tide, it is likely that the floc size is related to erosion and

deposition. Presumably (micro)flocs erode from and deposit to the bed throughout the tidal cycle. Higher in the water column these (micro)flocs may further grow into larger (macro)flocs.
Tidal changes in floc size and more important settling velocity will then be the result of erosion and deposition of the suspended sediment, which depends on the current velocity, bed shear strength and availability of the sediment. Chapter 5 showed that it was possible to explain 42% of the variance in the floc settling velocity by a sinusoidal fit of the floc settling velocity variation as a function of the tidal phase.

The classical concept where a larger SSC causes a larger collision frequency and therefore larger flocs is certainly not wrong and was shown in several laboratory experiments (e.g. Cornelisse, 1990; Van Leussen, 1994). However, in the Dollard estuary this process does not seem to have a large impact on the mud floc sizes and settling velocities, since seasonal fluctuations in SSC should in that case have an effect on the mud floc size and settling velocity. Erosion and deposition of sediment in the form of (micro)flocs under influence of the tide seems to be the dominating factor that determines floc sizes at least at mid-depth in the tidal channel of the Dollard estuary. So on a tidal time scale it is not just the SSC but especially the hydrodynamics that determines the floc size.

6.2.4 Salinity

In chapter 4 the investigations of several authors on the effect of salinity on floc size were reviewed. It showed that the classical concept of salt flocculation at the limnic-brackish boundary is superseded, most likely as a result of the organic coatings around the flocs. Van Leussen (1994) however states that salinity remains an important parameter in the flocculation of estuarine sediments. Not at the upper estuary with a few ‰ salinity, there organic coatings may retard the flocculation rate. At higher salinities, more to the seaward end of the estuary, Van Leussen observed the largest macroflocs. There the double layer thickness may be sufficiently reduced for bridging between particles by polymers to become effective (Van Leussen, 1994).

Effects of seasonal salinity changes on the floc size were not observed in the Dollard estuary (chapter 4). This indicates that salinity is not a direct steering parameter for the floc size in the Dollard estuary. That corresponds with the findings of Eisma et al. (1991a) who also found no relation between salinity and *in situ* floc size.

It seems that the impact of salinity may differ along the estuary with its salinity gradient. Salinity changes may also occur at specific location due to the tidal excursion and due to seasonal changes in freshwater input. It remains uncertain whether salinity will have an effect on the flocculation of the suspended sediments. In the Dollard estuary salinity effects were not observed.

6.2.5 Biopolymers

Biopolymers may form mucus around flocs, which acts as some sort of glue. This increases the flocculation ability of the flocs. Polymer chains that extend out of the suspended particles may also increase the chance of effective collisions to occur.

On a seasonal time scale the observations of floc size and phytoplankton showed that during the decline of spring plankton bloom floc sizes in the Dollard substantially increased (chapter 4). Other factors like salinity, water temperature and wave height did not seem to have a direct influence on the seasonal fluctuation of floc sizes.

Mass flocculation of diatoms into macroflocs (marine snow) has regularly been observed by several authors in the field (Alldredge & Silver, 1988; Kranck & Milligan, 1988; Alldredge & Gottschalk, 1989; Riebesell, 1991) and in mesocosms (Riebesell, 1989; Passow & Alldredge, 1995). The occurrence of large flocs only at the end of the phytoplankton bloom in the Dollard is therefore consistent with the observations found in literature of mass flocculation at the end of blooms. The large flocs observed on 29 may 1996 are suggested to be caused by biopolymers excreted by phytoplankton or bacteria.

The concentration of carbohydrates in the sediment was used as a measure of the amount of biopolymers present. The maximum concentrations of carbohydrates occurred during the bloom and not at the decline of the bloom. Only during the decline of the bloom were the suspended mud flocs in the Dollard estuary significantly larger. Therefore the quantitative amount of carbohydrates is probably not a good steering parameter to describe the stickiness of the suspended particles.
Biological cohesion of flocs is therefore probably more dependent on the ‘glue’ quality of the biopolymers than on the absolute quantity. The quantity as well as the quality of the biopolymers may depend on the species composition, concentration and physiological state of phytoplankton and bacteria.

Chapter 4 showed that biological processes are very important for the flocculation of fine sediment during the decline of a plankton bloom. This may have impact on the seasonal variation in fine-grained sediment dynamics.
In chapter 5 it shown that there is no clear relation between floc size and floc settling velocities, as the floc settling velocity depends on size as well as density. Due to a large density decrease when flocs grow larger, the positive effect of a floc size increase on the floc settling velocity is highly moderated. Due to this effect the large mud flocs measured on 29 May 1996 did not have a higher settling velocity than flocs measured throughout the rest of the year. This means that although biological processes may have a very large effect on the floc size, their effect on the floc settling velocity and hence the suspended sediment fluxes was limited.
In other estuaries than the Dollard estuary or at different occasions than the spring plankton bloom of 1996 the circumstances may differ.
It remains unknown to what extent biological effects on the settling velocity of mud flocs are moderated by the low density of these flocs under such different circumstances.

6.2.6 Water temperature

The water temperature does not seem to directly affect the flocculation process. Nevertheless, it does affect the viscosity of the water. A particle with a fixed size and density settles faster in warm water than in cold water. According to Krögel and Flemming (1998), such temperature effects cause differences in the average settling velocity of the sediment in summer and winter. In chapter 5 seasonal effects on floc size and settling velocity were studied, and temperature effects on floc size or on settling velocity were not observed. In the previous section it was hypothesised that floc sizes/and settling velocities depend on erosion and deposition of sediments throughout the tide, and the residence time of the flocs in the water column. The same settling velocity variations occur throughout the tide in summer and in winter. Flocs in winter may then be larger or denser to compensate for the temperature effect. Differences in floc size and settling velocity between summer and winter were not observed. So calculation of floc densities based on Stokes law automatically leads to denser flocs in winter. Unfortunately it is not possible to check whether such increased floc densities really occur in winter.

6.3 Floc size and settling velocity variations through the tide and the seasons

6.3.1 Floc size vs. settling velocity

The floc settling velocity is a function of floc size and floc density. On some occasions (e.g. in the decline of the spring plankton bloom of 1996) increases in floc sizes were accompanied by such decreases in floc density that the floc settling velocity remained more or less constant. In general however increasing floc sizes correspond with increasing floc settling velocities. But presumably due to the heterogeneity of the suspended material, from organic material to quartz grains and from porous flocs to dense flocs, it was not possible to establish a clear relationship between floc size and floc settling velocity.

6.3.2 Tidal channel, tidal time scale.

In the previous section it was shown that variations in settling velocity in the Dollard estuary mainly occur on the time scale of the tide. The seasonal variation is less important. This tidal variation seems to be mainly controlled by the erosion and deposition of the muddy sediments. That means that the hydrodynamics determine the maximum settling velocity of the flocs that occur. Larger and faster settling flocs simply disappear from the water column by sedimentation. The upward sediment flux by turbulent diffusion is represented by u_*, and the deposition preference is represented by the settling velocity w_s. Van Rijn (1993) gives the following table for the relation between the u_*/w_s ratio in relation to the suspended sediment distribution over the depth.

Table 6.1 Suspended sediment distribution over the depth as a function of the ratio between u_* and w_s (Van Rijn, 1993)

u_*/w_s	Suspended sediment distribution over the depth
0.5	Suspended sediment in near bed layer
1.25	Suspended sediment upto mid depth
2.5	Suspended sediment upto water depth
25	Suspended sediment almost uniformly distributed over depth

Calculations of the u_*/w_s ratio in the Dollard estuary resulted in values of about 2 around slack water and about 25 at maximum current velocities. This shows that around slack water settling of the mud flocs is likely to occur. This settling is further enhanced by buoyancy effects. A positive feedback mechanism developed in which decreasing turbulence production caused increasing concentration gradients and vice versa (Van der Ham, 1999). These buoyancy effects were not taken into account by calculating the u_*/w_s ratio and would lead to a much lower ratio when sedimentation causes a concentration gradient that damps turbulence. Field measurements show a rapid sedimentation during decelerating current velocities (chapter 3) which can be ascribed to buoyancy effects (Van der Ham, 1999).

It seems that the settling velocity of mud flocs in the Dollard tidal channel depends on the turbulent mixing in the water column. Flocculation processes seem fast enough to provide flocs with such large settling velocities that the maximum floc settling velocity is dominated by the turbulent mixing in the water.

If so the settling velocity of the flocs in the Dollard tidal channel depends on the turbulent mixing and the sediment availability on the channel bed. These factors can be represented by the tidal phase. It was possible to explain 42% of the variance in the floc settling velocity by a sinusoidal fit of the floc settling velocity variation as a function of the tidal phase. This led to the following simple but quantitative model for the settling velocity of the suspended mud flocs in the Dollard tidal channel:

$$W_s = a + b\cos(\tfrac{2p}{T}(t+c)) \qquad (6.1)$$

Where Ws is the floc average settling velocity, T is the tidal period (T=12.4h), t is the time in hours to high water, and a, b and c are constants. This model was fitted to the settling velocity data in the “Groote Gat” tidal channel. This resulted in the following constants: a= 2.75mm/s, which is the average settling velocity, b= -0.71mm/s, which determines the range of settling velocities and c= -1.15 hour, which means that there is a phase lag of the minimum settling velocity of 1 hour and 9 minutes after high water. This relation between settling velocity and tidal phase may be more useful for modelling purposes than assuming a constant floc settling velocity. It is also a better model than a model of the type:

$$W_s = aC^n \qquad (6.2)$$

Where Ws is the settling velocity, C is the suspended sediment concentration and a and n are constants. In chapter 5 it was shown that the constants a and n show a strong variation among estuaries (Dyer, 1989), along the Ems-Dollard estuary (Van Leussen, 1994) and also during different seasons on the same location (chapter 5). This suggests that the settling velocity only indirectly depends on the SSC via the erosion and deposition that occurs throughout the tidal cycle.

6.3.3 Tidal Channel, seasonal time scale

On a seasonal time scale floc size changes occurred especially related to the decline of a plankton bloom. However, the much larger flocs had such a low density that there was hardly any effect on the floc settling velocities. So at least in this case, this plankton bloom did not affect the floc settling velocities and therefore also did not affect suspended sediment transport. The larger flocs could however be of biological significance as they provide a habitat for micro-organisms.

6.3.4 Tidal flat, tidal time scale

Above the tidal flat floc size measurements were undertaken by the Cilas laser particle sizer and settling velocity measurements with the Owen tube. Both instruments could only be used to determine relative differences in floc size/settling velocity of the flocs. Measured floc size increases were not necessarily mirrored by settling velocity increases. This may partly be the result of density decreases of growing flocs. The largest flocs occurred at slack water when turbulence levels were low. This seems to be related to floc breakup by turbulent shear during flood and ebb. Floc settling velocity measurements with the Owen tube were inconsistent. It was impossible to draw conclusions from this data. There is, however, a weak indication that settling velocities on the tidal flat are on average higher during the flood than during the ebb.

6.3.5 Tidal flat, seasonal time scale and along the estuary

Measurements above the tidal flat were mainly conducted in 1997. During this period there was no large plankton bloom and seasonal changes in floc settling velocity were not observed. Furthermore measurements were undertaken on 3 locations along the Dollard estuary with increasing mud content of the bed. These measurements also did not show spatial changes in floc settling velocity.

6.3.6 Fine-grained cohesive sediment dynamics

The effect of floc size and settling velocity variations in the Dollard estuary on net sediment transport can best be assessed by incorporating these variations into a 3D numerical model for the Ems/Dollard estuary. That is outside the scope of this thesis.
It is therefore only possible to qualitatively address some likely effects:

- The large settling velocities at maximum current velocities in the tidal channel causes rapid settling of the suspended sediment when the current starts to decelerate. This settling is further enhanced by buoyancy (Van der Ham, 1999). During the flood most water has been transported onto the tidal flats and to the shallower landward side of the estuary. Here such fast settling material is likely to deposit to the bed. During the ebb most water has been transported seaward into the deep tidal channel. Here settling will also occur but will take more time as the channels are deeper. It is also more likely that more deposited material will be resuspended by the current from the tidal channel bed, than from the tidal flats, since the current velocities in the tidal channel are higher. All this will promote a residual landward sediment flux.

- There is a weak indication from the Owen tube data that the largest settling velocities above the tidal flats occur during the flood. If this is true, it promotes a residual sediment flux onto the tidal flats.

Suspended sediment transport in the Dollard estuary is more extensively dealt with in Dyer et al. (in press) and Ridderinkhof et al. (2000).

6.4 General conclusions

Temporal floc size and settling velocity variations in the Dollard estuary were mainly determined by turbulent shear, biopolymer concentration and indirectly by the suspended sediment concentration. Salinity and water temperature did not play an important role. Spatial variations were measured on a limited spatial scale, along the ‘Groote Gat’ tidal channel. On this spatial scale no variations in floc size and settling velocity were observed in the Eulerian measurements on the tidal flats. The variations in the Lagrangean measurements in the tidal channel were most likely the result of temporal variations and not of spatial variations.

In the tidal channel increasing current velocities probably cause resuspension of (micro)flocs followed by further flocculation in the water column. This leads to a floc size and settling velocity increase. When the current decelerates, the larger and faster settling flocs settle which leads to a decrease in size and settling velocity of the suspended flocs. The settling of the flocs is further enhanced by buoyancy effects that cause turbulence damping. The above processes lead to a strong relation between SSC and floc size / settling velocity. This relation results from the process of erosion and deposition of the flocs and not from an increased collision frequency of the flocs. Therefore mainly the hydrodynamics determines the floc sizes and settling velocities on the tidal time scale and not the collision frequency due to a high SSC.

Floc size limitation as a result of floc breakup by turbulence probably occurs above the tidal flat and in the near bed zone of the tidal channel. Mud flocs are very fragile, so mud flocs that travel through the near bed zone may easily break due to the high turbulent shear in that zone. As turbulent shear diminishes around slack water this explains why the largest mud flocs above the tidal flat were observed around slack water.

The average floc settling velocity in the upper water layers of the tidal channel was 2.75 mm/s with a tidal variation of ±0.7mm/s. In the near bed zone the average settling velocity of the flocs was reduced to values between 0.1 and 0.8 mm/s, probably as a result of turbulence breakup (chapter 3;Van der Ham, 1999)

Floc settling velocity variations in the Dollard tidal channel could be modelled by a simple sinusoidal fit of the floc settling velocity as a function of tidal phase. This model explains 42% of the variance. Since the seasonal variation in settling velocity is low this model can be applied throughout all seasons, and may be valuable tool for modelling suspended sediment transport in the Dollard estuary.

Extremely large flocs did appear during the decline of a plankton bloom in the spring of 1996. These flocs were likely to result from an increased stickiness of the flocs due to the excretion of biopolymers by plankton and/or bacteria. The biological cohesion of the flocs is probably more dependent on the ‘glue’ quality of the biopolymers than on the absolute quantity. The quantity as well as the quality of the biopolymers depends on the species composition, concentration and physiological state of phytoplankton and bacteria.

There is no clear relation between floc size and floc settling velocity as the floc settling velocity depends on size as well as density. Due to a large density decrease when flocs grow larger the positive effect of a floc size increase on the floc settling velocity is highly moderated. Due to this process, the extremely large flocs observed in the decline of the 1996 spring plankton bloom did not have a very high settling velocity. Therefore the seasonal variation in settling velocities was negligible compared to the tidal variation.

The settling velocities measured above the tidal flat showed a different behaviour than the floc sizes. This may result from floc density changes and advection of flocs from the tidal channel onto the tidal flats during the flood period, but may also result from measurement errors, as the Owen tube measurements were rather inconsistent. There is a weak indication from this data that the largest settling velocities above the tidal flats occur during the flood. If this is true, it promotes a residual sediment flux onto the tidal flats.

At high water slack the average water depth in the Dollard is smaller than during low water slack, because at high water the shallow tidal flats are immersed, and at low water only the relatively deep tidal channels are immersed. More sediment deposition will therefore occur during high water on the tidal flats, than during low water in the deep tidal channels. This promotes a landward residual sediment flux. The tidal variation in floc settling velocities further enhances this process since the largest settling velocities occur between maximum current velocity and slack water in the tidal channel as well as on the tidal flats.

THE SETTLING OF MUD FLOCS IN THE DOLLARD ESTUARY, THE NETHERLANDS

SUMMARY

Chapter 1 Introduction and literature review
Morphological changes of estuarine channels and tidal flats depend on erosion, sediment transport and deposition. This thesis focuses on a small part of this system: the settling of mud flocs in an estuary. Because mud is cohesive it tends to form mud flocs. These flocs have a higher settling velocity than the constituent particles. This is very important for sediment deposition, as there would be little accumulation of fine-grained material, if the suspended fine sediment particles would not aggregate (Partheniades, 1984; Van Leussen, 1994)
This thesis is based on measurements of the size and settling velocity of mud flocs in the Dollard estuary on different time and spatial scales. It tries to answer the following questions:
How large are mud flocs in the Dollard estuary and how fast do they settle?
Which processes determine the size and settling velocity of mud flocs?
Which processes are the most important, and on which time or spatial scale?
Can floc size and settling velocity be quantified as a function of the above processes?
To answer these questions many measurements took place in the Dollard estuary, but first the processes that could determine the size and settling velocity of mud flocs were identified from a literature review.

Mud flocs in the water column may originate from resuspension from the bed and from flocculation in the water column. Flocculation depends on collisions between flocs. The number of collisions (the collision frequency) and the chance that colliding flocs stick together (the collision efficiency) are therefore important.

- The collision frequency depends on the suspended sediment concentration (SSC), since more flocs leads to more collisions. It also depends on the turbulence in the water, since velocity differences between flocs also lead to collisions.

- The collision efficiency depends on electrical charges of the mud particles and the presence of biological polymers that act as some sort of glue and sticks the flocs together.
  Mutual repulsion of mud particles due to their generally negative charge is related to the thickness of the electrical double layer and this double layer thickness depends among others on the salinity of the water. Biological polymers, that stick mud particles together, are excreted mainly by phytoplankton and bacteria.

- Salinity and water temperature influence the density and viscosity of the water. This may also affect the settling velocity of suspended mud flocs.

Especially the measurements of size and settling velocity of mud flocs were very difficult. Mud flocs are very fragile and they will break as a result of ordinary sampling. Therefore they were measured *in situ* by the Video *In Situ* or VIS (an underwater camera), The Cilas925 (an *in situ* laser particle sizer) and a Braystoke SK110 Owen tube (an *in situ* settling tube). Only the VIS provided absolute floc size and settling velocity measurements with a reasonable accuracy. It could however not be used above the tidal flats, nor near the sediment bed because the instrument is very large. The Cilas and Owen tube only provided information about relative increases or decreases of floc size and settling velocity respectively. These latter two instruments were used above the tidal flat.

Chapter 3 Tidal variations in mud floc size and settling velocity. The impact of fluid shear and the suspended sediment concentration on flocculation and breakup.

In October 1995 and in several months of 1996 floc size and settling velocity measurements with the VIS took place throughout the tidal cycle in the “Groote Gat” tidal channel. All these measurements showed a tidal variation in floc size and settling velocity. The largest and fastest settling flocs showed a positive relation with the SSC. During ebb and flood when current velocities were high, large flocs and large SSC occurred simultaneously. Floc sizes larger than 300 µm occurred and settling velocities ranged from 1.5 to 3.5 mm/s with an average settling velocity of 2.75 mm/s.

Above the tidal flat however, the Cilas measured maximum floc sizes at high water when the current velocity and turbulent shear are low, and not during ebb or flood.

It seemed that during ebb and flood, the floc sizes above the tidal flat were limited by turbulent shear. In the tidal channel no evidence of floc breakup was found, since maximum floc sizes occurred around maximum current velocities.

Turbulent shear at the level of the Cilas above the tidal flat and the level of the VIS in the tidal channel was calculated. The shear at the Cilas and VIS was however comparable and could not explain the observed differences between tidal flat and tidal channel. Above the tidal flat however, the measurements took place at 30 cm above the bed and in the tidal channel at about 1.9 m above the bed. The close proximity of the bed above the tidal flat, with high fluid shear along this boundary, probably caused floc breakup near the bed and resuspension of the broken flocs during ebb and flood tides. This may explain the smaller flocs above the tidal flat during high current velocities. This is in contrast with the tidal channel, where the water is deeper and the frequency by which flocs approach the bed is much lower. Furthermore the VIS measurements took place at a further distance from the bed than the Cilas measurements, which further diminishes the effect of near bed floc breakup on the floc sizes at the level of the VIS. It seems that near bed shear and the proximity to the bed have an important influence on mud floc size and settling velocity.

Chapter 4 Mud floc size variations on a seasonal time scale. The impact of a phytoplankton bloom.
From the floc size and settling velocity measurements that took place during different seasons, the seasonal variation of suspended mud floc sizes in the Dollard estuary was investigated. Factors like salinity, water temperature and wave height did not seem to have a substantial influence on the seasonal fluctuation of floc sizes. Suspended sediment concentration and turbulence mainly affect the tidal variation of floc size.
Biological processes however may have a large impact on the seasonal floc size variation, and cause larger flocs. Such a process was observed in the Dollard estuary on 29 May 1996, at the end of a plankton bloom. At the end of this bloom, polymer exudates of phytoplankton and bacteria probably increased the stickiness of the flocs. This caused floc sizes larger than 1000 μm. Measurements during this plankton bloom suggested that biologically assisted flocculation does not depend on the absolute quantity of the biopolymer exudate, but on the 'glue' quality of the polymers. The quantity as well as the quality of the biopolymers may depend on the species composition, concentration and physiological state of phytoplankton and bacteria.

Chapter 5 Temporal variation of floc size and settling velocity in the Dollard estuary
Both the tidal and seasonal variations in floc sizes and settling velocities were reviewed in this chapter and they were used to elucidate the processes that cause these variations. Furthermore the relation between floc size and settling velocity was studied. According to Stokes law, larger flocs have a higher settling velocity. But when the floc size increases the density also decreases, and smaller densities lead to lower settling velocities. There was no clear relation between floc size and settling velocity as the floc settling velocity depends on size as well as density. Due to large density decreases when flocs grow larger, the positive effect of a floc size increase on the floc settling velocity was highly

moderated. On 29 May 1996 very large mud flocs (> 1000 µm) were measured in the decline of a plankton bloom. Their settling velocity, however, was not larger than usual compared to other measurements due to the very low density of these flocs.

On the tidal time scale there is a relation between SSC and floc size/settling velocity. Such a relation was measured by many authors and is the reason why the settling velocity is often expressed as an exponential function of the SSC: $W_s=aC^n$, where W_s is the settling velocity, C is the suspended sediment concentration and a and n are constants.
On the seasonal time scale however there was no relation between SSC and floc size/settling velocity. Furthermore, Dyer (1989) showed that the constants a and n vary a lot between estuaries. Van Leussen (1994) showed that a and n also varied within the Ems/Dollard estuary and this thesis showed that a and n also vary at different times. It is clear that the relation between SSC and floc settling velocity can be very variable.

Therefore, the observed relations between settling velocity and SSC are likely to be (at least partially) indirect relations. Not the SSC itself, but erosion and sedimentation of flocs, depending on the current velocity, probably determine the size and settling velocity in the water. The floc size and settling velocity depends much less on the floc collision frequency, which is directly determined by the SSC.
Therefore SSC and floc size/settling velocity correlate on the tidal time scale, since they both depend on erosion and deposition of mud by the current velocity. On the seasonal time scale SSC variations do not directly depend on erosion and deposition but for example on a shift in the turbidity maximum. Therefore SSC does not correlate with floc size and settling velocity on a seasonal time scale.

As the settling velocity in the Dollard estuary does not directly depend on the SSC it can not be quantified as a function of the SSC. But the settling velocity does directly depend on the erosion and deposition that takes place during the tidal phase. Therefore, the settling velocity can be expressed as the following function of tidal phase:
$W_s = a + b\cos(\frac{2p}{T}(t+c))$, Where W_s is the floc average settling velocity, T is the tidal period (T = 12.4 h), t is the time in hours to high water, and a, b and c are constants. This model was fitted to the data and the constants were a = 2.75 mm/s, which is the average settling velocity, b = -0.71 mm/s, which determines the range of settling velocities and c = -1.15 hour, which means that there is a phase lag of the minimum settling velocity of 1 hour and 9 minutes after high water. The settling velocity variations could only be quantified in the tidal channel and not above the tidal flat or near the sediment bed since it was impossible to measure absolute floc sizes in these locations (chapter 2)

Chapter 6 The size and settling velocity of fine-grained suspended sediment in the Dollard estuary. A synthesis.
Most changes in floc size and settling velocity in the Dollard that were measured can be explained with a flocculation model presented by Winterwerp (1998;1999). He claims that floc sizes are limited by turbulent shear and residence time. If flocs are long enough in suspension their size is limited by turbulent shear and increasing shear will lead to

decreasing floc sizes. If flocs are only for a limited period in suspension, their size is not limited by turbulent shear. They will settle before reaching an equilibrium floc size. Increasing turbulent shear will in this case lead to increasing floc sizes until floc size is limited by floc breakup. So turbulent shear and residence time are important flocculation parameters.

SSC is indirectly an important flocculation parameter. The SSC is an indicator of the erosion and deposition that takes place, and these erosion and deposition mainly determine the floc sizes and settling velocities.

Effects of salinity and water temperature on floc sizes and settling velocity in the Dollard estuary were not observed

Biopolymers excreted by phytoplankton and bacteria may especially at the end of a plankton bloom also have a large effect on mud floc size. Effects on the settling velocity of such biological mud flocs depend on the (decreased) density of these flocs.

From this thesis one can conclude that turbulent shear and residence times play an essential role in flocculation dynamics. Furthermore this thesis showed that biological factors, like the excretion of biopolymers by plankton and/or bacteria at the end of a plankton bloom, may be just as significant for flocculation dynamics as physical factors. Finally this thesis showed that settling velocity variations can to a certain extent be quantified as a function of tidal phase. Such quantitative relations may help to improve cohesive sediment transport models.

HET BEZINKEN VAN SLIBVLOKKEN IN HET DOLLARD ESTUARIUM

SAMENVATTING

Hoofdstuk 1 Inleiding en literatuuronderzoek.
Morfologische veranderingen van getijgeulen en getijplaten hangen af van erosie, transport en depositie van sediment. Dit proefschrift richt zich op een klein deel van dit systeem: het bezinken van slibvlokken in een estuarium. Slib is cohesief en daardoor vormen afzonderlijke slibdeeltjes slibvlokken. Deze vlokken bezinken sneller dan de afzonderlijke slibdeeltjes doordat ze groter zijn. Dit proces is van groot belang voor de depositie van slib. Zonder flocculatie van slibdeeltjes zou er nauwelijks sprake zijn van slibdepositie (Partheniades, 1984; Van Leussen, 1994).
Dit proefschrift is gebaseerd op metingen van de grootte en valsnelheid van slibvlokken in het Dollard estuarium op verschillende tijd en ruimteschalen. Het probeert de volgende onderzoeksvragen te beantwoorden:

- Hoe groot zijn slibvlokken in het Dollard estuarium en hoe snel bezinken zij?
- Welke processen bepalen de grootte en valsnelheid van slibvlokken?
- Welke van deze processen zijn het meest belangrijk, en op welke tijd en ruimteschalen?
- Kunnen vlokgrootte en valsnelheid worden gekwantificeerd als een functie van bovengenoemde processen?

Om deze vragen te kunnen beantwoorden zijn er vele metingen uitgevoerd in het Dollard estuarium. Daaraan voorafgaand zijn eerst de processen die potentieel een rol spelen bij de flocculatie van slib geïnventariseerd aan de hand van een literatuuronderzoek dat is weergegeven in hoofdstuk 1.

Slibvlokken in de waterkolom kunnen als slibvlok zijn opgewerveld vanaf de bodem, of ze zijn in de waterkolom ontstaan door flocculatie. Flocculatie hangt af van botsingen tussen vlokken. Het aantal botsingen (frequentie van de botsingen) en de kans dat botsende deeltjes aan elkaar blijven plakken (efficiëntie van de botsingen) spelen daarbij een rol.

- De frequentie van de botsingen hangt af van de sediment concentratie in het water. Hoe meer slibdeeltjes er aanwezig zijn, hoe meer botsingen. De frequentie van botsingen hangt ook af van de turbulentie in het water, want snelheidsverschillen tussen vlokken leiden tot botsingen.
- De efficiëntie van de botsingen hangt af van de elektrische lading van de slibdeeltjes en de aanwezigheid van biologische polymeren die, als een soort lijm, de vlokken aan elkaar kleven.

  Over het algemeen zijn slibdeeltjes negatief geladen en stoten ze elkaar af. Deze afstoting hangt af van de dikte van de elektrische dubbellaag rondom de deeltjes, en deze dubbellaag dikte hangt weer af van onder andere het zoutgehalte (saliniteit) van het water. Hoe zouter het water hoe dunner de dubbellaag, hoe minder de deeltjes elkaar afstoten. Biologische polymeren die vlokken aan elkaar kleven worden vooral uitgescheiden door fytoplankton en bacteriën in het water.

- Saliniteit en water temperatuur beï nvloeden de dichtheid en viscositeit van het water. Hierdoor verandert de valsnelheid van een slibdeeltje in het water.
- Vlokken groeien door flocculatie, maar ze kunnen breken doordat turbulente wervels in het water de vlokken uit elkaar trekken. Hierdoor wordt de vlokgrootte gelimiteerd. Het breken van vlokken treedt vooral op nabij de bodem waar de turbulentieintensiteit door bodemwrijving het hoogst is.
- Vlokgrootte en valsnelheid zijn ook afhankelijk van de voorgeschiedenis van een vlok. Een vlok heeft tijd nodig om te groeien, totdat de groei door turbulentie en vlokafbraak wordt gelimiteerd en er een soort dynamische evenwicht ontstaat. Vaak zal een vlok al naar de bodem bezonken zijn voordat zo’n evenwicht kan ontstaan. Daarom is de verblijftijd van een vlok in het water een belangrijke parameter.

Uit het literatuuronderzoek in hoofdstuk 1 is geconcludeerd dat de grootte en valsnelheid van slibvlokken vooral afhangen van: De voorgeschiedenis (verblijftijd) van de vlok, de turbulentie intensiteit, de sediment concentratie, de saliniteit, de concentratie biologische polymeren en de water temperatuur.

Hoofdstuk 2 Veldwerk en methoden.

Vlokgrootte en valsnelheid, sediment concentratie, stroomsnelheid, waterstand, golfhoogte, water temperatuur, saliniteit, concentratie biologische polymeren en meteorologische data zijn allen gemeten op verschillende lokaties en op verschillende tijden in het Dollard estuarium (fig. 2.1). Deze metingen vonden plaats met onderzoeksschepen van Rijkswaterstaat, een kleine boot (de Geos), een groot platform op de Heringsplaat in de Dollard (BOA brug), een meetpaal in de getijgeul “het Groote Gat” en met een meetframe op de Hooge plaat en Bunderriet getijplaten in de Dollard.
Vooral metingen van vlokgrootte en valsnelheid waren erg moeilijk. Slibvlokken zijn zeer fragiel en zij breken bij het nemen van een watermonster. Daarom werden ze *in situ* gemeten met de Video *In Situ* of VIS (een onderwater camera), met de Cilas925 (metingen van deeltjesgrootte met behulp van laserdiffractie) en met een Braystoke SK110 Owen tube (een combinatie van waterhapper en valbuis voor het meten van valsnelheden). Alleen met de VIS konden absolute vlokgroottes en valsnelheden worden gemeten. De VIS is echter zo groot dat hij niet boven getijplaten of nabij de bodem kon worden gebruikt. Boven de getijplaten werden daarom de Cilas en de Owen tube gebruikt. Deze laatste twee instrumenten konden echter alleen gebruikt worden om relatieve toe en afnames van vlokgrootte of valsnelheid vast te stellen. Om diverse redenen waren ze niet in staat om absolute vlokgroottes of valsnelheden te meten.

Hoofdstuk 3 Variaties in vlokgrootte en valsnelheid gedurende een getijcyclus. De invloed van turbulentie en sedimentconcentratie op flocculatie en vlokafbraak.

In oktober 1995 en in enkele maanden in 1996 zijn vlokgroottes en valsnelheden gemeten met de VIS in de getijgeul “Het Groote Gat”. Al deze metingen lieten vergelijkbare variaties zien in vlokgrootte en valsnelheid gedurende het getij. De grootste en snelst

vallende vlokken werden gelijktijdig geobserveerd met de hoogste sediment concentraties tijdens eb en vloed als ook de stroomsnelheid hoog is. De grootste vlokken waren groter dan 300 µm en valsnelheden varieerden tijdens het getij van 1.5 tot 3.5 mm/s, met een gemiddelde valsnelheid van 2.75 mm/s.
Metingen met de Cilas boven de getijplaat toonden echter dat daar de grootste vlokken voorkwamen tijdens hoogwater, als de stroomsnelheden, sediment concentraties en turbulentie intensiteit laag is.
Tijdens eb en vloed werd de vlokgrootte boven de getijplaat blijkbaar gelimiteerd door vlokafbraak als gevolg van turbulentie. In de getijgeul werden geen aanwijzingen voor een dergelijke vlokafbraak gevonden, omdat daar de grootste vlokken juist voorkomen rond de maximale stroomsnelheden als de turbulentie intensiteit hoog is.

Op basis van de gemeten stroomsnelheden is de turbulentieintensiteit bij de VIS in de getijgeul en bij de Cilas boven de getijplaat berekend. Deze intensiteit bleek vergelijkbaar en kan daarom niet de verschillen in vlokgroottevariaties tussen getijgeul en getijplaat verklaren. Boven de getijplaat vonden de metingen plaats op 30 cm boven de bodem. In de getijgeul vonden de metingen circa 1.9 m boven de bodem plaats. Heel dicht bij de bodem neemt de turbulentieintensiteit snel toe. Vermoedelijk zijn slibvlokken boven de getijplaat gebroken tijdens eb en vloed toen ze dicht bij de bodem kwamen, waarna ze weer zijn opgewerveld. Daardoor bleven de vlokken klein tijdens eb en vloed. De getijgeul is veel dieper waardoor vlokken minder vaak nabij de bodem kunnen breken en weer worden opgewerveld. Tevens vonden de metingen in de getijgeul veel verder vanaf de bodem plaats, waardoor de invloed van de bodem op vlokafbraak ook kleiner is. Het is waarschijnlijk dat de turbulentieintensiteit bij de bodem en de nabijheid van de bodem vlokafbraak bevorderen. Daardoor is vlokafbraak nabij de bodem een belangrijk proces dat vlokgroottes en valsnelheden kan bepalen.

Hoofdstuk 4 Vlokgrootte variaties op de tijdschaal van seizoenen. De invloed van een fytoplankton bloei.
Met de VIS metingen die gedurende verschillende seizoenen hebben plaatsgevonden is de seizoensvariatie in vlokgrootte bepaald. Uit de metingen bleek dat saliniteit, water temperatuur en golfhoogte geen belangrijke factoren waren. Sediment concentratie en turbulentie spelen vooral een rol op de tijdschaal van het getij. Vooral biologische processen kunnen een grote rol spelen bij seizoensvariaties in vlokgroottes en valsnelheden. Op het einde van een planktonbloei op 29 mei 1996 werden zeer grote vlokken (groter dan 1 mm) waargenomen. Deze grote vlokken werden waarschijnlijk veroorzaakt door biologische polymeren die werden uitgescheden door fytoplankton en bacteriën. Uit metingen van de concentratie biologische polymeren bleek dat "biologische flocculatie" niet direct afhangt van de absolute concentratie biopolymeren, maar meer van de kleverigheid van verschillende polymeren. De hoeveelheid en de kleverigheid van de biopolymeren hangt af van de soortensamenstelling, concentratie en fysiologie van fytoplankton en bacteriën.

Hoofdstuk 5 Temporele variatie van vlokgrootte en valsnelheid in het Dollard estuarium.

Zowel getij- als seizoensvariaties in vlokgrootte en valsnelheid zijn in dit hoofdstuk gezamenlijk beschouwd. Op basis daarvan zijn de aansturende processen van deze variaties verklaard. Tevens is de relatie tussen vlokgrootte en valsnelheid nader beschouwd.

Volgens de wet van Stokes bezinken grote vlokken sneller dan kleine vlokken. Als vlokken groter worden neemt hun dichtheid echter af, en kleinere dichtheden leiden weer tot lagere bezinksnelheden. Op basis van de metingen kon tussen vlokgrootte en valsnelheid geen duidelijke relatie worden gevonden. Dit komt doordat de valsnelheid van een deeltje van zowel de vlokgrootte als de dichtheid afhangt. Doordat de dichtheid van vlokken afnam als deze vlokken groter werden, werd de toename van de valsnelheid als gevolg van de grotere vlokken deels tenietgedaan door de lagere dichtheid van de vlokken. Op 29 mei 1996 werden zeer grote vlokken gemeten (> 1mm) aan het einde van een planktonbloei. Toch waren de valsnelheden van deze vlokken niet hoger dan normaal, doordat de dichtheid van deze vlokken zeer laag was. In het algemeen was er echter wel sprake van een geringe toename in valsnelheid als vlokken groter werden.

Op de tijdschaal van het getij correleren de sediment concentratie en de vlokgrootte/valsnelheid met elkaar. Zo’n relatie tussen valsnelheid en sediment concentratie is waargenomen door vele auteurs. De valsnelheid wordt vaak uitgedrukt als een exponentiële functie van de sediment concentratie: $W_s=aC^n$. W_s is de valsnelheid, C is de sediment concentratie en a en n zijn constanten. Op de tijdschaal van seizoenen was in de metingen echter geen sprake meer van correlatie tussen sediment concentratie en vlokgrootte/valsnelheid. Dyer (1989) heeft laten zien dat bovenstaande constanten a en n sterk variëren tussen verschillende estuaria. Van Leussen (1994) heeft laten zien dat a en n ook binnen het Eems/Dollard estuarium variëren en dit proefschrift laat zien dat a en n ook variëren door de tijd heen. Uit dit alles blijkt duidelijk dat de relatie tussen sediment concentratie en valsnelheid zeer variabel is.

De geobserveerde correlaties tussen valsnelheid en sediment concentratie zijn waarschijnlijk (in ieder geval gedeeltelijk) indirecte correlaties. Niet de sediment concentratie zelf, maar de erosie en sedimentatie van vlokken, afhankelijk van de stroomsnelheid, bepaalt waarschijnlijk de grootte en valsnelheid van de vlokken. Dat wil zeggen dat de sediment concentratie waarschijnlijk veel minder belangrijk is voor de grootte en valsnelheid van de vlokken, dan werd gedacht op basis van de geobserveerde relaties tussen valsnelheid en sediment concentratie. Op de tijdschaal van het getij correleren valsnelheid en sediment concentratie met elkaar omdat beiden afhangen van de erosie en sedimentatie van slib door de getijstroming. Op de seizoenstijdschaal zijn variaties in slibconcentratie niet het directe resultaat van erosie en depositie, maar bijvoorbeeld het resultaat van een verschuiving van het troebelheidsmaximum. Daarom is er op deze seizoenstijdschaal geen correlatie meer tussen sediment concentratie en vlokgrootte/valsnelheid.

Omdat de valsnelheid van vlokken in de Dollard niet direct afhangt van de sediment concentratie kan deze valsnelheid ook niet worden gekwantificeerd als een functie van de sediment concentratie. De valsnelheid is afhankelijk van erosie en depositie van slibvlokken onder invloed van de getijstroming. De valsnelheid kan daardoor worden uitgedrukt als een functie van het getij:

$$W_s = a + b\cos(\tfrac{2p}{T}(t + c))$$

W_s is de gemiddelde valsnelheid, T is de getijperiode (T=12.4h), t is de tijd tot hoog water in uren, en a, b en c zijn constanten. Dit model werd gecalibreerd aan de data en de constanten waren: a= 2.75 mm s^{-1}, dit is de gemiddelde valsnelheid, b= -0.71 mm s^{-1}, dit is het bereik van de valsnelheid rond het gemiddelde, en c= -1.15 uur, dat betekent dat er een fase verschil is tussen valsnelheid en getij waardoor de minimale valsnelheid 1 uur en 9 minuten na hoog water optreedt.

Hoofdstuk 6 De grootte en valsnelheid van fijn sediment in het Dollard estuarium. Een synthese.

De meeste gemeten variaties in vlokgrootte en valsnelheid in de Dollard kunnen worden verklaard met behulp van een flocculatiemodel gepresenteerd door Winterwerp (1998;1999). Hij stelt dat de vlokgrootte wordt gelimiteerd door turbulentie en verblijftijd. Als vlokken lang genoeg in suspensie blijven wordt hun grootte gelimiteerd door turbulentie en zal toenemende turbulentie leiden tot kleinere vlokken. Als vlokken slechts een beperkte tijd in suspensie zijn wordt hun grootte niet gelimiteerd door turbulentie. Zij bezinken voordat ze een evenwichts-vlokgrootte bereiken. In zo’n geval leidt toenemende turbulentie tot een toename van de vlokgrootte, totdat een evenwicht tussen vlokgroei en afbraak is bereikt. Oftewel turbulentie en verblijftijd zijn belangrijke flocculatie parameters. De sediment concentratie is indirect een belangrijke flocculatie parameter. De sediment concentratie is een indicator voor de erosie en depositie die plaatsvindt, en deze erosie en depositie bepaalt vlokgrootte en valsnelheid.

Effecten van saliniteit en water temperatuur op vlokgrootte en valsnelheid in de Dollard zijn in de metingen niet waargenomen.

Biopolymeren, uitgescheiden door fytoplankton en bacteriën, kunnen vooral aan het einde van een planktonbloei de vlokgrootte fors doen toenemen. Effecten op de valsnelheid van de vlokken hangen af van de (afgenomen) dichtheid van deze vlokken.

Uit dit proefschrift kan worden geconcludeerd dat turbulentie en verblijftijd essentiëel zijn voor de flocculatiedynamiek. Voorts laat dit proefschrift zien dat biologische factoren, vooral aan het einde van een planktonbloei, even belangrijk kunnen zijn voor de flocculatiedynamiek als fysische factoren. Tenslotte toont dit proefschrift dat valsnelheidsvariaties tot op zekere hoogte kunnen worden gekwantificeerd als een functie van het getij. Met zulke kwantitatieve relaties kunnen transportmodellen van fijn sediment worden verbeterd.

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CURRICULUM VITAE

Ik ben geboren op 17 oktober 1970 te Hengelo. Ik ben opgegroeid in Wilnis en volgde mijn middelbare schoolopleiding aan het Veenlandencollege te Mijdrecht. In 1989 haalde ik daar het diploma VWO. In september 1989 begon ik mijn studie Fysische Geografie aan de Universiteit Utrecht. Ik ben afgestudeerd in april 1994 (cum laude), met als specialisatie Fysisch-geografische proceskunde.

Tijdens mijn doctoraal veldwerk heb ik de invloed van lange golven op het zandtransport in de brandingszone op het strand van Egmond aan Zee onderzocht. Later heb ik als student-assistent nog een datarapport gemaakt voor het kustgenese onderzoek in Egmond aan Zee. Mijn stage bij het waterloopkundig laboratorium was gericht op het bodemtransport van zand in de Deltagoot.

Na deze studie ben ik bij de vakgroep Fysische Geografie van de Universiteit Utrecht, gestart met mijn promotieonderzoek naar de grootte en valsnelheid van slibvlokken in de Dollard, wat heeft geleid tot dit proefschrift.

Sinds 1 januari 2000 werk ik als adviseur rivieren en rivierbeheer bij HKV LIJN IN WATER waar ik me heb verdiept in de rivierkunde en de sedimentdynamiek in riviersystemen.