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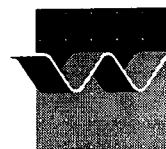
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## Eindrapport

# Quantification of Biogeomorphological Variables for Dutch Tidal Systems

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TITLE: Quantification of Biogeomorphological Variables for Dutch Tidal Systems

**ABSTRACT:**

The implementation of the effects of the most relevant biological components into the morphodynamic modelling package Delft3D is one of the goals of the projects "Salt marsh cycles" (Z2827), and "Quantification Biomorphological Variables Westerschelde" (Z2837). This report deals with the quantification of the impact of biota on the morphodynamics, work carried out in the framework of both projects.

The assessment of the state-of-the-art on the quantifications of bio-geomorphological interactions in estuarine systems and the definition of the follow-up studies form the body of the work carried out in the year 2001. This report is an account of this work, which forms the basis of the coming activities, and gives an outlook on the activities planned for the next years.

Incorporating biota in a morphodynamic model requires input from both biologists and morphologists. An important aspect of this report is therefore the exchange of knowledge between the two disciplines of biology and morphology. For this reason the report also gives an overview of the biological components of the Dutch estuarine systems and describes some aspects of morphodynamic modelling, with a short introduction to the Delft3D modelling package. The report ends with the description of how the Delft3D model can be improved by implementing the effects of biology.

**REFERENCES:** The report describe the outcome of the two projects: 'Quantification of Biogeomorphological Variables Westerschelde' (Z2837), that is a part of the Doelsubsidie' framework, and 'Salt Marsh Cycles' (Z2827), that is a part of the 'Delft Cluster' framework.

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# I Introduction

In recent years biological components have been recognised as potentially important factors for the morphodynamic behaviour of estuarine systems. Studies like INTRMUD, ECOFLAT (European Commission) and EMPHASYS (MAFF project, HR Wallingford, U.K.) point to that direction. However, for a large extent the magnitude of the effects of biota on the physical environment and the associated spatial and temporal scales are not yet known. One way to quantitatively assess them is to model them. Based on the available data on field observations and on literature, the present study aims at incorporating the effects of biota in an existing morphodynamic model, the Delft3D package, and at studying them with this newly-created tool. This report is an account of the first stage in a process to do that.

The implementation of the effects of the most relevant biological components into the morphodynamic modelling package Delft3D is actually one of the goals of two distinct research projects: 'Salt marsh cycles' (Z2827) and 'Quantification of Biomorphological Variables Westerschelde' (Q.B.V. Westerschelde - Z2837). The first project is carried out within the framework of the Delft Cluster research, while the second is part of the 'doelfinancierings- programme' of WL | Delft Hydraulics and RWS. Both projects deal with the quantification of the effects of biota on the functioning of estuaries and tidal basins. The Delft Cluster project, 'Salt marsh cycles', aims at understanding and quantifying the ecological and morphological conditions favouring formation and degradation of salt marshes and at assessing the role of salt marshes in the development of an estuary as a whole. The role of biota is also studied and quantified in the project 'Quantification Biogeomorphological Variables Westerschelde', but with focus on macrozoobenthos and microphytobenthos and on the Western Scheldt estuary. The two projects can therefore be considered complementary to each other and for this reason they have been joined together into a single study, entitled: 'Quantification of Biogeomorphological Variables for the Dutch Tidal Systems'.

The approach of the whole study was discussed during the Workshop held in Delft on August 27<sup>th</sup> 2001 and during the meeting held in Yerseke on December 7<sup>th</sup>.

The final choice was that of adopting a 'bottom-up approach'. The study will first consider the effects of salt marshes on the estuarine morphodynamics and later also the effects of macrozoobenthos and microphytobenthos. The quantitative assessments will start with the study of the salt marsh functioning at the 'micro-scale' and will later be extended to the larger spatial scales. The largest spatial scale considered in the study will be the 'whole cross-section'. Studying the salt marsh functioning at the micro-scale involves the modelling of the morphodynamic processes that occur among salt marsh vegetation. A typical micro-scale model grid is of the order of meters with a single computational grid cell of approximately 10 centimetres. The next step will be that of scaling-up effects and processes for studies on larger scales, for which a single grid cell may have the size of the whole micro-scale model. The largest-scale studies will also account for the effects of microphytobenthos and macrozoobenthos.

Incorporating biota in a morphodynamic model requires input from both biologists and morphologists. An important aspect is here therefore the exchange of knowledge between the two disciplines of biology and morphology. This report provides thus also a brief introduction into each other's expertise. In Chapter 2 an overview is given of the biological components of the Dutch estuarine systems, while in Chapter 3 some aspects of morphodynamic modelling are presented. Here also a short introduction to the Delft3D modelling package is given, of which a more comprehensive description can be found in Appendix D.

An overview of the state-of-the-art in the quantification of bio-geomorphologic interactions is given in Chapter 4. This chapter presents also the results of a specific literature study and of the 'in-house' experience of WL | Delft Hydraulics. The literature study focused on the quantification of the biological impact on the morphodynamic processes of estuaries, considering all the typical biological components of the Dutch intertidal areas, from salt marsh vegetation to macrozoobenthos. Papers and reports were selected on the basis of their usefulness for the quantification of the impact. General descriptions of the biological components and qualitative analyses were thus disregarded, unless of particular relevance for other aspects of the study, such as the model schematisation. The literature was collected through the help of experts in the different fields, within and outside WL | Delft Hydraulics. A selection of the most relevant papers can be found in Appendix C, where they are shortly described using a standard format.

Chapter 5 deals with the modelling of the impacts of biota on the local morphodynamics and consists of two parts. The first part introduces the algorithms necessary for the implementation of the effects of biota on the local hydrodynamics in the model Delft3D, with emphasis on salt marsh vegetation. The second part deals with the model set-up and includes some aspects of the study scales.

Appendix A contains an account of the general meetings that have taken place.

### ***Project team***

The project team consists of Alessandra Crosato, Mindert de Vries, Zheng Bing Wang and Ilka Tánczos.

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## **2 Biological components of Dutch tidal systems**

### **2.1 Introduction**

This chapter deals with the biological components of Dutch intertidal systems that most clearly interact with their physical environment. It focuses on partially and totally submerged vegetation, zoobenthos and algae on intertidal flats. Section (2.2) gives a short general description of the system, while the occurring flora and fauna are described in the following sections of this chapter (Sections 2.3 and 2.4).

### **2.2 Intertidal flats**

An intertidal flat is defined as an area of muddy to sandy sediment regularly flooded by the tide, which lies between the low- and high-water-spring tidal levels. Intertidal flats are dynamic shoreline formations which can shift in position, alter in shape, increase or decrease in height over time. Their shape is determined primarily by the supply of sediment and the capacity of the currents and waves to transport sediment, but can be modified substantially by wave action and by the presence of algae and macrophytes which tends to reduce scour and stabilise the sediment. The sediment composition is primarily influenced by the local hydrodynamics.

In exposed areas, sediment is coarser and features such as ripples and megaripples can be formed. In sheltered areas, by contrast, the sediment consists of fine material, fine sand, silt or clay, generally termed as 'mud'. Mud can be defined as a wet fine sediment mixture, having cohesive properties, that consists of clay, silt, sand and organic material, the content of clay being no less than 15%. Where the soil is muddy almost no ripples are found.

In the Western Scheldt intertidal flats include shoals (platen), which are surrounded by permanent (non-tidal) channels, and mudflats (slikken), which lie close to the estuarine banks. They have different sediment characteristics, mainly due to their different exposition to currents and sediment supply.

Examples of mudflats are shown in Figures 2.1 and 2.2.



Figure 2.1. Mudflat near Wieringen (Wadden Sea).



Figure 2.2. Mudflat near Waarde (Westerschelde).

Mudflats are often backed by *salt marshes*. The salt marsh is a vegetated area typically formed by salt-resistant plants in a characteristic zoning, strongly dependent on inundation



frequency (see Figure 2.3). In The Netherlands salt marshes are mostly backed by dikes or dunes.

The shoals often present pioneer vegetation on their highest parts.



Figure 2.3. Salt marsh bordered by mudflat near Hellegat (Westerschelde)

Biologists commonly distinguish an *Upper*, *Middle* and *Lower* zone on an intertidal flat, as depicted in Figure 2.4.

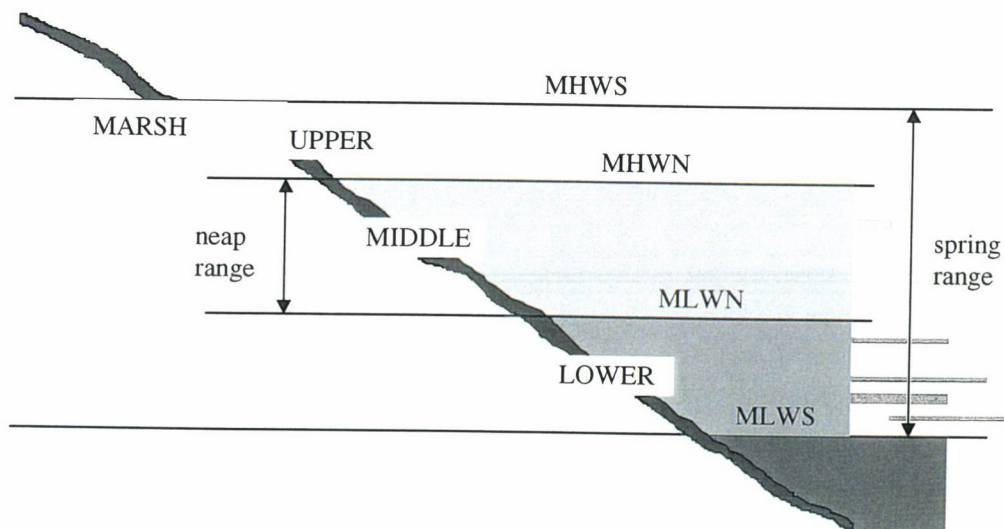


Figure 2.4. Subdivision of an intertidal flat.

The *Upper Zone* is the least inundated part of the intertidal flat, lying between the mean high-water-neap and the mean high-water-spring tidal levels. Thus, it is inundated only near high water. It is here that salt marshes can be found (Figure 2.5).

The *Middle Zone* of the intertidal flat is located between the mean low-water-neap and the mean high-water-neap tidal levels. This is the typical elevation of low-dynamic part of the intertidal flat and presents a muddy bottom. It is largely unvegetated, with extreme environmental conditions for all organisms to deal with: it is inundated during each tide and at low tide it is exposed to solar irradiation, rain, high and extremely low temperatures (in the winter) and wind. Therefore most of the mudflat inhabitants (macrozoobenthos) are found underneath its surface (infauna). In the Western Scheldt the total biomass of all organisms living within and on a mudflat can reach a few hundreds grams (wet weight) per  $m^2$ .

The *Lower Zone* is the part of the intertidal flat lying between the mean low-water-neap and the mean low-water-spring tidal levels. This region is exposed near low water and its lower range is only exposed during low water spring, occurring approximately once every two weeks. This is the highest-dynamic zone of intertidal flats and typically has a sandy bottom.

To correctly estimate the duration of inundation/exposure of each point on a intertidal flat, it is necessary to know the shape of the tidal curve in that area for a whole tidal cycle that includes neap and spring tides.

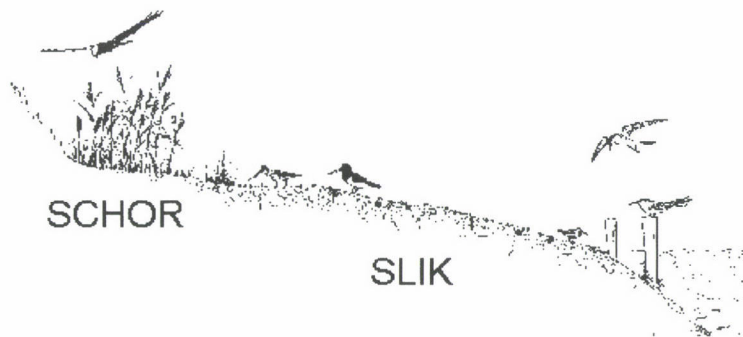


Figure 2.5. Impression of a salt marsh ('schor') and adjacent mudflat ('slik'). Source: Schorrenwerkgroep - Natuurpunt Antwerpen-Noord vzw ([http://www.scheldeschorren.yucom.be/nederlands/sitemap\\_nl.html](http://www.scheldeschorren.yucom.be/nederlands/sitemap_nl.html))

## 2.3 Vegetation

### 2.3.1 Salt marsh vegetation

Salt marshes prosper in relatively sheltered coastal areas, with enough sediment available to stimulate accretion. Macrophytes begin to appear at the highest bottom levels, with inundation times (percentage of time during which an area is flooded) lower than approximately 10%. The presence of vegetation generally results in an enhanced sediment trapping and enhanced accretion rates.

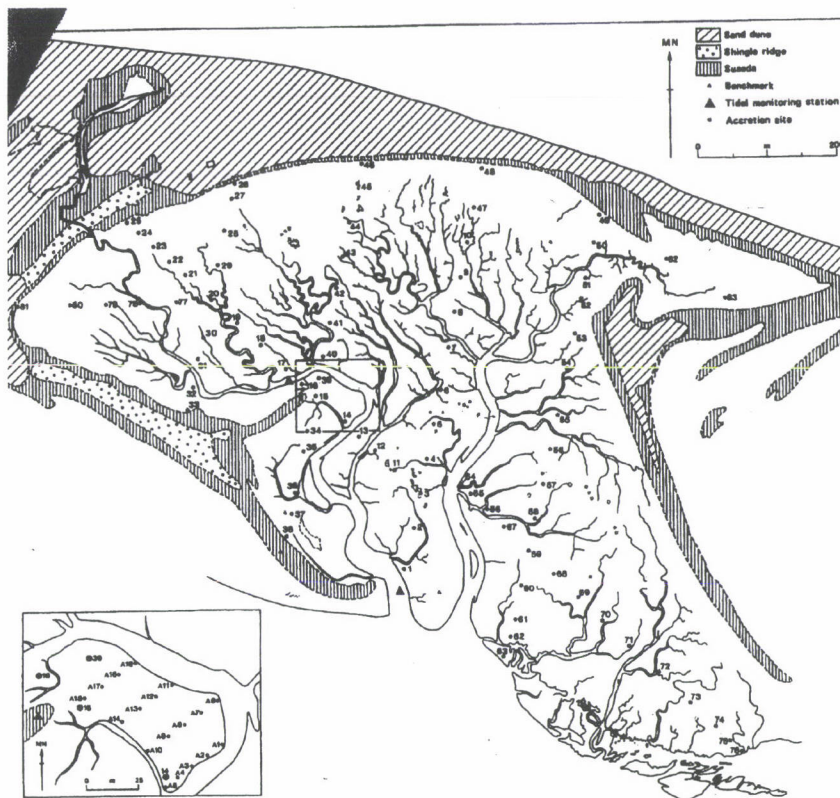


Figure 2.6. An upper view of the channel pattern of a salt marsh (From Stoddart et al. 1989).

Looking at a salt marsh from above reveals the characteristic branched pattern of channels, as can be seen in Figure 2.6. Up to three or four orders of channels can be distinguished depending on the size of the salt marsh. The main channels have a width of the order of meters while the smallest channels, or *gullies*, are only 10 to 30 centimetres wide. Because of their drainage function the channels are an essential part of the salt marsh.

The vegetation distribution is patchy at the edges of the salt marsh to get more dense and uniform closer to land. However, open spaces covered with a thin layer of water are found there as well. The sediment is deposited along the channels forming a somewhat elevated edge. In the summer a thick mud layer is building up on the unvegetated parts of the salt marsh. This sediment is transported on to the rest of the marsh when the water levels rise after summer. Along the channels cliffs may be observed.

In Figure 2.7 the location of salt marshes in The Netherlands are indicated.

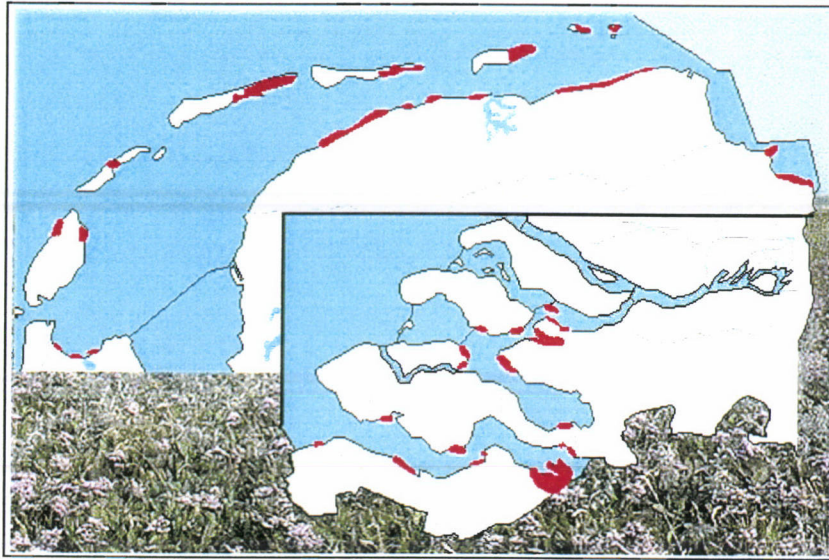


Figure 2.7. Distribution of salt marshes in the Netherlands (source: [www.waddenzee.nl](http://www.waddenzee.nl))

Salt marsh vegetation is clearly zoned. This zoning is determined by salinity levels and by the dryness and oxygenation of the roots and thus by inundation frequency and duration. The vegetation in the lower salt marsh (pioneer zone) can have a patchy distribution, here one can find circle-shaped clusters of *Spartina*, separated by bare flat. If the density inside the clusters is high, the water flows around and over the clusters rather than through them. The density of the clusters (distance between them) affects the local hydrodynamics.

Typical species found in the pioneer zone of a Dutch salt marshes are *Salicornia* and *Spartina anglica*. A little higher appears the sea meadow grass (*Puccinellia/kweldergras*). Still higher species such as *Limonium*, *Aster* and *Artemisia* become typical. The highest zone is the home of the least salt resistant species such as *Elymus* and reed species.

Typically, density and length of the plants increase with the soil elevation. For instance *Salicornia* is distributed sparsely and will not exceed a length of 30 centimetres (Figure 2.8). *Aster* (see Figure 2.9D) can grow to above 1 meter of height and produces a stiff stem with many branches and leaves. Middle and upper zones can be densely vegetated with thousands of stems per square meter (see for instance figure 2.9C). The vegetation of the marsh will change during the year. This means that height and density will increase during the spring and summer. During the winter season much of the vegetation will die and will be washed away.



Figure 2.8.  
*Salicornia sp.*, Glasswort/Zeekraal  
(source: [www.waddenzee.nl](http://www.waddenzee.nl))



A



B



C



D

Figure 2.9. Brackish water marshes in the Western Scheldt. A, B and C Hellegatpolder schor, and D Sieperdaschor, with Sea Aster in the foreground (source RIKZ-RWS 2001)

A large part of the salt marshes in the Western Scheldt estuary started their development in the 1930s, when the new species *Spartina* was introduced, and are now in the same stage. Besides the salt marshes located in At present many salt marshes are eroding and are fronted by a cliff (up to a height of 2 m.). The pioneer zone is almost absent.

Table 2.1 gives the development of the total salt marshes surfaces in the period 1935-1989 (Vroon *et al.*, 1997).

Table 2.1 Development of salt marshes (ha) in the eastern part of the Westerschelde from 1935 to 1989 (after Vroon *et al.*, 1997)

Year	1935	1957	1965	1977	1989
Young marsh	450	650	35	60	10
Adult marsh	2135	2247	3035	2210	2375
Total	2585	2897	3070	2270	2385

Survey of the salt marshes is a part of the Rijkswaterstaats' MWTL program. This survey has the following goals (Koppejan, 2000):

- gain insight in the nature and quality of the vegetation at the salt marshes
- provide information on the changes in salt marsh area

The marshes that are being monitored are listed in Table 2.2.

Table 2.2 Salt marshes in the Westerschelde (from Koppejan, 2000)

Name	vegetated area 1998 (ha)	vegetated area 1995 (ha)	vegetated area 1993 (ha)	vegetated area 1990 (ha)
Sloehaven	31.5		29.9	
Kaloot	7.8		14.9	
Zuidgors	50.2		54.7	
Schor bij Baarland	9.5		9.7	
Biezelingse Ham	4.6		5.2	
Schor bij Waarde	90.4		93.5	
Schor bij Bath	44.0		49.3	
Appelzak	14.0		13.4	
Hooge Platen	21.4		1.5	
Hooge Springer	66.1			
Hoofdplaat	8.5		7.5	
Paulinapolder	48.6		36.6	
Hellegatpolder	21.4		22.4	
Knuitershoek	6.8			
Baalhoek	2.1		2.9	
Platen van Valkenisse	13.7		9.9	
Saeftinghe	2078.4			2039.8
Sieperdaschor	105.9	92.1		

### 2.3.2 Microphytobenthos and cyanobacteria

On the surface of an intertidal flat, high biomasses of benthic primary producers, microphytobenthos, can be found. Unicellular diatoms (Figures 2.10 and 2.11) and cyanobacteria are the most important species groups. Benthic diatoms can be divided into two groups, based on the mechanism used for moving through the sediment. The first group, the epipsamic species, consists of diatoms which attach themselves to a sediment particle. They are dependent on sediment reworking and can not actively influence their position within the bed. The other group, the epipellic species, are able to move through the sediment by themselves. To do so they secrete extracellular polymeric substances (EPS), which are polysaccharides. This allows them to 'climb' on top of the sediment, where light availability is abundant during low tides. EPS works as a glue, sticking sediment particles together. In this way these algae and bacteria may form a thin film (Figure 2.12) on the surface that increases the stability of the sediment. During storm-periods, parts of this film can be eroded away. In that case the bare surface may be colonised by the algae that have survived by digging centimetres or even decimetres deep into the sediment.

Bivalves and worms living in the intertidal utilise this biomass for feeding. If the grazing pressure of worms and bivalves is high, the existing biomass of these primary producers can be reduced whilst the productivity is maintained at a high level. Worms and bivalves themselves are eaten by fish and birds. Given the estimation that around 50-80% of the primary production in for example the Wadden Sea is accounted for by the productivity of microphytobenthos, the importance of these algae for the food web is clear.

On an intertidal flat the algae and bacteria film are mainly found on the less exposed and more silty parts of the flat. It seems that the more exposed sandy edges of the flat are less suitable habitats.

During the year, the species composition of the primary producers on the flat changes. In the spring, the diatoms are prominent and blooming. If nitrate-concentrations are low, cyanobacteria can dominate. This observation indicates that water quality is related to the algae species composition found on the flats. It is assumed that these changes in species composition affect the formation of the algae-film on the sediment and of the food-availability for animals grazing on the algae.

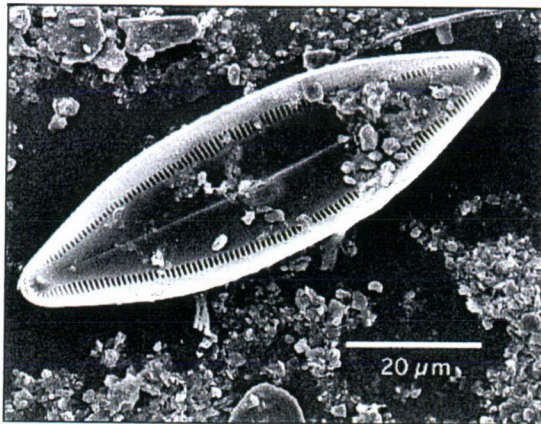


Figure 2.10.  
Benthic diatom *Caloneis africana* (source:  
<http://www.sci.sdsu.edu/salton/SaltonSeaHomePage.html>)

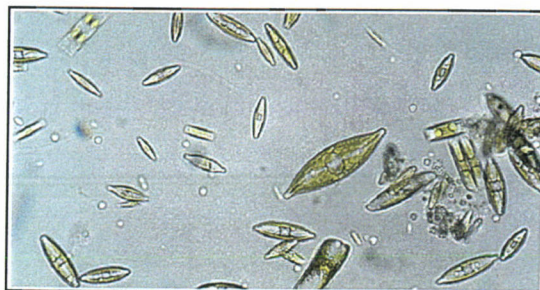


Figure 2.11.  
Benthic diatoms occurring in the Wadden Sea (source:  
[www.waddenzee.nl](http://www.waddenzee.nl)).

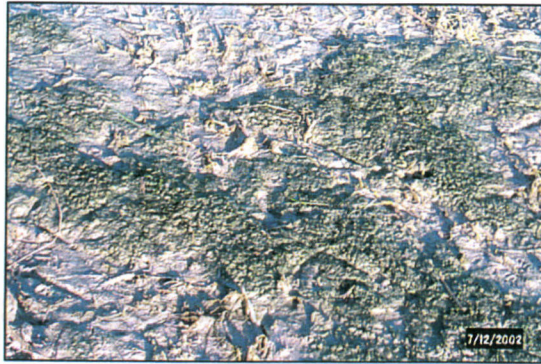


Figure 2.12.  
Algae film on intertidal flat.

### 2.3.3 Macroalgae

Macro-algae don't have a differentiated root, stem and leaf system. Their 'leaf' is called 'thallus'. Macro-algae species such as *Ulva* (Figure 2.13) can reach lengths up to 2 or 3 meters. Macro-algae reproduction involves microscopic spores that are transported by currents. Most of the macro-algae are found on hard substrates with the thallus attached to stones or shells. However, some species exist as free floating individuals.

Eutrophication of water can cause extensive development of macro-algae such as *Ulva* or *Enteromorpha* (Figure 2.14) in, for example, the Wadden Sea. This can lead to mortality of benthic species underneath due to anaerobic conditions. The distribution of the macroalgae is strongly linked to inundation time. The higher the zone relative to the tide, the more the species can resist desiccation. On intertidal flats *Ulva* and *Enteromorpha* species are found on places where the wave action and current speeds are not too intensive.

*Ulva* is a green algae, that is common in the intertidal areas of the North Sea. The growth season of *Ulva* starts in April and an individual plant can reach a length of several meters in a few months. If the plant is detached from its substrate, it continues to grow until it is beached. After beaching the plant will die. If large quantities of this species are heaped for instance near the high water mark, it can kill benthos underneath and leave black anaerobic spots of sediment.



A



B



Figure 2.13. A *Ulva lactuca* (Sea lettuce, Zeesla), B *Ulva* sp. growing on intertidal area in the Eastern Scheldt.



*Ulva* sp. (Gutweed, Darmwier).

### 2.3.4 Submerged macrophytes

A small number of macrophytes can live in marine environments, i.e. at lower intertidal or subtidal locations. The sea grass species *Zostera marina* (Figure 2.15) and *Zostera noltii* (Figure 2.16) are the only species occurring in the Dutch coastal waters. *Zostera marina* is a perennial plant. Its roots are at least 2 centimetres in diameter, with leaves that reach lengths of a meter and a width of half a centimetre. It can still be found in the Oosterschelde, Grevelingen and Veerse Meer. In the intertidal zone, *Z. marina* develops less broad leaves.

The second species *Zostera noltii* is much smaller and is an annual plant. Its roots are about two millimetre in thickness. Its leaves do rarely exceed a length of 25 centimetres with a width of one millimetre. It is found in the Oosterschelde, in the Wadden Sea near Terschelling and along the coast of Noord-Groningen.



Figure 2.15. *Zostera marina* (Eel-grass, Groot zeegras, source: [www.waddenzee.nl](http://www.waddenzee.nl))



Figure 2.16. *Zostera noltii* (Sea-grass , Klein zeegras, source: [www.waddenzee.nl](http://www.waddenzee.nl))

Sea grass needs light and therefore clear water for its photosynthesis. The plant will utilise its root system to extract nutrients from the sediment. In eutrophic conditions, algae can compete with sea grass due to more efficient production and light limitation. Both types of sea grass require some fresh water influence for a sustainable habitat. Experiments in the Grevelingen have shown that larger leaves and roots are developed if the salinity is reduced. Relative to the extensive areas in the Wadden Sea in the years before the closure of the Afsluitdijk, at present only a small area of sea grass remains.

Sea grass beds are utilised by many other species. For many fish and invertebrates species the beds are spawning and nursery habitat. Bird species such as Brent geese and Wigeon are feeding on the sea grass.

## 2.4 Zoobenthos

The most common zoobenthic species (Figure 2.17) in the Dutch tidal areas are the mussel (*Mytilus edulis*), the cockle (*Cerastoderma edule*), the lugworm (*Arenicola marina*), the ragworm (*Nereis diversicolor*) and the Baltic tellin (*Macoma baltica*). Their distribution, composition and abundance is affected by abiotic parameters, such as grain size and silt content of the substrate, inundation time, bottom slope and current speed, but also temperature, salinity and light. Biotic factors that play a role include predation, competition and the presence of vegetation. Recursively the presence of benthos can affect the characteristics of the intertidal flat.



Figure 2.17. Benthos remaining on a sieve after sampling of an intertidal flat. Source: Schorrenwerkgroep - Natuurpunt Antwerpen-Noord vzw ([http://www.scheldeschorren.yucom.be/nederlands/sitemap\\_nl.html](http://www.scheldeschorren.yucom.be/nederlands/sitemap_nl.html))

Worms are an important part of the fauna of the intertidal flat. They are a main food source for fish and bird species. Some worms, such as the rag-worm *Nereis* (zager) are mobile and dig through the sediment. Others live in permanent burrows and build tubes that can be seen above the sediment surface (for example *Lanice*/schelpkokerworm).

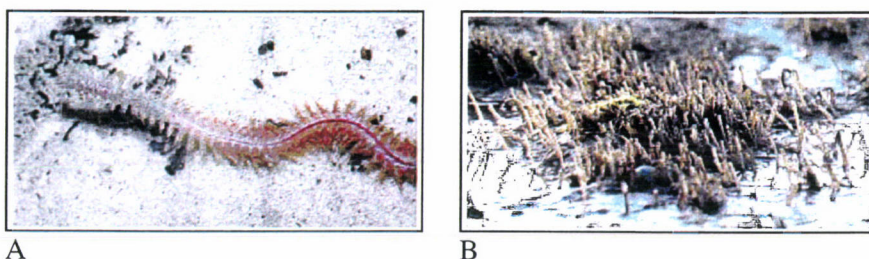


Figure 2.18. A *Nereis diversicolor*, B *Pygospio elegans*. Source: Schorrenwerkgroep - Natuurpunt Antwerpen-Noord vzw ([http://www.scheldeschorren.yucom.be/nederlands/sitemap\\_nl.html](http://www.scheldeschorren.yucom.be/nederlands/sitemap_nl.html)).

Many different systems are used by zoobenthic species to obtain food. Filter feeders filter food particles from the water phase. *Pygospio* species (Figure 2.18) catch food particles using sticky tentacles. Some worms feed by consuming bulk sediment and extracting bacteria out of it. The shrimp *Calianassa* feeds by scraping bacteria of the walls of its tubes. Figure 2.19 illustrates the different behaviours of some zoobenthic species.

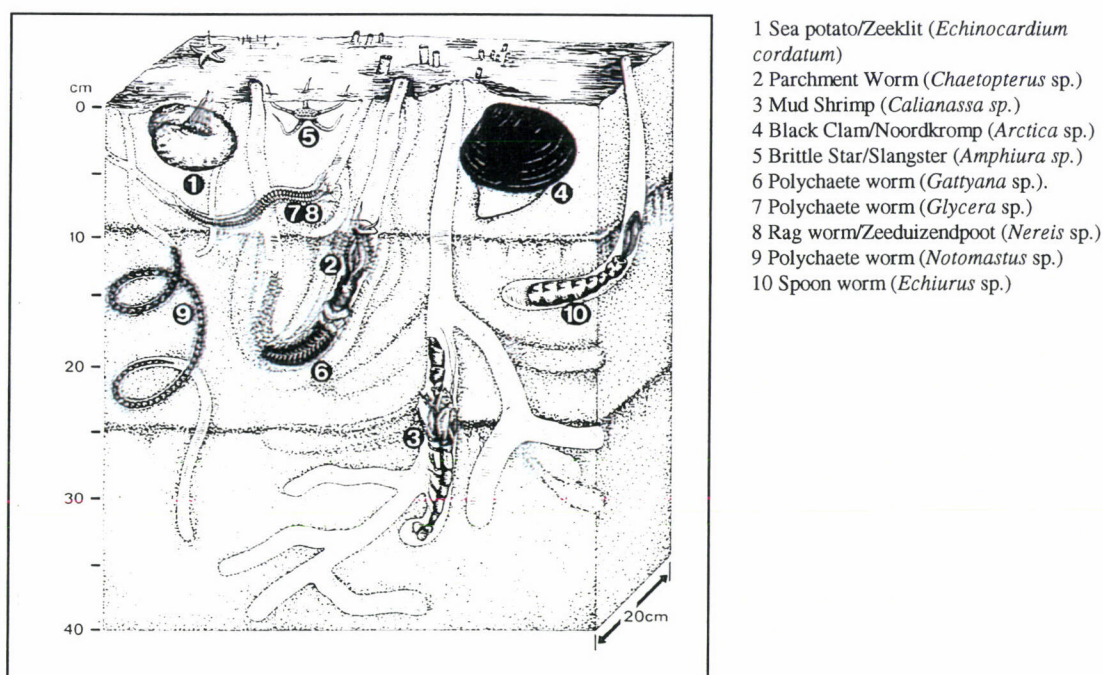


Figure 2.19. Schematised drawing of zoobenthos activity in a subtidal North Sea bottom. Source: De Noordzee, P. de Wolf, ISBN 90 6255 365 6.

Several types of bivalves live in the intertidal flat. They are linked to the surface via their siphons. These siphons provide the animal with fresh water and food-particles. Well known and common species are the cockle (*Cerastoderma*) and *Macoma*. Muddy areas in general have higher biomass and species diversity than sandy bottoms. This seems to be linked to the availability of more food and less dynamic environments.

As an example, two filter feeding species are described in some detail: cockles and mussels. These species are commonly found in the Westerschelde.

The cockle (Figure 2.20) is a filter feeder that can be found at about 5 centimetres depth in the sediment. It is connecting to the water phase by means of two tubes (siphons) and feeds on plankton and organic matter that it filters from the volume of water that is pumped through its siphons (approx. half a litre per hour). In filter feeder rich systems such as Oosterschelde, Grevelingen and the Wadden Sea the total water volume is filtered each few weeks.

The cockle is a mobile species that can burrow through the sediment. It can move tens of centimetres per day. Its distribution is limited to 20 meters water depth up to the intertidal areas in sandy sediments. There is a well established relationship between cockle mortality and the severity of a winter. Also wave action and water currents are of importance to its distribution. If there is too much dynamics near the bottom, the cockle settlement will be negatively impacted.

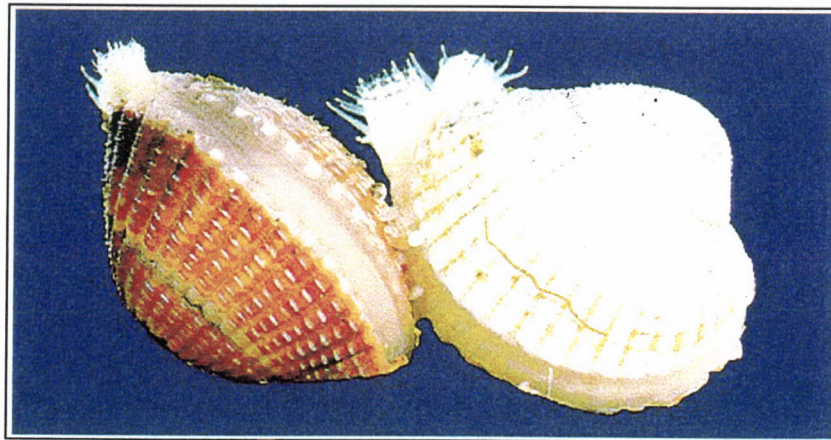


Figure 2.20. The cockle (*Cerastoderma edule*) Source: [www.waddenzee.nl](http://www.waddenzee.nl).

The mussel (*Mytilus edulis*) is a reef builder, and can be found in large banks attached to each other or to hard substrate. A small cluster of mussels is shown in Figure 2.21. It is a bivalve and can be found in many locations along the Dutch coast. Just like the cockle the mussel is a filter feeder. Its larvae are free floating and will attach to suitable substrates such as wrecks, breakwaters, poles, shells and existing mussel banks. The existence of old mussel or other bivalve banks is important as suitable substrate in muddy, soft substrate environments such as the Wadden Sea. For mussel larvae this is the habitat of choice. There are little remaining 'old' mussel banks in the Wadden Sea. The area has been reduced from 4000 ha. in 1978 to 100 ha in the early 90ies. At present (early 2000) we can observe a small improvement: the older beds have increased to 500-600 ha. A mussel bed will influence the sediment composition in its surroundings. Due to the intensive filtering, many fine particles will be coagulated and excreted by the mussel. Mussels pump 2 liters of water per hour. In

some estuaries mussels (both natural beds and culture lots) may filter the whole water mass within one week

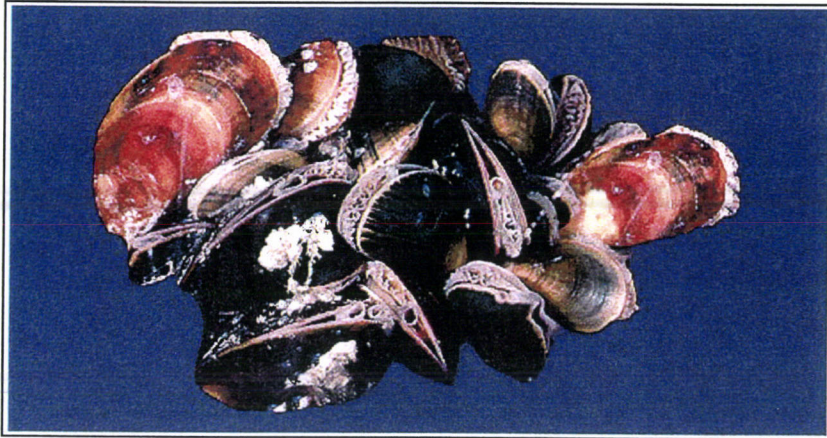


Figure 2.21. The mussel (*Mytilus edulis*). Source: [www.waddenzee.nl](http://www.waddenzee.nl).

The population of every benthic species has a specific spatial distribution pattern. This can be uniform with the individuals evenly spread, in specific shapes as bumps, troughs or waves, or of a patchy type, with aggregations which seem randomly disseminated. The spatial distribution of a population can also have a typical dimensional-scale: specific patterns can be recognised, for instance, at the scale of hundreds of meters, at the scale of tens of meters or at the scale of meters. The aggregations typical of a patchy distribution also have specific sizes.

For every species distinct distribution patterns and scales can be expected for the different life stages (larvae, adult). When also considering that all biological processes (spawning, life-stages, growth, death) have a seasonality, we can expect that the spatial distributions of the benthic populations also reflect typical temporal scales, such as the season (time-scale of the yearly climate changes, in terms of temperature, typical hydrological periods, etc.), the month (time-scale of a whole tidal cycles), the day, the tide. Thus physical and biological forcing, population and community dynamics all give rise to spatial and temporal structures. It is therefore essential to take into account the consequences of choosing a certain size for the computational area and resolution when planning computational tests to study the interactions between the biotic and abiotic factors (De Brouwer et al., 2001).

## 3 Morphodynamic modelling

### 3.1 Introduction

Morphodynamic models can be divided in process-based and behaviour-oriented. Models of the first type aim at describing the physical processes as well as possible, they are mostly based on theories leading to a mathematical description of the physical processes with a deterministic approach. Data are used for calibration and validation purposes only. The models of the second type are based on the use of empirical or semi-empirical parameters, derived from observations, computational tests performed with process-based models, stochastic and probabilistic studies, and on parameterised descriptions of some of the processes governing the system dynamics, allowing for more inaccuracy (Stive and Walstra, 1998).

Process-based models are more complicated and for long-term studies the computational effort is large and errors can accumulate. Therefore these models are usually used for short-term detailed studies on relatively small areas. Behaviour-oriented models are less accurate and less general, but are useful for long-term predictions at large spatial scales.

To get an insight on the interactions between biology and geo-morphology in tidal systems the physical phenomena need to be understood. This can be achieved only by means of a process-based model, to be calibrated and validated on good and complete sets of data.

With a three-dimensional process-based model the functioning of, for instance, a salt marsh can be studied in detail, even at the scale of the smallest gullies and single plants (micro-scale). Once the processes operating at this scale are understood, the model can be used to study the processes operating at larger scales, provided that the relevant micro-scale phenomena can be parameterised.

This chapter lists a number of parameters that are important for the study of the estuarine morphodynamics and ends with a short introduction to the process-based Delft-3D model.

### 3.2 Morphodynamic parameters

The morphology of sandy coasts and estuaries are changing constantly under the influence of hydraulic and aeolian forces. Sediment is set into motion and settles again to form a broad spectrum of morphological features, like dunes, ripples and channels. These features then act upon the forces that shaped them by affecting the movement of water and wind.

The processes governing the morphodynamic behaviour of coasts and estuaries can roughly be divided in three groups, those connected to

1. the water motion,
2. the bottom characteristics and processes,

### 3. sediment transport.

An short overview of the most important processes and parameters is given below, with emphasis on the situation in estuaries. For a more in-depth discussion of these topics the reader is referred to the books of van Rijn (1990, 1993, 1998). Large part of the text below is taken from van Ledden (2001).

#### 3.2.1 Water motion

The flow in estuaries is complex and three-dimensional and is caused by a combination of currents and short waves. Currents are induced by the tide, wind and river discharge, but also density currents due to salinity differences and high sediment concentrations can be important for the estuarine water circulation. The impact of currents on the sediments on the bottom surface is twofold. Firstly, currents induce a shear stress at the bed surface, which is important for the exchange of sediments between the water column and the bed. Secondly, currents transport sediment from one site to another.

Short waves are generated by the wind and by passing ships and can significantly intensify the bed shear stress. Therefore wave action can play an important role in stirring up the sediment from the bottom and bringing it into suspension. Its influence is determined by wave height and length in combination with the local water depth and bottom slope. In shallow waters waves eventually break, dissipating a large part of their energy.

An important aspect of the water motion is its turbulence. Although it is often described as a random phenomenon, turbulence can be characterised as eddy-like movement of single water particles. Turbulence is responsible for the exchange of particles and therefore plays a significant role in sediment transport. Its magnitude is expressed by the turbulent kinetic energy,  $k$  [ $\text{m}^2 \text{s}^{-2}$ ].

#### 3.2.2 Bottom

The local bottom topography, which is determined by the size of the sediment grains, by the presence of bedforms, such as ripples or dunes, vegetation and biological formations, such as tubes and shells, plays an important role for the movement of water and sediment. It determines the bottom roughness which influences the friction between the bottom and the moving water. In mathematical modelling the bottom roughness can be described in various ways, such as: the Nikuradse roughness length, the Manning coefficient and the Chezy parameter.

When excluding biological factors, it can be stated that in general the increase of presence of mud on the bottom surface, for instance by local deposition of fine particles, decreases the bottom roughness. This is due to the decrease of the particle sizes with respect to sand and to the reduction of ripples, which on a muddy bottom eventually become absent. However, the formation of larger bedforms, such as ridge and runnel features, which can develop on muddy soils (Dyer, 1998) might have the opposite effects.

There are several possible reasons for changes in the bed composition. At the bed-water interface the sediment composition can change due to changes in the upward and downward fluxes of sand and mud. The bottom composition can also change due to vertical mixing of sediment particles. Vertical mixing can be due to both abiotic and biotic contributions: the presence of small-scale disturbances at the bed-water interface (e.g. ripples) and biological activity (e.g. bioturbation by organisms). The latter is often called 'local biological mixing' (Boudreau, 1997). Organisms can also cause horizontal mixing, when they transport sediment from one site to another. Another biological source of sediment having a different composition than that on the bed is called 'biodeposition'. Vertical mixing and biodeposition are treated in Section 4.2.2.

### 3.2.3 Sediment transport

When the flow velocity at the bottom exceeds a critical velocity (or critical bottom shear stress), sediment is set into motion. For sand this critical value can be related to the 'Shields parameter'. This is a dimensionless parameter that represents the balance between flow strength and sediment transportability and is an indicator of morphodynamic activity.

Sand can be transported as bed load or as suspended load. Bed load occurs at the bed-water interface, suspended load in the water column. A major difference between bed-load and suspended-load transport is that bed-load transport almost instantaneously adapts to the local flow conditions, while suspended-load transport is also determined by the upstream conditions. For low sediment concentrations, mud is only transported in suspension. For high concentrations mud can also be transported in a layer near the bed, which is called 'fluid mud'.

Turbulent mixing is important to keep sediment in suspension. The turbulent 'mixing capacity' is expressed by the *eddy diffusivity*, which is proportional to the turbulent intensity or kinetic energy, and to the size of the turbulent eddies.

## 3.3 The Delft3D modelling package

WL | Delft Hydraulics has developed the process-based Delft3D modelling package. This is a fully-integrated system of models for a multi-disciplinary approach and three dimensional (3D) computations for coastal, riverine, lacustrine and estuarine areas.

Delft3D is composed of a number of modules, each addressing a specific domain of interest, such as flow, near-field and far-field water quality, wave generation and propagation, morphology and sediment transport, together with pre-processing and post-processing modules. All modules are dynamically interfaced to exchange data and results where process formulations require.

To perform morphodynamic calculations on intertidal flats the following modules of the Delft3D system have to be used: Delft3D-sediment-o-nline and Delft3D-MOR. With these modules one can simulate wave propagation, currents, sediment transport, morphological developments and water quality aspects in coastal, river and estuarine areas (Roelvink and Van Banning, 1994).



The newest version of the Delft3D package is called Delft3D-sediment-on-line. In this version the modules FLOW, SED and MOR are not seen as separate entities anymore. The Delft3D-sediment-on-line version allows for the simulation of flow, transport of sediment (as bed and suspended load) and bed level changes, at the same time step. The effects of density currents, due to suspended sediment concentration, can be implicitly taken into account. This formulation is suited especially for high dynamic processes, where short-term bed level changes affect the local hydrodynamics.

Until recently it was common practice to model the sand and mud fractions separately, i.e. without mutual interaction. This could lead to spurious results, as e.g. the erosional properties can already change with the addition of a few percent of mud (Mitchener et al, 1996). In the year 2000, van Ledden developed a research model, based on the Delft3D software package, that simulates simultaneously the transport of sand and mud (2001). Process formulations, based on the common expressions for sand and mud, have been modified to take into account the effect of the mud content. Bed level changes depend on both suspended sand and mud exchange at the bed-water interface and on bed load transport gradients. The bed composition, denoted by the mud content, is time-dependent and non-uniform in horizontal and vertical direction.

The wave module is based on the 'HISWA concept' (Holthuijsen et al., 1989). This module solves the spectral wave action balance equation assuming a frequency spectrum of fixed shape, allowed to propagate within a directional sector of less than 150°, on a two-dimensional rectangular grid. The model takes into account the effects of shoaling and refraction, dissipation by bottom friction and wave breaking, current refraction and wave blocking. Recently, the 'SWAN concept' (Ris, 1997) has been integrated into the Delft3D-MOR model. In contrast to its predecessor HISWA, SWAN is fully spectral over the total range of wave frequencies, over the complete directional sector of 360°. The latter implies that short-crested random wave fields propagating from widely different directions (or 'multi-modal wave fields') can now be accommodated.

For more details on the Delft3D package the reader is referred to the WL | Delft Hydraulics internet site: [www.wldelft.nl](http://www.wldelft.nl). Appendix D contains specification of the used modules.

## **4 Effects of biota on morphodynamics: state of the art**

### **4.1 Introduction**

The goal of this study is to model and quantify the biological impact on the morphodynamics of tidal systems, with focus on the Western Scheldt estuary. With this objective in mind a literature review was conducted to get a good overview of the state of the art on the topic. The results are described in Section 4.2. In Section 4.3 a summary of the knowledge gained at WL | Delft Hydraulics is given. The chapter ends with a summary of the most relevant findings, Section 4.4.

### **4.2 Literature review**

The literature study focused on the quantification of the biological impact on the morphodynamic processes in estuaries, considering all the typical biological components of the Dutch intertidal areas, from salt marsh vegetation to macrozoobenthos. Papers and reports were selected on the basis of their usefulness for quantification's. General descriptions of the biological components and qualitative analyses were thus disregarded, unless of particular relevance for other aspects of the present study, such as the model schematisation.

The literature was collected through the help of experts in the different fields, within and outside WL Delft Hydraulics. They are: John Widdows and Rose Wood (Plymouth Marine Laboratory, United Kingdom), on macrozoobenthos and microphytobenthos; Anouk Blauw (WL), on the modelling of the effects of microphytobenthos on bottom erosion/sedimentation; Henk Verhey (WL), on the effects of macrophytes and reed on river morphodynamics; Peter Herman and Tjeerd Bouma (NIOO-CEMO), on benthos and salt marshes; Norbert Dankers (Alterra) and G.C. Cadée (NIOZ), on macrozoobenthos; Dick de Jong and Harm Verbeek (RIKZ, Middelburg), on the Western Scheldt situation; Erik Epping (NIOZ) and Walther van Kesteren (WL), on the role of microbenthos in altering the bottom characteristics.

The results of the literature review are organised per biological component and presented below. The most relevant pieces of literature are listed in Appendix C, where they are shortly described using a standard format.

#### **4.2.1 Salt marsh vegetation and sea grass**

Although salt marsh vegetation and submerged macrophytes (sea grass) are distinct biological components of intertidal areas, they are treated simultaneously. Two arguments support this reasoning:

1. both salt marsh vegetation and sea grass consist of aggregates of vascular plants with a root system (macrophytes);

2. to a certain extent, the physical functioning of salt marshes and sea grass fields are comparable. In both cases it has to do with water and sediment flow through or above a vegetation field. In Table 4.1 the similarities and differences between salt marshes and sea grass fields are listed.

Table 4.1 Similarities and differences between salt marshes and sea grass fields

Similarities	Differences
<ul style="list-style-type: none"> <li>• basic principles of flow alteration with respect to the flow on bare bottom.</li> </ul>	<ul style="list-style-type: none"> <li>• stiffness: sea grass is more flexible;</li> <li>• sea grass is more often totally submerged, while salt marsh vegetation is more often dry or partially submerged.</li> </ul>

### Flow

The effect of submerged vegetation on the water flow has been studied by several researchers, both in the field and in the laboratory. In the present review only a few representative studies are mentioned. Appendix C provides a more complete list of pieces of literature dealing with macrophytes and hydrodynamics, compiled by Chris Stolker (WL).

The presence of vegetation primarily changes the bed roughness, by altering the typical logarithmic shape of the velocity profile. In fact plants act as a set of flexible roughness elements protruding from the bottom. Upon a vegetated bed two velocity profiles, separated by a discontinuity, develop: within the plants the profile is linear and above the plant tops is logarithmic (Shi *et al.*, 1996, Pethic *et al.*, 1990). Within the plants the current velocity is lower than in the undisturbed flow and above the vegetation it is higher.

During inundation salt marsh vegetation either sticks partially out from the water surface or is completely submerged, depending on the 'inundation event' (e.g. normal spring tide, storm surge). When the plants are not completely submerged, a logarithmic velocity profile cannot develop.

In a flume experiment Gambi *et al.* (1990) measured velocity profiles within and in front of a *Zostera marina* (sea grass) field of different densities. They found an increase of the velocity above the canopy while the current speeds inside the canopy (between the plants) were reduced. At all velocities and densities tested this reduction increased with increasing distance from the leading edge of the plant bed. All the profiles above the canopy fitted a log-profile relationship while inside the vegetation the profiles had a different shape.

### Waves

The presence of vegetation also affects wave characteristics. For this reason reed and perennial grasses species are often used for protection of banks subject to the attack of waves. An example is given by Longyou *et al.* (1995) who describe the protection of embankments and coasts of China by *Spartina atierniflora*.

Fonseca and Cahalan (1992) measured the wave energy reduction, derived from the wave height, over one-meter section for four sea grass species. They found no significant differences: the average reduction for all species at various densities and water depths was 44%.

### Turbulence

Leonard en Luther (1995) found a logarithmic decay of turbulence intensity over a salt marsh surface measured from the edge (Figure 4.1). Turbulence intensity was defined as the root-mean-square value of the variation in current velocity. They also found variations in

kinetic energy reduction as a result of differences in plant species and density (see Figure 4.2 and Table 4.2).

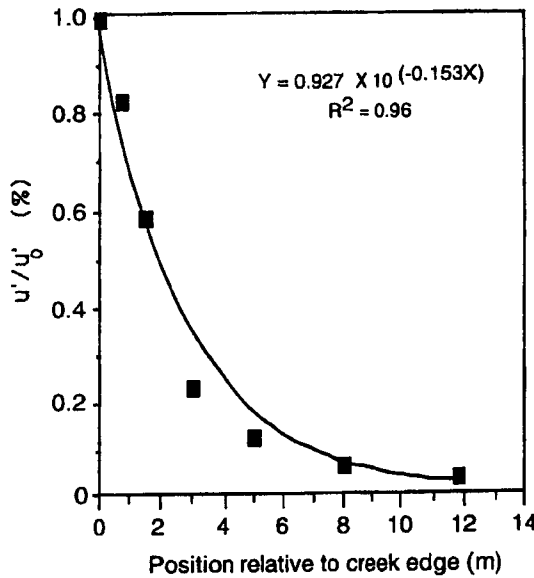


Figure 4.1. Reduction of turbulence intensity into the marsh (Leonard and Luther, 1995).

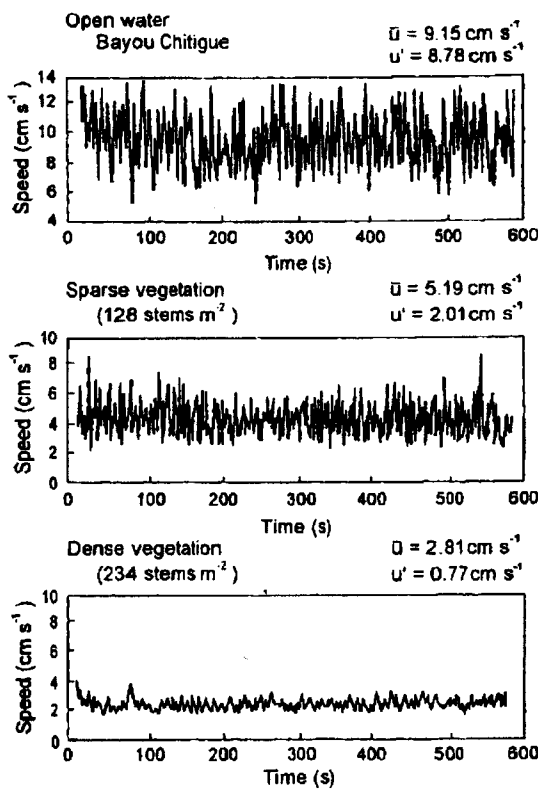


Figure 4.2. Time series of velocity at open water and two different stem densities (Leonard and Luther, 1995).

Table 4.2 Characteristics in the study of Leonard en Luther (1995)

Parameter	West-central Florida	Southeast Louisiana
tidal range	0.8 m (mean)	30-60 cm (spring tide) 10-20 cm (neap tide)
inundation depth	45 cm (during summer spring tides)	<20 cm (during normal spring tides)
dominant species	<i>Juncus roemerianus</i>	<i>Spartina alterniflora</i>
density	625 stems m <sup>-2</sup>	0-225 stems m <sup>-2</sup> (low) 176-370 stems m <sup>-2</sup> (high)

plant length	~1.5±0.2 m (emergent during normal flooding)	28±5 cm (submersed during extremely high tides)
mean flow speeds		open water: 9.15 cm s <sup>-1</sup> 128 stems m <sup>-2</sup> : 5.19 cm s <sup>-1</sup> 234 stems m <sup>-2</sup> : 2.81 cm s <sup>-1</sup>
turbulent intensities (u')	open water: 1.59 cm s <sup>-1</sup> 210 stems m <sup>-2</sup> : 0.8 cm s <sup>-1</sup> 350 stems m <sup>-2</sup> : <0.5 cm s <sup>-1</sup>	open water: 8.78 cm s <sup>-1</sup> 128 stems m <sup>-2</sup> : 2.01 cm s <sup>-1</sup> 234 stems m <sup>-2</sup> : 0.77 cm s <sup>-1</sup>
reduction of kinetic energy	dense: 1 order of magnitude.	sparse: 1 order of magnitude. dense: 2-3 orders of magnitude.

**Sedimentation and erosion**

The flow pattern through submerged vegetation does not allow sediment from above the vegetation to settle (separated flow) Pethick *et al.* (1990). Thus mainly sediment from within the vegetation will be able to settle on the bottom. Settling rates can be expected to be higher within the vegetation, due to the reduced current velocities. Stumpf (1983) mentions the sticking of particles to the stems of the plants as an explanation for the observed reduced concentration of the smallest sediment particles that would otherwise remain in suspension, even within the vegetated area.

Clusters of vegetation in the pioneer zone are often characterised by a higher bed level than the surrounding (bare) flat. Pethick *et al.* (1990) found spatial differences in accretion just in front of vegetation and inside the clusters, which might explain this phenomenon.

In a salt marsh, channels are the main source of sediment. The channel system plays an important role on the sedimentation process (Stoddart *et al.*, 1989; Stumpf, 1983) and on the spatial distribution of plant species (Sanderson *et al.*, 2001). Under normal (tide and spring tide) conditions, sediment accumulates at the edges of the channels. During inundation of the marsh the reduction of turbulence leads to the deposition of sediment mainly near the edges of the marsh (along the channels). Stumpf (1983) found an exponential decrease in suspended sediment concentration with distance from the channel edge (Figure 4.3). According to Stumpf, 1983 and Ehlers *et al.*, 1993 storms can play an important role in the transport of this material to the higher places of the marsh.

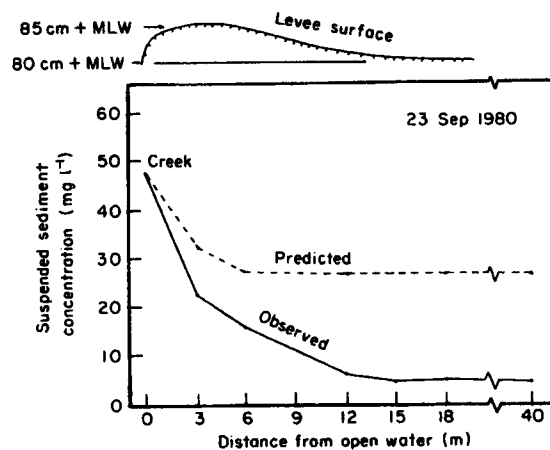


Figure 4.3 Predicted and observed suspended sediment concentration as a function of distance from the creek edge (Stumpf, 1983).

Biogeomorphology (the effects of plants on sedimentation and erosion) of marshes has been treated also by Pasternack *et al.* (2000), Pasternack & Brush (in press) and Dyer *et al.* (in press).

#### 4.2.2 Macrozoobenthos

The effects of zoobenthic organisms can be mainly seen on sediment structure and chemistry and on sediment dynamics (biodeposition and bioresuspension). The effects on the local hydrodynamics are smaller and indirect, mainly through changes of the bottom roughness.

A good overview of the interactions between the benthic organisms and their environment is given by Arntz et al. (1999). According to them the role of benthic organisms in the functioning of marine ecosystems has often been underestimated. Lee & Swartz (1980) give a more specific overview of the effects of benthic organisms. Their work focuses on the biological processes affecting the distribution of pollutants in marine sediment and mainly deal with biodeposition and bioturbation. Both works do not provide quantitative information, but can be used to get a general picture of the role of benthos in forging the marine ecosystems.

An insight on the physical mechanisms governing water flow and sediment dynamics in shallow marine environments, with and without biological mediation, is provided by Paterson (1997) and Paterson & Black (1999). These publications are particularly suited for those researchers who don't have a technical background and want a simple but thorough description of the morphodynamic processes that interact with or are affected by biota.

When considering their effects on sediment, zoobenthic organisms can be grouped according to three dichotomies (Lee & Swartz, 1980):

- **Epifaunal/Infaunal.** *Epifauna* include species that feed on the surface, but occasionally burrow into the sediment. *Infauna* include species that live in the sediment.
- **Mobile/Stationary.** *Mobile* fauna are those animals that move through the sediment on a regular basis, thereby disrupting the sediment structure. Fauna that move only during times of stress or reproduction are not considered mobile and are named *stationary*.
- **Deposit/Suspension feeding.** *Suspension feeders* ingest particles located in the water column and *deposit feeders* ingest particles on or in the bottom.

The effects of benthic organisms on the local morphodynamics can be classified as follows:

- **Biodeposition.** The term "biodeposition" is restricted here to the deposition of faeces and pseudofaeces by *suspension (filter) feeders*. Faecal pellets production by deposit feeders change sediment characteristics, but does not add material to the bottom. Faeces from suspension feeders, on the other hand, are a source of new sediment material, they are aggregates of small particles that would otherwise remain in the water column. There is also an indirect form of biodeposition: sticky material produced on the bottom holds material which would otherwise be resuspended. This indirect form of biodeposition is small when compared to the effects of filter feeders and is here disregarded.
- **Bioresuspension.** Bioresuspension occurs when animals actively move particles resulting in resuspension.
- **Bioturbation.** Bioturbation is the destabilisation of the bottom caused by the presence of fauna and is mainly caused by feeding and locomotion activities. Bioturbation can modify

patterns of sediment stratification and, by exposing deeper material to resuspension (vertical mixing), affect the transport of particles and pollutants between the sediment layers. This effect is important when studying the distribution of contaminants in the sediment. One of the most important mechanisms increasing the erodibility of fine sediments is an increase in porosity. Biogenic reworking alters the particles spatial arrangement in the sediment. Feeding and borrowing activities break up the cohesive structure of silt-clay sediment and counteract compaction. As a result, porosity and water content increase, compaction and bulk density decrease. However, for sandy substrates reworking does not always result in an increase of porosity: the effects of reworking on porosity depend on the sediment grain size.

- **Indirect biostabilisation.** This is the decrease of bottom erosion due to the presence of benthic organisms, which, by increasing the bottom roughness, lowers the near-bed velocity. The bottom erodibility limit (critical shear stress) remains (almost) the same, but the ultimate effect is that the bottom erodes less.
- **Direct biostabilisation.** This is the bottom stabilisation due to the binding effects of roots, anchorages or by cover. Cover is given, for instance, by mussel and oyster beds, where the underneath bottom is protected by a coat of shells anchored to each other and to the soil. The presence of high densities of these organisms decreases the bottom erodibility: a higher shear stress is needed to erode the bottom. Instead, lower densities may have the opposite effect.
- **Indirect effects on hydrodynamics.** This is the lowering of velocity due to the increase of bottom roughness caused by the presence of benthic organisms.

#### **Biodeposition by suspension feeders**

Filter feeding organisms (suspension feeders) can increase deposition rates by a factor two or more (Graf & Rosemberg, 1997) and for this reason, when modelling the sediment dynamics, biodeposition should be taken into account as an extra source of sediment flux to the bottom. Haven & Morales-Alamo (1966) suggested that in the Wadden Sea *Cardium* and *Mytilus* populations annually deposit 100,000 and 25,000-75,000 tons, respectively. Oost (1995) presents much higher amounts. For the whole Dutch Wadden Sea he estimates (based also on Dankers et al. 1989) an annual production of biodeposits by *Mitilus edulis* variable between 3,100,000 and 17,700,000 tons, with the conclusion that biodeposits significantly influence sedimentation patterns in the Wadden Sea.

Ten Brinke (1993) estimated the total biodeposition rate by *Mytilus edulis* in the Oosterschelde as 661,000 tons/year, assuming filtering rates of juveniles and adults equal to 0.8 and 1.6 l/(individual×hour), respectively, and an average sediment concentration of 10 mg/l. Despite this very high value which is a results of a high biomass, Ten Brinke concludes that biodeposition by mussels hardly influences suspended sediment concentrations and net sediment accumulation inside the basin. In fact biodeposits seemed to be quickly resuspended by the currents, leading to the conclusion that in the Oosterschelde the sediment transport processes are governed by the local hydrodynamics.

Some biodeposition rates from different studies are given in Table 4.3a and Table 4.3b.

Table 4.3a. Biodeposition rates (source: Lee &amp; Swartz, 1980)

Species	Individual rate mg/(ind. day)	Total rate g/(m <sup>2</sup> year)	Comments	Reference
<i>Cardium edule</i>	648	-	Faeces, wet weight	Haven & Morales-Alamo (1966)
<i>Cardium edule</i>	420	-	-	Pryor (1975)
<i>Mya arenaria</i>	25	-	faeces	Haven & Morales-Alamo (1966)
<i>Mytilus edulis</i> (mussel)	240-5400	-	Pseudofaeces, 7 cm mussel, sexton range 12-280 mg/l	Widdows et al. (1979)
<i>Mytilus edulis</i> (mussel)	4.3	-	Ash-free weight, faeces and pseudofaeces?, 0.475 g-dry wt mussel.	Tenore & Dunston (1973)

Table 4.3b Biodeposition rates (source: Graf &amp; Roseberg, 1997)

Species	Total rate g C/(m <sup>2</sup> year)	Comments	Reference
<i>Cerastoderma/Mya arenaria</i>	0.2(0.08)	Field measurements	Muschenheim & Newell (1992)
<i>Mytilus edulis</i> (mussel)	70	Field measurements	Roseberg & Loo (1983)
<i>Mytilus edulis</i> (mussel)	2.0-5.3	Field measurements	Loo & Roseberg (1989)

The feeding rates of suspension feeders have often been measured in laboratory through the assessment of the clearance rates in the water column (diminishing of the water turbidity due to active filtering). Clearance rates can be then directly related to faecal pellet production. Oost (1995) measured both pellet production and clearance rates of *Mytilus edulis* and found that the pellets had an equivalent quartz grainsize ten times larger than the original suspension material. Biodeposits thus settle much faster than the original suspension. Filtering rates are the volume of water filtered per unit of time by the animals. When the concentration of the sediment in the water column is known, the clearance rates can be computed as the product 'concentration per unit of water volume times filtering rates'.

The feeding rates of suspension feeders are believed to be influenced by the current velocity. John Widdows et al. (2002) performed laboratory and fields studies to determine the effect of current velocity on the clearance rates of mussels, but found no relation between this and the current velocity for mussels from the mouth of the Exe estuary (SW England), at least in the velocity range 0.05-0.8 m/s. This result is in agreement with other studies on mussels from dynamic areas. Jenner et al. (1998) observed a significant reduction of clearance rates for mean current velocities higher than 1.8 m/s. When considering the Dutch tidal systems, all characterised by high dynamics, clearance rates can thus be assumed constant for velocities lower than 1.8 m/s.

Clearance rates and thus biodeposition rates are related to the animal body weight in a logarithmic way (Møhlenberg & Rusgard, 1979). The age of the bivalves or the size (that is related to the age) are thus important variables for the estimate of the clearance rates of the animals.



### Bioturbation

Cadée (2001) provides a good review of bioturbating organisms and their effects on the sediment. In Figure 4.4 is a representation of some bioturbating organisms (Cadée, 1984).

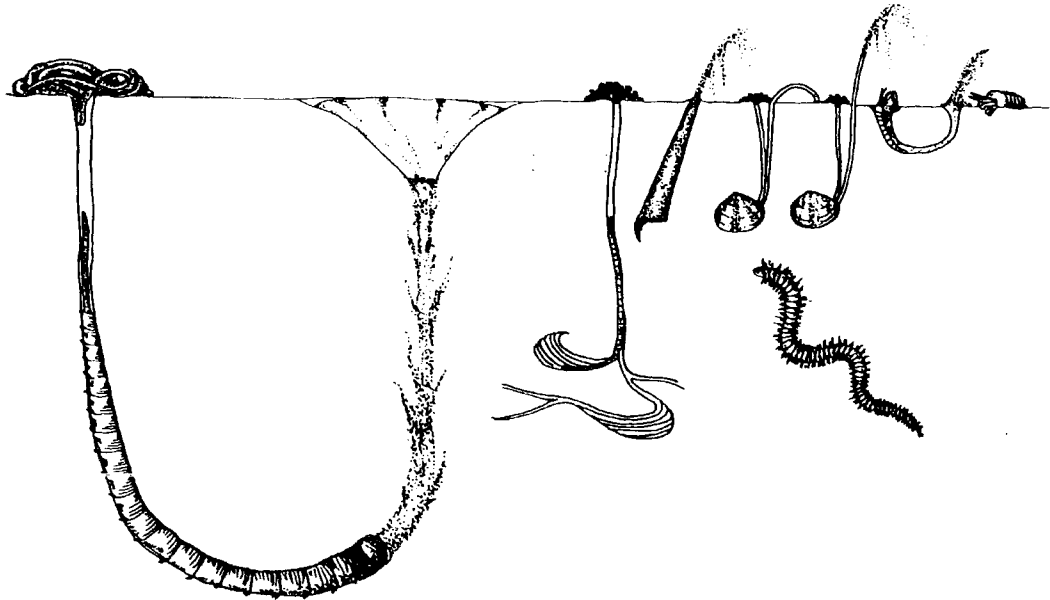


Figure 4.4. Bioturbating organisms. From left to right: *Arenicola marina*, *Heteromastus filiformis*, *Pectinaria sp.*, *Macoma balthica*, *Corophium volutator*, *Hydrobia ulvae*. Below right: errant polychaete crawling through sediment. After Cadée (1984).

The effects on the sediment (sediment reworking) of the polychaete, funnel feeder, surface feeder, *Arenicola marina*, are quantified by Cadée (1976). The effects of the polychaete, subsurface feeder, *Heteromastus filiformis* are quantified by Cadée (1979). The effects of the bivalve, surface feeder, *Macoma balthica*, that act as bioturbator and as diatom eater, are treated by Bouma et al. (2001a) and (2001b), by Widdows (2000a) and by Herman et al. (2000).

### Bioresuspension by deposit feeders

Resuspension of sediment is influenced by shear stress at the sediment-water interface and by type, abundance and reworking time of infauna. The total sediment resuspension (due to both biotic and abiotic factors acting contemporarily) can be expressed by the following expression (Davis, 1993):

$$R_t = R_p + R_{pb} + R_b$$

$R_t$  = total resuspension

$R_p$  = physically governed resuspension term, it varies as a function of currents, depth and wave height and can be related to the bottom shear-stress (physical shear)

$R_b$  = direct biological resuspension term, it varies with species, abundance and activity rates (temperature)

$R_{pb}$  = physical-biological interaction resuspension term

Davis (1993) provides a general scheme on the role of biology in sediment resuspension (Figure 4.5). He mainly studied the resuspension enhanced by infaunal bivalves *Nucula annulata*, *Macoma tenta* and *Yoldia limatula* and other benthic organisms. He performed laboratory experiments on silt-clay natural sediment from the Central Long Island Sound ( $D_{50} = 0.011$  mm) and on organisms (deposit feeders) collected in the same place or in the Narragansett Bay. He measured resuspension rates both in presence of physical shear, to estimate the interaction between organisms and physical shear,  $R_{pb}$ , and without physical shear, to estimate  $R_b$ . His results show that the presence of *Nucula* increases resuspension 2-3 times, for shear levels between 2 and 12 dyne/cm<sup>2</sup>. Non motile *Macoma tenta* and *Mulinia lateralis* slightly increased the curve and only at maximum abundance's. The results of Davis (1993) are summarised in Figure 4.6.

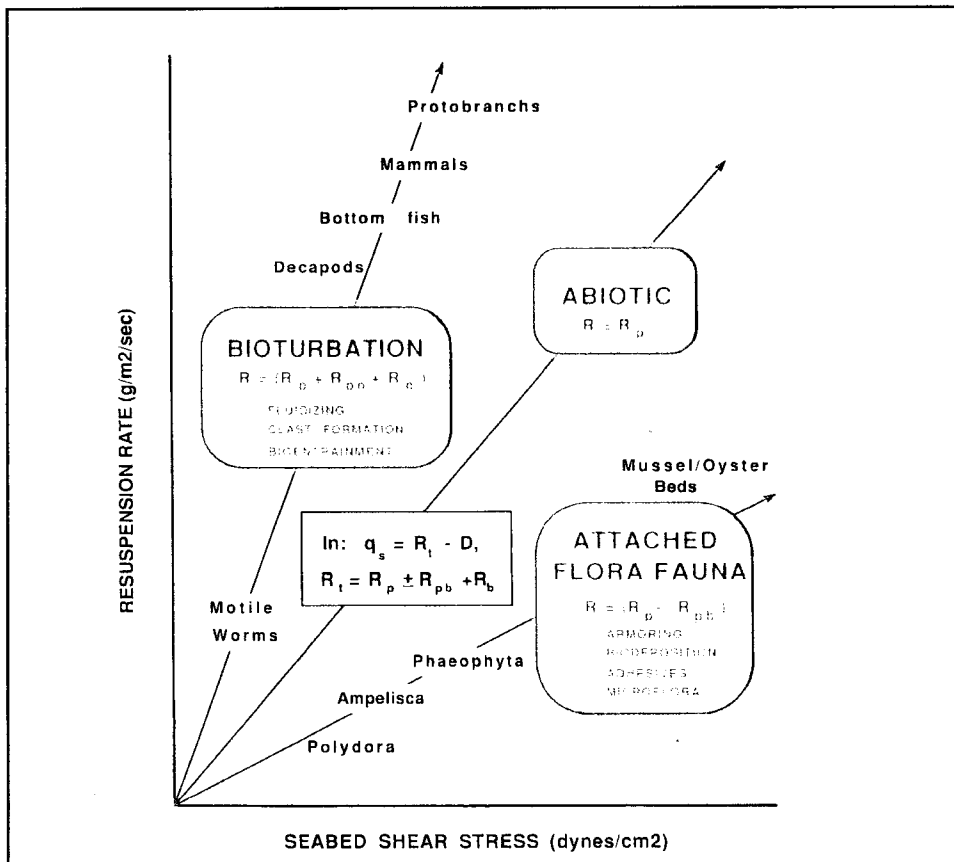
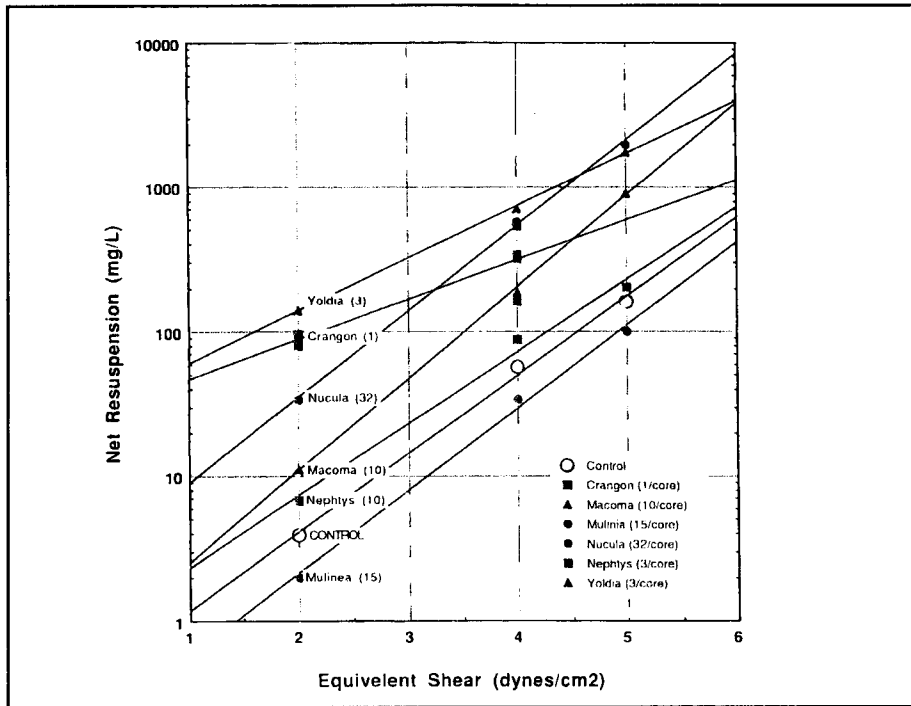


Figure 4.5 General scheme on the role of biology on sediment resuspension (Davis, 1993)



Legenda:

- = control curve
- = Crangon
- ▲ = Macoma
- = Mulinia
- = Nucula
- = Nephtys
- ▲ = Yoldia

Figure 4.6. Effects of various fauna common to Central Long island Sound on net resuspension. Since species affect cohesion and water content their individual effects are redundant rather than additive (Davis, 1993).

**Effects of tubicolous fauna on bioturbation and indirect biostabilisation**

Dense populations of tubicolous fauna can stabilise an otherwise mobile sediment and increase deposition of fine material, by mechanisms of indirect stabilisation. However, when the density of the tubes is lower than a certain value, the presence of tubes has the opposite effect and increases the bottom erodibility. The effects of sparse tubes then become comparable to the sediment destabilising effects of isolated roughness elements. Eckman et al. (1981) provide a graph in which a threshold line separates the two situations in which tubes have a stabilising or a destabilising effect on the sediment. The line is given as function of tube diameter and tube density (Figure 4.7). The transition between destabilising and stabilising effects occurs when roughly one-twelfth of the surface (8%) is occupied by tubes.

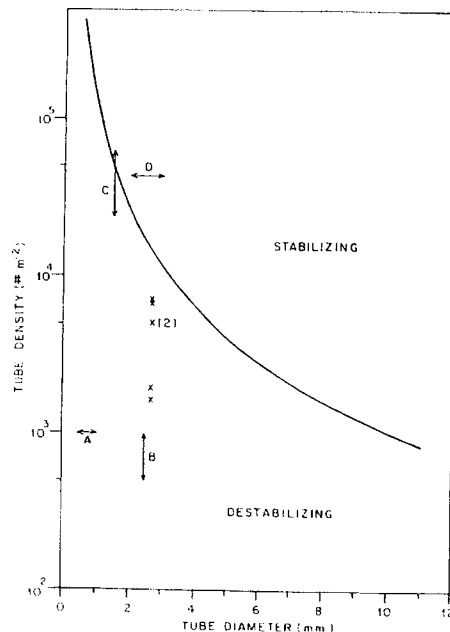


Figure 4.7. Minimum tube density required to stabilise sediment as a function of tube diameter (Eckman et al., 1981).

Eckman et al. (1981) measured the critical shear velocity for transport,  $u_{*c}$  (the higher the critical velocity the less the sediment is erodible) and the relative critical shear stress  $\tau_c$  ( $u_{*c}$  and  $\tau_c$  are related to each other) within the cluster of *Owenia* tubes and compared them with the values of sediment without tubes. With isolated tubes local scour was noted at a shear stress less than 25% the critical shear stress for sediment without tubes (destabilisation). At varying densities (all below the stabilisation line) initial motion occurred at shear stresses that varied among experiments from 23% to 33% of the critical shear stress for motion of sediment without tubes. At all densities tested, general sediment motion occurred at bed-averaged shear velocities significantly less than that required to transport sediments on a bed without tubes (shear velocities 50-62% of the shear velocity for undisturbed bed, for tube densities between 0.504 and 0.694 tubes/cm<sup>2</sup>).

Luckenbach (1986) studied the hydrodynamic effects of *Diopatra cuprea* (a polychaete) tubes on the stability of natural sediments. He observed that sediments which contained tubes had natural macrofaunal densities larger than five times those of sediments without tubes. He concluded that sediment changes due to a richer benthic population around the tubes, rather than alterations of the near-bed flow due to the tubes, are the responsible for the lowering of the erosion thresholds. Combining this result with the results of Eckman et al. (1981), who performed experiments on tubes without an enriched benthic population and found that the tubes alone were already responsible for lower erosion thresholds, it can be concluded, that the effects of low densities of tubes (lowering of the erosion thresholds: destabilisation) are often strengthened by the presence of a richer benthic population around the tubes.

#### Direct biostabilisation (reef builders)

Mussel (*Mytilus edulis*) and oyster reefs protect the sediment from erosion in direct and indirect ways. The shell cover and the anchorages protect the underneath soil from erosion, while the increase of bottom roughness due to the presence of the shells reduces the near-bed velocity and thus the capacity of the current to erode the sediment. However, for low

densities of shells, a sandy soil may become more erodible. This increased bottom erodibility is primarily due to scouring around the clumps of mussels, that act as single roughness elements, just like tubes at low densities.

Widdows et al. (2002) quantified sediment erodibility in relation to current velocity, mussel bed density and the nature of the sediment/substrate by means of laboratory experiments carried out on sediment and bivalves from the mouth of the Exe River (SW England). The lowest  $u_{cr}$  (critical velocity for erosion) were found on sandy substrate for mussel bed densities equal to 25% and 50% (destabilisation). For mussel bed densities higher than 85% the critical velocities resulted higher than in the control case without mussels (biostabilisation). For a cohesive muddy substrate (46% silt) a linear relationship between sediment erosion, current velocity and mussel density had been previously demonstrated by Widdows et al. (1998b). The quantifications of Widdows et al. (2002), in terms of values of the critical velocity as function of mussel bed density, are strongly related to the type of soil used and thus not generalisable, for this reason they are not shown here.

Widdows et al. (2002) conclude that the opening-up of mussel beds and the reduction in density resulting from shell fishing is likely to make mussel beds more vulnerable to erosion by tidal currents and storms, particularly in exposed areas and with a sandy substrate.

#### **Indirect effects on hydrodynamics**

Benthic organisms modify the bottom microtopography and increase the bottom roughness. The highest roughness values are given by mussel and oyster beds and clusters of tubes. No quantifications were found in the literature studied.

### 4.2.3 Microbenthos

#### Introduction

Microbenthos consists of microphytobenthos (microalgae), fungi, and bacteria. Some aspects of the influence of bacteria and fungi on sediment properties can be found in a review by Paterson (1997). This study focuses, however, on the effect of diatoms on sediment stability.

#### Sediment stability

The stability of a sediment surface, or erosion resistance, can be measured *in situ* or in laboratory. In the latter case sediment samples are collected from the field and brought as intact as possible to a laboratory. Several devices have been developed to measure erosion resistance directly in the field: Kornman and De Deckere (1998) use an *in situ erosion flume* (described in detail in Houwing, 2000), Widdows *et al.* (2000b and 1998b) use an *annular flume* (described in Widdows *et al.*, 1998a) and Underwood & Paterson (1993a and 1993b) use a *cohesive strength meter* (described in Paterson, 1989). Comparison of four types of *in situ* measurement equipment can be found in Tolhurst *et al.* (2000), who conclude that the erosion thresholds measured by these instruments are comparable, but the amount of material which is eroded differs, depending on the duration of induced shear stress steps. In general, once the algal film has been removed by the current (e.g. when  $U_{crit}$  has been exceeded), sediment erosion of the subsoil rapidly increases (Underwood and Paterson, 1993a; Widdows *et al.*, 2000a).

Diatoms secrete extracellular polysaccharides (EPS), which increase the cohesion of sediment, favours the deposition of fine particles and protects the soil against erosion (Herman *et al.*, 2001; de Brouwer *et al.*, 2000). Although diatoms enhance sediment stability, there is a balance between stabilisation by these algae and bio-destabilisation by bioturbating and deposit feeding species that feed on microphytobenthos (Herman *et al.*, 2000; Widdows, 2000a). In addition, the presence or absence of macrofauna is also by itself important for the resulting soil erodibility (Underwood and Paterson, 1993a; Kornman and De Deckere, 1998). Underwood and Paterson showed this by measuring the shear strength over a period of one week at a site where diatoms and macrobenthos had been killed. At this site the sediment erosion resistance was considerably higher than at the control site. They concluded that it is the total benthic community that determines the physical properties of the bed. These findings are summarised in Table 4.4.

Table 4.4 Mean shear strength and standard deviation of sprayed (with poison) and control site, measured with a "Pilcon shear vane" (Underwood and Paterson, 1993a).

Day	Sprayed site		Control site	
	Mean (kN m <sup>-2</sup> )	SD	Mean (kN m <sup>-2</sup> )	SD
0	2.9	0.14	1.0	0.28
1	2.43	0.15	0.85	0.1
2	2.35	0.5	0	0
3	2.57	0.37	1.05	0.31
4	2.83	0.54	1.46	0.10
5	2.53	0.54	0.58	0.14
6	2.18	0.48	0.83	0.29
7	2.72	0.42	0.73	0.32

Another important aspect to take into account when studying sediment stability are spatial and temporal variations. For example, the diatom distribution over the surface of a flat may be patchy and may change considerably in time (De Brouwer *et al.*, 2000).

The work of Van de Koppel *et al.* (2001) deals with the study of a positive feedback between diatoms growth and silt content in sediment using a simple mathematical model, tested against both experimental and field data. The results of this relevant work can explain the difficulty to predict diatom presence for a certain range of values of shear-stress or silt content, difficulty already pointed out by other researchers (Crosato *et al.* 1999, Thoolen *et al.* 1997). In fact, according to Van de Koppel *et al.*, with the same environmental conditions two equilibrium configurations are possible: a high diatoms density together with a silt-rich soil or a low diatom density together with a sand-rich soil. This may explain the patchy distribution that is often observed for diatoms.

Widdows *et al.* (2000b), Austen *et al.* (1999) and Underwood and Paterson (1993b) found that erodibility of the flats surface increases with increasing bed level (lower diatoms densities). The results of Underwood and Paterson are shown in Table 4.5. In this table also the difference between a treated site (weekly biocide spraying) and a control site is shown.

Table 4.5 Data from the biocide treated and untreated sites at Aust (Underwood and Paterson, 1993b)

Shore position	Shear strength (kN m <sup>-2</sup> )				Significant difference? t-test	Critical shear stress (N m <sup>-2</sup> )				Significant difference? t-test
	Treated		Control			Treated		Control		
	mean	SD	mean	SD		mean	SD	mean	SD	
Upper	1.96	0.89	1.18	0.56	Yes P<0.05	2.9	1.9	2.7	1.2	No P>0.76
Middle	1.67	0.77	0.82	0.53	Yes P<0.01	1.7	0.8	2.0	1.3	No P>0.58
Lower	0.74	0.66	0.33	0.55	No P>0.12	1.0	1.2	1.1	1.3	No P>0.86

Temporal variation in diatom biomass (Stapel and De Jong, 1998) affect sediment stability on a seasonal scale (Kornman and De Deckere, 1998). Quantitative results of these seasonal variations are shown in Tables 4.6 and 4.7. However, variations in erosion resistance are not determined by diatoms only.

Table 4.6 Erosion thresholds measured by Kornman and De Deckere (1998)

Date	Average erosion threshold (Nm <sup>-2</sup> )
Beginning of March	0.2
Around 23 April	0.5
22 May	0.6
End of June	0.1
July	0.1

Table 4.7 Characteristics from Widdows *et al.* (2000a)

Site	Mass eroded at 30 cm s <sup>-1</sup> (g m <sup>-2</sup> )	E <sub>max</sub> at 30 cm s <sup>-1</sup> (g m <sup>-2</sup> s <sup>-1</sup> )	E <sub>mean</sub> at 30 cm s <sup>-1</sup> (g m <sup>-2</sup> s <sup>-1</sup> )	U <sub>crit</sub> (cm s <sup>-1</sup> )
<b>Ecoflat 1: May-June 1996</b>				
1	65 ± 11	0.28 ± 0.05	0.045 ± 0.005	28.2 ± 1.6
2 ( <i>in situ</i> )	-	0.04	-	~ 30
2	29	0.10	0.03	27.9
3	6.8	0.05	0.01	34.6
5	39.5	0.43	0.03	27.2
<b>Ecoflat 2: August-September 1996</b>				
1	2068 ± 98	6.02 ± 0.31	2.00 ± 0.32	11.95 ± 0.9
2	390 ± 73	1.67 ± 0.44	0.33 ± 0.05	15.3 ± 0.9

3	457 ± 91	2.15 ± 0.14	0.51 ± 0.14	19.2 ± 0.1
3 <sup>a</sup>	216	0.60	0.20	20.3
5	943 ± 154	7.49	1.08	13.7 ± 0.9

$E_{max}$  = maximum erosion rate

$E_{mean}$  = mean erosion rate

$U_{crit}$  = velocity at which SPM concentration > 50 mg l<sup>-1</sup>

#### 4.2.4 Macro-algae

The impact of macro-algae on the physical environment can, in principle, be described using the same formulations as proposed for emerged and submerged macrophyte vegetation. However, the typical characteristics of macro-algae, such as: density of individuals, leaf area and stiffness, will change the interaction with currents and waves. In addition, given the extreme suppleness and large area of the leaves, it can be expected that the underneath sediment (if the density of macro-algae is large enough) is protected from currents. Another impact is the smothering of bottom species after coverage of the sediment surface with macro-algae.

#### 4.2.5 Combined effect of different types of biota

To test the importance of biotic effects on sediment transport over a tidal cycle, Wood (2000) developed a one-dimensional model to simulate the impact of densities of *Macoma baltica* (bioresuspension) and of microphytobenthos (biostabilisation) on cross-shore water and sediment movement, including resuspension and deposition processes. *Macoma* feeds on microphytobenthos, thus high densities of *Macoma* usually correlate with low densities of microphytobenthos and vice-versa.

The model of Wood was meant as a tool for experimental investigation and not a predictive one for a particular area. The erosion threshold (critical shear stress) was taken as a linear function of surface *chlorophyll* concentrations, which she considered as an indicator of microphytobenthos (based on the observations in the Western Scheldt by Widdows et al. (2000a). The population densities of *Macoma* and microphytobenthos were assumed spatially variable.

The modelling of the effects of *Macoma baltica* on resuspension rates and soil erosion was based on the studies performed by Widdows et al. (1998 a and b) and Willows et al. (1998) in laboratory and in the field.

The model was applied to the Spurn Bight and the Mersey. The levels of tide heights, biota densities and external sediment levels were investigated. Wood did not study the effects of wind waves, of surges and cycles longer than the spring-neap tidal cycle. She concluded that the effect of *Macoma* in combination with that of microphytobenthos on the sediment resuspension increases upper shore deposition and is equivalent to doubling the offshore sediment supply in the model.



## 4.3 Effects of vegetation on hydrodynamics: the experience of WL | Delft Hydraulics

### 4.3.1 Introduction

The effect of vegetation on the run-off of river floodplains and the wave damping capacity of reed have been studied extensively by the river group of WL | Delft Hydraulics. Wave dumping was experimentally studied in view of the possible damage to the river shore of waves generated by large ships. The main findings of this still ongoing research are in line with the results of the literature review as presented above. In this section only those aspects which were not treated in Section 4.2 are highlighted. These concern the principle of scour around (patches of) vegetation and numerical implications of the spatial distribution of vegetation.

A set of experiments were recently conducted in the tidal flume of WL | Delft Hydraulics to study the effect of submerged vegetation on turbidity. The findings were in line with those reported in the literature (Houwing et al., 2000). The results have been used to develop an adaptation of a 1DV (one dimensional vertical) model for water motion and sediment concentration, to simulate the effects of submerged vegetation on the vertical velocity and sediment concentration profiles. This is discussed in Subsection 4.3.4.

### 4.3.2 Scour

The presence of a stem increases the flow velocity close to the stem, which causes local scour. Both scour depth and amount of eroded material may be estimated with scour formulas originally designed for bridge piers and large objects, making a distinction between totally and partially submerged plants and between single stems and vegetation clusters.

For partially-submerged conditions and a water depth larger than twice the stem diameter, the scour near the stems may be determined by (Hoffmans *et al.*, 1997):

$$S = S_e \cdot f(t) \quad \text{with } S_e = 1.5 D f'(u/u_{cr})$$

in which:

S = scour depth at time t

$S_e$  = equilibrium scour depth

D = stem diameter

u = flow velocity

$u_{cr}$  = critical flow velocity

When considering clusters of vegetation, the diameter D in the formula becomes the diameter of the cluster and in that case it may become large when compared to the water depth. When this is true one should use the scour formulas designed for large objects.

If the water depth is less than 0.5 times the diameter then the scour is a function of the water depth (h):

$$S = S_e \cdot f(t) \quad \text{with } S_e = 1.5 h f'(u/u_{cr})$$

For condition  $0.5 < h/D < 2.0$  the scour depth is in between.

When vegetation is totally submerged the water is not only forced to flow around the vegetation, but may also flow over the plants. This probably reduces the scour depth, but quantitative figures for this specific case are not available. The water flow over the vegetation may cause scour downstream of clusters and downstream of larger areas covered with vegetation. In this situation the scour may be estimated by making an analogy with the scour downstream of a sill.

Similar scour equations have been derived for waves, which incorporate wave characteristics, such as significant wave height  $H_s$  and peak period  $T_p$ . Also for combined wave and flow action indications are available on how to estimate the scour.

Recently, experiments have been carried out with a large offshore structure with a height of about half the water depth. This configuration is comparable to a submerged shrub or clumps of grasses.

### 4.3.3 Numerical implications of spatial distribution

The species composition and the spatial distribution of a vegetation field affect the local roughness. An example of a subdivision of 'roughness types' can be found in Verheij (2001), who distinguishes different types of 'ecotypes'. Besides influencing the roughness, the spatial distribution pattern of such a 'roughness type' has also numerical implications. For example, in case of a large grid size it is possible that the vegetation is spread regularly, but also irregularly, with grouping of clusters surrounded by bare land or other irregular planimetric distributions within the same grid-cell.

The current method to account for vegetation in the modelling, used by the Directie Oost (Rijkswaterstaat), is to compute a roughness value as a function of the ratio between vegetated and non-vegetated surfaces (weighted average). However, this method has never been verified. Moreover, the spatial distribution pattern of the vegetation is not accounted for.

Klaassen and Van Velzen (1999) describe a method which deals with the modelling of different spatial distribution patterns. They distinguish types of different spatial distributions (Figure 4.8) and describe a method which takes these patterns into account. They define two different spatial compositions having the least influential and the most influential effect on hydraulic conditions, respectively (parallel/one group and random distribution).

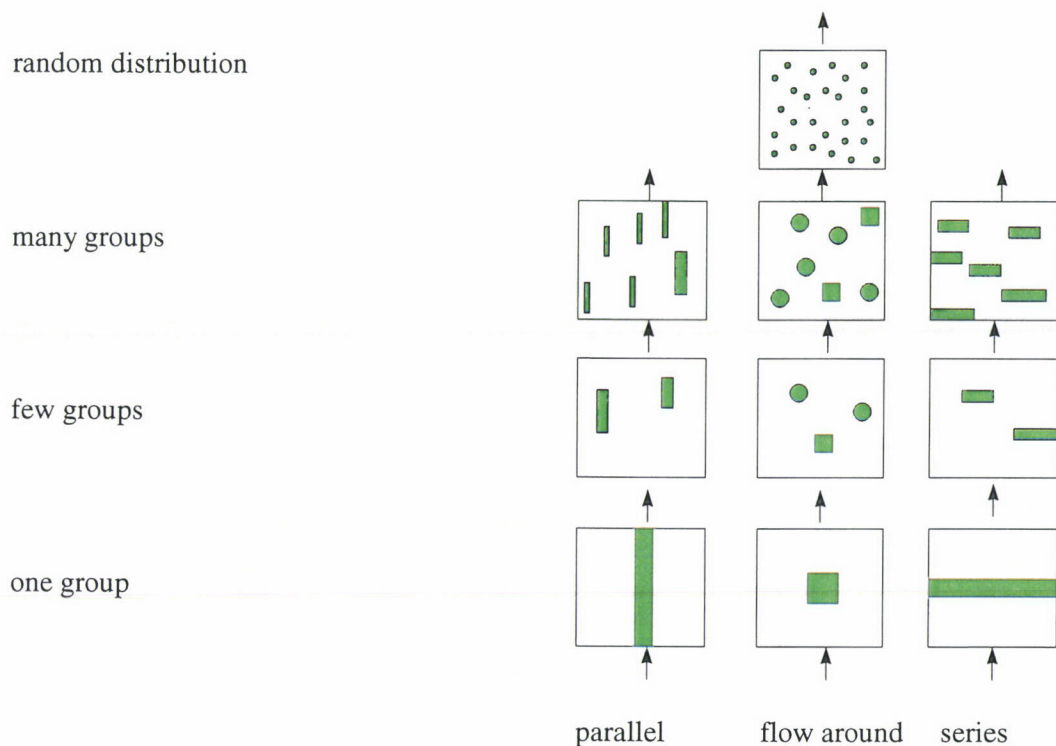


Figure 4.8. Different vegetation patterns (Klaassen and Van Velzen, 1999).

#### 4.3.4 A 1DV-model to simulate the effect of submerged vegetation

In the years 1999 and 2000 a set of flume experiments have been conducted to study the effect of submerged vegetation on water motion and turbidity under several hydraulic conditions, including waves. Plants of different length and flexibility were used. The results were similar to those reported in Section 4.2 (Houwing et al 2000).

To obtain a verified mathematical definition of water and sediment flow in presence of vegetation, an existing one-dimensional vertical model, the '1DV-model', for sediment concentration profiles was adapted to incorporate the effects of vegetation. In the model, the plants are represented by cylindrical stems of a certain length, characterised by a diameter,  $d$ , and drag coefficient  $C_d$ . The latter should have a value close to one, since the plants are assumed to have a cylindrical shape. Vegetation density is incorporated by the number of stems per unit area. The last three parameters are a function of distance from the bottom,  $z$ , and are user-specified.

An extra friction force is added to the momentum equation, so that the flow through the plants results slowed down. Along the vertical this causes an increase of the velocity above the plants, since it is imposed that the discharge remains constant. The effect on turbulence generation and dissipation is incorporated in the 1DV-model by an adaptation of the  $k$ - $\epsilon$ -model that calculates the turbulent mixing.

The adapted 1DV-model has been applied to several data sets with satisfying results (Oberon, 2001). A more extensive description of the model is given in Appendix B.

## 4.4 Summary and conclusions

The literature studied and the experience gained at WL | Delft Hydraulics show that the present knowledge can be used to quantify some aspects of the impact of biota on the local morphodynamics, but much remains still to be done. Most of the times the quantitative values obtained in previous works cannot be generalised and directly applied to the Dutch situation, since they are often strongly dependent on the conditions present in the field, where the measurements were carried out, or in the laboratory, such as the soil composition, the presence of biota, the species and even the hydrodynamic forcing.

Macrophytes and macroalgae can have significant effects on velocity profiles, of which they affect both shape and magnitudes. Next to this, plants influence the production and dissipation of turbulence and wave energy. The magnitude of the effects depends on the plant characteristics: length, stiffness, density and shape. These parameters are mostly unknown and should be assessed by means of a specific research in the international literature, by field or laboratory observations and by means of computational tests. Roots of macrophytes can also have a profound effect on the bottom strength. Moreover, the presence of roots decreases the amount of sediment per unit volume (see Figure 4.9) and the soil density. Depending on the plant species, the scour could also be of importance for the local water flow. In the present study the effects of macroalgae (*Ulva*) are not taken into account.

Benthic fauna affects the hydrodynamics in an indirect manner only, by increasing the bottom roughness. This may cause also a decrease of bottom erosion. A higher bottom roughness lowers the near-bed velocity, the erodibility limit (critical shear stress) remains (almost) the same, but the ultimate effect is that the bottom erodes less.

Direct effects of zoobenthos may be observed at the bottom. Faecal pellets production by filter feeders (mussels and oysters) are a source of new sediment material, since they are aggregates of small particles that would otherwise remain in the water column. The results of some works (ten Brinke, 1993) can be directly used to quantify biodeposition as a function of animal number, animal size, filtering rates and sediment concentrations. Some animals actively move the sediment particles, that end up in resuspension (*Macoma*). The model of Wood (2000) has a promising approach and the results of Widdows et al. (1998 a and b) and Willows et al. (1998) can be used for quantitative estimations of *Macoma* densities and effects.

Feeding and locomotion activities of infauna can result in exposing deeper material to resuspension (vertical mixing). However vertical mixing is disregarded in this phase of the study.

One of the most important mechanisms increasing the erodibility of fine sediments is an increase in porosity. Biogenic reworking alters the particles spatial arrangement of the sediment. Feeding and borrowing activities break up the cohesive structure of silt-clay sediment and counteract compaction. As a result, porosity and water content may increase, compaction and bulk density may decrease. The quantitative values that can be found in literature are strongly site-dependent and cannot be used for the western Scheldt study. For this reason bioturbation should be quantified on the study site by means of field or laboratory observations.

The presence of mussel and oyster beds has a direct stabilisation effect, since the bottom is protected by a coat of shells anchored to each other and to the substrate. However these protection effects are obtained only for high shell densities, for a 25-50% cover the erosion of sandy soils results increased. This is due to the scour produced by the presence of clusters of shells that act as single roughness elements. The same occurs when a bottom is covered by tubes. Findings from international literature can be already used to quantify the effects of tubicolous fauna and mussel beds (Eckman et al. 1981, Luckenbagh, 1986, Widdows et al. 1998b and 2002).

Microphytobenthos (diatoms) has the major effect of stabilising the bottom by gluing the sediment with EPS. The approaches of Wood (2000) and van de Koppel et al. (2001), together with the results of the monitoring campaign of Widdows et al. (2000a), carried in the Western Scheldt, can be used for the modelling and for quantitative estimations.

The next chapter deals with how these effects can be implemented in the Delft3D package to allow for a three dimensional simulation of the impact of biota on the local morphodynamics.



Fig. 4.9. The roots of salt marsh vegetation.

## 5 Modelling the impact of biota on morphodynamics

### 5.1 Introduction

The effects of biota on morphological developments of salt marshes and mudflats in an estuarine system like the Western Scheldt or Wadden Sea can be assessed either by modelling a specific area in the estuary or by studying a schematic case. The latter allows for a better understanding of the effects of biota in more general terms. Modelling a specific area is more suitable for verification of the conclusions drawn from the simplified situation. This reasoning stands at the base of the choice to study the effects of biota in three steps:

1. initial assessment, based on an schematised and simplified case, with emphasis on the relevant processes (computational tests on the micro-scale);
2. parameterisation of the results to be used for larger scale model studies and macro-scale modelling (estuarine cross section);
3. verification of the conclusions drawn on a specific site in the Western Scheldt estuary and, if possible, also on a specific site in the Wadden Sea.

This chapter deals with the way the impact of biota can be implemented in the Delft3D modelling package. Section 5.2 describes the algorithms, while Section 5.3 deals with the model set-up.

### 5.2 Modelling the effects of biota on morphodynamic parameters

The biological components described in Chapter 2 and 4 are subdivided in three major groups:

- 1) Macrophytes. In a large part of the water column there is a direct effect on flow velocity, turbulence and wave propagation. Due to the presence of roots the critical shear stress of the bottom sediments may increase, while at the same time the roots decrease the amount of sediment per unit volume at the top layer. Vegetation has a strong seasonal character (growth, mortality) to be taken into account in the modelling.
- 2) Macrozoobenthos. Depending on the species considered this type of biota has a destabilising or stabilising effect on the bottom. In general the presence of macrozoobenthos increases the bottom roughness, which affects the velocity profile and the local sediment transport. Suspension feeders enhance biodeposition: they filter the fine particles in suspension and release them lumped in faeces on the bottom. Reef and tube builders, besides increasing the bottom roughness, at high densities may stabilise the bottom and make it less erodible, at low densities may destabilise the bottom and make it more erodible. Depending on the species considered macrozoobenthic density has a seasonal character (mortality, migration), to be considered in the modelling.

- 3) Microphytobenthos. This type of biota produces stabilising biopolymers (EPS) and decreases the local sediment erodibility. Microphytobenthos has a strong seasonal character (bloom, mortality) and a patchy distribution, both to be taken into account in the modelling.

The algorithms to model the impact of biology on morphodynamics are discussed below.

### 5.2.1 Macrophytes

#### *Effects on velocity*

If one is primarily interested in the effects of macrophytes on the mean velocity and water levels of, for example, a river reach a 2D-approach is sufficient. In this case the effects of vegetation can be simply incorporated in the bottom roughness, represented by, for instance, the Chézy-coefficient. Klopstra et al. (1987) developed an analytical expression for the flow velocity through and above the vegetation. The value of the Chezy coefficient to be applied can then be derived from the vertical velocity profile. This Chezy value can be transformed into a 'Nikuradse roughness length' to be used as input parameter for the Delft3D model.

The disadvantage of this approach for a three-dimensional computation is that the extra resistance introduced to reproduce the effects of vegetation would negatively affect the modelling of the cells close to the bottom. Moreover, the increased bottom roughness appears in the sediment transport calculations too. These are based on the assumption that the bottom consists of sediment only and consequently an increased bottom roughness would result in an overestimation of the transported sediment. The vertical velocity profile computed with this roughness value would not be correct, the velocity at the bottom would be too high with respect to the velocity between the plants and that above the plants too low. To avoid this disadvantage it is necessary to differentiate between the bottom roughness ( $\tau_{bed}$ ) and the roughness caused by the presence of the plants ( $\tau$ ).

To study the impact of biota on the estuarine morphodynamics it is necessary to model salt marsh processes accurately and therefore the sediment transport should be simulated as good as possible. This means that the described 2D-approach is, for the purpose of this study, not sufficient. The choice is therefore that of implementing a routine to incorporate vegetation in the three-dimensional model Delft3D, instead. This is obtained by adapting the vertical flow distribution and turbulence according to the already tested 1DV-model approach, as discussed in Section 4.3.4.

#### *Effects on waves*

Next to the effects on flow velocity and turbulent mixing, vegetation causes wave damping and general energy dissipation (Tánczos and Cornelisse, 1999, Verheij et al. 1994 and 1995). The module Delft-3D-WAVE computes wave height and wave energy spectrum for every grid-cell. Energy dissipation is obtained by adding the bottom dissipation due to the combination of orbital flow and currents to the dissipation due to wave breaking. To derive the dissipation by wave breaking, the bottom height has to be adapted to include the presence of the plants. To increase the energy dissipation at the bottom the wave friction coefficients  $c_{fw}$  and  $c_{fc}$  can be increased at those locations where vegetation is present.

The information from the wave module is transformed into a time-averaged flow. Implementing the 1DV-model adaptation would therefore properly model the effect of vegetation on the net flow due to waves and currents. However, the peak orbital velocity and excursion,  $U_8$  and  $A_8$ , respectively, as used in many sediment transport formula, are derived as a function of wave height, wave length and water depth, without taking into account the presence of vegetation. Since these are important parameters for the calculation of the both bed load transport of non-cohesive sediment and the reference height to be used in the suspension transport, it is necessary to change the numerical procedures so far adopted to properly include the effects of vegetation. The correct approach for this has to be further investigated.

### ***Critical shear stress***

The enhancement of the critical bottom shear stress for sediment motion due to the presence of vegetation has to be accounted for as well. For cohesive sediment this aspect is relatively easy to implement, since the critical shear stress for erosion is an input parameter in Delft3D. The same is true for the parameter that determine the deposition rates, the critical shear stress for deposition.

For sand the critical shear stress is determined as a function of the sediment characteristics and cannot be altered via an input parameter. In this case, to incorporate the effects of plants, an option is that of adding a coefficient with a value larger than unity to the algorithm. It could be that for unidirectional flow conditions, when the flow velocities inside a vegetation field are very low, this addition has a negligible effect on the morphological calculations. However, when waves are present the consequences may be more relevant. Therefore this option remains a point for further study.

### ***Bottom***

Roots of plants may change the bottom porosity, either by effecting the packing or by 'taking in the place of sediment' (see figure 4.8). The latter can be accounted for in the model by adapting the input parameter that represents the initial sediment mass at the bed per unit area. To simulate a looser packing this has to be accompanied by a lower threshold for motion or a larger erosion rate.

On a larger time scale the dead plant material may also change the composition of the bottom.

## **5.2.2 Macrozoobenthos**

The presence of macrobenthic species in the Westerschelde can be assessed on the works of Ysebaert et al. (in press), Crosato et al.(1999) and Herman et al. (2001), using the data measured and analysed in the framework of the projects BEON, ECOFLAT (E.U. Environment and Climate Programme: ENV4-CT96-0216) and INTRMUD(E.U. Mast3 Programme).

### ***Hydrodynamics***

The effect on the hydrodynamics of macrozoobenthos can be modelled by increasing the bottom roughness. However, this may cause a problem in the sediment transport modelling



as already discussed above. A possible solution is to decrease the value of the sediment mass per unit area or increase the porosity of the bed (both in input) at the same time.

### ***Biodeposition***

Direct biodeposition by filter feeders (mussels, oysters, cockles) can be modelled as extra sedimentation source, since it concerns only those suspended particles that would not deposit otherwise. This may be achieved by careful calibration of the critical shear stress for deposition. However, this should be further studied. Rates of biodeposition can be derived from literature (see Chapter 4).

### ***Bioturbation and biostabilisation***

Bioturbation and biostabilisation are important effects of the presence of reef and tube builders. Densities of mussels higher than 85% cover and of tube builders higher than 8% cover stabilise the bottom, lower densities have the opposite effect. These effects can be taken into account by locally changing the critical shear stress for erosion, which is an input parameter.

For the quantification of bioturbation due to *Macoma baltica* a possible approach is that adopted by Wood (2000) (Section 4.2.5), who calculated the erosion rates as a function of velocity (shear stress) and *Macoma baltica* densities.

## **5.2.3 Microphytobenthos**

As mentioned above the stabilising effect of microalgae can be modelled by an increase in the critical shear stress for erosion as a function of algal biomass. The latter can be related to the surface *chlorophyll* concentration. Wood (2000) and Blauw et al. (personal communication) used this approach in the ECOFLAT project, with good results.

Another promising approach is that adopted by van de Koppel et al. (2001).

## **5.3 Model set-up**

As mentioned in the introduction of this chapter, in the next phases of this study the impact of biota on the estuarine morphodynamics will be assessed in three steps.

### ***First step: micro-, meso scale<sup>1</sup> study***

The modelling will start with the reproduction of vegetation-current-wave interactions at the scale of a laboratory experiment. This first step will utilise data available from an experiment executed in the wave-current flume of WL | Delft Hydraulics.

As a next step the modelling will focus on the functioning of a single gully and adjacent salt marsh plants, starting with a micro-scale study (grid-cell size of tens of centimetres). Since a salt marsh contains channels of different orders and sizes, the model study will be conducted for increasing grid sizes, where the results of the smaller ones will be parameterised to be used on the larger scale studies. Zoobenthos and microphytobenthos, mainly located on the mud flat fronting the salt marsh, may also play a role on the morphodynamic behaviour of the salt marsh, therefore computational tests will be performed to check their influence at every model scale. The study of the salt marsh

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<sup>1</sup> The adopted definition of the spatial scales is that described in de Brouwer et al. (2001)

functioning needs to be performed first, because it implies changes in the model code: implement the adapted version of the 1DV-model, implement changes to simulate the wave behaviour in presence of vegetation etc.. These changes will be later verified against field data sets.

***Second step: macro-scale study***

The micro-, meso-scale study will be followed by the modelling of the estuarine morphodynamics at the macro-scale taking into account the effects of the local biota. The macro-scale is the typical spatial scale of a complete intertidal flat and of the estuarine cross section (the cross-section typically includes the salt marsh, the mudflat in front of it and the main estuarine channel). For the study of the impact of biota at the macro-scale the model will also include the effects of zoobenthos and microphytobenthos, which may be important for the morphodynamic behaviour of the mudflat and of the salt marsh. The scenarios studied will differ from each other on the presence/absence of specific ecotopes (upper salt marsh, low dynamics intertidal flat etc.), of certain biological populations and on the climatic and hydrodynamic conditions considered (ordinary summer conditions, storms etc.).

***Third step: verification***

Finally the conclusions resulting from the micro-scale and the macro-scale studies will be tested on a specific site in the Western Scheldt or Wadden Sea.

In the next section the model set-ups to be used in these different steps are discussed.

**5.3.1 Micro-, meso-scale simulations**

As discussed above, the channels form an important part of the salt marsh. Figure 2.6 shows that they form a more or less regular fractal-like pattern. Although the dimensions vary, the overall shape is more or less the same. To study the processes the model set up as shown in Figure 5.1 will be used.

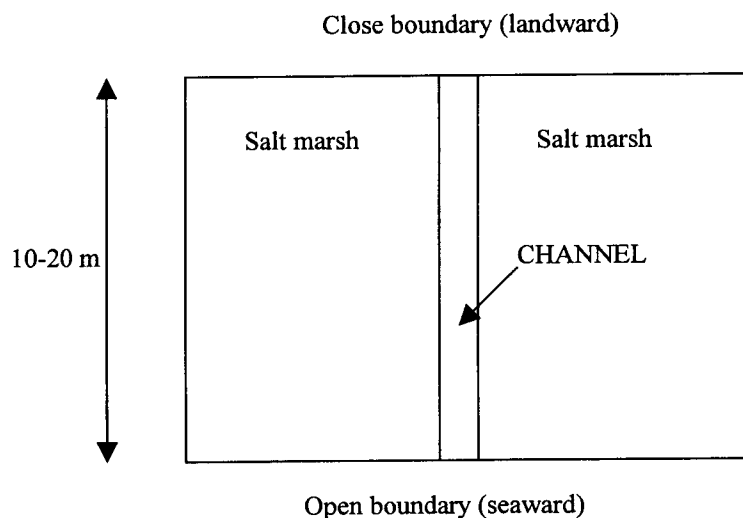


Figure 5.1. Model set up for simplified case.

The spatial resolution of the study is an important computational parameter: low resolution means use of a large computational grid and high resolution implies a small computational grid. The size of the grid determines which are the processes and features that can be detected and studied with the computational tests.

To account for the range in channel width the computational grid size should be adapted. For the smallest channels (see Figure 2.2) the computational cell will be in the order of  $10 \times 10$  cm and the total size of the study area no more than  $10 \times 10$  to  $20 \times 20$  meters. For the larger channels this will be an order of a magnitude larger (meso-scale study).

### 5.3.2 Macro-scale scale simulations

Once the study of the processes at the micro-scale has been finished, the study will continue at larger scales. The largest scale of this study will be the macro-scale, that is the characteristic spatial-scale of a whole estuarine cross-section. At this scale the total study area of the micro-scale study (side 10-20 m, Figure 5.1) becomes a single computational cell. For this reason some results will have to be parameterised. This means that the working of a typical micro-scale cell (which includes salt marsh vegetation and a gully), with and without biota will be described by some well-defined parameters.

The schematisation of a whole cross-section to model the impact of biota at the macro-scale has to be based on the features present in the Western Scheldt and Wadden Sea. Therefore this Section continues with a short description of the most important characteristic of these Dutch systems.

#### *The Western Scheldt*

In the Netherlands the Scheldt estuary is a multi-channel estuarine system. It is possible to identify several morphological cells, defined by the local residual circulation of flow and sediment circulation. This determines a repetitive pattern of channels and shoals of with two main configurations:

1. In its western part, from Vlissingen to Hoek van Baarland (estuarine sections 5 and 6 according to Jeuken, 2000), the estuary can be defined as a multiple-channel intertidal system, with three/four channels separated by two/three intertidal areas, often crossed by smaller channels. The main channels present a clear hierarchy, in which two main channels can be distinguished.
2. In the reach Hoek van Baarland-border between Belgium and The Netherlands (estuarine sections 1, 2, 3 and 4 according to Jeuken, 2000) the estuary can be defined as a two-channel system, with one central intertidal area, often crossed by secondary channels.

In its Belgian part, from the Dutch border to Antwerpen, the estuary is a single-channel intertidal system, in which large intertidal areas are located only at the inner side of the channel bends. These intertidal areas are drained by branching gullies.

The salt marshes in the Western Scheldt are backed by dikes and erode at their waterside, where they often fronted by a cliff. Usually salt marshes are present at one side of the cross-

section only. The pioneer zone of the salt marshes is absent and the clay-rich low-dynamic intertidal area is very limited.

In the central area of the cross-section there is an intertidal flat, that is often crossed by secondary channels which connect the main channels (Jeuken, 2000). A low-dynamics area, with a clay-rich bottom, abundant macro fauna and microphytobenthos, but sparse macrophytes and macroalgae, is often present in the central part of the intertidal flat.

### *The Wadden Sea*

In the Dutch Wadden Sea several tidal basins can be distinguished as morphodynamic independent entities. They all are tidal lagoons except the Eems Dollard, which is an estuary. A typical section of a single (idealised) lagoon with the Dutch coast at one side and at the other the landward shoal of a Wadden island, is characterised by several channels and intertidal flats. The system is backed by dikes. The intertidal flats between the channels are generally too low to house salt marsh vegetation. When present, at the landward side of the tidal basin salt marshes are artificially protected against erosion by brushwood groins perpendicular to the coastal line. The intertidal areas are incised by a network of branching drainage channels and gullies and for this reason the channels have a clear hierarchy.

In Figure 5.2 a schematised cross-section is depicted containing the typical features of the two systems.

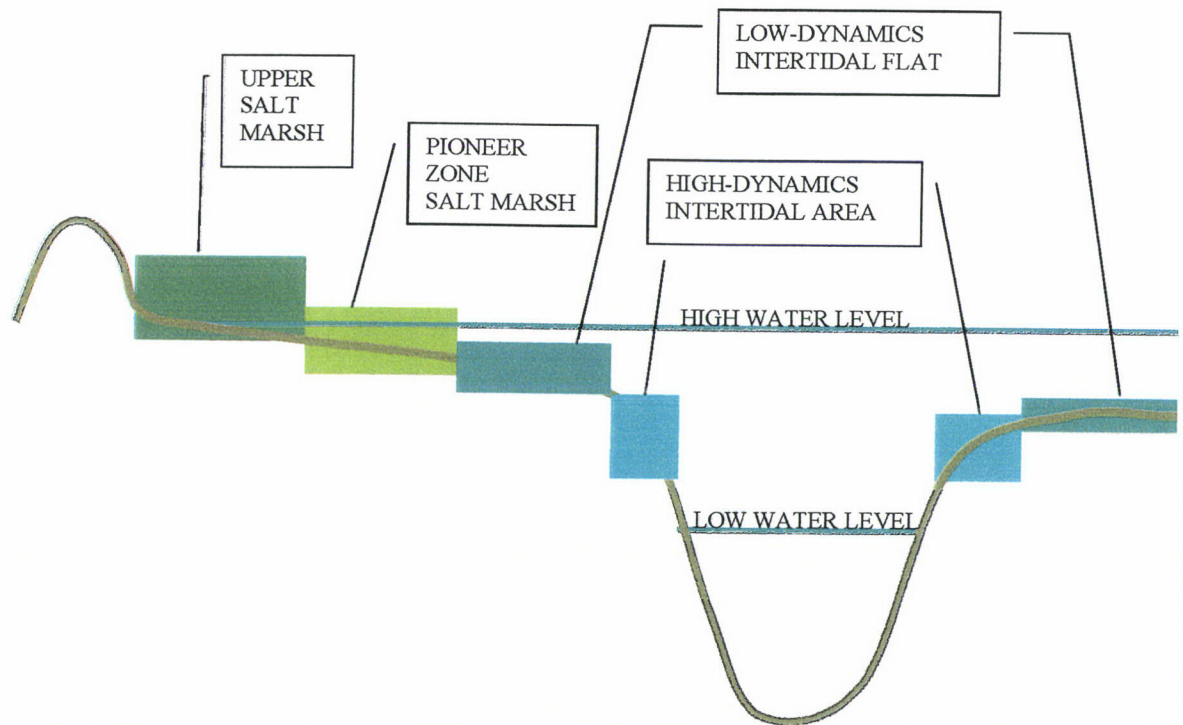


Figure 5.2. Schematised cross section containing the typical elements as occurring in the Western Scheldt and the Wadden Sea.

Due to the model requirements on the imposition of the boundary conditions, the open boundaries should preferably not become dry: to prevent instabilities and numerical artefacts there should be always water flowing through an open boundary. For this reason the boundary opposite to the dike should not be placed on an intertidal area, but in the middle of the channel. Therefore the computational cross-section will be that depicted in

Figure 5.3, in which higher and lower intertidal areas lay at the same side of the channel. Although strongly simplified this cross-sectional unit still retains all the necessary components to study the role of biota on the morphodynamic changes, as well as the interactions between the salt marsh and the intertidal flat at its water front

For a proper assessment of the bio-geomorphological interactions the spatial dimensions of the macro-scale model are important. To avoid influence of the imposed boundary conditions, the study area should be far enough from the boundaries. Also the dimensions of the single ecotopes should be correctly taken into account. They should be based on the findings of previous studies, such as BEON (Wintermans et al. 1995, 1996 and Thoolen et al. 1997), INTRMUD (Crosato et al; 1999), HABIMAP (de Jong, 1999) and ECOFLAT. An example of the subdivision in ecotopes related to inundation time is given in Figure 5.3. Note that more parameters than inundation time only should be taken into account to define position and dimension of the single ecotopes, as for instance water depth, local slope, velocity, local energy dissipation, etc..

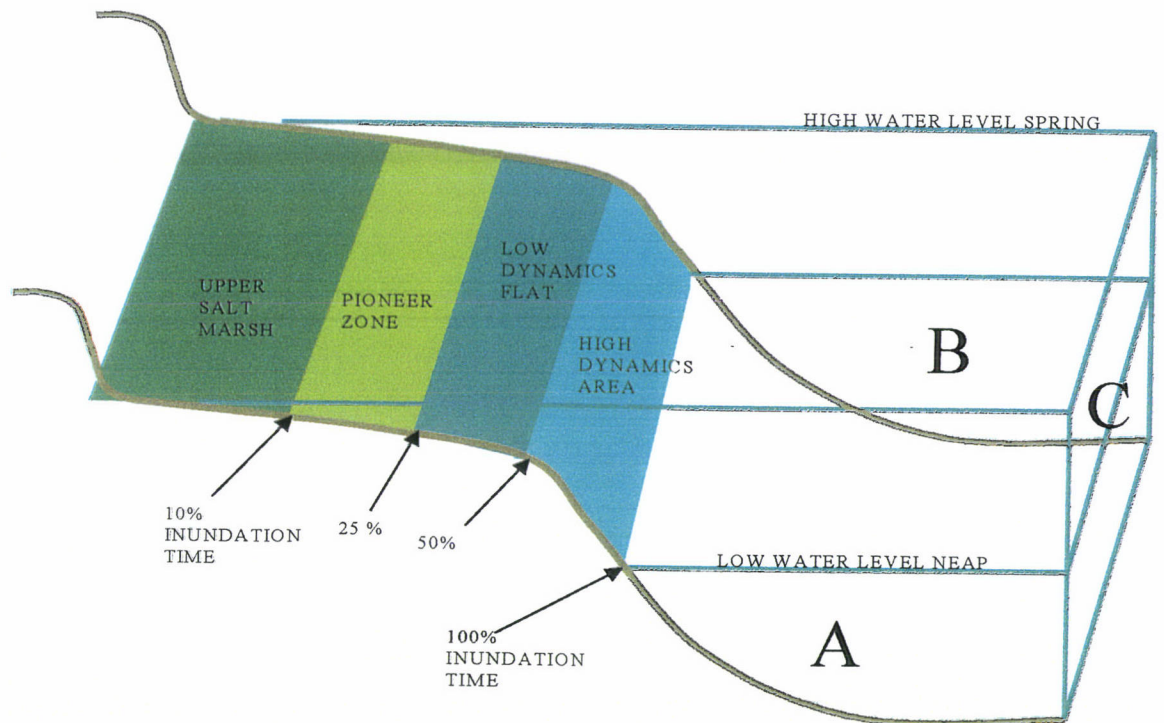


Figure 5.3 Example of a division in ecotopes based on inundation time only.

## 6 Conclusions and outlook

The effects of the three major biological components have to be implemented in Delft3D with different approaches. These are listed below. For all biological components the temporal variations will be based on literature and expert opinion.

### 6.1.1 Macrophytes

To quantify the impact of macrophytes it is necessary to change the code of the program Delft3D, in its parts that describe the hydrodynamics and suspended sediment transport. This will be done by implementing a new routine for the vertical profiles of velocity and sediment concentration, based on the already existing and tested 1DV-model. The waves will have to be treated separately. The verification of the new code requires a large number of data from the field and from the laboratory. For this reason a field campaign on an intertidal area in the Western Scheldt estuary has been planned for the year 2002 (see below). Furthermore also the results of the laboratory experiments executed in 1999-2001, concerning interaction of current, waves and vegetation will be used for the model verifications.

### 6.1.2 Zoobenthos

The effects of the benthic fauna will be modelled, when possible, through existing input parameters. The values to be imposed will be partially derived from the literature and partially from the field and laboratory measurements planned for the year 2002 (see below). The effects of zoobenthos are of different types, these are listed below with the possible approach for implementation.

Resuspension by *Macoma baltica*: the model of Wood (2000) has a promising approach and the results of Widdows et al. (1998 a and b) and Willows et al. (1998) can be used for quantitative estimations of *Macoma* densities and effects.

Bioturbation: the quantitative values on the changes of the soil characteristics due to the presence of biota that can be found in literature are strongly site-dependent and cannot be used for the Western Scheldt. For this reason bioturbation should be quantified on the study site by means of field and laboratory observations.

Increase of bottom roughness by presence of tubes and epifauna (mussel beds, snails): computational tests based on values derived from the literature and expert opinion.

Changes of bottom erodibility due to high or low densities of shells and tubes: findings from international literature can be already used to quantify the effects of tubicolous fauna and mussel beds (Eckman et al. 1981, Luckenbagh, 1986, Widdows et al. 1998b and 2002).

Biodeposition by suspension feeders: biodeposition rates can be computed on filtering or clearance rates, animal number, animal size, sediment concentrations, the values can be derived from the literature (ten Brinke, 1993).

### 6.1.3 Microphytobenthos

The effects of microphytobenthos on the bottom erodibility will be modelled either through input parameters (critical shear stress), using, for instance, the approach of Rose Wood (2000) or by changes in the program code. The comparison between the models of Wood (2000) and van de Koppel et al. (2001) might give an insight on the best approach to follow. This analysis will be carried out in the next phase of the study. The results of the monitoring campaign of Widdows et al. (2000a), carried in the Western Scheldt, can be used for quantitative estimations.

## 6.2 Field measurements

The lack of quantitative data for the verification of the adapted model and for the definition of the values to be imposed to the input parameters show the strong need to carry out measurements. For this reason NIOO-CEMO, RIKZ and WL | Delft Hydraulics will jointly carry out a survey campaign in the year 2002. The study site will be located in the Western Scheldt estuary, but has not been defined yet. The study site will have the following characteristics:

1. sufficient clear zoning of salt marsh vegetation types (including pioneer types);
2. it will be located in area with sufficient wave action;
3. it will present a good development of primary, secondary and tertiary gullies in the salt marsh;
4. it will be located in area with high benthic biomass.

Most important research topics will be:

- how is the salt marsh filled with water during flood;
- how does the salt marsh drain its water during ebb;
- how are the waves attenuated within the salt marsh;
- what are the characteristics of the vegetation of the salt marsh;
- what are the factors affecting sediment transport to and from the salt marsh.

The parameters to be measured are:

- bathymetry and height of the salt marsh area;
- location and profile of the gullies;
- current speed (profiles), wave spectra, suspended sediment at various locations;
- critical shear stresses;
- sediment characteristics;
- ground water level ;
- vegetation height, density and vertical structure;
- benthic biomass and specie composition.

## 6.3 Modelling outlook

The chosen approach to study the impact of biota on the local morphodynamics is the 'bottom-up analysis'. The quantitative assessments will start with the study of the salt marsh functioning at the 'process-scale', which involves the modelling of the

morphodynamic processes that occur among salt marsh vegetation and operate at the micro-scale. A typical micro-scale model grid is of the order of meters with a single computational grid cell of approximately 10 centimetres. This will be first approached by schematisation of a known laboratory experiment. After that an 'idealised' field case will be defined at the same spatial scale. The next step is then that of scaling-up effects and processes for studies on larger scales, for which a single grid cell may have the size of the whole micro-scale model. The larger-scale studies will also account for the effects of microphytobenthos and macrozoobenthos. These studies will utilise the data obtained from the field.



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## A Relevant meetings

### Main results of the Workshop held on August 27<sup>th</sup>, 2001

The project “Quantification Biomorphological Variables Westerschelde” (Z2837) started with a workshop held on August 27<sup>th</sup> 2001 at WL | Delft Hydraulics. The aim of the workshop was that of identifying the biological components that mostly affect the local morphodynamics, with particular interest in zoobenthos and microphytobenthos.

The workshop consisted of introductory presentations followed by a brainstorm session on the question: “how to quantify the effects of biota (benthos and vegetation) on the estuarine morphodynamics”. This question was relevant, since an important goal of the project is to model these effects with a process-based computational model.

An important message of the experts present was: ‘start simple and try to identify the principal components of the system channel-intertidal flat-salt marsh, step by step’. As a result of all discussions, a table, listing the influence of the different biological components on the morphodynamics, was constructed at the end of the meeting, that is summarised in Table A.1.

Table A.1 The influence of biological groups on abiotic parameters

	roughness/ boundary layer	grain size	critical shear stress	sediment porosity	sedimentation
bioturbators	+		--	--	
grazers (diatom eaters)			-		
stabilizers (diatoms)	+		++	-	+
suspension feeders		+	--	+	++
reef builders (mussels)	+	-	+	-	+
macrophytes (sea grass)	+	-	++	++	+
salt marshes	+	-	++	++	++
macroalgae	+		++		

+ = increase

- = decrease

The experts who attended the workshop are listed in the table below.

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### Meeting on the modelling of vegetation, Yerseke 7<sup>th</sup> of december

At this meeting the set up for the modelling of saltmarsh vegetation was discussed. To get a good idea of the setting, an excursion to two saltmarshes formed an important part of the meeting.

A saltmarsh is formed by a system of channels crossing (mud)flats at different scales and having a fractal character. The smallest channels are no more than 20 to 30 centimeter in width, while the largest can be as wide as 1 to 2 meters. There is a negative correlation between width and depth: the smaller channels have smaller width-to-depth ratios.

The vegetation pattern is patchy at the edges of the saltmarsh and rather dense closer to land. However, open spaces covered with a thin layer of water are found there as well. Along the channels cliffs may be observed. It could also be observed that the roots form a significant part of the bottom. Sediment is deposited along the channels forming a somewhat elevated edge.

In the summer a thick mud layer builds up on the unvegetated parts of the salt marsh. This sediment is transported on to the rest of the marsh when the water levels rises, after summer.

During the meeting discussions it was decided to start the study of biotic and abiotic processes on a very schematised, 'academic', saltmarsh plot, at the micro scale. This means a small gully surrounded by a mudflat with vegetation on it, total size of the plot some tens of meters, computational grid size tens of decimeters. The aim of studying the processes on such a small system is to better understand all phenomena controlling the salt marsh functioning (biotic and abiotic). The results of the micro-scale study can be later parameterised and used for larger-scale studies. The largest spatial scale studied, at the end of this upscaling process, will be the macro-scale. This is the scale of the cross-section and of a complete salt marsh, including the bald mudflat front and the main estuarine channel.

The people present at the meeting are listed below.

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## B Model adaptation to include vegetation

### Adaptation of Delft3D to include the effects due to the presence of vegetation

A numerical 1DV model for flow in and above vegetation was developed by *Stelling, Van Kester* and *Uittenbogaard* of WL | Delft Hydraulics. Their model is based on the DELFT3D model equations and additional formulations for flow through plants were added.

Additional parameters for plants are:

- Drag coefficient,  $C_D(z)$
- Typical diameter of branches or stems,  $\phi(z)$ ;
- Number of cross sections of stems or branches per  $m^2$ ,  $n(z)$ .

These parameters are all dependent on  $z$  and can be defined for each vertical layer of the model. This allows for multiple bifurcation of vegetation, as in a tree, by adjusting the number of cross sections, the diameter of stems and the drag coefficient (leaves) per depth-layer.

The model uses the specific plant area  $A_p$  per  $m^2$  horizontal cross section, i.e. dimensionless:

$$A_p(z) = \frac{\pi}{4} \phi^2(z) n(z) \quad . \quad (1)$$

This specific area is used to compute the  $z$ -dependent flow velocity  $u(z)$  spatially averaged over the cross section occupied by water in between the vegetation ( $1-A_p$ ) in the momentum equation.

The user specifies the depth-averaged horizontal velocity  $U$ . The current  $U$  is interpreted as flow rate and the computation tends to satisfy:

$$U = \frac{1}{d + \zeta} \int_{-d}^{\zeta} \{1 - A_p(z)\} u(z) dz \quad , \quad (2)$$

with the bed at  $z=-d$  and free surface at  $z=\zeta$ . Consequently, the  $z$ -dependent velocity  $u(z)$  in (2) is the velocity, spatially averaged over the cross section occupied by water in between the leaves, stems or branches.

The following drag force is added to the momentum equation for  $u(z)$ :

$$F(z) = \frac{1}{2} \rho_0 C_D \phi(z) n(z) |u(z)| u(z) \quad [N / m^3] \quad , \quad (3)$$

per unit fluid volume and using reference density  $\rho_0$ . In the 1DV horizontal momentum equation, the drag force per computational layer of thickness  $\Delta z$  therefore equals  $F(z)\Delta z$ .

Eq. (3) is based on turbulent flow or wakes downstream of each stem/branch/leaf. Eq. (3) is not applicable to laminar flow (should be linear then). In principle,  $C_D$  depends on the Reynolds number related to the stem diameter but it is questionable whether details of the shape of the stems or leaves are well known for determining  $C_D$  accurately. Here we expect tuning and sensitivity analysis by the user.

Likewise, the effective height of the plant is flow dependent because of the drag forces bending the stems, tending to align them into flow direction. In principle, this bending can be accounted for simply by solving the static equations for the force balance on a thin rod subjected to (3) while using the elasticity modulus of the rod. Again the question is whether the rigidity of the stems can be estimated?

Presently, it is assumed implicitly that the bending of stems is incorporated in input or the stems are considered as infinitely rigid.

Similar to (2), the specific area  $(1-A_p)$  occupied by fluid is considered as representative for the possibly  $z$ -dependent cross sectional area that is available for the vertical exchange of horizontal momentum, turbulence-properties, sediment etc. Consequently,  $(1-A_p)$  appears in the vertical exchange of horizontal in the following 1DV momentum equation:

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} = \frac{\rho_0}{1-A_p} \frac{\partial}{\partial z} \left\{ (1-A_p)(\nu + \nu_T) \frac{\partial u}{\partial z} \right\} - F \quad (4)$$

In (4), the horizontal pressure gradient is adjusted such that (2) is satisfied i.e. including the  $z$ -dependent specific area  $(1-A_p)$ .

For the 1DV model, the equation for Turbulent Kinetic Energy  $k$  simplifies to

$$\frac{\partial k}{\partial t} = \frac{1}{1-A_p} \frac{\partial}{\partial z} \left\{ (1-A_p)(\nu + \nu_T / \sigma_k) \frac{\partial k}{\partial z} \right\} + T + P_k - B_k - \varepsilon \quad (5)$$

in which appears again the specific area  $(1-A_p)$  of fluid but also the additional turbulence source term  $T$ . The remaining terms are production  $P_k$  by velocity shear, dissipation  $\varepsilon$  and conversion  $B_k$  into potential energy. The source term  $T$  equals the power spent by the mean flow due to work against the drag force  $F$  i.e.

$$T(z) = F(z)u(z) \quad (6)$$

In (6) and (3), laminar effects are neglected i.e. all work done by the mean flow is transferred into turbulence without notable direct viscous dissipation.

Similar to (5), the following equation for dissipation rate  $\varepsilon$  in the  $k$ - $\varepsilon$  model is expressed by

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{1-A_p} \frac{\partial}{\partial z} \left\{ (1-A_p)(\nu + \nu_T / \sigma_\varepsilon) \frac{\partial \varepsilon}{\partial z} \right\} + T \tau^{-1} + P_\varepsilon - B_\varepsilon - \varepsilon \quad (7)$$

in addition to the usual terms appears source (6), now divided by dissipation time scale  $\tau$ .

This dissipation time scale depends on the size  $L(z)$  of the eddies generated by, or limited in size by the smallest distance between the stems:

$$\tau = \frac{1}{c_{2\varepsilon}\sqrt{c_\mu}} \left( \frac{L^2}{T} \right)^{\frac{1}{3}}, \quad (8)$$

Note that for smaller  $L$  the dissipation time scale reduces and increases dissipation and reduces turbulence levels. The increased dissipation can be understood by the truncation of the largest turbulence length scales to the size controlled by the distance between stems. Finally, this length scale  $L(z)$  is related to the typical horizontal grid size of the fluid between the stems and/or mutual distance between plants through:

$$L(z) = c_l \left\{ \frac{1 - A_p(z)}{n(z)} \right\}^{\frac{1}{2}}, \quad (9)$$

where  $c_l$  is a coefficient reducing the geometrical length scale to the typical volume-averaged turbulence length scale. For channel flows with the expression between brackets replaced by the channel width and with a parabolic profile for the mixing length then  $c_l \approx 0.07$ .

Of course,  $n(z) > 0$  must hold. Expression (9) is an approximation: rigid stems or grids are assumed. In case of turbulence downstream of a single grid or screen and at roughly 10 mesh sizes downstream of the grid, the initial length scale  $L$  equals roughly the grid's mesh size. If the stems are very thin then their individual wakes, provided these still exist despite viscous effects, will not merge and then (9) is not applicable. In other words, for exceptional cases, closure (9) is subject to improvements.

Finally, the 1DV equation for mass concentration of particulate matter with rising velocity  $w_s$  reads:

$$\frac{\partial c}{\partial t} + \frac{1}{1 - A_p} \frac{\partial}{\partial z} \{ (1 - A_p) w_s c \} = \frac{1}{1 - A_p} \frac{\partial}{\partial z} \left\{ (1 - A_p) (D + \Gamma_T) \frac{\partial c}{\partial z} \right\} \quad (10)$$

The result is a 1DV model that is able to compute vertical profiles for velocity  $u(z)$ , turbulent kinetic energy  $k_t(z)$ , turbulent dissipation  $\varepsilon(z)$  and eddy viscosity  $\nu_t(z)$ .

## C Literature review

**Austen, I., T.J. Andersen, K. Edelvang, 1999. The influence of benthic diatoms and invertebrates on the erodibility of an intertidal mudflat, the Danish Wadden Sea.**

Study site	Lister Dyb, Danish Wadden Sea
Aim of the study	Examine the erodibility of mudflat surfaces governed by physical and biological factors.
Type of study (field measurement, flume study/experiment, modelling)	field measurement
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	macrozoobenthos, microphytobenthos
Species studied	diatoms, <i>Hydrobia ulvae</i> (deposit feeding, surface grazer snail)
Parameters studied	erosion threshold
Temporal scale	No
Information available on spatial scale?	Yes
Quantitative information?	Yes
Relevant for the Westerschelde?	Field conditions can be compared with the Westerschelde
Conclusions	positive correlation between diatom biomass and erosion threshold, negative correlation between diatom biomass and numbers of <i>H. ulvae</i> , negative effect of <i>H. ulvae</i> on sediment erodibility (especially faecal pellets)
Key relationships/algorithms	see figures
Remarks	erodibility of faecal pellets, relationship of diatoms and macrobenthos, many significant regressions

**Daborn, G.R., C.L. Amos, M. Brylinsky, H. Chritian, G. Drapeau, R.W. Faas, J. Grant, B. Long, G.M.E. Perillo, M.C. Piccolo, 1993. An ecological cascade effect: migratory birds affect stability of intertidal sediments.**

Study site	Starrs Point, Minas Bay, USA (av. tidal range 11.5 m, silty-sand: <20% clay)
Aim of the study	determine relative importance of atmospheric, oceanographic and biological factors to sediment erodibility.
Type of study (field measurement, flume study/experiment, modelling)	field measurement
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	microphytobenthos, macrobenthos
Species studied	diatoms, <i>Corophium volutator</i> (grazer, burrowing amphypod), <i>Calidris pusilla</i> (migratory shorebird)
Parameters studied	critical shear velocity
Temporal scale	hours (period of emersion), weeks
Information available on spatial scale?	No
Quantitative information?	Yes
Relevant for the Westerschelde?	Principles described also hold for the Westerschelde (migratory shorebirds)
Conclusions	Short term variations in sediment stability are controlled by diatoms, which increase stability, and grazing macrofauna, which graze on diatoms the first hour after emersion of the flat. Long term sediment stability can only be studied through comprehensive, interdisciplinary field studies, since (many) biological factors play a role.
Key relationships/algorithms	
Remarks	Emphasises the importance of a biological cascade of primary producer-grazer-predator and the effect on sediment stability properties.

**Davis W. R. (1993), "The role of bioturbation in sediment resuspension and its interaction with physical shearing":**

Study site	Laboratory tests with field sediment and wild macrobenthic organisms.
Aim of the study	Quantification of bioresuspension.
Type of study (field measurement, flume study/experiment, modelling)	Laboratory tests in an annular flume and a Particle Entrainment Simulator, using silt-clay ( $D_{50} = 0.011$ mm) sediment from Central Long Island Sounds, and organisms from Long Island Sound and Narragansett Bay.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	macrozoobenthos
Species studied	<i>Nicula annulata</i> (bivalve) <i>Yoldia limatula</i> (bivalve) <i>Macoma tenta</i> (bivalve) <i>Mulinia lateralis</i> (bivalve) <i>Crangon septemspinosa</i> (decapod) <i>Nephtys incisa</i> (polychaete) at densities common LIS: 1, 3, 10, 32 individuals per $0.01 \text{ m}^2$
Parameters studied	Concentrations of suspended solids at shear stress levels 2, 3, 4 and $5 \text{ dyne/cm}^2$
Temporal scale	The experiment was conducted at steady-state conditions (usually one hour or less of constant hydrodynamic forcing).
Information available on spatial scale?	No
Quantitative information?	Yes net resuspension as a function of equivalent shear (Figure 7) and in the text.
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	The species tested can be compared with species living in the Dutch waters.
Conclusions	Some quantifications to be used in terms of % increase of resuspension rates.
Key relationships/algorithms	Curves of net resuspension ( $\text{mg/l}$ ) against bottom shear stress ( $\text{dyne/cm}^2$ ) with and without organisms. $qs = R - D$ ; $Rt = Rp + Rpb + Rb$ ( $qs$ = particle flux, $R$ = resuspension rate, $D$ = deposition rate, $Rt$ = total resuspension, $Rp$ = physical resuspension, $Rpb$ = resuspension due to physical-biological interaction, i.e. through altered roughness, $Rb$ = bio resuspension independent from physical shear, i.e. ejected material, fecal material)
Remarks	Nice general scheme on the role of biology in sediment resuspension.

**Eckman, J.E., A.R.M. Nowell, P.A. Jumars, 1981. Sediment destabilization by animal tubes.**

Study site	Laboratory tests
Aim of the study	Study on whether the presence of animal tubes stabilize or destabilize the bottom. Study of sediment erodibility as a function of the density of a tube builder polichaete worm.
Type of study (field measurement, flume study/experiment, modelling)	Recirculating seawater flume using wilde organisms collected from False bay, Washington, and fine sand sediment ( $D_{50} = 169 \mu\text{m}$ ).
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	macrozoobenthos
Species studied	<i>Owenia fusiformis</i> (tube builder polichaete)
Parameters studied	Critical shear velocity: $u_{*c} = (\tau_c/\rho)^{1/2}$ ( $\tau_c$ = critical shear stress, $\rho$ = flow density)
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	Yes initial motion in presence of animal tubes is defined by bed-averaged critical shear stress ( $\tau_c$ ), this is given as percentage of the $\tau_c$ for a smooth bed without animals (Table 1).
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	The general graph provided can be used for the specis common in the Western Scheldt ( <i>Pygospio</i> ).
Conclusions	Low densities of tubes destabilize the sediment, only densities higher than 14500 individuals/m <sup>2</sup> have a bottom stabilizing effect.
Key relationships/algorithms	None.
Remarks	Important graph defining the minimum tube density required to stabilize the sediment: Figure 1. Interesting discussion.

**Ehlers, J., K. Nagorny, P. Schmidt, B. Stieve, K. Zietlow, 1993. Storm surge deposits in North Sea salt marshes dated by  $^{134}\text{Cs}$  and  $^{137}\text{Cs}$  determination.**

Study site	Sylt (Wadden Sea)
Aim of the study	study storm surge deposits by means of identifying shell layers, supported by cesium dating.
Type of study (field measurement, flume study/experiment, modelling)	field measurement
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Salt marsh
Species studied	-
Parameters studied	Sedimentation, subsidence
Temporal scale	decades
Information available on spatial scale?	No
Quantitative information?	No
Relevant for the Westerschelde?	-
Conclusions	Shell layers can be used as indicators for storm surges. Thus the history of sedimentation at salt marshes can be reconstructed.
Key relationships/algorithms	-
Remarks	



**Fonseca, M.S., J.A. Cahalan, 1992. A preliminary evaluation of wave attenuation by four species of seagrass.**

Study site	-
Aim of the study	study wave energy reduction of four species of seagrass and compare with salt marsh vegetation data (?)
Type of study (field measurement, flume study/experiment, modelling)	flume study
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	macrophytes
Species studied	<i>Halodule wrightii</i> , <i>Syringodium filiforme</i> , <i>Thalassia testudinum</i> , <i>Zostera marina</i>
Parameters studied	wave energy, through wave height (using $E = 1/8 \rho g H^2$ )
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	All species, stem lengths and densities gave comparable reductions of wave energy (40% over a one meter vegetation field)
Relevant for the Westerschelde?	All species studied are seagrasses, of which only <i>Zostera marina</i> occurs in the Westerschelde
Conclusions	All species give comparable reduction of wave energy. Plant morphology (shape, flexibility), height (relative to water depth) and density of vegetation should be treated as being equally important.
Key relationships/algorithms	
Remarks	

**Gambi, M.C., A.R.M. Nowell, P.A. Jumars, 1990. Flume observations on flow dynamics in *Zostera marina* (eelgrass) beds.**

Study site	-
Aim of the study	analyse mechanism of flow modification, quantify flow and flux reduction and estimate turbulence intensity
Type of study (field measurement, flume study/experiment, modelling)	flume study, using juvenile plants to create realistic plant to flume dimensions compared to field observations
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	macrophyte
Species studied	<i>Zostera marina</i>
Parameters studied	shear velocity ( $U^*$ ), turbulence intensity
Temporal scale	No
Information available on spatial scale?	Yes, variations at the scale of one meter
Quantitative information?	Yes
Relevant for the Westerschelde?	<i>Zostera marina</i> does occur in the Westerschelde, but is not abundant (found only at one location, see Koppejan, 2000)
Conclusions	velocity profiles in front of and above the canopy were logarithmic. Velocities above the canopy increased, while they dropped within. Differences between densities were not found.
Key relationships/algorithms	
Remarks	

**Graf, G., R. Rosenberg, 1997. Bioresuspension and biodeposition: a review.**

Study site	-
Aim of the study	Quantitative descriptions of biodeposition and bioresuspension.
Type of study (field measurement, flume study/experiment, modelling)	Review
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Macrozoobenthos
Species studied	<i>Mytilus edulis</i> (suspension feeder bivalve) <i>Cerastoderma edule</i> (susp. feeder bivalve) <i>Mya arenaria</i> (susp. feeder bivalve) <i>Nereis diversicolor</i> (filter feeding polichaete) <i>Diopatra cuprea</i> (tube builder) and others
Parameters studied	Indirect bioresuspension Direct bioresuspension Indirect biodeposition Direct biodeposition (due to suspension feeders: musselbeds)
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	Yes Direct biodeposition (Table 1)
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Yes
Conclusions	Organisms can modify particle fluxes by a factor 2 or more.
Key relationships/algorithms	No
Remarks	

**Herman, P.M.J., Middelburg, J.J., Heip, C.H.R., 2001. Benthic community structure and sediment processes on an intertidal flat: results from the ECOFLAT project.**

Study site	Westerschelde estuary, Molenplaat intertidal flat.
Aim of the study	Study the interactions between the benthic community and sediment processes and of benthic food web.
Type of study (field measurement, flume study/experiment, modelling)	Field measurements and modelling.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Zoobenthos and microphytobenthos
Species studied	<i>Arenicola marina</i> , <i>Cerastoderma edule</i> , <i>Macoma baltica</i> , <i>Mya arenaria</i> , <i>Hydrobia ulvae</i> and microalgae.
Parameters studied	Mud content in sediment, sediment resuspension, bottom shear stress.
Temporal scale	Seasonal.
Information available on spatial scale?	From the micro-scale (to be scaled with the water depth) to the scale of the entire flat (meso-scale). Modelling grid size ~ 30 m.
Quantitative information?	No
Relevant for the Westerschelde?	Yes
Conclusions	Microalgal biomass accumulates easlier with increasing mud content in the sediment, the effects of biota on their environment fits the concept of 'ecosystem engineering' (presence of positive feed backs between benthic microalgae and mud sedimentation). Suspension feeders ( <i>Cerastoderma edule</i> and <i>Mya arenaria</i> ) prevalently feed on pelagic micro algae and resuspended benthic algae are not a major component in their diet. Surface grazers ( <i>Hydrobia ulvae</i> ) prevalently feed on benthic microalgae. Deposit feeders ( <i>Macoma baltica</i> and <i>Arenicola marina</i> ) feed on both pelagic and benthic micro algae.
Key relationships/algorithms	No
Remarks	This work is important to understand the interactions between biota and sediment processes, but not for quantifications of bioturbation/biostabilization.

**Kornman, B.A., E.M.G.T. de Deckere, 1998. Temporal variations in sediment erodibility and suspended sediment dynamics in the Dollard estuary.**

Study site	Dollard, Dutch Wadden Sea sediment distribution: 80 to 20 % < 53 $\mu\text{m}$ Nikuradse roughness height: $k_s = 3 \cdot 10^{-4}$ m (i.e. $3 \cdot D_{90}$ ).												
Aim of the study	Study the influence of the biological activity on sediment erodibility in an intertidal setting. The investigation focused on the temporal variations in erodibility and its effect on sediment resuspension from a flat.												
Type of study (field measurement, flume study/experiment, modelling)	Field measurements.												
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Microphytobenthos.												
Species studied	Diatoms.												
Parameters studied	Critical shear stress.												
Temporal scale	Season and year.												
Information available on spatial scale?	No												
Quantitative information?	Yes												
	<table border="1"> <thead> <tr> <th>Date</th> <th>Av. erosion threshold (<math>\text{Nm}^{-2}</math>)</th> </tr> </thead> <tbody> <tr> <td>Beginning of March</td> <td>0.2</td> </tr> <tr> <td>Around 23 April</td> <td>0.5</td> </tr> <tr> <td>22 May</td> <td>0.6</td> </tr> <tr> <td>End of June</td> <td>0.1</td> </tr> <tr> <td>July</td> <td>0.1</td> </tr> </tbody> </table>	Date	Av. erosion threshold ( $\text{Nm}^{-2}$ )	Beginning of March	0.2	Around 23 April	0.5	22 May	0.6	End of June	0.1	July	0.1
Date	Av. erosion threshold ( $\text{Nm}^{-2}$ )												
Beginning of March	0.2												
Around 23 April	0.5												
22 May	0.6												
End of June	0.1												
July	0.1												
Relevant for the Westerschelde?	The Wadden Sea is also situated at the Dutch coastal zone.												
Conclusions	Due to the presence/abundance of diatoms the erosion threshold exceeds the maximum shear stress during summer months, thus preventing erosion of sediment from the flat. During (late) summer the erosion threshold decreased, probably due to the presence of bioturbating and grazing of macrozoobenthos												
Key relationships/algorithms													
Remarks	The influence of a total diatom population on suspended sediment concentrations is suggested.												

**Lee H. II, R.C. Swartz, 1980. Biological processes affecting the distribution of pollutants in marine sediments. Part II: biodeposition and bioturbation.**

Study site	-
Aim of the study	Description of all the biological processes affecting the distribution of pollutants.
Type of study (field measurement, flume study/experiment, modelling)	Review.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	All benthic organisms, classified on feeding, mobility and as epifaunal/infaunal.
Species studied	Many
Parameters studied	Biodeposition: deposition of feces and pseudofeces by filter-feeders; bioturbation of vertical sediment stratification; particle transport; bottom stabilizing processes: microbial binding, tubes, macroalgae, sea grass; erosion and resuspension; fluid transport; biological interactions.
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	Yes
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Table II-biodeposition rates.
Conclusions	Yes
Key relationships/algorithms	In this book biological activity is analysed from the point of view of the distribution of pollutants (in sediment). The conclusion is that the effects of benthic organisms have been up to now underestimated.
Remarks	No algorithms Nice organisation to be adopted Good literature list.

**Leonard, L., M. Luther, 1995. Flow hydrodynamics in tidal marsh canopies.**

Study site	West-central Florida/Southeast Louisiana (USA)
Aim of the study	determine spatial variability of tidal flow speeds in mars canopies, assess the distribution of flow energy, identify variations in the vertical velocity profile
Type of study (field measurement, flume study/experiment, modelling)	field measurements
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	salt marsh vegetation
Species studied	<i>Spartina alterniflora</i> , <i>Juncus roemerianus</i>
Parameters studied	flow speed, turbulence intensity
Temporal scale	No
Information available on spatial scale?	Yes, different species, denities and positions from the creek edge
Quantitative information?	Yes
Relevant for the Westerschelde?	Yes, species are comparable to those found in the Westerschelde
Conclusions	Salt marsh vegetation affects turbulent characteristics at various scales: their presence generates turbulence, but also dissipates energy.
Key relationships/algorithms	turbulence reduction for <i>Spartina alterniflora</i> : $Y = 0.99 * 10^{(-0.0044 * X)}$ turbulence reduction for <i>Juncus roemerianus</i> : $Y = 1.02 * 10^{(-0.0028 * X)}$ with X = plant density and Y = turbulence at the marsh relative to the edge of the creek
Remarks	Article discusses many different aspects of salt marshes, can therefore be used as a nice introduction into the subject

**Moeller, I., T. Spencer, J.R. French, 1997. Wind wave attenuation over salt marsh surfaces: Preliminary results from Norfolk, England.**

Study site	Norfolk, UK
Aim of the study	investigate changes in wave characteristics over a sand flat and an adjacent salt marsh
Type of study (field measurement, flume study/experiment, modelling)	Field measurements
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Salt marsh vegetation: high marsh and low marsh (pioneer zone)
Species studied	No specific species studied, common species at the study site are: <i>Salicornia</i> spp., <i>Spartina anglica</i> , <i>Limonium vulgare</i> , <i>Aster tripolium</i> , <i>Halimione portulacoides</i>
Parameters studied	Turbulence (wave damping)
Temporal scale	minutes
Information available on spatial scale?	Yes
Quantitative information?	Yes
Relevant for the Westerschelde?	Species also occur at salt marshes in the Westerschelde
Conclusions	The tidal flat is important in reducing wave height and wave energy. Reductions over the salt marsh surface were far greater than those over the bare flat.
Key relationships/algorithms	-
Remarks	



**Paterson, D.M., 1997. Biological mediation of sediment erodibility: ecology and physical dynamics.**

Study site	-
Aim of the study	Review on biostabilisation.
Type of study (field measurement, flume study/experiment, modelling)	Review. This review deals with mechanisms for biostabilisation (Table 1) and discusses predictive relationships.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Benthic fauna and flora.
Species studied	Many, in short
Parameters studied	Coefficient of biological stabilisation: % stabilisation increase over control.
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	Yes Table 2 - measured biostabilisation from the literature (bacteria and diatoms).
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Yes
Conclusions	It is only where a single mechanism of biostabilisation is dominant that a single parameter for a biological effect is likely to be the best predictor of sediment behaviour.
Key relationships/algorithms	None
Remarks	This article, together with Paterson & Black (1999), is a good basis to analyse the mechanisms of biostabilisation (and bioturbation).

**Pender, G., P.S. Meadows, J. Tait, 1994. Biological impact on sediment processes in the coastal zone.**

Study site	Upper Clyde Estuary (West coast of Scotland)
Aim of the study	Design relationships to relate the population of two benthic organisms to increased or decreased sediment shear strength.
Type of study (field measurement, flume study/experiment, modelling)	Review of laboratory findings using sediment and organisms from the Firth of Clyde. Data are used to derive relationships. The sediment can be classified as slightly silty sand ( $D_{50} = 300 \mu\text{m}$ ). Three population densities were used (Table 1). The experiments included control (no organisms), single and mixed species tests.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Zoobenthos.
Species studied	<i>Nereis diversicolor</i> (borrowing polichaete) <i>Corophium volutator</i> (borrowing amphypod)
Parameters studied	Water content in sediment (% of dry sediment) Permeability ( $\text{m/s} \times 10^{-5}$ ) Sediment shear strength ( $\text{kN/m}^2$ )
Temporal scale	
Information available on spatial scale?	
Quantitative information?	Yes Table 3- effect of the organisms on sedimentation (mg suspended sediment per ml); Table 4 - effect on shear strength ( $\text{kN/m}^2$ ) $\tau_b$ for the two single species studied and for the mixed situation (equivalent population).
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Yes
Conclusions	The two species increase sediment resistance, the derived relations can be used for engineering purposes.
Key relationships/algorithms	$\tau_t = \tau_s + \tau_b$ ; $\tau_t = (1 + \gamma)\tau_s$ ( $\tau_t$ = total sediment shear strength; $\tau_s$ = abiotic component of sediment shear strength - control; $\tau_b$ = biotic component of sediment shear strength; $\gamma$ = coefficient of the relative change due to the presence of biology)
Remarks	Nice Figure 2 to be reported.

**Pethyck, J.S., D. Legget, L. Husain, 1990. Boundary layers under salt marsh vegetation developed in tidal currents.**

Study site	-
Aim of the study	to offer a physical explanation for the pattern of accretion observed both in the field and in flume studies
Type of study (field measurement, flume study/experiment, modelling)	flume study
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	salt marsh vegetation
Species studied	<i>Spartina anglica</i>
Parameters studied	shear stress ( $U^*$ ) and roughness length ( $Z_0$ )
Temporal scale	
Information available on spatial scale?	Yes, measurements were conducted at several distances from the vegetation edge (up to 2.60 m)
Quantitative information?	Yes
Relevant for the Westerschelde?	Species occurs in the Westerschelde
Conclusions	Logarithmic profile is altered, a complex velocity profile is formed. Vegetated zones smaller than 2 m can be expected to receive lower accretion rates than larger vegetated areas or bare flats.
Key relationships/algorithms	
Remarks	

**Sanderson, E.W., T.C. Foin, S.L. Ustin, 2001. A simple model of salt marsh plant spatial distribution with respect to a tidal channel network.**

Study site	Petaluma Marsh, CA, USA
Aim of the study	Create a model in which spatial distribution of salt marsh vegetation is related to channel distribution and size.
Type of study (field measurement, flume study/experiment, modelling)	modelling
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	salt marsh vegetation
Species studied	<i>Salicornia virginica</i> , <i>Spartina foliosa</i> , <i>Scirpus robustus</i> , <i>Frankenia salina</i> , <i>Jaumea carnosa</i> , <i>Grindelia stricta</i> , <i>Atriplex patula</i> , <i>Cuscuta salina</i> , <i>Distichlis spicata</i> , <i>Achillea millefolium</i> , <i>Lepidium latifolium</i> , <i>Rumex crispus</i>
Parameters studied	
Temporal scale	No
Information available on spatial scale?	Yes
Quantitative information?	No
Relevant for the Westerschelde?	Method might be applicable to the Westerschelde situation
Conclusions	The presented model using pattern and size of marsh channels to predict salt marsh species distribution works well. It shows the importance of tidal channel networks in salt marsh ecosystem and structure
Key relationships/algorithms	Transformed CISD (Cumulative Inverse Squared Distance): $q = \text{floor}\{[\log_{10}(\omega_0 * d^{-2})] * 3\} + 14$ $q$ = particular location in the salt marsh $d$ = distance between location and influential channel $\omega_0$ = weighting factor based on channel order the floor function rounds a number down to the nearest multiple of significance.
Remarks	Does not deal with the effect of salt marsh vegetation on physical processes, but of a physical property (spatial distribution of channels) on salt marsh vegetation. A very simple algorithm gives very good results.

**Stoddart, D.R., D.J. Reed, J.R. French, 1989. Understanding salt-marsh accretion, Scolt Head Island, Norfolk, England.**

Study site	Scolt Head Island, Norfolk, England
Aim of the study	gain insight in the spatial variability in accretion and the mechanisms for sediment supply at a salt marsh
Type of study (field measurement, flume study/experiment, modelling)	field measurement
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	salt marsh
Species studied	General salt marsh community ( <i>Armeria maritima</i> , <i>Puccinellia maritima</i> , <i>Limonium vulgare</i> , <i>Aster tripolium</i> , <i>Halimione portulacoides</i> )
Parameters studied	sediment deposition
Temporal scale	Decades
Information available on spatial scale?	Yes, an area is being monitored of 55 ha.
Quantitative information?	No
Relevant for the Westerschelde?	Yes, the study site is a protected back barrier salt marsh
Conclusions	The creek system greatly influences the spatial variations in accretion of the salt marsh. Marsh accretion may be determined not only by sediment availability, but also by mobilisation and transport within the marsh system.
Key relationships/algorithms	-
Remarks	

**Stumpf, R.P, 1983. The process of sedimentation on the surface of a salt marsh.**

Study site	Delaware, UK
Aim of the study	Study the sediment transport in a creek and a marsh and comparing settling rates of sediment with actually deposited sediment
Type of study (field measurement, flume study/experiment, modelling)	field measurements
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	salt marsh vegetation
Species studied	<i>Spartina alterniflora</i>
Parameters studied	suspended sediment concentration
Temporal scale	No
Information available on spatial scale?	Yes
Quantitative information?	No
Relevant for the Westerschelde?	Species occurs in the Westerschelde.
Conclusions	The importance of storms in sediment (re)distribution at the salt marsh surface is emphasised.
Key relationships/algorithms	-
Remarks	

**Underwood, G.J.C., D.M. Paterson, 1993a. Recovery of intertidal benthic diatoms after biocide treatment and associated sediment dynamics.**

Study site	Severn Estuary
Aim of the study	investigate rapid colonisation of a biocide treated site, compare bed properties with untreated site
Type of study (field measurement, flume study/experiment, modelling)	field experiment
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	micropohytobenthos
Species studied	diatoms
Parameters studied	sediment shear strength
Temporal scale	one week
Information available on spatial scale?	No
Quantitative information?	Yes
Relevant for the Westerschelde?	Yes
Conclusions	Sediment shear strength is negatively influenced by sediment water content. Sediment water content is influenced by the presence of diatoms and macrofauna.
Key relationships/algorithms	
Remarks	Comparison between natural site and 'artificial' site, therefore result can not be used, although processes described give good insight.

**Van Eerdt, M.M., 1985. The influence of vegetation on erosion and accretion in salt marshes of the Oosterschelde, The Netherlands.**

Study site	Krabbenkreek, Oosterschelde, The Netherlands
Aim of the study	study the influence of vegetation (root strength) on cliff erosion and the relation between establishment of seeds and erosion/deposition of sediment.
Type of study (field measurement, flume study/experiment, modelling)	field and laboratory measurements: tensile strength of root systems is measured and related to cliff stability
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	salt marsh vegetation
Species studied	<i>Spartina anglica</i> , <i>Limoneum vulgare</i>
Parameters studied	erosion resistance
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	No
Relevant for the Westerschelde?	Species as well as cliff formation are also found in the Westerschelde
Conclusions	A difference in effective reduction of cliff erosion is found between the two species. Generative spread of <i>S. anglica</i> is not very likely, due to sediment reworking conditions. Seedlings can only survive in areas which are already vegetated
Key relationships/algorithms	-
Remarks	-



**Widdows, J., J.S. Lucas, M.D. Brinsley, P.N. Salkeld, F.J. Staff, in press: Helgol. Mar. Res. 2002. Investigation of the effects of current velocity on mussel feeding and mussel bed stability using an annular flume.**

Study site	Exe Estuary (SW England)
Aim of the study	Determine effects of current velocity on the clearance rate of mussels, quantify sediment erodibility.
Type of study (field measurement, flume study/experiment, modelling)	Laboratory tests using an annular flume, animals collected from the mouth of Exe Estuary (SW England), local sediment sand (125-250 $\mu\text{m}$ ) and sand with pebble stones (0.5-3.0 cm). Field measurements of current velocities.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Zoobenthos: reef builder
Species studied	<i>Mytilus edulis</i> (mussel, bivalve)
Parameters studied	Feeding (clearance) rates of mussels at increasing current velocity; erodibility/stability of the mussel bed as a function of population density; sediment resuspension as a function of population density.
Temporal scale	The tide
Information available on spatial scale?	No
Quantitative information?	Yes: clearance rate as a function of current velocity (Figure 1); vertical current profiles above mussel beds (Table 1: 100% cover); sediment erodibility (Figure 3: 100 % cover on sand, Figure 4: effects of population density on sand); critical erosion velocity (Figure 5: sand); sediment mass eroded (Figure 6: sand + pebbles)
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Yes, mussels are very common in the Western Scheldt
Conclusions	Measurement results.
Key relationships/algorithms	None
Remarks	Good quantifications

**Widdows, J., M.D. Brinsley, P.N. Salkeld, C.H. Lucas, 2000a. Influence of biota on spatial and temporal variation in sediment erodability and material flux on a tidal flat (Westerschelde, The Netherlands).**

Study site	Molenplaat, Westerschelde
Aim of the study	"...quantify spatial and temporal changes in sediment erodability and material fluxes in relation to physical variables and biological factors... " (and more)
Type of study (field measurement, flume study/experiment, modelling)	flume study using intact, undisturbed cores.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	macrozoobenthos, microphytobenthos
Species studied	algal biomass, <i>Mya arenaria</i> , <i>Macoma Balthica</i> , <i>Cerastoderma edule</i>
Parameters studied	mass of sediment eroded, maximum and mean erosion rates, critical erosion velocity, suspension feeding/biodeposition rate
Temporal scale	spring and late summer
Information available on spatial scale?	Yes
Quantitative information?	Yes
Relevant for the Westerschelde?	Yes
Conclusions	Variations in sediment erodability are a result of the balance between stabilisers and destabilisers, but the role of biodepositors also needs to be considered. Central parts of the flat were more stable and erosion potential was higher in September compared to June.
Key relationships/algorithms	
Remarks	The whole spectrum of biostabilisation, bioturbation and biodeposition is being reviewed in a spatial and temporal perspective.

**Widdows, J., S. Brown, M.D. Brinsley, P.N. Salkeld, M. Elliott, 2000b. Temporal changes in intertidal sediment erodability: influence of biological and climatic factors.**

Study site	Humber Estuary (England), upper shores of Skeffling and Paull cohesive mudflats.
Aim of the study	Investigate biotic and abiotic factors determining spatial-temporal changes of sediment erodibility.
Type of study (field measurement, flume study/experiment, modelling)	Field measurements of sediment erodibility and laboratory experiments to quantify the effects of <i>Macoma</i> on sediment erodibility. Use of annular flumes.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Benthos
Species studied	<i>Macoma baltica</i> (deposit feeding bivalve, bioturbator) algal film (biostabilisator)
Parameters studied	Threshold of erosion, erosion rates and sediment mass eroded
Temporal scale	Short-term (days during a spring-neap cycle) and long-term (seasonal annual cycles) changes of sediment erodibility.
Information available on spatial scale?	small and large scale
Quantitative information?	yes: sediment properties (Table 1); bioturbation <i>Macoma</i> (3.1.1. text); critical erosion velocity and <i>Macoma</i> (Figure 4)
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Yes
Conclusions	No evidence of seasonal variations of <i>Macoma baltica</i> densities, but rather of interannual variations caused by cold winters.
Key relationships/algorithms	None
Remarks	Inter-annual cycles of <i>Macoma</i> densities due to cold winters. salt marsh accretion before and after storm, and presence of <i>Macoma</i> .

**Widdows, J., M.D. Brinsley, M. Elliott, 1998a. Use of *in situ* flume to quantify particle flux (biodeposition rates and sediment erosion) for an intertidal mudflat in relation to changes in current velocity and benthic macrofauna.**

Study site	Skeffling mudflat near the mouth of the Humber Estuary (England)
Aim of the study	Quantify particle flux (biodeposition + resuspension), sediment erodibility and critical erosion velocity.
Type of study (field measurement, flume study/experiment, modelling)	In situ experiments with an annular flume to measure particle fluxes across sediment-water interface with increasing current velocity (shear stress) and changing macrofauna community (structure and density). Time: april 1995.
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Macrozoobenthos
Species studied	<i>Cerastoderma edule</i> (bivalve, susp. feeder) <i>Macoma baltica</i> (bivalve suspension feeder)
Parameters studied	Biodepositoin rates ( $\text{g}/(\text{h m}^2)$ ) shear stress computed using a log velocity profile (Pa); sediment erosion rates as a function of current velocity (10-50 cm/s, 10 cm above the bed) and animal density
Temporal scale	
Information available on spatial scale?	Study of large scale (km) and small scale (m) differences
Quantitative information?	Yes; type of sediment (Table 2); macrofauna densities (Table 4) clearance rates (l/h) total sedimentation and biodeposition rates ( $\text{g}/(\text{h m}^2)$ ) for a velocity of 5 cm/s, during a period of 45-60 minutes (Table 3), erosion rates with macrofauna (Table 5).
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Yes
Conclusions	Maximum biodeposition rates up to one order of magnitude larger than mean sedimentation rates in absence of organisms.
Key relationships/algorithms	None
Remarks	The fiels conditions (sediment and zoobenthos) can be compared to Western Scheldt

**Widdows, J., M.D. Brinsley, P.N. Salkeld, M. Elliott, 1998b. Use of annular flumes to determine the influence of current velocity and bivalves on material flux at the sediment-water interface.**

Study site	Humber Estuary (England)
Aim of the study	To investigate material flux and erosion of marine sediments with and without macrofauna.
Type of study (field measurement, flume study/experiment, modelling)	Laboratory experiments Macoma and sediment from Skeffling mudflat, animal densities: 250, 500, 1000 and 1500 individuals/m <sup>2</sup> , silt content > 95%. Mussels and sediment from Cleethorpes musselbed (outer Humber estuary) (silt content 46%).
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	Macrozoobenthos.
Species studied	<i>Macoma baltica</i> (infaunal bivalve, deposit feeder, bioturbator) <i>Mytilus edulis</i> (epifaunal bivalve, suspension feeder, reef builder) <i>Cerastoderma edule</i> (bivalve)
Parameters studied	Biodeposition rates
Temporal scale	No
Information available on spatial scale?	No
Quantitative information?	Yes: sediment resuspension and <i>Macoma</i> densities (Figure 1); biodeposition and <i>Mytilus</i> (Figure 2); Susp. sediment and <i>Mytilus</i> (Figures 3-4).
Relevant for Western Scheldt (e.g. do species occur in the W.S.)	Maximum recorded biodeposition rates <i>Mytilus edulis</i> Oosterschelde = 25 g/(h m <sup>2</sup> ) Smaal et al. 1986).
Conclusions	At a density of 1500 per m <sup>2</sup> <i>Macoma</i> increases sediment resuspension/erodibility by 4-fold. Mussel beds (density > 1400/m <sup>2</sup> , 50-100% cover) reduce sediment erosion by 10-fold (the balance between net biodeposition and net erosion occurs at 20-25 cm/s, maximum biodeposition rates 40 times natural sedimentation).
Key relationships/algorithms	None
Remarks	Be careful when using biodeposition rates. The given values refer to velocity of 5 cm/s.

**Wood, R., 2000. A model of biotically-influenced sediment transport over an intertidal transect.**

Study site	Humber (Skeffling) and Mercy, UK
Aim of the study	to study the combined effect of both physical and biological processes on sedimentation and erosion at a tidal flat through the use of a computational model.
Type of study (field measurement, flume study/experiment, modelling)	modelling
Biological component (salt marsh vegetation, macrozoobenthos, microphytobenthos, macroalgae, macrophytes)	tidal flat
Species studied	<i>Macoma balthica</i> , microphytobenthos
Parameters studied	sedimentation and erosion
Temporal scale	short time scale (month) computations are compared with larger time scale (decades) sedimentation and erosion
Information available on spatial scale?	Yes, a transect of a tidal flat is being modelled
Quantitative information?	No
Relevant for the Westerschelde?	Yes
Conclusions	The model shows the impact of biota on sedimentation and erosion at a flat. Extrapolating the result to a larger time scales is difficult, because inter-annual variations were not modelled.
Key relationships/algorithms	sediment erosion rate: $E = k * (mxsed(n,u) - erodeds)$ if $ u  > u_{crit_e}$ and $mxsed(n,u) > erodeds$ otherwise $E = 0$ $mxsed(n,u)$ : maximum erodable sediment for <i>Macoma</i> density $n$ and current speed $u$ $erodeds$ : amount of sediment eroded since the erosion commenced. $k$ and $n$ : experimentally determined  critical erosion threshold: $u_{crit_e} = 0.01(0.402c_{phyll} + 15.934)$ $c_{phyll}$ : chlorophyll concentration in the surface sediment (derived from data from Widdows et al., 2000a)
remarks	nice attempt to model influence of biota on sedimentation and erosion

**SELECTED LITERATURE ON ROUGHNESS OF FLEXIBLE SUBMERGED VEGETATION (Chris Stolker)**

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