Seasonal variations of suspended sediment and diatoms in the Western Scheldt

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Summary

The Western Scheldt is a well-studied estuary. A lot of research is carried out, because different interest all play a role in the Western Scheldt. The most well known probably are the use of the channel for shipping and the ecological value of the area. This study is part of the project ‘Analysis of biogeomorphological interactions in the Western Scheldt’, which is one of the ‘Doelfinanciering’ projects within the Research & Development program of WL|Delft Hydraulics. The goal of this project is to gain new knowledge in the field of biogeomorphological interactions through the analysis of these interactions in the well-studied Western Scheldt (Crosato et al., 2000). Biogeomorphology is the study which concentrates on interactions between biological and (geo)morphological processes.

This study focused on the possible relationship between seasonal variations of suspended sediment concentration (SSC) and diatom biomass. In order to determine whether a relationship exists, the effect of other parameters on these seasonal variations was also studied. This was accomplished to prevent the risk of finding a spurious relationship between SSC and diatom biomass. This approach resulted in a literature study and the analysis of data. The literature study was necessary to provide the theoretical background, the data analysis was used for the quantification of the identified relationships.

The literature survey showed that SSC variations do not affect diatom biomass in the Western Scheldt. Turbidity, caused by both SSC and organic matter, is too high throughout the year for diatoms to be active during inundation of the flats. Diatom, which are in fact algae, depend on the availability of light for their growth. The role of diatoms on SSC variations is an indirect one. Diatoms do not influence deposition of sediment, but they do play a role in stabilising fresh deposits. When this occurs on a large scale during a period of time, then suspended particles are constantly removed from the water column.

A relation scheme was proposed in which all identified parameters and their relationships were summarised. Among the parameters that play a role in the seasonal variation of SSC and diatom biomass are wind, rain, discharge and biological activity. The flats play a role through seasonal changes in accretion and erosion of fine grained sediment. The interaction between SSC and diatoms takes place at the flats.

Data acquisition and analysis was used to investigate the contribution of the various parameters to SSC and diatom biomass variations. It showed that wind is an important parameter, probably through the influence on hydrodynamic conditions. This was a result of the analysis of both short term, high frequency measurements and long term, low frequency measurements.

The performed regression analyses explained only part of the SSC and diatom biomass variations. This indicates that the parameters on which no information was selected play a role. Also the fact that the analyses were performed on the scale of the entire estuary might contribute. Some indications for this assumption were provided in the analysis of spatial variations of SSC, discharge and chlorophyll a. Future research should aim at combining spatial and temporal scales and the use of other types of data and analysis techniques.
I Introduction

1.1 Background

The Western Scheldt accommodates four very different interests (Salden, 1998). It is of economical importance both to the harbour of Antwerp, acting as shipping channel, and for sand mining activity. It is also of ecological value, because the channels, flats and salt marshes provide a unique habitat for various types of fish, birds, plants and benthic (i.e. sediment inhabiting) species. Finally there is the safety matter. The Western Scheldt is the only estuary in the Southwest of The Netherlands which has not been closed by the ‘Delta works’, which were constructed after the storm surge flooding of 1953. These often conflicting interests are one of the reasons why a lot of research has been, and still is being carried out in the Western Scheldt.

This study is part of the project ‘Analysis of biogeomorphological interactions in the Western Scheldt’, which is one of the ‘Doelfinanciering’ projects within the Research & Development program of WL|Delft Hydraulics. The goal of this project is to gain new knowledge in the field of biogeomorphological interactions through the analysis of these interactions in the well-studied Western Scheldt (Crosato et al., 2000). Within the project a research study could be carried out by an M.Sc. student of Delft University of Technology (TU Delft). Prior to this study, I wrote my own research proposal, which was also part of the project. The proposal was written during an internship at the National Institute for Coastal and Marine Studies (RIKZ) in Middelburg. The RIKZ is also closely involved in the project.

Biogeomorphology is the study which concentrates on interactions between biological and (geo)morphological processes. From an ecological point of view this is not a new concept, since ecology concentrates on the interactions between living organisms and their (abiotic, i.e. non living) environment. For (geo)morphologists, however, it is new. Until recently the main goal of morphological studies was to understand the basic physical behaviour of estuarine systems. But two aspects are becoming increasingly important. First the physical understanding increases and the question becomes more and more relevant to what extent non-physical factors play a role in the morphological behaviour of estuarine systems. Secondly, ecologists are interested in using morphological knowledge, because of the close relationship between biological activity and the environment.

Seasonal variations of suspended sediment and diatoms

This study concentrates on seasonal variations of both suspended sediment concentration (SSC) and the biomass of benthic diatoms (from now on indicated as diatom biomass) in the Western Scheldt. In this study suspended sediment is defined as those inorganic particles with a grain size diameter < 63 μm, which are found in the water column. Diatom is the generic term for all sediment inhabiting unicellular algae with a silicon skeleton, which can be found on the tidal flats.
The seasonal variation of SSC is shown in Figure 1-1. Samples were collected in the channel on a monthly interval at one meter below the water surface. Monthly averaged values from six measuring points over the period 1990-1999 are shown. For diatom biomass, measurements were carried out on a monthly interval at 20 different transects containing over 100 sample points. The measured parameter is chlorophyll $a$ (leaf green), which is the indicator for diatom biomass. Chlorophyll $a$ is measured per gram sediment.
Figure 1-2 shows averaged values of all sample points over the period 1987-1999. The data concerning SSC and diatom biomass were provided by the RIKZ.

SSC clearly shows a seasonally varying behaviour, with highest values during the winter period, lowest values in the summer and increasing and decreasing values during fall and spring respectively. Chlorophyll a shows a peak in May and high values in June and July as well. In general a behaviour can be observed which is opposite to the SSC variation: just when the diatom biomass is high, SSC values are low and vice versa. The fact that long term average values are presented indicates that this is not an incidental observation.

The opposite trend in the figures suggest that SSC and diatom biomass might be related. This idea is supported by the fact that diatoms are capable of retaining fine grained sediment to the flat surface. Thus, an increase/decrease in diatom biomass might lead to decreasing/increasing SSC values. On the other hand, changes in SSC values might influence diatom biomass. Both suspended sediment and organic matter cause the water to be turbid. This turbidity determines the amount of light that can penetrate the water column to a certain depth. During inundation of the flats diatom growth, which depends on light, is limited due to this turbidity. Thus, a decrease in suspended sediment concentration might have a positive effect on diatom growth during inundation of the flats.

1.1.2 Objectives

The goals of this study can be described as follows:

- to determine the relationship between seasonal variations of SSC and diatom biomass in the Western Scheldt as well as the influence of other parameters on these variations in a qualitative manner.
- to perform data acquisition on the parameters that were identified and to analyse these data in order to quantify the identified relationships.

1.2 Approach

The main interest of this study lies in the interaction between SSC and diatom biomass, but other parameters will also be included in the study. If SSC and diatom biomass were only dependent on each other, and completely independent from other parameters, there would be no reason for these variations to act on a seasonal scale. Apparently, one or more forces are active that trigger changes in one or both parameters. It could be possible that one or more parameters are present, which play a dominant role in the variation of either SSC or diatom biomass or both. If a relationship would then be found between these two it would be of minor importance. It could also be that there is no relationship at all. So in order to determine whether a relationship between SSC and diatom biomass variations exists, the effect of other parameters needs to be considered.

To be able to deal with the interaction between SSC and diatom biomass as well as the influence of other parameters an approach will be applied that is outlined on the left hand side of Figure 1-3. A forcing, functioning as an input signal, acts on a system. Within the system the forcing is processed, which results in an output signal. In this study there are two output signals, i.e. the seasonal variation of SSC and the seasonal variation of diatom
biomass. The forcing consists of various parameters, which are independent because they only act as input for the system. The system itself can be defined as those processes in the Western Scheldt that determine the SSC and diatom biomass output signals. The resulting methodological concept is presented on the right hand side of Figure 1-3.

From this approach follows that the seasonal variations of SSC and diatom biomass that were shown in Figure 1-1 and Figure 1-2 are a result of the processes that occur in the underlying system. However, their mutual interaction and their interaction with other parameters are a part of the processes that occur in the estuary. So, upon identifying their relationship, these processes need to be studied.

![Methodological concept diagram](image)

### 1.2.1 Limitations and assumptions

The purpose of this study is not to discuss suspended matter behaviour in detail, nor to treat all relevant biological and physical processes influencing diatom populations in detail. In both fields there still is a lot of research going on, aiming at basic theoretical understanding. The interesting aspect of this study is that it combines existing knowledge from different research fields. This is why some issues will not be considered in this study. These include:

- influence of water quality and pollution
- influence of limiting silicate availability for diatoms
- influence of competition between diatoms
- influence of deposition of sediment at salt marshes

Furthermore, some aspects that will be treated are also common in estuaries other than the Western Scheldt. However, some issues are specific for the Western Scheldt. The objective of this study is to focus only on the Western Scheldt. Thus, general aspects will not be outlined separately.

### 1.3 Outline of the report

The identification of the independent parameters and the processes will take place through a literature study which is described in chapter 2. This will provide the qualitative filling-in of the methodological concept described above. Next, using data analysis the relationships
that were identified qualitatively will be analysed. The data analysis will be performed in chapter 3. The selected data and the criteria for selection will be discussed, as well as the implications of these data for the analyses that can be performed. In chapter 4 not only the results are discussed, also the performed analyses and the relation to the literature study will be treated. Finally, chapter 5 will provide the conclusions and recommendations.

Thus the identified relationships will be given some weight in a quantitative sense. By doing so it will be possible to put the specific relationship between seasonal variations of SSC and diatom biomass in perspective. Finally, in chapter 5 the conclusion and recommendations of this study will be presented.

1.4 General description of the Western Scheldt

Figure 1-4: The Scheldt estuary (Verlaan et al., 1998)

The catchment area of the River Scheldt covers about 21000 km$^2$ in the north-west of France, the west of Belgium and the south-western part of The Netherlands (Verlaan et al., 1998). The Scheldt estuary reaches from Vlissingen to Gent covering a distance of some 160 km (Salden, 1998). This is the area where the tide has a distinct influence on the water level at the river. At Gent weirs prevent the tidal motion from protruding further up the river. The Dutch part of the estuary is called the Western Scheldt and is approximately 60 km long.
The Western Scheldt is a tidally dominated coastal system (De Vriend et al., 1998). It has a moderate tidal regime. At Vlissingen the average tidal difference is about 4 metres, at Antwerp about 5.5 metres. This increase is caused by the geometry of the estuary. The spring-neap tidal difference at Vlissingen ranges between 3 and 4.5 metres.
2 Analysis of processes

2.1 Introduction

This chapter provides an analysis of factors and processes contributing to the seasonal variations of suspended sediment concentration and diatom biomass. This analysis is to a large extent based on existing literature and does not aim at quantifying the recognised relationships. It provides only the theoretical background, quantification will take place in the next chapter using data analysis. The approach of this chapter is based on the methodological concept in the previous chapter (Figure 1-3).

First, the independent parameters will be treated, which need to be taken into account when dealing with suspended sediment and diatoms. All of these factors play a role in the processes involving either suspended sediment or diatoms, or both. These parameters are independent because they influence processes in the estuary without being influenced themselves by these processes. Most parameters vary on a seasonal scale, which may indicate their role in the seasonal variation of SSC and diatom biomass.

Next, the processes are treated that influence SSC and diatom biomass and in which the independent parameters play a role. A subdivision is made between processes that play a role in the channel and processes that are of importance at the flats. This is done, based on the fact that SSC is measured in the channel, thus being a characteristic of the channel, while diatoms are only found at the flats. Despite treating these processes separately, the interaction between SSC and diatoms will become clear.

Finally, the processes in the channel and the processes at the flats will be combined in one conceptual model at the end of this chapter. In a relation scheme all independent parameters and processes that were discussed will be combined. Because the relation scheme only reflects the existing relationships and not their temporal character, in conclusion some attention will be given to the seasonal aspects.

2.2 Independent parameters

2.2.1 Tide

The tidal wave along the Dutch coast is of the M2 type: two high water periods and two low water periods occur every day (to be exact a ‘tidal day’ lasts 24 hours and 50 minutes). Next to this daily variation there is a spring-neap cycle of approximately two weeks. The tide acts as a major forcing in the Western Scheldt (see 1.2.1). Two aspects need to be considered that are important for SSC and diatom biomass variations. These are the vertical tide and the horizontal tide.
Vertical tide

During high water periods the flats are inundated. This makes them subject to occurring hydrodynamic conditions at that time. Sediment exchange between the water column and the flat bed can take place through deposition of suspended sediment and erosion and transport of particles from the flat surface.

Inundation of the flats also affects biological activity. The turbidity of the overlying water decreases light availability. This limits the growth of diatoms, which is light dependent. Furthermore, diatoms are active in the top layer of the flat surface. Thus, they are also subject to the hydrodynamic conditions.

Horizontal tide

The horizontal displacement of water has two major effects on suspended sediment concentration. First, the current velocity keeps fine material in suspension. Detailed measurements, presented by Van Maldegem et al. (1999), show this influence. During a tidal cycle SSC values change rapidly as a result of changing current velocities. Peak values occur just after the maximum current velocity. Comparison of measurements between two locations and at several depths indicate that the Western Scheldt is a well-mixed system. In the same report the effect of the neap-spring variation is mentioned. During spring tide SSC values are higher than during neap tide due to differences in current velocities.

The second effect concerns the exchange of sediment with the North Sea. Within a tidal cycle around 1.3 billion m$^3$ of water enters and leaves the Western Scheldt (Salden, 1998), the so called tidal prism. This water displacement covers a distance of approximately 20 km (Van Maldegem, 1999). This enables the exchange of suspended sediment between the estuary and the sea, which makes the seaward boundary a possible source for the supply of suspended sediment. Of course loss of sediment may also occur at this boundary.

2.2.2 River discharge

The discharge of the Scheldt into the estuary consists of rainwater, which falls in the catchment area of the river. Along with fresh water, the river also transports suspended matter. Where the fresh water meets the salt water an accumulation of suspended sediment is present, which is called the turbidity maximum. The turbidity maximum is located between Antwerp and the Dutch-Belgian border (Salden, 1998; see Figure 1-4). Under average discharge conditions the mixing zone of fresh and salt water reaches from Rupelmonde to Hansweert. However, the exact location of this zone depends on river discharge and can shift over a distance of up to 20-30 km (Verlaan et al., 1998). Discharges range from 20 m$^3$/s in the summer to 600 m$^3$/s during the winter period and higher discharges are associated with a higher supply of suspended sediment (Salden, 1998).

River discharge plays a role in the supply of sediment and in the spatial variation of SSC and the location of the turbidity maximum and the mixing zone. It also influences the salinity in the Western Scheldt. Salinity is of biological importance, since most species
grow either in fresh water or in salt water environments. Relatively few species can survive in the transition zone. However, in all of the Western Scheldt diatoms are present.

2.2.3 Wind

Wind plays a role in the processes in the Western Scheldt through wave activity and the influence of wind on water levels. For both, the combination of wind speed and wind direction determines the magnitude of the effect. Wind speed varies seasonally, with highest average values in winter. The average wind direction for the Western Scheldt is south-west.

Waves

Waves are generated through friction between air and water. A higher wind speed leads to higher waves. The same holds for a longer fetch, i.e. a longer stretch of water surface in the direction the wind is blowing. The fetch depends on the wind direction. In the Western Scheldt most waves are generated locally, i.e. within the estuary. Only near the inlet waves coming from sea may enter. The influence of waves lies in the energy dissipation of breaking waves. Braking waves are found at the flats. Since waves propagate in downwind direction, it is this direction that determines which flats are subject to wave attack. The height of a wave determines the amount of energy dissipation.

De Jonge and Van Beusekom (1995) investigated the effect of wind induced resuspension of mud and diatoms in the Ems estuary. For SSC, they found a linear relationship between concentrations in the channel and the averaged wind speed of three high-water periods preceding sampling. For chlorophyll a also a linear relationship was found. They also found that a doubling in wind speed has a far greater effect on resuspension from the flats than a doubling in current velocity. In general the combined effect of waves and currents, whether it being wind driven currents or tidal flow, have a far greater effect than either of these separately. The principle behind this, is that waves resuspend material which is transported by the current.

The effects of waves on resuspension and the subsequent resettlement has been pointed out in a review paper by Anderson (1983). Above the flats suspended sediment concentrations can increase to high levels, but resettlement occurs within a few days. For ship waves settlement even occurs at the time scale of minutes. Although not wind induced, ship waves play an important role, since the channel of the Western Scheldt is used intensively for shipping.

Water levels

Wind causes set-up and set-down of water levels. This effect is again related to fetch. For the Western Scheldt northerly and southerly winds have little effect. In these cases, the wind blows perpendicular to the main axis of the Western Scheldt and the fetch is short. The opposite can be stated for easterly and westerly winds.

Another important issue to address is the effect of set-up of the North Sea. This effect can be much larger than the (local) effect generated within the Western Scheldt. The maximum
fetch within the estuary is in the order of tens of kilometres, while the fetch in the North Sea can be hundreds of kilometres. At the scale of the North Sea, the 'gap' formed by the Channel between England and France is very small. Thus, when the wind direction is north-west, the body of water does not escape, but is pushed up in the southern region of the North Sea. This causes set-up of the water level at the seaward boundary of the Western Scheldt and in the estuary itself.

Suspended sediment concentration and diatom biomass might be influenced by the set-up of water levels through the increased time the flats are subject to hydrodynamic conditions and thus to erosive forces (including wave attack). For diatoms also light availability decreases.

2.2.4 Rain

Rain was already mentioned as being important for river discharge. Discharge values reflect the seasonal variation of rainfall in the catchment area of the river Scheldt. However, that concerns rainfall outside of the Western Scheldt area itself. Within the Western Scheldt rainfall has another effect. When a raindrop hits the surface of a flat, the impact alters the microtopography of the bed (roughness and water content both increase, salinity decreases). This results in a surface which is more susceptible for erosion (Anderson, 1983 and references therein). Thus, rain can have a very local effect, although the temporal variation probably dominates over the spatial effect, since effective rain showers will most probably occur in the whole Western Scheldt at the same time.

2.2.5 Temperature

The influence of temperature on biology is very clear: biological activity is highly related to changes in temperature. Small size organisms like diatoms react faster to temperature changes than large(r) organisms. For macrofaunal species (like worms, fish, shellfish, snails) temperature increase in spring causes them to start reproduction. Since mortality is generally high in the winter season, the number of individuals is low in spring compared to the end of summer. So, often it takes until fall for the total faunal population to reach its peak.

Flat surface temperature is influenced by emersion/inundation and solar radiation. During emersion, temperatures can vary on an hourly basis, due to the availability of sunlight (day or night, the presence of clouds).

Water temperature effects viscosity and turbulent characteristics. Lower water temperatures may lead to lower deposition and resuspension rates as a result of lower biological activity, leading to lower water content of the bed (see section 2.4). So in general, suspended sediment movement can be expected to be higher in summer and fall than in winter and spring, since water temperature changes more gradual, with highest values in (late) summer and fall (Anderson, 1983).
2.2.6 Light and nutrients

Although not of physical influence, light availability is an important biological factor. Light availability shows seasonal behaviour, through changes in the length of nights and days. Light is used for photosynthesis by plants and algae. In particular, phytoplankton and microphytbentos (diatoms being the most important species) are the primary producers in estuarine environments. Primary production by phytoplankton in particular is influenced by turbidity, since light availability in the water column is limited. The influence of light limitation is shown in Figure 2-1: in turbid estuaries where the import of organic material is high, the yearly primary production remains low.

![Graph showing the relationship between net import of organic material and primary production.](image)

Figure 2-1: Primary production as a function of the net import of organic material in estuaries around the world (Salden, 1998, after Heip et al., 1995). Estuaries which are light limited are indicated with ■, the others with ◆.

The total primary production by phytoplankton is light limited in the Western Scheldt while nutrient supply is not the limiting factor for primary production (Salden, 1998). This makes diatoms important primary producers in the Western Scheldt, since diatoms have the advantage that they are not hindered by turbid waters during emersion of the flat surface. Although nutrients are sufficiently available, they need to be mentioned, since nutrient supply is important for primary production and for the growth of diatoms. Diatoms depend on the supply of nutrients from the water column. The availability of nutrients depends on the supply of nutrients to the flats and thus on the combination of bed level and water level variation.

2.3 Processes in the channel

This section focuses on the processes that influence temporal variations of suspended sediment concentration in the channel. Since SSC is a characteristic of the water column, the interest lies in processes that are responsible for adding particles to or extracting particles from the water column.
2.3.1 Sediment supply and loss

Various balances for fine grained sediment are available for the Western Scheldt, but these are all based on yearly net fluxes. According to Van Maldegem et al. (1999) the net import of fine particles (<63 μm) into the Western Scheldt is $0.1 \times 10^6$ tons per year, of which the largest part is imported from sea. Most of this material is stored at the salt marshes (Land van Saeftinge). Verlaan et al. (1998) state that the supply of marine material is more or less equally distributed over a year, while the supply of fluvial material (i.e. sediment coming from the river) varies considerably with discharge. However, not much is known about the net fluxes at the seaside during winter and summer. The Antwerp harbour is an important area for sedimentation of both fluvial and marine fine grained sediment (Salden, 1998). Again holds that information on net fluxes on a seasonal scale is not available.

2.3.2 Storage at the flats

The mechanism of internal redistribution of sediment has been indicated by Frostick and McCave (1979). For the Deben estuary (England), they calculated that an internal shift of sediment must take place. They based this conclusion on measured accretion of the flats in spring and summer and subsequent erosion in fall and winter. The amount of accreted material was too big to be supplied by the sea and the river alone. Fine grained sediment that was stored at the channel walls in the winter, was transported up the flats. This was also observed visually. The reverse process occurred in fall and winter. Salden (1998) indicates that accretion of tidal flats in summer and erosion in winter also occurs in the Western Scheldt. When not all of the eroded material from the flats is stored at the channel walls, but a part stays in suspension, this will contribute to an increase in SSC values.

2.3.3 Storage at the channel bottom

Another possible source and sink within the estuary is the channel bottom, or rather the bottom layer of the channel. Van Maldegem et al. (1999) measured SSC at various depths. The greatest depth was NAP-17 m, approximately 2 m above the bottom of the channel. It was already indicated in 2.2.1 that the current velocity is the dominant factor in SSC variations (on a daily and neap/spring scale). During the turn of the tide SSC values decrease dramatically, indicating settlement of large quantities of sediment into the lowest part of the water column. When the current velocity increases again, this sediment is subsequently resuspended into the higher reaches of the water column. For the amount of sediment that will settle, not only the current velocity is important, but also the length of the turn of the tide during which settlement can occur.

The tide and neap/spring induced current velocities are not seasonally dependent. However, due to storms and set-up of the water level, hydrodynamic conditions in fall and winter are more fierce. This leads to higher average current velocities and more turbulence in the channel in fall and winter than during the spring and summer period. The period during which settlement of particles can take place reduces. As a result, the particles will not settle in the bottom layer as much as they will in the summer. More sediment is kept in suspension in the winter months.
2.3.4 Aggregates

Suspended matter consists of silt and clay particles (grain diameter 2-63 μm and <2 μm respectively) and organic matter. Due to the cohesive character of the clay particles they tend to stick together with silt particles, forming flocs. This so-called flocculation is influenced by salinity, but also binding substances which are a result of biological activity are important in the formation of these aggregates. Aggregates differ from individual particles in size and density. They settle more easily, which means that larger aggregates are more abundant at the bottom than at the surface of the water column. Thus the suspended sediment concentration is also higher at the bottom (Edelvang and Austen, 1997).

Settling velocities also vary on a seasonal scale. Ten Brinke (1997) found highest settling velocities in late summer. This seasonal variation is probably caused by differences in shear (currents and turbulence) and aggregate strength. Aggregate strength is influenced by the presence of organic material, which has a binding effect. Perhaps also water temperature plays a role through viscosity (see 2.2.5).

2.3.5 Shift of the mixing zone

Suspended sediment concentrations do not only vary on a temporal scale, but also spatially (Salden, 1998 and Villars and Vos, 1999). At the location of the turbidity maximum values are highest. Average concentrations decrease until Hansweert. This is the zone where mixing of fresh and salt water takes place. Between Hansweert and Vlissingen concentrations are more or less constant. It was already indicated in 2.2.2 that changes in river discharge cause the mixing zone to shift over a distance of up to 20-30 km. If the suspended sediment concentration gradient moves along with the shifting mixing zone, this affects SSC in the eastern and middle range of the Western Scheldt. In this area the suspended sediment concentration increases with a seaward shift of the mixing zone.

2.3.6 Dredging

Dredging, or rather the dumping of dredged material within the estuary (the so-called 'rondpompen' in Dutch) causes an increase in suspended sediment concentration. However, this has a short term local effect (Van Maldegem et al., 1999). Only when dumping takes place near a measuring point (i.e. within the distance these particles can travel in one flood or ebb period), an increase in SSC will be observed. Due to strong mixing, the effect will disappear quite rapidly.

2.3.7 Summary

Variations of suspended sediment concentration can best be described using the principles of a sediment balance. The channels, containing suspended sediment, act as the control volume. The exchange of suspended sediment at sea takes place through tidal action. Gross fluxes per tidal cycle are high (tidal prism), net fluxes are a result of longer term (yearly, or perhaps seasonal) residual transports. The channel bottom and the tidal flats act as sources and sinks for suspended sediment within the Western Scheldt. This is summarised in Figure 2-2.
The effects of the formation of aggregates is part of the interaction between the channel, the flats and the channel bottom. Although mainly a spatial variation, the shift of the mixing zone is part of the fluxes at the Belgian-Dutch border.

### 2.4 Processes at the flats

Through sedimentation and erosion the flats can act as sources and sinks for suspended sediment. In order to establish whether seasonal influences exist, which trigger this phenomenon, all processes that are of interest at the tidal flats need to be investigated. The first subsection will be dedicated to diatoms, in order to gain some general knowledge on diatom life. An indication of the governing seasonal influences will be given. This subsection will largely be based on a report by Stapel and De Jong (1998). Next, an overview will be given of processes controlling deposition of sediment, sediment stability and erosion of sediment respectively.

#### 2.4.1 About diatoms

Benthic diatoms are sediment inhabiting, unicellular algae. They are the main constituent of the microphytobenthos community in the Western Scheldt, which consists of algae, fungi and bacteria. Diatoms use chlorophyll $a$ (leaf green) for photosynthesis, which means they depend heavily on light availability. During inundation of the flats, light availability is limited, due to the turbidity of the overlying water column. During (daytime) emersion however, light is sufficiently available. This gives benthic diatoms an advantage compared
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to the phytoplankton, that lives in turbid waters continuously. It also implies that diatoms
may be important primary producers in turbid estuaries (like the Western Scheldt) and act
as an important food source for other (higher) organisms.

Diatoms are found in the top centimetres of the bed, but for photosynthesis they need to be
on top of the sediment, since light only penetrates a few mm into the surface. Within the
group of diatoms a large number of species can be distinguished. However, two main
groups can be recognised, based on the mechanism used for movement to the flat surface.
The first group are the epipsamic species. These diatoms attach themselves to a sediment
particle and are dependent on sediment reworking. They cannot actively influence their
position within the bed. The other group, the epipelic species, consists of motile algae,
which are capable of working their way up to the flat surface. They do so by secreting
extracellular polymeric substances (EPS) during locomotion, which is mucus consisting of
polysaccharides ("sugar"). EPS glues sediment particles together and has an influence on
sediment stability, which will be discusses in 2.4.3. The epipelic species contribute more to
diatom biomass than the epipsammic species.

During a bloom period, large densities of diatoms are known to form algal mats. These mats
sometimes are visible as a brownish jelly-like layer. Total replacement of a diatom
community takes about one week, which indicates that a diatom population adapts very
quickly to temporal changes in environmental conditions.

Seasonal variation of diatom biomass

According to Stapel and De Jong (1998) seasonal changes in light availability, temperature
and turbidity, caused by both suspended particles and organic matter (like phytoplankton),
do not play a role in seasonal variations of diatom biomass. This conclusion was drawn,
based on numerous studies and comparison of observations in both the Western Scheldt and
the Eastern Scheldt (also located in the southwest of The Netherlands). Light and
temperature of course vary seasonally, but this is not reflected in diatom biomass
measurements that are carried out throughout the Western Scheldt and which are presented
by Stapel and De Jong (1998). At some flats a very distinct seasonal trend is present, while
at other flats diatom biomass is either low or high throughout the whole year. As far as
turbidity is concerned, in the Western Scheldt values are too high throughout the year for
diatoms to grow during inundation. Seasonal changes in SSC do not influence turbidity in
such a way that it allows diatoms to grow during inundation of the flats. Factors that might
play a role in the seasonal variation of diatoms are the influence of hydrodynamic
conditions, the composition of the total diatom population (epipsamic versus epipelic
species) and grazing of diatoms by macrofauna. However, little is known about these
influences.

2.4.2 Sediment deposition

For sediment deposition at the flats the same principle holds as in the channel. Around high
water slack, current velocities are low enough for particles to settle. Not only the current
velocity needs to be low enough, also turbulence plays a role (wind waves). Net
sedimentation will take place, when the erosion rate due to the subsequent ebb current is less than the deposition rate.

Deposition rates are also influenced by biological activity. Some species feed on nutrients in the water column, which they filter out of the water. By doing so, also inorganic particles are filtered, which are deposited on the flat surface as faeces. Large densities of suspension feeders might have a significant effect on deposition rate. In summer and fall this effect will be greater since biological activity in winter and spring is low.

The influence of diatoms on the deposition of sediment also needs to be addressed. Kornman and De Deckere (1998) state that the presence of large amounts of diatoms enhances the trapping of deposited sediment due to the presence of EPS at the flat surface. This contributes to decreasing values of SSC that were measured above a flat in the Ems estuary. However, Stapel and De Jong (1998) indicate that light availability is too low during inundation of the flats for diatoms to be active. This indicates that diatoms do not actively contribute to the removal of particles from the water column. Therefore, in order for diatoms to enhance the trapping of deposited sediment, sediment particles must first settle onto the flat surface. Thus, hydrodynamic conditions need to be favourable for sediment deposition before trapping can occur.

2.4.3 Sediment stability

Sediment stability plays an important role in the erosion process. In order for erosion of the flat surface to occur, the forces inducing erosion need to exceed the resistance of the bed to these forces. Both resistance against erosion and the bed shear stress (the erosive force) vary in time. In order to understand why and when erosion takes place, sediment stability will be treated separately from erosion.

Water content, consolidation, and porosity are closely related. They reflect the physical properties of the bed. Dewatering, consolidation and decreasing porosity increase sediment stability. These are a function of bed level and the presence of diatoms and macro fauna. At higher bed levels more dewatering occurs, because air exposure times are longer. Thus more resistance will be built up. This effect is very clear for flats that are constantly exposed to air during neap tide, when no inundation occurs at all (Widdows et al., 2000). Wind, temperature and solar radiation play an important role. Wind causes set-up of water levels in the winter, influencing exposure time. Temperature and solar radiation are higher in the summer period. Thus, a tidal flat will tend to dewater more during the summer.

The presence of diatoms also increases sediment stability. A lot of research effort has been carried out to understand the underlying principles. As has been indicated, motile (i.e. mobile) diatoms secrete mucus, which enables them to move around in the sediment. These polysaccharides bind sediment particles together. Diatom populations can cover large areas of the flat surface, binding all material in that area. Fresh deposits will be ‘colonised’, since diatoms will move upward in order to be at the surface again. By doing so, they stabilise deposited sediment and enhance the stability of the bed. Underwood and Paterson (1993) showed this by comparing deposition and erosion rates at two different sites (see Figure 2-3). One site contained diatoms (indicated with C), at the other site all organisms were killed.
frequently through biocide treatment (S). At both sites initial deposition rates were equal, but at the treated sites the fresh deposits were washed away again. At the untreated site deposits were retained.

![Deposition and erosion in the Severn estuary at a treated site (S) and an untreated site (C) (Underwood and Paterson, 1993). The figure represents the bed level relative to the initial level at the start of the measurements.](image)

Although the presence of diatoms increases sediment stability, it influences dehydration negatively. This has an effect, that is also reflected in the work of Underwood and Paterson (1993). They established that the presence of diatoms increased erosion resistance, but once these were washed away from the flat surface, erosion rates were high compared to the biocide treated site. At that site dehydration and consolidation of the initial surface were higher, leading to much higher erosion resistance. The fact that also bioturbating (i.e. sediment reworking) macrofauna was killed during treatment played an important role in the magnitude of dewatering and compaction. This also indicates the interest of macrofauna on erosion resistance. Organisms like worms dig channels through the bed, reaching 4 to 40 cm deep (Pender et al., 1994), increasing water content and porosity of the sediment up to considerable depths and thus affecting sediment stability.

A more indirect effect is that of grazing macrofauna. Widdows et al. (2000) investigated the effect of the clam *Macoma balthica* on sediment stability. This species is a deposit feeder, feeding on diatoms. The presence of this bivalve decreased erosion resistance, which can be partially explained by decreased diatom numbers.

### 2.4.4 Sediment erosion

The main forces causing erosion are currents and waves (Ridderinkhof, 2000, De Jonge and Van Beusekom, 1995). Rain may also play an important role (Anderson, 1983 and references therein). The impact of a raindrop alters the roughness of the bottom and changes the water content and the salinity of the bed, making the bed more susceptible to erosion.
Some species feed on fresh deposits (deposit feeders). Their faeces consist of pellets which are more easily erodible than the (stabilised) flat surface. These pellets are also found in the channels, which indicates that they are indeed eroded of the flats (see 2.3.4). Others produce mounds of sediment, which are clearly visible to the eye. Some species make use of tubes, which may protrude above the flat surface. At a small scale, this biological activity effects the microrelief of the flat surface. Thus, the roughness of the bed is influenced.

Erosion actually takes place when the erosive forces acting on the flat surface exceed the resistance of the bed. Both these forces and the resistance are seasonally dependent. Diatoms enhance stability in a period that hydrodynamic forces decrease.

2.4.5 Summary

Diatoms are not responsible for deposition of sediment, wind plays an important role through (the absence of) wave activity. However, this does not mean that diatoms do not contribute to decreasing SSC values. Diatoms enhance the stability of freshly deposited sediment, which prevents it from being eroded by the subsequent tides. By doing so during a period of time, fine grained sediment can accumulate at the flats. Again, hydrodynamic conditions need to be favourable to prevent diatoms and sediment to be immediately washed away during subsequent flooding of the flats.

As was shown, biological activity plays an important role at the flats. Various species contribute to sediment deposition, reworking and resuspension. The stability of a tidal flat depends to a large extent on the composition of the total benthic population. Diatoms contribute to sediment stability and act as a food source to other organisms.

Although temperature cannot be used to explain diatom biomass, it has already been pointed out that it has an effect on other biological processes. This concerns mainly the activity and the abundance of macrofauna, which subsequently influences diatom biomass and sediment related processes. Next to these biological components, hydrodynamic conditions and rain are important for both diatom biomass variations and sediment related processes.

2.5 Conceptual model

In section 2.2 the independent parameters involved in the seasonal variations of SSC and diatom biomass were presented and in sections 2.3 and 2.4 the processes that are of importance were outlined, following the approach described in section 1.2. Since the most important parameters and processes and their relationships have been identified, it is now possible to create an overview in which these relationships are reflected. This overview is given in Figure 2-4. Some remarks will be made to clarify this scheme.
The grey shaded squares are the independent parameters described in section 2.2. Nutrients are not taken into account and also light is left out, based on the findings of Stapel and De Jong (1998) which were described in 2.4.1. Some of these parameters (current velocity, waves and water level) are composed out of one or more other parameters, but they operate independently with reference to SSC and diatom biomass variations. The ovals reflect those parameters which were introduced to describe the processes in the Western Scheldt involving seasonal variations of SSC and diatom biomass. They are a function of the independent parameters and the interactions that take place within these processes. Notice that SSC and diatoms themselves are part of these processes. The arrows reflect the relationships that were identified. Most arrows are provided with a plus or a minus sign. The sign reflects the effect of an increase of one parameter on the other. For example, an increase in wind speed has a positive effect on the formation of waves. The effect of biological activity on erosion and stability of the flat surface can either be positive or negative depending on the type of activity that is displayed by various species.

Some aspects which are relevant to the relation scheme will be clarified. First, in 2.3.7 a suspended sediment balance was presented as a result of the identification of processes in the channel (see Figure 2-2). The terms in this balance are represented in the relation scheme by the numbers 1 to 4 (see Figure 2-4) with:
1) exchange of sediment at the seaward boundary.
2) sediment exchange with the channel bottom.
3) net supply of sediment from the river.
4) exchange of sediment with the flats.

Secondly, the relationship between water level set-up and diatoms needs some explanation. The key factors here is turbidity, which plays a role in diatom biomass through wind
induced water level changes. When set-up of the water level occurs, the inundation time of the flats increases. This reduces the exposure time of diatoms to light due to turbidity and thus their possibility for growth. The importance of inundation as a function of water level does not only apply to diatom growth, during inundation of the flats also sediment exchange takes place. The duration of the inundation is of importance, since it determined the amount of sediment that can be deposited and the duration of waves attacking the flat surface. The reason that water level is not directly coupled to sediment deposition and erosion, is due to the fact that inundation of the flats itself does not have an effect on these processes, wind does. Besides that, it is a combination of water level and bed level that determines inundation.

Finally, temperature is coupled only to biological activity and not to sediment stability and SSC (through changes in viscosity etc.). The influence of these relationships are thought to be inferior to biological activity and hydrodynamic effects respectively. Hydrodynamic conditions include wind, waves, water level and current velocity. This is in itself a complex set of parameters. In the channel hydrodynamic conditions are dominated by the current velocity, at the flats wind has an effect through waves and water level variations. The combination of waves and set-up of the water level is crucial to the deposition and erosion processes and also for diatoms. Whether set-up or set-down of the water level occurs depends on wind direction. Water level variations have an effect on current velocity, since extra volumes of water are displaced.

Up until now the relation scheme has been discussed, but nothing has been said about the seasonal variations of the various parameters. Temperature of course has a very clear seasonal influence. However, biological activity is not coupled directly to changes in temperature. The peak in numbers and size of most species is reached at the end of summer and during fall. This is the period that aggregate formation will reach its peak, and diatoms suffer the most from grazing by macrofauna. Rain showers have a negative effect on diatoms and a positive effect on SSC. The impact is less during inundation of the flats. Most rain fall occurs in fall and winter. Discharge values are highest in the winter. The question remains whether the supply of sediment is linear with discharge. Average wind speeds are higher during the winter, when more storms occur. Wave activity increases during the winter and wind induced water level variations will cause the flats to be inundated less regularly than during summer.

As an illustration of how to visualise the seasonal effect of various parameters reference is made to a study by Anderson (1983). In a review study he analysed seasonal processes influencing deposition and erosion of fine grained sediment at flats in several northern estuaries. Figure 2-5 (from Anderson, 1983) shows the relative importance of each physical and biological parameter.
Most of these parameters were also identified in this chapter. Flora reflects both diatoms and plants, which were not included in this study, because they are mainly found at the salt marshes. Ice is not a common phenomenon in the Western Scheldt and dewatering was recognised but thought to be determined by other factors. Note that this parameter is represented by a dashed line and question marks, which indicates the uncertainty in the course of the line.
3 Data analysis

3.1 Introduction

The approach that was presented in chapter 1 provided the basis for studying all parameters and processes that are involved in temporal variations of suspended sediment and diatom biomass. It was postulated that more than just the direct relationship between SSC and diatom biomass needs to be considered. In chapter 2 all these parameters and processes and their relationships were identified. However, in the approach it was also indicated that not only the identification is of importance. The magnitude of the effect of the parameters needs to be studied in order to determine the relative importance of each parameter to SSC and diatom biomass variations. It might be, for instance, that the deposition and erosion of particles is dominated by hydrodynamic conditions and the presence of diatoms by biological activity. This would indicate that the relationship between SSC and diatom biomass is weak or non existent, since both variations are dominated by different processes. Thus, quantification of all parameters needs to be carried out. The goal of this chapter is to provide an insight into the role that the parameters have in these variations, based on the relationships that were identified in the previous chapter.

First, data collection is discussed. Some restrictions will be pointed out and the selected data will be presented. The implications for the relationships that can be studied will be outlined and the relation scheme from Figure 2-4 will be adjusted to fit the selected data. Next, different types of data analysis will be discussed. The selected data will be related to these types of analysis. This will result in an appropriate analysis approach. The types of analysis that will be performed will also be discussed. Finally, the results of the analyses will be presented, followed by a discussion.

3.2 Data collection

3.2.1 Criteria

The Western Scheldt is a well studied estuary. Data are being generated each year, as a result of both (long term) monitoring programs and incidental research programs. To deal with this wide variety of databases, some choices were made on which data to use for the analysis. First, only existing in situ data will be used, in stead of remote sensing or computed data. The main reasons are that these type of data are the most realistic and relatively easy to obtain. Secondly, the available data should at least contain information on all seasons. Specific, project oriented studies often combine a short measuring period with a high measuring frequency. A lot of data is being generated over a small time span and in a small area. Thus, the measuring period often does not exceed one season. Furthermore, the spatial scale of measurement is too small to be able to say something about the large scale variations of SSC, which clearly exceed the scale of, for example, a single flat. That is why
the choice is made only to study parameters on which data is available for at least one whole year.

### 3.2.2 Selected data

The data that were selected can be divided into two groups, based on measuring period and interval of measurement. An overview of these two different sets of parameters is given in Table 3-1.

Table 3-1: Summary of available data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Location</th>
<th>Period</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC</td>
<td>Terneuzen</td>
<td>Oct 1998 - Sept 2000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Water level</td>
<td>Terneuzen</td>
<td>Oct 1998 - Sept 2000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Astronomical tide</td>
<td>Terneuzen</td>
<td>Oct 1998 - Sept 2000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Hansweert</td>
<td>Oct 1998 - Sept 2000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Hansweert</td>
<td>Oct 1998 - Sept 2000</td>
<td>10 minutes</td>
</tr>
<tr>
<td>SSC</td>
<td>6 locations</td>
<td>1990 - 1999</td>
<td>4 weeks</td>
</tr>
<tr>
<td>Chlorophyll a</td>
<td>Tidal flats Westerschelde</td>
<td>1990 - 1999</td>
<td>1 month</td>
</tr>
<tr>
<td>Bed level</td>
<td>Tidal flats Westerschelde</td>
<td>1990 - 1999</td>
<td>1 month</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Vlissingen</td>
<td>1990 - 1999</td>
<td>1 month</td>
</tr>
<tr>
<td>Rain</td>
<td>Vlissingen</td>
<td>1990 - 1999</td>
<td>1 month</td>
</tr>
<tr>
<td>Discharge</td>
<td>Schaar van Ouden Doel</td>
<td>1990 - 1999</td>
<td>10 days</td>
</tr>
<tr>
<td>Water level</td>
<td>Terneuzen</td>
<td>1990 - 1999</td>
<td>10 minutes</td>
</tr>
</tbody>
</table>

The first set of parameters contains very detailed information over a two year period (October 1998-September 2000). These data are part of a database that was provided by the RIKZ. SSC measurements are carried out to monitor the effects of the building of a tunnel under the Western Scheldt. The construction of this tunnel started in 1999. The fine grained material that is released during the drilling of the tunnel is dumped in the Western Scheldt. In order to study the effects of this dumping, a monitoring campaign started in the fall of 1998. At two fixed places in the channel, viz. Terneuzen and Baalhoek, suspended sediment concentrations are measured. The results are recorded at ten minute intervals. The Terneuzen data was chosen, because it provides information on SSC at three depths (4 m., 11 m. and 17 m. below NAP, which is the Dutch reference level). Besides these SSC data, this database also contains the information on water levels, wind speed and wind direction, also at a ten minute interval. Data on the astronomical tide were obtained using RIKZ’s ‘Getijgenerator’.

The second set of parameters contains data concerning a period of ten years. In the Western Scheldt, suspended sediment concentration is one of the parameters which is measured as a part of the large scale monitoring of the Dutch waters (MWTL). Surface samples (one meter below the surface) are taken at an average four week interval at six different locations...
in the channel (Vlissingen, Terneuzen, Hoekseweert, Hoedekenskerke, Wielingen and Schaar van Ouden Doel).

Chlorophyll \( a \) measurements are carried out on a monthly interval at ca. 20 different sites, distributed over the entire estuary. Each site is situated on a tidal flat and consists of a transect of 3 or 4 sample points (sometimes more). For the top layer of the sediment chlorophyll \( a \) levels are determined.

Bed level represents the deposition and erosion as was defined in the relation scheme in (Figure 2-4). In most cases, the bed level is measured at the same locations where samples are taken to determine chlorophyll \( a \) levels. Measurements are also carried out once a month and in most cases these two measurements are combined. So data are available at the same day.

The discharge at Schaar van Ouden Doel equals the discharge that is measured at Rupelmonde plus 21\%, to compensate the additional discharge that occurs between the two locations. The fact that the tidal influence is present in the river Scheldt, makes that only an averaged discharge over a ten day period is available. The discharge data at Schaar van Ouden Doel were present at the RIKZ.

Rain and wind speed data (total values and average values respectively) were obtained from the annual weather reports of the KNMI, the Dutch Meteorological Institute. The water level measurements that are used, were carried out at the tidal station in Terneuzen. The data were provided by the RIKZ.

### 3.2.3 Implications

Comparing the selected data with the independent and dependent parameters that were identified in chapter 2 and summarised in Figure 2-4 shows that information on some parameters is missing:
- Current velocity;
- Exchange of sediment with sea;
- Waves;
- Biological activity;
- Temperature;
- Sediment stability.

Measurements of current velocity are available for a period of three months, but not on all seasons. Thus these data were not selected, because a minimum of one year of data is required. Because information on biological activity is not available, there is no reason to use data on temperature, since this parameter does only affect biological activity (see Figure 2-4).

Based on the information that will be used for analysis, the relation scheme can be adjusted accordingly. The result is shown in Figure 3-1, where some concessions had to be made to deal with the lack of information. The figure shows that of all available parameters, only discharge and bed level are directly related to SSC. All other parameters are linked with
SSC through bed level changes. Wind is thought to be representative for wave activity in the Western Scheldt. Therefore it is coupled directly to diatoms and bed level variations, instead of through waves. An increase in wind speed has a negative effect on diatoms and bed level. Diatoms are directly related to bed level, instead of through sediment stability. An increase in diatoms leads to an increase in bed level.

![Relation scheme based on available parameters](image)

**3.3 Analysis approach**

When dealing with temporal influences, two types of parameters exist. There are slowly varying parameters like discharge and temperature and there are parameters, like rain and wind, which have a more event-like effect through storms and rain showers. The effect of these events on SSC and diatoms was indicated in chapter 2. When diatoms are removed from the flats, their presence is restored in one week. The effect of wind induced resuspension of sediment disappears in a number of days. Two types of analysis are possible in studying the relationship between SSC and diatoms and the influence of other parameters. These analyses focus on short term events or on long term trends.

In the event analysis the interval and magnitude of the events play a role. For example, after a storm diatoms need to recover, because they were eroded off the flats. The intensity of the storm determines the amount of diatoms that were removed. The interval between two of these storm events determines whether the diatom population can restore itself completely. In fall and winter both intensity and frequency of storm events are higher.
It could even be that a single storm decreases the strength of a total diatom population to a level where recovery does not occur any more, because less intense events with a higher frequency also start having an effect. This would then indicate certain threshold values in the relationship between events and diatoms. This might also work the other way round: one or two days of sunshine in spring might cause the diatom population to increase to a level where they can withstand events that they could not withstand before. The example above illustrates that one single event does not explain seasonal variations. This implies that in this type of approach conclusions can only be drawn, when the effect of events are studied during all seasons.

The trend analysis is less detailed. It deals with the variation of parameters within a year and between years. Thus, for example, the effect of extreme high discharges on SSC during one winter can give information on the influence of the river as a source for suspended sediment. In the same way the effect of a rainy summer or a stormy winter on SSC and diatom biomass can be analysed. Also seasonal variations can be studied.

Next to temporal variations, also the spatial scale is of interest. For diatoms, chlorophyll a levels at a flat represent the diatom biomass of that specific flat. For SSC this reasoning is not valid. SSC measurements at a location are not confined to that specific location, because of the influence of the tide. Suspended sediment is exchanged throughout the Western Scheldt by the horizontal movement of water. This implies that SSC values, measured at a specific location, are a result of processes that occur in a larger part of the estuary. If the flats should play an important role in SSC variations, then another consequence is, that changes in SSC in the Western Scheldt cannot be explained by studying deposition/erosion at a single flat. All flats will have to participate.

Investigating spatial variations also contributes to the understanding of the effect of certain parameters on SSC and diatom biomass variations. For example, flats that are facing the dominant wind direction will probably be more influenced by wave attack than flats that are protected from waves. When this result in differences in diatom biomass between these flats, it indicates the influence of waves.

As was indicated, there are two types of analysis. These are a temporal analysis, which can be divided onto an event and a trend approach, and a spatial analysis. The question remains how the selected data fit into these types of analysis. Based on measuring period and frequency already two sets of parameters were distinguished (Table 3-1). The first set, with SSC, water level and astronomical tide at Terneuzen and wind speed and direction at the nearby Hansweert, contains information at one location. This short term set is suitable for the analysis of events. Because information on all parameters is available on a ten minute interval, a high degree of detail is obtained. The second set, the long term data, can best be used for the analysis of trends, since for most parameters information is present on a monthly interval. For SSC, chlorophyll a, and bed level also spatial information is available.

The techniques that will be used in the various data analyses depend on the type of data that is analysed. Time series plots, scatter plots, regression techniques and also Fourier analysis and the least-squares method will be used depending on the type of data that is analysed.
3.4 Results

3.4.1 Short term data

Only data on SSC, wind speed and direction and water levels are available. This puts some restrictions to the type of events that can be studied. The relationship between wind and water level is a direct one according to the relation scheme. Deviations of the measured water level from the predicted astronomical tide can be analysed as a function of wind speed.

Wind and water level are both indirectly related to SSC through bed level. Thus, variations in SSC can be studied as a function of wind, through wind induced resuspension, and of water level. When a relationship is found between increasing wind speed (storms) and increasing SSC values, this will provide somewhat indirect evidence of the effect of wind (in particular waves) on resuspension of sediment from the flats.

Figure 3-2 shows the temporal variation of the predicted and the measured water level. The values that are shown are averages over two tidal cycles (24 hours and 50 minutes). The influence of the neap/spring tidal cycle is still clearly visible in the signal of the predicted tide. Also a seasonal variation can be distinguished, with higher water levels in the winter that during the summer. The measured water level differs from predicted one, differences are larger in the winter period than in the summer. Remarkably, sometimes the difference between the measured and the predicted water levels averaged over two complete tidal cycles is more than one meter.

In Figure 3-3 the temporal variation of the suspended sediment concentrations at the Terneuzen measuring location is shown for the NAP-4 m and NAP-17 m depths. Again, these values are averages of two tidal cycles. Two types of variations are visible, a rapid one and a slow one. The rapid variation represents the influence of the neap/spring tidal cycle, the slow one is a seasonal trend, with highest values in winter. The data for the summer months (July-September) are missing, as well as the NAP-11 m data. This will be discussed in 3.5.

Figure 3-4 shows the wind speed and the difference between measured and predicted water levels, both as a function of wind direction. Average values are taken per degree wind direction (with 0° is North, 90° is East, 180° is South), so 360 dots per parameter are shown. The following observations can be made:

- The highest average wind speeds are recorded around 200 degrees. This corresponds to South to Southwest, which is also the dominant wind direction for the Western Scheldt area.
- The water level variation shows a very different behaviour. At 0-200 degrees the measured values are (on average) lower than the predicted ones, while the set-up of the water level is largest at 270-315 degrees.
3.4.2 Long term bed level and chlorophyll $a$

This analysis will focus on seasonal variations of bed level at all flats in the Western Scheldt, with an expected accretion in spring and erosion in fall. Also variations of chlorophyll $a$ will be studied. Since bed level and chlorophyll $a$ are measured at the same locations, also the relationship of diatoms and bed level can be studied. This can provide some insight into the role of diatoms in retaining sediment to the flat surface.

The relationship between chlorophyll $a$ values and the position at the flats is shown in Figure 3-5. Average chlorophyll $a$ values and the number of observations are given for 10 centimetre intervals. The high values at NAP-1300 mm are caused by one specific measuring point. Apart from that, it can be seen that chlorophyll $a$ levels increase with increasing bed level.

Bed level changes show different long term behaviour at various flats, as can be seen in Figure 3-6. To study the effect of these changes on chlorophyll $a$, this parameter is also included in the graphs:

a) This point has accreted ca. 1.3 meter in a period of nine years. With some exceptions, chlorophyll $a$ levels do not exceed 2.00 $\mu$g/g (microgram per gram sediment).

b) This point shows some structural erosion of 2 meters in nine years. Chlorophyll $a$ levels are comparable with the situation in Figure a).

c) A very stable point. Bed level varies only 40 mm in a period of five years. Chlorophyll $a$ levels are considerably higher (order 10-45 $\mu$g/g) than in the previous examples.

d) This is a very unstable point. First erosion occurs (more that 2.5 meter in 2 years), followed by accretion (more than 1 meter in 3 years). Chlorophyll $a$ levels are lowest, with maximum values of ca. 5 $\mu$g/g.

The specific relationship between bed level dynamics and chlorophyll $a$ levels is reflected in Figures 3-7 and 3-8. The first figure shows the average chlorophyll $a$ values as a function of the maximum bed level variation that occurred within one year. One measurement around 3500 mm, with a low chlorophyll $a$ value, is not shown. When the bed level variation at a certain location is high within one year, average diatom biomass is low. However, when variations are low high values as well as low values of diatom biomass are measured. The second figure shows the same relationship, but for maximum bed level variations that occurred over the full ten year period of measurement. The same pattern can be distinguished as in the yearly variations of bed level.

3.4.3 Long term temporal variation

In the analysis of temporal variations the interest lies in the influence of all parameters other than bed level on SSC and chlorophyll $a$. The aim is to determine whether one or more parameters dominate over the other ones with reference to SSC and diatom biomass variations. As can be seen from the list of parameters (Table 3-1), all parameters are measured at different locations, different moments in time and at different frequencies. To be able to analyse all parameters on a temporal scale, some measures were taken to make this analysis possible. First, an averaging of all spatial information had to take place. This is a valid approach, since it has already been indicated that for SSC and diatoms the interest
lies in the 'cumulated effect' of processes in the entire estuary and not a single flat or measuring point. Secondly, monthly averaged values were used for all parameters. Since the interest of this analysis lies in trends that occur at a seasonal and yearly scale, it is not necessary to have more detailed information than is provided by these monthly averaged values.

To obtain these spatially averaged, monthly average values, the following assumptions were made:
- SSC: information on all measuring locations is averaged into one SSC value;
- Chlorophyll a: all available data will be averaged per month;
- Wind speed: measurements at Vlissingen are representative for the entire Western Scheldt;
- Rain: measurements at Vlissingen are representative for the entire Western Scheldt;
- Discharge: discharge can be thought to be representative for the amount of sediment that is supplied by the river Scheldt, the effect of this supply are equal for the entire Western Scheldt;
- Water level: by averaging per month, a lot of information on the tidal scale is lost. However, the interest does not lie in tidal variations, but in set-up or set-down of the water level. Although monthly values may be expected to be near the average (NAP), differences might still occur.

The analysis itself consists of four parts, i.e. a univariate regression, a multiple regression, a comparison of winter and summer patterns and a time series analysis. First, monthly averaged values and yearly averaged values for the period 1990-1999 are shown in Figure 3-9 and Figure 3-10 respectively.

The univariate regression will show to what extent diatom biomass, rain, wind speed discharge and water level can be used to explain SSC. Rain, wind speed, discharge and water level are used to explain chlorophyll a values. SSC is not included because changes in SSC do not affect diatom biomass. Although according to Figure 3-1 discharge is not coupled to diatoms, it is added to make the analysis complete (no harm is done by doing so). In the univariate regression analyses one-on-one relationships are studied. SSC and chlorophyll a are considered to be the dependent variables, the other parameters are the independent variables (only when diatom biomass is used to explain SSC will chlorophyll a act as an independent variable). In this analysis the correlation of the parameters is taken into account also. Expressed as a formula, the univariate regression analysis can be represented as:

$$y = a + b \cdot x,$$

in which $y$ is the dependent variable (SSC or chlorophyll a) and $x$ is one of the other parameters. For the multiple regression analysis, more than one parameter will be considered for the explanation of SSC and diatom biomass values. While the univariate regression is represented by a one dimensional relationship, a multiple regression analysis has more dimensions, depending on the number of parameters that are included. Thus, the formula is as follows:

$$y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 + a_3 \cdot x_3 + \ldots + a_n \cdot x_n.$$

Regression will be applied on all possible combinations of parameters.
The comparison of summer and winter patterns will again be based on the univariate regression analysis. For the analysis a distinction will be made between summer and winter data. Here, the summer months are April to September, the winter months are October to March. Again the univariate regression technique will be used for this analysis, but this time the analysis is used to produce trend lines.

Finally, an analysis is made of the time series of the various parameters. In the previous analyses the periodicity in the signal has not been taken into account, only the values mattered. In this analysis a Fourier transformation will be performed. Frequency spectra will give some information on the contribution of different frequencies to the signals of the various parameters. Also, the least squares method will be used, which will provide more insight into the phase differences between the various parameters. For all parameters, this method uses the original data to create a signal which, in these cases, consists of a single sine wave.

**Univariate regression**

Table 3-2 summarises the analyses that were performed for SSC, Table 3-3 for chlorophyll $a$, in which:

- $r$ = correlation coefficient
- $R^2$ = explained variance
- $p$ = significance ($p < 0.05$: reliability > 95%)
- n.s. = not significant, the performed regression is not reliable (see also the p-value)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$r$</th>
<th>$R^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorophyll $a$</td>
<td>-0.491</td>
<td>0.241</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Rain</td>
<td>-0.041</td>
<td>n.s.</td>
<td>&gt; 0.05</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.435</td>
<td>0.189</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.443</td>
<td>0.196</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Water level</td>
<td>0.010</td>
<td>n.s.</td>
<td>&gt; 0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$r$</th>
<th>$R^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>0.034</td>
<td>n.s.</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>Wind speed</td>
<td>-0.407</td>
<td>0.166</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Discharge</td>
<td>-0.326</td>
<td>0.106</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Water level</td>
<td>-0.175</td>
<td>n.s.</td>
<td>&gt; 0.05</td>
</tr>
</tbody>
</table>

The correlation coefficients and regression analyses show the following output:

- SSC and chlorophyll $a$ are negatively correlated, SSC and wind speed and discharge are positively correlated. The correlation with rain and water level is weak compared to the other parameters. The regression analyses for rain and water level are not significant.
- Chlorophyll $a$ and wind speed and chlorophyll $a$ and discharge both are negatively correlated. Again regressions with rain and water level are not significant.
• The explained variance ($R^2$) of all the parameters is low, which indicates that none of these parameters play a dominant role in SSC or diatom biomass variations.

Multiple regression

Table 3-4 (Multiple regression for SSC) and Table 3-5 (Multiple regression for chlorophyll $a$) actually consist of more than one table. The number of parameters with which the multiple regression was performed is indicated above each table. For each different number of parameters the three combinations with the highest scores for $R^2$ are shown.

Two remarks will be made on how to 'read' the tables:

• The coefficients reflect the linear model, in which the coefficient of the intercept equals $a_0$, and a parameter equals $x_i$ with corresponding coefficient $a_i$.

• The p-values (between 0 and 1) express the significance of the null hypotheses, which are that all coefficients are zero. A high p-value (>0.95) indicates that there is no reason to believe that the hypothesis is incorrect, the coefficient that was found is likely to be zero. A low p-value (<0.05) indicates that it is likely that the hypothesis can be rejected.

Table 3-4: Multiple regression for SSC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$</th>
<th>Coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.325</td>
<td>-27.396</td>
<td>0.014</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>13.173</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>-1.139</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.309</td>
<td>-26.144</td>
<td>0.021</td>
</tr>
<tr>
<td>Wind speed</td>
<td>12.987</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-1.118</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.305</td>
<td>37.427</td>
<td>0.003</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-3.345</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>5.030</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>3 parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.394</td>
<td>9.829</td>
<td>0.469</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-2.983</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>9.907</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-0.992</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.372</td>
<td>59.970</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-3.518</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>0.128</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-0.621</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.341</td>
<td>-14.008</td>
<td>0.238</td>
</tr>
<tr>
<td>Wind speed</td>
<td>9.623</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>0.085</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-1.142</td>
<td>&lt;0.001</td>
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</tr>
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</table>

4 parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$</th>
<th>Coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.426</td>
<td>19.094</td>
<td>0.167</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-2.853</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>7.038</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>0.076</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-1.018</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.394</td>
<td>10.119</td>
<td>0.458</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-2.939</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rain</td>
<td>-0.019</td>
<td>0.758</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>9.966</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-0.953</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.372</td>
<td>60.565</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-3.474</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rain</td>
<td>-0.020</td>
<td>0.752</td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>0.129</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-0.578</td>
<td>0.023</td>
<td></td>
</tr>
</tbody>
</table>

5 parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$</th>
<th>Coefficients</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.427</td>
<td>19.672</td>
<td>0.157</td>
</tr>
<tr>
<td>Chlorophyll $a$</td>
<td>-2.783</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Rain</td>
<td>-0.030</td>
<td>0.624</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>7.091</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Discharge</td>
<td>0.077</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Water level</td>
<td>-0.958</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>
The following observations can be made for SSC:

- Some intercepts have negative coefficients, but a negative SSC value is not possible. This is inherent to the applied linear approach, which is used for the regression technique.
- In all regression analyses where rain is involved, the p-values of this parameter indicate that the coefficient is unlikely to be unequal to zero. Neither is it likely to assume that the coefficients are zero. This makes rain a very uncertain parameter for explaining SSC variations, which was also the outcome of the univariate regression.
- The highest score for $R^2$ does not exceed 0.50 which indicates that these parameters do not explain more than half the SSC variation.

Table 3-5: Multiple regression for chlorophyll $a$

2 parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$</th>
<th>Coefficients</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.210</td>
<td>11.187</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Rain</td>
<td></td>
<td>0.017</td>
<td>0.013</td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td>-1.020</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.179</td>
<td>-12.059</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td>-1.033</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Water level</td>
<td></td>
<td>0.042</td>
<td>0.182</td>
</tr>
</tbody>
</table>

3 parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$</th>
<th>Coefficients</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.216</td>
<td>10.644</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Rain</td>
<td></td>
<td>0.018</td>
<td>0.011</td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td>-0.875</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Discharge</td>
<td></td>
<td>-0.004</td>
<td>0.358</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.210</td>
<td>11.348</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Rain</td>
<td></td>
<td>0.016</td>
<td>0.036</td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td>-1.045</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Water level</td>
<td></td>
<td>0.007</td>
<td>0.843</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.183</td>
<td>11.603</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td>-0.906</td>
<td>0.001</td>
</tr>
<tr>
<td>Discharge</td>
<td></td>
<td>-0.003</td>
<td>0.430</td>
</tr>
<tr>
<td>Water level</td>
<td></td>
<td>0.043</td>
<td>0.174</td>
</tr>
</tbody>
</table>

4 parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R^2$</th>
<th>Coefficients</th>
<th>P-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.216</td>
<td>10.809</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Rain</td>
<td></td>
<td>0.017</td>
<td>0.032</td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td>-0.900</td>
<td>0.001</td>
</tr>
<tr>
<td>Discharge</td>
<td></td>
<td>-0.004</td>
<td>0.359</td>
</tr>
<tr>
<td>Water level</td>
<td></td>
<td>0.007</td>
<td>0.838</td>
</tr>
</tbody>
</table>
For the diatom biomass holds:

- All intercepts have p-values <0.001. Thus, the coefficients are very likely to be correct (unequal to zero) in all performed analyses.
- For all regression analyses involving discharge and water level, p-values indicate that these two parameters are very unreliable for explaining chlorophyll **a** values.
- P-values of rain are relatively high (but still <0.05) compared to wind speed. However, again relatively speaking, rain does a lot better in explaining chlorophyll **a** than in SSC.
- The highest score for $R^2$ does not exceed 0.25, suggesting that over 75% of the variation in the chlorophyll **a** data could not be explained by the parameters that were used.

Each of the above regression analyses leads to a unique model for explaining SSC or chlorophyll **a** values. Therefore, technically speaking these analyses cannot be compared. Another technique was used to compare these analyses objectively, which is the stepwise regression with backward elimination. This technique finds the optimum set of parameters, by starting with regression using all parameters. When a weak parameter is removed from the analysis, the loss of explained variance is weighed against the gain of a degree of freedom in the analysis. Parameters are removed until a criterion is being met. Thus the strongest combination of parameters, based on both explained variance and the degrees of freedom, remains. For explaining SSC values, the optimum set of parameters contains chlorophyll **a**, wind speed and water level. For explaining chlorophyll **a** values, only wind remains.

**Summer and winter differences**

Using the univariate regression technique, trend lines were used to visualise the different relationships of the various parameters that exist during summer and winter. Unfortunately, all summer and winter regression analyses appeared to be not significant, so the interpretation of the graphs could not result in a reliable conclusions.

**Time series**

The results of the Fourier analysis are shown in Figure 3-11. All parameters show a distinct peak in amplitude corresponding to the frequency of 1/year. SSC and chlorophyll **a** both show no great peaks other that at this one frequency, while water level, and rain, and to a lesser extend wind speed, also show larger peaks at higher frequencies. This indicates that for these parameters the seasonal behaviour dominates, but variations also take place with higher frequencies.

For the least squares analysis a signal was reproduced using only one frequency, that of 1/12 months. In this way all parameters are sine shaped, but with different amplitudes and phases. The seasonal variations are shown in Figure 3-12. In particular the phase differences are of interest:

- SSC, wind speed and discharge are exactly in phase.
- SSC, wind speed and discharge are in counter-phase (180°) with chlorophyll **a**.
- Rain and water level are 90° out of phase with SSC, discharge and wind.
The effect of the phase differences on the linear regression technique can be seen in the scatter plots in Figure 3-13. Two parameters which are out of phase form a circle-like shape. This can be compared with the plot of a sine as a function of a cosine with the same amplitude. Such a plot forms a perfect circle. Two sine functions which are either in phase or in counter-phase from a straight line. The more circle-like shapes and the flat ovals say something about the scatter in the data. Regression using the data which form the flat ovals will give high values of explained variance, since the points are more or less on a straight line. Circle-like shape will give low values of explained variance, because of the scatter of the data. In Figure 3-13 especially the effect of the phase difference of water level becomes visible. In relation to SSC the measurements almost form a perfect circle.

3.4.4 Long term spatial variations

The analysis of spatial variations focuses on SSC and chlorophyll a. Two issues will be treated. SSC at three locations, viz. Vlissingen, Hansweert and Schaar van Ouden Doel, which are situated in the western part, central part and eastern part respectively, will be compared with each other and compared with discharge. Next the spatial variation of chlorophyll a will be analysed.

**SSC variations at three locations and relationship with discharge**

The original data on SSC (at three locations) and discharge are shown in Figure 3-14. Vlissingen is located in the Western part of the Western Scheldt (at the seaward boundary), Hansweert is located in the central region and Schaar van Ouden Doel in the Eastern part. Discharges are available for Schaar van Ouden Doel as well.

The following observations can be made:
- SSC values at Hansweert do not have the same high peak values during the winter as Vlissingen and Schaar van Ouden Doel.
- The peak values of discharge in the winters of 1994 and 1995 are not reflected in the SSC values of Schaar van Ouden Doel. At this location, some SSC peaks during other winter periods are even higher, while at those times discharge is lower.

Univariate regression analyses were performed, where discharge was used as the independent variable and SSC at the three locations as the dependent ones. All analyses were significant with the highest $R^2$ (0.255) for Vlissingen and lowest value for Hansweert (0.051). The $R^2$ for Schaar van Ouden Doel was lower than for Vlissingen (i.e. 0.118).

Figure 3-15 shows the averages per month of all data. While discharge shows considerable increase from October to April, all three SSC signals do not. In fact SSC at Schaar van Ouden Doel shows a decrease in December and January.

**Spatial differences in chlorophyll a**

Spatial variations of chlorophyll a are presented in Figure 3-16. A distinction is made between flats that are situated in the western part of the Western Scheldt and the eastern
part (west and east from Hansweert respectively). Also a difference is made between flats that are located on the north shore, the south shore and flats that are in the centre, surrounded on both sides by channels.

- The north and south shores in the western part and the north shore in the eastern part have a much more distinct seasonal variation than the central flats and the flats on the south shore in the east.
- Except during the peak period (May) the flats on the south side in the western part have the highest values. Chlorophyll $a$ variations are much larger on the north shore than on the south shore.
4 Discussion

In this chapter, the results of the data analysis will be discussed first. Here, the same subdivision is applied as in the presentation of the results. Next, some remarks will be places by the data analysis itself. Finally, some feedback will be provided to the model concept.

4.1 Results

4.1.1 Short term data

In the short term data analysis the SSC data were not used to analyse events. There are two main reasons why this decision was made. First, a lot of measurements were inaccurate due to failure or malfunction of the equipment. This concerned all data at the NAP-11 m signal and the data at the NAP-4 m and NAP-17 m level of the summer of 1999 (June till September). That is why these data were left out of Figure 3-3. Secondly and most important, the tidal influence dominates the SSC signal. Therefor these data can not be coupled directly to wind. Several attempts were made to filter out the tidal and neap/spring variation, the most important were through the use of moving averages and Fourier transformation. With the aid of moving averages the tidal variation could be removed without too much loss of information. Removing the neap/spring variation meant averaging over a period of two weeks. In this way, too much information was lost for an event analysis to be successful. The Fourier transformation produced a signal without tidal or neap-spring influences, but, due to the nature of the technique, spurious waves were generated within the SSC signal, which made it unsuitable for the analysis of events.

Water level variations show different behaviour during winter and summer. In the winter differences between measured and predicted water levels are high, in the summer they are low. It appears that wind direction rather than wind speed plays an important role. At 0-200 degrees the measured values are lower than the predicted ones, set-up of the water level occurs at 200-360 degrees. These effects can be coupled to water level variations of the North Sea, as was indicated in 2.2.3. It proves that water level variations at the North Sea dominate the water level variations in the Western Scheldt. Figure 3-2 showed deviations from the predicted water level can amount to a meter or more.

4.1.2 Long term bed level and chlorophyll a

Figure 3-5 shows an increase of chlorophyll a levels with bed level. This indicates the role of inundation and turbidity. At higher locations inundation times are shorter and more light is available which increases the possibilities for diatom growth. If measurements at even higher locations would have been present, chlorophyll a values would probably have decreased again with increasing bed level due to the limitation and desiccation of nutrients and dehydration of the bed.
Upon studying bed level changes, no clear seasonal trend can be detected in the bed level measurements. Therefore, the cumulative effect of accretion in spring and erosion in fall at all the flats can not be studied, because it is not reflected in the measurements. Probably, the measured variations reflect morphological changes (sand) rather than deposition and erosion of fine grained particles. All figures show the influence of bed level dynamics on diatom biomass. For both the short term (within one year) and the long term (10 years) variations, dynamic locations have low values of diatom biomass. This indicates that bed level dynamics has a large effect on diatoms. At locations which are less dynamic, more diatoms are present. The highest amounts of diatoms are found at the least dynamic locations. Locations which show little bed level variations contain both high values and low values of chlorophyll a. This shows that, in the absence of bed level dynamics, other factors control diatom biomass.

Do the bed level measurements indicate that no seasonal trend is present in the Western Scheldt, or does it mean that this type of measurement is just not appropriate for the variations under consideration? When talking about fine grained sediment, accretion and erosion will be much less (in the order of millimetres) than the bed level variation which can be seen in Figure 3-6. The measurements show variations that are in the order 10-1000 times greater. The seasonal trend could still exist, only at another scale which is not reflected in these measurements. If indeed the large scale accretion and erosion of sand dominate the measurements, this raises the question if trapping of fine grained sediment occurs when accretion takes place (and the release of fine grained sediment during erosion). This would provide a whole new dimension to the discussion of the flats as sources and sinks for fine grained sediment. Indeed Salden (1998) indicates that in the Western Scheldt a lot of fine grained sediment is stored in the bottom layer.

4.1.3 Long term temporal variation

Based on the correlation coefficients and the univariate, the multiple and the stepwise regression, it can be concluded that rain is not an important parameter for explaining either SSC or diatom biomass variations. The same holds for water level, although this parameters did occur in the stepwise regression for SSC. Although based on artificial signals, the phase differences found in the least squares method may indicate why these relationships are weak. Figure 3-13 shows, in particular for water level, that a phase difference of 90° with SSC and chlorophyll a causes a lot of scatter in the plots, which will result in low correlation coefficients and weak regressions.

Water level is a somewhat complicated parameter in the long term analysis. For the seasonal variation, the interest lies in short term variations of the water level. It was shown in the short term analysis that wind, especially wind direction, plays an important role in these variations. However, the parameter used in this long term analysis is the actual water level at a ten minute interval, averaged over one month. Thus a lot of high frequency information is averaged out. This is also reflected through the Fourier analysis, which showed that, based on these monthly averaged values, water level still has higher frequency amplitudes.
Chlorophyll $a$ appears in almost all regression analyses on SSC. The correlation coefficient and the univariate regression even indicate that of the parameters under consideration, chlorophyll $a$ has the closest match to SSC. However, the correlation coefficient and the explained variance of the various analyses are low. Also wind is an important parameter, for explaining both SSC and diatom biomass variations, even though it is not directly coupled to either SSC or diatoms (according to Figure 2-4).

The parameters in the long term analysis explain only part of the variation ($R^2$) of SSC and chlorophyll $a$. Possible explanations are:

- Other factors. Data on some of the parameters that were identified in chapter 2 was not available.
- Spatial variations. Wind and rain are measured at one single station which was thought to be representative for the entire Western Scheldt. SSC and chlorophyll $a$ are measured throughout the entire estuary and values were averaged. This was done to be able to perform an analysis based on temporal information only.
- Different characteristics of the parameters. Some parameters are represented by a value that reflects a whole month (average wind speed per month, rainfall per month), while on other parameters monthly data are available based on a single sample per month (SSC and chlorophyll $a$).
- Indirect influences. None of the parameters has a direct influence on SSC, only rain and water level are directly coupled to diatoms.

### 4.1.4 Long term spatial variations

In using discharge as independent parameter, the explained variance of SSC at Vlissingen is higher than at Schaar van Ouden Doel. The opposite would be expected, because the variation at Vlissingen can be expected to be related more to sea, while discharge has a greater influence in the eastern part of the Western Scheldt as far as the supply of fresh water, the mixing with salt water and the shift of the mixing zone is concerned. For the supply of sediment this reasoning does not hold. It could be that the relation between discharge and the supply of sediment is not linear for all discharges. This would occur especially during extreme high discharges. A second explanation could be that the SSC variations at Schaar van Ouden Doel are influenced by the shifting of the mixing zone.

For the chlorophyll $a$ variations that were found in Figure 3-15 wind speed could explain the difference in pattern between North and South shores in the western part. With the main wind direction being Southwest, the north shores are more subject to wind waves in the winter months than the south shores. The south shores are on the lee side. The peak in May of the North shore, that exceeds the one on the south, might be explained by the fact that the north shore is facing southward, thus profiting more from sunshine. This could be a combined effect with decreasing wave attack in spring. The difference between the north and south flats and the central flat in the western part is striking.

### 4.1.5 Summary

The data analysis was used to investigate the contribution of the various parameters to SSC and diatom biomass variations. It shows that wind is an important parameter, even though
wind effects were only studied indirectly (due to the lack of information on for example waves). Both wind speed and wind direction influence various other parameters (waves, water level, hydrodynamic conditions in general), which have an effect on SSC and diatom biomass variations. This was shown in the short term as well as in the long term analyses.

On a seasonal scale the performed analysis shows that rain does not play an important role in SSC and diatom biomass variations. Possible effects may occur on a smaller time scale, without having an influence on the seasonal variations under consideration.

Stepwise regression indicates that chlorophyll $a$, wind and water level are the most important parameters for explaining SSC variations. For chlorophyll $a$ only wind remains. The analysis of bed level and chlorophyll $a$ indicates that bed level dynamics is another important parameter for explaining diatom biomass. Highly dynamic locations have a low diatom biomass. Besides that, bed level shows different behaviour at different location and the measurements do not reflect a seasonal behaviour of accretion and erosion of fine grained particles.

The performed regression analyses explain only part of the SSC and diatom biomass variations. This indicates that also the parameters on which no information was selected play a role. Also the fact that the analyses were performed on the scale of the entire estuary might contribute. Some indications for this assumption were provided in the analysis of spatial variations of SSC, discharge and chlorophyll $a$.

### 4.2 Data analysis

Some aspects concerning the choices that were made in the data analysis will be discussed. First, something needs to be said about the averaging of the spatial information that was available on SSC and chlorophyll $a$. Chlorophyll $a$ measurements have a much higher degree of spatial detail than the long term SSC measurements. So in this study the SSC data prevented the studying of temporal variations on a smaller spatial scale. This was one of the reasons to average all spatial information out. Another reason, indicated in 3.3, was that the assumption was made that all flats have to participate in the deposition and erosion of fine grained sediment in order to have an effect on SSC variations. Averaging out all spatial information made a temporal analysis possible at the cost of the loss of spatial information on chlorophyll $a$.

The above illustrates that data on different parameters could not easily be combined spatially and temporally, because measuring location, measuring frequency and the moment in time of measurement differ. Thus, with these data it is very hard to obtain a higher degree of detail. However, for some parameters more detail in both the spatial and temporal scale could be provided through the use of computer models. Combination of this type of data with the in situ data could prove to be valuable. However, that approach was not followed in this study. It was also not possible to generate new data specifically for this research, because of the lack of time and money.

Also the analysis technique that was used needs to be mentioned. The regression analysis is a linear technique (see 3.4.3) and its limitations are met when non-linear effects play a role.
The parameters used in the analysis were all considered to have linear relationships with SSC and diatom biomass. However, for wind speed even another aspect needs to be considered, which was already indicated in 3.3. The data on wind speed are monthly averaged values. The implication is that wind speeds during a storm event are averaged out. Thus a single storm cannot be found in the wind speed data, while it may have an effect on the process of resuspension of diatoms and fine grained sediment.

4.3 Feedback to the model concept

In chapter 2 a model concept was proposed in which the relevant parameters and processes influencing seasonal variations of SSC and diatom biomass were reflected. On selecting data only information on a limited set of parameters was available. The criteria for selecting data played a role in this limitation. Information was lacking on hydrodynamic conditions, sediment exchange with sea and biological activity. Comparing Figure 2-4 and Figure 3-1 shows that some concessions were made in the data analysis to be able to study relationships between the parameters.

Actual quantification of relationships did not take place, due to the character of the data and the techniques that were used. However, the analyses did provide some useful information. Upon analysing the data it showed that rain does not contribute to seasonal variations. The effect of a rain shower probably has a more short term effect. Wind is an important parameter for SSC and diatom biomass, although according to the original model concept it only has an indirect influence through waves and water level variations.

In the model concept three types of temporal behaviour of the parameters are present. These are slowly varying parameters like temperature, parameters which can show large variations in a short time (wind and rain) and parameters with a periodic variation (tidal movement). The analyses that were performed focused on the first two types of parameters, which were indicated by trend analysis and event analysis respectively. Of these two the trend analysis provided the most information. Using different approaches, the other temporal scales could be studied in more detail.
5 Conclusions and recommendations

5.1 Conclusions

The goals of this study consisted of two parts. The first was to determine the relationship between seasonal variations of SSC and diatom biomass in the Western Scheldt as well as the influence of other parameters on these variations in a qualitative manner. The second was to perform data acquisition on the parameters that were identified and to analyse these data in order to quantify the identified relationships. The first goal resulted in a literature study, which was necessary to provide a theoretical background. Data analysis was performed after the identification of relevant parameters had taken place.

The literature survey showed that SSC variations do not affect diatom biomass in the Western Scheldt. Turbidity, caused by both SSC and organic matter, is too high throughout the year for diatoms to be active during inundation of the flats. Diatom, which are in fact algae, depend on the availability of light for their growth. The role of diatoms on SSC variations is an indirect one. Diatoms do not influence deposition of sediment, but they do play a role in stabilising fresh deposits. When this occurs on a large scale during a period of time, then suspended particles are constantly removed from the water column.

A relation scheme was proposed in which all identified parameters and their relationships were summarised. Among the parameters that play a role in the seasonal variation of SSC and diatom biomass are wind, rain, discharge and biological activity. The interaction between SSC and diatoms takes place at the flats.

Data was selected and analysed. The different character of the data sets made quantification of identified relationships difficult, but some information was provided by the analysis. The main part of the analysis consisted of long term temporal analyses using regression techniques. Rain proved to be relatively unimportant, while the indication is that wind speed is a strong parameter for explaining SSC and diatom biomass variations. However, data on several identified parameters was missing.

In the performed temporal analysis spatial variations were averaged out and a very coarse approach was applied. Some spatial variations were indicated, but not extensively analysed. A different analysis approach could combine both the temporal and the spatial scale. The use of other data, both in situ and data from computer models, can provide useful information. Also more data should be collected on SSC and diatom biomass variations.
5.2 Recommendations

- Current velocities were available only during one season. It would be interesting to monitor this parameter throughout the year, since current velocity is coupled directly to SSC. Furthermore, it will probably reflect wind induced changes in hydrodynamic conditions. Hydrodynamic computer modelling could also provide information on this parameter.

- Not much information with a high measuring frequency was available. These type of measurements are often times consuming and expensive. Nonetheless, analysing events might reveal some more interesting relationships, especially for the parameters wind and rain.

- A sediment balance at a seasonal scale should be developed. Sediment exchange between the Western Scheldt and the North Sea should be included in this balance on a seasonal scale.

- The bed level measurements that were used do not reflect the deposition and erosion of fine grained sediment. In the literature some indication was found that deposition occurs during the summer at the flats in the Western Schelt followed by erosion in the winter. This should be thoroughly investigated.

- It is hard to separate time and spatial scales. This study focused mainly on temporal variations. A study into the spatial variations of the identified factors and processes, or a combination of both spatial and temporal scale could provide some valuable insights.

- The proposed model concept can be used in the future as the basis for further research.
References


A Results of data analysis
Figure 3-2: Measured and predicted water level at Terneuzen over a two year period. Averages were calculated for subsequent periods of two tidal cycles (24 hours and 50 minutes) using data with a 10 minute interval.
Figure 3-3: Suspended sediment concentration at two depths (NAP-4 m and NAP-17 m) at Terneuzen over a two year period. Averages were calculates for subsequent periods of two tidal cycles (24 hours and 50 minutes) using data with a 10 minute interval.
Figure 3-4: Wind speed and water level (measured-predicted values) as a function of wind direction. Averages per degree of wind direction were calculated using data with a 10 minute interval over a period of two years.
Figure 3-5: Average chlorophyll $a$ and number of observations per 100 mm bed level.
Figure 3-6: Temporal variation (10 years) of bed level and chlorophyll \(a\) values at four measuring locations. Different types of bed level variation can be distinguished: accretion (a), erosion (b), stable (c) and unstable (d).
Figure 3-7: Average annual chlorophyll $a$ values as a function of maximum annual bed level variation for all individual measuring point using 10 years of data. One measurement falls outside the figure (bed level variation ca. 3500 mm).

Figure 3-8: Average chlorophyll $a$ values over a 10 year period as a function of maximum bed level variation within that same period.
Figure 3-9: Monthly averaged values for 6 parameters. Data was used over a 10 year period.
Figure 3-10: Yearly averaged values for 6 parameters for the period 1990-1999
Figure 3-11: Frequency spectra for 6 parameters. $A^2$ is the square of the amplitude at the given frequency.
Figure 3-12: Time series for 6 parameters, which were smoothed by the least-squares analysis technique. These series were reproduced from the original data using a single sine function with a frequency of 1/12 months.
Figure 3-13: Data from the least-squares analysis of the 6 parameters as a function of SSC and chlorophyll $a$. Each oval is a scatter plot of one of the parameters consisting of 12 points, which are connected with a line.
Figure 3-14: Temporal variation over a ten year period (1990-1999) of SSC at Vlissingen, Hansweert and Schaar van Ouden Doel and discharge at Schaar van Ouden Doel.
Figure 3-15: Monthly averaged values over a ten year period (1990-1999) of SSC at Vlissingen, Hansweert and Schaar van Ouden Doel and discharge at Schaar van Ouden Doel.

Figure 3-16: Monthly averaged chlorophyll a levels for different flats. A subdivision is made between flats in the eastern part and the western part of the Western Scheldt and also a distinction is made between flats on the northern shore, the southern shore and flats that are surrounded by channels (indicated as ‘CENTRE’).