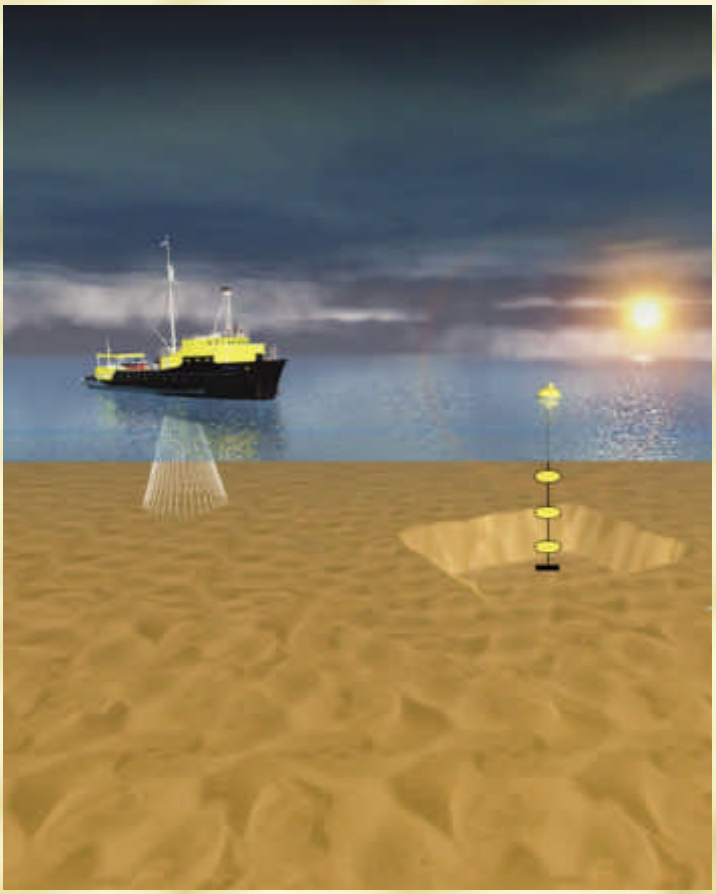
Sediment dynamics on the shoreface and upper continental shelf, a review



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Early men of the Clovis culture appeared in North America some 12000 years ago, when the sea level was still very low. What is more reasonable than to suppose such men ranged over the forested lowland that is now continental shelf? ... How were they to know or care that in a few thousand years the area was to be drowned by the advancing sea, any more than New Yorkers know or care that when the remaining glaciers melt, the ocean will rise to the 20th story of their buildings? *K. O. Emery, Scientific American September 1969*

Abstract

Sand transport processes and sediment and bedform dynamics are reviewed with emphasis on the measured processes on the shoreface between the seaward edge of the surfzone and the upper continental shelf on time scales from seconds to a year. The studies reviewed here were done off California, in the northern Gulf of Mexico, at Nova Scotia, on the Ebro delta, at Duck, New Jersey, southeastern Australia and New Zealand, and in the North sea off the UK, Belgium and the Netherlands. Each environment has its own specific forcings and processes, which emphasises the need for long-term synchronous field measurements of various parameters at the site of interest. In general, bedload transport is more important than suspended load transport except during severe storms or swell. Various types of ripples prevail, but in the heavy storms the (transition to) upper plane bed states do occur at water depths far beyond the depth of morphological closure of the surfzone.

The number of studies is sufficient to identify a number of shortcomings of present knowledge:

i. for the shoreface conditions, shear stress and hydraulic roughness models give widely varying results and have not been tested and calibrated a range of datasets; this leads to high uncertainties concerning the bed shear stress components for sediment transport;
ii. there are many environments in which neither waves nor currents dominate but interactions between waves and currents are not well understood;
iii. there is no concensus on definitions of bedforms and states, especially in conditions with both waves and currents; in addition the genesis of a number of bed states is not well understood;
iv. coastal, near-bed density-driven currents derived from riverine fresh-water outflow can cause a net shoreward current with a potentially first-order effect on annual sediment transport, but this effect has not been quantified empirically;
v. the exchange of sediment between surf zone, shoreface and shelf may be important for coastal sediment budgets on longer time scales (decades), but virtually nothing is known about the magnitude and the direction of the net exchange (for different grain sizes);
vi. there are very few datasets with measurements of both bedload and suspended load transport and hydrodynamics at high near-bed resolutions, and none that allow the probabilistic integration to annual transport on the shoreface.

Contents

1. Introduction

The objective of this report is to review the sand transport processes and related bed states in inner, shallow shelf regions and on the shoreface seaward of the surfzone. The dynamics of this region, and the exchange of sediment with the surfzone, are largely unknown. It is only in the past decade that a number of datasets were published that include wave and flow dynamics, suspended sediment concentrations as well as bedform dynamics and derived bedload transports. The datasets have been collected in various environments with different dominant forcings. It is the question to what extent the insights obtained in one environment are generically applicable to other environments. The insights from the available datasets will be discussed thematically to identify gaps in the generic knowledge.

The background for this review is the planned SANDPIT measurement campaign off the Dutch coast. In the near future sand mining will be required for nourishing beaches for coastal protection against the effects of the changing climate and the sealevel rise, and for land reclamation. The objective of SANDPIT is to improve sand transport- and morphodynamic models for the middle and lower shoreface, in order to facilitate the assessment of sand mining effects on coastal behaviour. The nearer to the coast a pit is dredged, the higher the danger of coastal erosion due to the local sand extraction. On the other hand, the further from the coastline the dredging is carried out, the higher the costs. The SANDPIT project undertakes the development and testing of models to assess the near- and far-field effects of sand mining on the shoreface. In an extensive field campaign the wave and flow conditions as well as the sediment transport will be measured for a year to investigate the near-bed sediment dynamics and to provide data for boundary conditions and for validation of the models.

This review is organised as follows. First a general introduction and definitions of the shelf region and shoreface are given, and the main forcings and boundary conditions identified. A regional overview is given of available datasets in the appendix, as well as the main findings for each region. Based on the appendix, the observed processes are discussed and hiates in knowledge are identified. It it then discussed how this knowledge can be applied generically to other sites, especially in Europe. One potential way is with shear stress and sediment transport models, so comparisons between model results and the field data are summarised. After this, the observations of bedforms and bed states is summarised. This was done after the discussion of model tests, because the interpretation and modelling of bed states and bedform dimensions appears to be dependent on shear stress models. Finally a look forward is given to the SANDPIT field site and measurements, and based on the review a number of working hypotheses is formulated. More general scientific conclusions and recommendations are given in the final section. Most sections can be read independent of other sections, except the SANDPIT discussion for which the description in the appendix of studies off the Dutch coast is the background.

1.1. Forcings on a geological scale

The shoreface is defined here as the realm in which waves are shoaling but not breaking in rather high-energy conditions (see figure 1) (Vincent 1986), while this is only the case for the inner shelf in extreme high-energy conditions. In many cases the transition from inner shelf to shoreface is not gradual but shows a distinct break in the bathymetry.

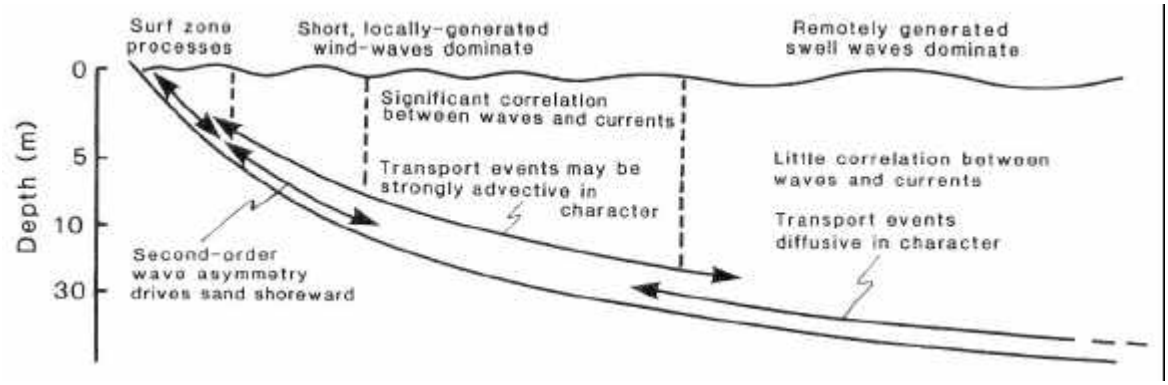

Figure 1. Definition sketch of the shoreface and inner shelf regions (Vincent 1986).

The shelf is bound at the ocean-side by the continental slope. The break between the shelf and the continental slope occurs at a depth of 40 m to 500 m below sealevel but on average at 130 m depth. At the lower end of the slope is the continental rise, which may be a deposit from sediments coming over the shelf edge and from erosion of the continental slope. The average slope of the continental slope is 0.0070, while that of the shelf is only 0.0017 (Encyclopedia Britannica 1990, vol. 25 p. 156). The world-wide average width of the continental shelf is 75 km, but varies from almost nothing (e.g. off Florida and Portugal) to 500 km (e.g. off Patagonia, off the most northern continents and the Great Australian Bight). Locally, there may be submarine valleys from glacial scour (e.g. off Norway), drowned rivers and river deltas (e.g. the Ganges fan in the Bay of Bengal) or extended fjords (e.g. Scripps Canyon off California). Some shelves are bound at the landward side by rocky coasts (e.g. New Zealand) or by soft sedimentary lowlands (e.g. The Netherlands). Obviously the depth, width and exposure to open ocean of the inner shelf are important boundary conditions for wave shoaling, amplification of the vertical tide and structure of the (horizontal) tidal currents.

During the glacials of the Quarternary (past 2.5 Myr) the sealevel fluctuated about 100 m globally between lowstand and highstand (present) positions. The shelves themselves have been affected by approximately 23 major sealevel fluctuations in the relatively short period of 2.5 Myr. This has had a profound effect on the shelf surface, which has been reworked by seawaves in surfzones 'passing by' and by currents as well as by continental processes like fluvial and glacial erosion and deposition (e.g. Pleistocene Rhine deposits off the Dutch coast). This climatic control is probably not entirely unique in the history of the Earth, but was not very common either. The reason is that at least a certain configuration of the continents is required for the solar irradiation due to Milankovitch orbital fluctuations to become effective enough for global cooling and sealevel lowering. Extended periods of either highstand or lowstand sealevels may have resulted in profoundly different shelf environments. It may have taken the many sealevel fluctuations to arrive at the morphology of the present shelves, and such energetic conditions may not have prevailed in extended periods with highstand or lowstand sealevels.

Near the present Dutch coast, a barrier system formed in the North Sea basin from fluvial sand, older transgressive sediments from previous transgressions. During the sealevel rise, the transgression involved continuous reworking of this sediment (Beets et al. 1995, Cleveringa 2000). In some parts of the shoreface, there is still sediment left in the bed from the barrier coast in an earlier stage. In other places, lag deposits are found which originate from winnowing of fines in higher-energy wave conditions at lower sealevels. Thus the present seabed sediment comes from different sources and has been subjected to many different forcings, which changed over time. The Holocene transgression changed the geometry and depth of the North Sea. The

consequences were modelled by De Kok (1994), Van der Molen and Van Dijck (2000), Van der Molen and De Swart (2001a,b). The dominant wave-induced sand transport mode changed from suspended load (before 6 kyr BP) to bedload due to the increasing water depth, and the overall wave-induced bedload transport direction in the later period was offshore for the Dutch coast. Since the landbridge between Britain and the continent opened (See e.g. Gibbard 1995) and the northern tidal influence increased, the tidal currents increased and changed from cross-shore to shore parallel. Although based on modelling, these patterns supposedly affected the sand supply to the coast (De Kok and Van der Molen and coworkers).

Summarising, forcings on geological temporal and spatial scales have been determined in the geological history of the region. These forcings are the boundary conditions for the present-day spatial and time scales of interest. Boundary conditions are the form of the basin or ocean (determining tidal amplifications and currents), the exposure to wind (fetch length for waves), the exposure to swell waves, the bathymetry of the inner shelf and shoreface (determining tidal currents and wave shoaling) and the composition of the sea bed.

1.2. Present-day processes and forcings

The present-day forcings on the shelf are wind and storm waves, swell waves, tides and fluvial inflow. In more detail, the following processes contribute to the net water motion in these regions:

1. Waves and wave-driven currents
2. Wind-driven currents and related upwelling and downwelling
3. Tidal currents and tidal asymmetry
4. Temperature- driven currents
5. Saline density-currents from fluvial fresh water inflow

Tidal, wave-driven, wind-driven and density-driven currents may dominate the flow during most of the year, whereas seawaves and seawave-driven currents only act on the bed in higher-energy conditions. The surfzone is the region where the waves start to break.

In the surfzone, morphological changes usually are large throughout the year, but taper off seaward of the breaking waves. This activity can be represented as an enveloping band around the mean bed level, in which bar migration and large-scale erosion or sedimentation cause fluctuations in the order of meters. Seaward, this band of activity tapers off to the so-called depth of closure, where morphological change is no longer measurable. The depth of closure is related to the time-scale of the measurements and to the measurement accuracy (Hoekstra et al. 1999). For example, the depth of closure at the Dutch coast at the time-scale of several years is 6-7 m below sealevel, while at the time-scale of the Holocene it extends as far seawards as the Strait of Dover. Changes smaller than 0.05-0.1 m usually cannot be detected with the current echosounding technology.

The absence of morphological change, however, does not mean that there is no sediment activity and no net sediment transport. Any activity may lead to exchanges of sediment between the shelf, the shoreface and the surfzone. Knowledge of the processes at the interface between these zones may therefore be important for long-term coastal sediment budget studies. This need not be limited to cross-shore sediment movement, but also extends to longshore sediment movement. Gradients in longshore sediment transport near the seaward boundary of the surfzone (where there is significant exchange between the surfzone and the upper shoreface) may also be

important for the coastal sediment budget (e.g. off The Netherlands, Van Rijn 1997).

Wright et al. (1991) formulated four working hypotheses for cross-shore sediment transport on the shoreface and upper shelf, partly based on the sediment conservation law:

1. cross-shore transport is produced by a combination of wave-, current-, and gravity-induced advective processes as well as by diffusive processes;
2. the relative contributions made by the different transport mechanisms vary temporally;
3. the frequencies of occurrence of the different transport mechanisms vary spatially as functions of regional shelf configuration and energy climate; and
4. equilibrium over periods of years or decades implies that the sum of all onshore sediment fluxes is equal to the sum of all offshore sediment fluxes.

These will be extended and refined in the section on the SANDPIT project for the Dutch coast based on the literature review in the next chapters.

1.3. Scope of this review

This review is limited in scope as follows. The time scale of processes and phenomena of interest ranges from seconds to years. Since more sophisticated measurement techniques became available only very recently, the review is heavily biased to publications of the last 10 years. The emphasis is on the upper shoreface, ranging from the seaward side of the surfzone to the inner shelf, whereas studies on the surf zone and on (laboratory) experiments are mostly ignored. Interactions between the surfzone itself and the shoreface are summarised as well as far as these were covered in the literature. Local features and short-term processes (10^0-10^1 m, seconds-hours) on the shoreface are identified that potentially can be extrapolated to a regional scale (10^2-10^3 m) and the annual time scale.

This means for instance that bedforms are included but shoreface connected ridges are excluded. Shoreface-connected ridges and other sand banks have a migration celerity in the order of one meter per year, while much more sediment is bypassed over the ridges in the form of migrating small-scale bedforms and suspended sediment transport (e.g. Van de Meene 1994, Van Lancker et al. 2000). The stability of these features is related to tidal current patterns (e.g. Stride 1982, Trowbridge 1995, Hulscher and van den Brink 2001) at a larger spatial scale than of interest here. In addition, they are therefore morphologically almost inactive on the time scale of interest and are therefore considered as morphological boundary conditions. For a review on the origin, classification and modelling of sand banks and ridges one is referred to Dyer and Huntley (1999).

The sediment type determines which processes can take place and are dominant. For instance, on muddy shelves, suspension may become so important that the mud becomes fluid and may even damp the turbulence significantly. This review is focussed on sandy shelves like the North Sea (where the SANDPIT field measurements are planned), possibly with a minor fraction of silt and clay, and also on coasts where the shelf is muddy but the shoreface is sandy.

2. Synthesis of sediment transport

A number of field datasets were identified in the literature. Because of the practical difficulties in measuring bedload sediment transport, most workers concentrated on measuring suspended sediment concentrations. The studies for each site are discussed together in the appendix. Table 1 (back of document) gives an overview of the datasets for the temporal and spatial scales of interest. The key parameters of the datasets and field sites are given in terms of wave and tidal conditions and sediment composition, and coded for further discussions. The ordering of studies and datasets in the appendix is done by region, from shallow to deep water and from early to recent publication date. Numbers in the text below refer to these studies (e.g. N2 refers to the second study off the Dutch coast given in the appendix).

The sophistication of the instruments has obviously consequences for the validity of the conclusions. Two electromagnetic current meters sample the flow profile in much less detail than an acoustic device that covers the profile at numerous levels above and very near the bed. Moreover, certain phenomena may simply be missed or misinterpreted with the former method. In addition, Osborne and Vincent (1996) warn that the position of high-resolution concentration and velocity sensors relative to the underlying bedforms is important: the phase relationship is such that it could give completely opposite transport values depending on the relative position.

The datasets reviewed in the appendix (see table 1 at the back of the report) exhibit a manifold of sediment transport driving forces and combinations of these forces. In addition, the forces vary with conditions, such as storm, swell or fair weather, or varying river discharge, or wind directions. Yet, some patterns seem to emerge in a thematic and geographical sense.

2.1. Directions of transport components outside the surfzone and in deep water

At the seaward boundary of the surf zone, the net suspended sediment transport during storms is seaward due to undertow, gravity transport or (decoupling) long waves at the New Zealand, Australia, Dutch and Duck sites. The relative contributions of these mechanisms are uncertain and depend on the local conditions. The undertow and the gravity effect always give seaward suspended transport, but the long waves may also give a landward component depending on phase lags in suspension and long wave orbitals. The presence of ripples may cause important phase lag effects between gravity waves and suspension, which can also lead to reverse net suspended transport directions (see chapter on bedforms).

The bedload transport on the other hand is often in the landward direction, as inferred mostly from ripple migration directions, and dominates in fair weather (Nova Scotia, Australia, Duck) due to wave asymmetry and possibly (that is, theoretically but not observably) Longuet-Higgins streaming and gravity-driven transport. It must be noted that the contributions of the latter two are theoretical and probably very small, but have never been quantified in measurements. In fair weather and swell waves off Duck, the suspended sediment was also directed landward. When swell waves interact with sea waves, the orbital velocities become skewed due to spectral bimodality (Nova Scotia site, Crawford and Hey 2001) and the bedload transport is seaward, while it is landward in sea waves only. With increasing wave asymmetry, the shear stresses during flow reversal were found to be oppositely directed in the near-bed (2 cm) layer and just above (in O2). The consequences for net transport directions are not known.

In special cases, mega-rip currents may drive seaward transport far beyond the surfzone (Short 1985). When nearshore and/or embayment topography prevents the development of a fully dissipative beach, large rip currents may be initiated that increase in strength and spacing as the

offshore wave height increases. They were observed on Narrabeen Beach (Australia), Scripps (USA), and Japan under breaking waves higher than 3 m. The rip currents developed flow velocities of 2-3 m/s and extended beyond 1 km offshore while the outer breaker zone ended only at about 300 m offshore.

At larger water depths, the cross-shore bedload transport also was landward while the suspended sediment transport was seaward (New Jersey). However, the bedload transport was seaward during heavy storms on the British North Sea shelf. At most sites, however, the dominant bedload transport vector is in the longshore direction due to tidal currents (e.g. North Sea).

At the Dutch Terschelling site (and probably along the Holland coast and at Duck, New Jersey (see figure 2) and Nova Scotia as well), there is a delicate balance with no significant cross-shore sediment transport at the seaward boundary of the surfzone. However, there is a strong tide-, wind- and wave-driven longshore sediment transport. Net loss or gain of sediment in coastal stretches may be related to gradients in longshore sediment transport: a zone with large transport relative to its upstream boundary may lead to erosion of that zone. This is at least the case in the surfzone, but possibly also just outside the surfzone.

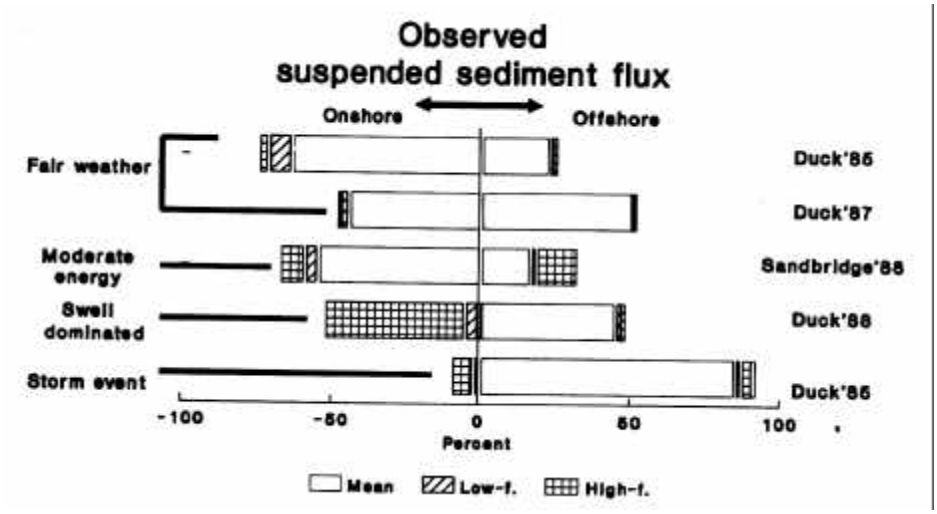

Figure 2. Comparison of the observed relative contributions of mean flows, high-frequency waves and low-frequency effects on the cross-shore sediment flux computed from the products of instantaneous suspended concentration and cross-shore velocity (Wright et al. 1991, figure 30).

In general, cross-shore sediment transport components seem to be well balanced. The bedload transport is usually shoreward whereas the suspended transport often is seaward at the seaward boundary of the surfzone, depending on the presence of ripples (see chapter on bedforms). The net transport is in the longshore direction of the tidal currents. The dominant transport mode at deep water (>10 m deep) is bedload (ripple and other bedform migration) during low and moderate energy conditions, whereas in the annually highest energy conditions the sheet flow regime with dominantly suspended load transport is attained in the direction of the net (wave-, wind- and tide driven) currents. So in deeper water the suspended load transport is often in the landward direction (except over heavily rippled beds).

2.2. Wave groups

It is well known that infragravity waves may determine the direction of wave-driven suspended sediment transport, whether they are coupled to the gravity wave field (outside the surfzone) or decoupled (inside the surfzone) (Ruessink 1998). In addition, recent measurements of intrawave flow and suspension (Williams et al. 2002, Vincent and Hanes 2002) demonstrate that groupiness of waves at large water depths has a significant increasing effect on suspended concentrations (see figure 3). Williams et al. found an increase of a factor 3 at 20 m water depth. Vincent and Hanes found comparable experimental results for shallower water with a wave record from Duck. Due to the time lag of suspended settling, the subsequent large waves in the group are able to increasingly suspend sediment, called 'pumping up' mechanism. In addition, the net settling velocity of the sediment is decreased by the near-bed flow.

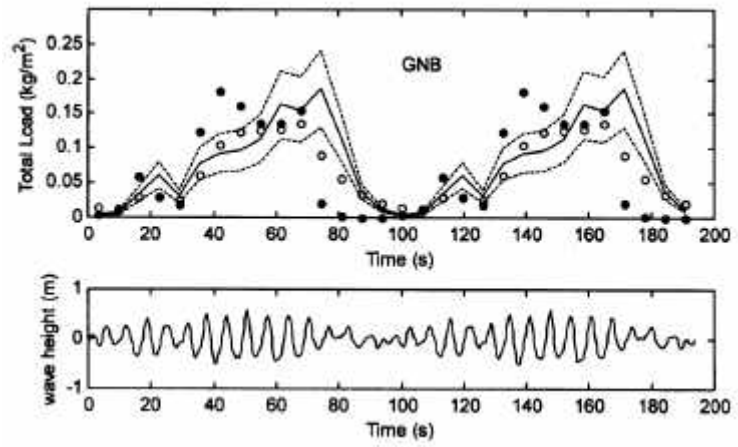

Figure 3. Effect of wave groups on the suspended sediment load as measured in the lab (open dots) and modelled (lines, dashed lines represent one standard deviation) by Vincent and Hanes (2002, their figure 7). The increasing concentration towards the end of the wave groups is due to the pumping up effect.

2.3. Wave-current interactions

The effect of combined waves and current on the flow velocities is that the near-bed velocities decrease due to the apparent roughness, which is created by the non-linear coupling of the waves and current and must be added to the roughness from ripples, bedload transport and grains (see Nielsen 1992, Van Rijn 1993, Fredsøe et al. 1999, Houwman 2000 for reviews). In general, the near-bed shear velocities are decreased by the addition of apparent roughness from wave-current interaction, especially for weak currents and high waves. From laboratory work it is clear that the angle between waves and currents is extremely important; opposing currents reduce the shear velocities even further, while perpendicular waves and current give the largest reduction (Van Rijn 1993). However, measurements of these effects in the field are scarce because detailed and accurate velocity profiles are needed to very small distances near the bed. An additional problem is that most analyses of wave-current interactions are based on models that predict the other factors contributing to the roughness, while different models are largely at variance with each other (see chapter on modelling).

Wave-current interactions were found to be important at the seaward boundary of the surfzone of Duck, where the presence of waves decreased the (modelled) net sediment transport

with a factor two compared to the net tidal current only. This effect was probably also found on the British North Sea shelf, where the tidal flow (measured at a few vertical positions only) just above the wave boundary layer was retarded due to an apparent roughness from wave-current interaction in the boundary layer. This agrees with findings on the Nova Scotia shelf, where the current felt an apparent roughness due to waves which was an order of magnitude larger than the roughness of ripples, bedload and grains. However, these results were obtained with low (vertical) resolution measurements and with modelling.

At Nova Scotia, the wave-current interaction was found to increase the grain shear stress within the wave boundary layer, based on a combination of modelling and measurements (with low vertical resolution) (Li et al. 1997). When either waves or currents are weak, the enhancement was limited to only 5%, while it was 20% with equal wave and current shear stresses in the same direction (within 30°). For waves and currents perpendicular, the shear stress enhancement again was only 5%.

Note that the reaction of shear stress above and within the wave boundary layer are opposite: the velocity above the boundary layer is smaller in wave-current interaction due to increased apparent roughness, whereas the shear stress is larger within the boundary layer. This is important for bedload transport and reference concentrations: the net suspended flux is also smaller in wave-current interaction, whereas the bedload transport and reference concentration are larger within the boundary layer. This seems to be the case for a weak current with colinear waves, whereas the effects are less well known in orthogonal waves and currents.

The friction by wave, current or combined wave-current ripples dominantly contributes to hydraulic roughness, whereas the bedload-related friction is smaller though significant, and only is dominant in sheet flow conditions when ripples are absent. In addition, bedload-related roughness in the presence of waves is one order of magnitude larger than in currents only.

Usually the role of waves in sediment transport is the suspension of sediment, which is then advected by net tidal, wind-driven or wave-driven currents (e.g. Vincent et al. 1998). This is especially the case when wave ripples are present. Interestingly, the wave-current interactions seem to vary between swell and storm conditions at Duck (Lee et al. 2002). During swell, vortices shed from small ripples enhanced the exchange above and below the wave boundary layer, leading to higher sediment concentrations above the boundary layer in swell than in storm. In storm conditions on the other hand, strong currents prevented the vortices from extending beyond the boundary layer. These findings, although speculative due to low vertical resolution of measured velocities, suggest that there is a complex interaction between ripples, the wave boundary layer and the overlying currents. Lee et al. suggested that the exchange would have been larger for larger ripples. Also Smyth et al. (2002) found evidence of vortex shedding in turbulence measurements over ripples in various conditions off Nova Scotia. These findings seem to confirm those of Lee et al. for the swell case without wind-generated currents above the wave boundary layer. Thorne et al. (2002) presented large-scale laboratory experiments with irregular non-breaking waves in a 4.5 m deep flume (no currents). The velocity and concentration profiles were measured in much more detail than at Duck. They concluded that the time-averaged concentration in the near-bed layer of twice the ripple thickness is best modelled with pure diffusion, whereas above this layer a combination of convection and diffusion (Nielsen 1992) or pure convection gave much better results.

In conclusion, the wave-current interaction at various strengths and directions of waves and currents are not well understood, and it is not clear when the grain shear stress plus bedload shear stress component is enhanced or retarded by the interaction. Yet this may have a first-order effect on the shear stress. It is also unclear how the increasing vortex shedding in increasing ripple height interacts with currents above the wave boundary layer.

2.4. Influence of rivers

Over time, rivers have delivered enough silt and clay sediment for the formation of a mid-shelf mud belt off California, possibly in the Gulf of Mexico and also off the Ebro delta (Puig et al. 2001), where the conditions (deep waters and sheltered conditions, respectively) favour deposition of this fine material. For the present study, the mud and sand delivery at that time scale can be neglected and the presences of the mudbelt can be taken as it is. In what follows, the location of the rivers is assumed to be in temperate climate zones, and only indirect effects on the flow will be considered.

The presence of fresh water, on the other hand, may have an effect on sediment transport on the shoreface. In the North Sea basin the river Rhine delivers enough fresh water to generate density-driven shoreward currents. These currents may cause a significant shoreward sediment transport (on the annual scale) outside the surfzone in water depths at least up to 20 m, although this has not yet been demonstrated with measurements. Van Rijn (1997) computed for the Dutch coast that the contribution of density-driven flow to the cross-shore sediment transport is of the same order and at least of secondary importance compared to tidal and wave-driven net cross-shore sediment transport. The Rhine ROFI (Region Of Freshwater Influence, where freshwater is found) extends along most of the western coast of the Netherlands, especially when the discharge is high, during neap tides and when sea waves are small (De Ruijter et al. 1992, 1997). Note that, if the ROFI is not kept in nearshore regions but allowed to disperse ofshore, then there will be no landward density-driven current.

The density stratification by the Rhine river plume is far from uniform. Apart from variations in river discharge, wind and wave conditions, there are two regular variations in the stratification. The first is a semidiurnal oscillation between a highly stable stratification and nearly full vertical mixing due to tidal straining (Simpson and Souza 1995), which takes place in the Rhine ROFI and elsewhere. The second is a tidal modulation of the river discharge leading to a pulsed discharge of fresh water and consequently a train of fresh water lenses.

It is conceivable that the density-driven current is more important in wet years with higher river discharge or with higher discharge peaks (see figure 4). Since the weather pattern responsible for the high discharges is not completely unrelated with the weather pattern responsible for storms, there might even be a (decadal?) correlation between storm events and high density-driven currents. This was found at Duck, where winter rains increased the fresh water input, while the wind direction allowed the buoyant plume to detach from Chesapeake Bay. It was also found to a limited extent on the mid-shelf off the Ebro delta, where the period of highest river flows and sediment discharges coincides with the most energetic wave conditions. However, density-driven currents of the fresh-water outflow of the Ebro river were not identified (Puig et al. 2001). This may be due to the relatively low average discharge (300-600 m^3/s) compared to the Rhine (2350 m^3/s) and the larger water depth. The presence of a weather pattern in the discharge and ROFI of the Rhine would also suggest that the ROFI will be affected by changes in river discharge due to climatic change. Although the effect is probably of secondary importance, climatic change may thus affect the sediment dynamics on the Dutch shoreface. On the other hand, climatic change may also lead to different storm patterns, while storm waves decrease density stratification.

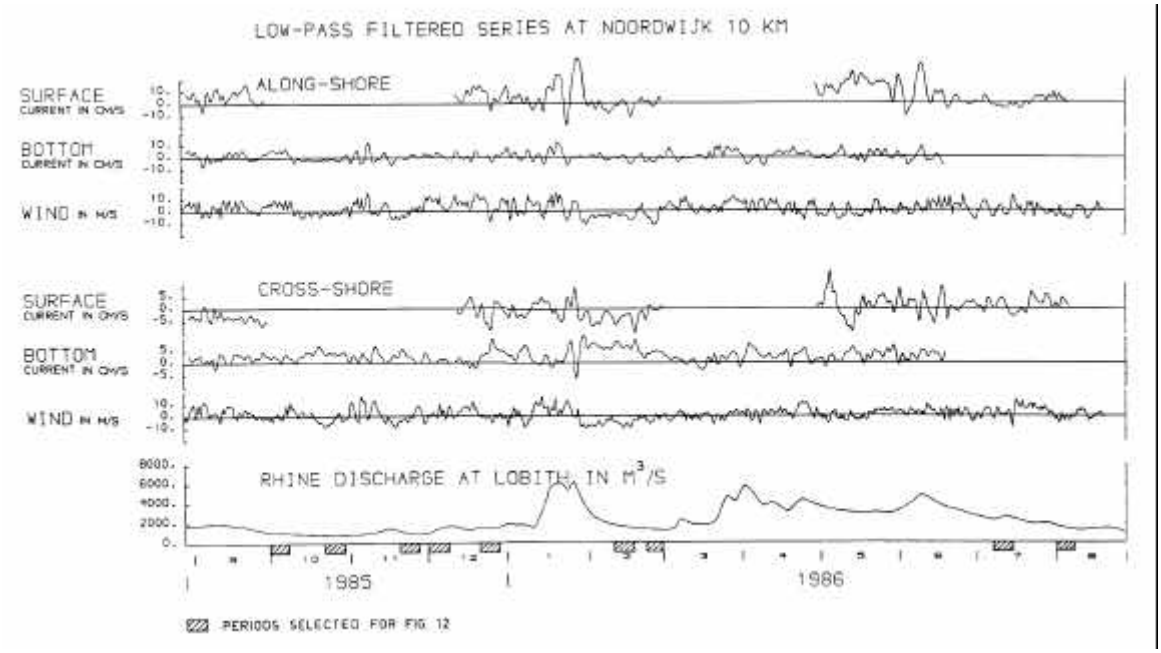

Figure 4. Low-pass filtered cross-shore (residual) current components in comparison with wind speed and river discharge of the Rhine for a full year. There seems to be a correlation between the peaks in river discharge and near-bed residual current, although the wind direction determines in part whether stratification can occur (Van der Giessen et al. 1990, figure 11).

Concluding, density-driven currents by fresh river water from moderate to large rivers may significantly affect the annual cross-shore sediment transport on the shoreface, but whether it is a first or second order effect is unknown. There may be strong seasonal and short-term temporal patterns, and potentially longer-term climatic effects although nothing is known about this. Spatial patterns may be due to the variations in river discharge, due to topographic features and also due to systematic changes in wind stress along the coastline (Samelson et al. 2002).

2.5. Graded sediment sorting

When the sea-bed sediment is graded, then the finer part is more often suspended and may be transported in different directions than the coarser part. In and just outside the surfzone this lead to a sea-ward fining trend on the Dutch and Duck shorefaces. Also on the tops of local topographic highs (e.g. shoreface-connected ridges off the Dutch coast) the sediment is coarser and better sorted due to increased winnowing by wave action (e.g. Van de Meene 1994).

There are indications from riverine literature that unimodal sediment mixtures have (nearly) equal critical bed shear stresses, which only become different with extreme grading or increasing bimodality of the sediment (Wilcock 1993, Kleinhans and Van Rijn 2002). This might imply the absence of mixture effects in incipient motion and bedload, although the suspended sediment advection will obviously still vary for the different grain sizes due to different settling velocities.

However, the critical bed shear stress for incipient motion is not the only factor at work; when sediment saltates or is in suspension, the difference in grain size and settling velocities causes much lower suspended concentrations for the coarse grades than for the fine. Consequently, the sea-bed surface may become depleted of fines, that is, armoured. The depth of

depletion of fines is related to the thickness of the so-called active layer. Reed et al. (1999) analysed analytically and numerically the effect of armouring on sediment transport on the shelf. They show that the modelled armouring increases with increasing hydrodynamic forcing and decreasing sediment sorting. In addition, the thickness of the active layer is crucial. A case study of sediment entrainment across the Eel River shelf (western US) show an order of magnitude change in the sediment entrainment rate with and without armouring. Moreover, the direction of concentration gradients of silt across the shelf can change sign. Cohesion effects were not included in this study, but the strong effects of armouring can be expected in sea beds with fine and coarse sand mixtures as well. Reed et al. conclude that bed armouring must be represented in models, regardless of the spatial or temporal modelling scales, and detailed vertical tracking of the grain size profiles is necessary as well (history effects and graded storm beds). These effects of grading in the bed and armouring of the bed surface are well known from extensive studies in rivers (e.g. Ribberink 1987, Kleinhans 2002). In the presence of ripples or dunes in the river, the bedform height and variation in height indeed determines the active layer thickness, while the vertical sediment sorting within the bedform (and in waning discharge or 'storm' sequences) create vertical grading in the bed.

Lee et al. (2002) applied the Wiberg et al. (1994) surface armouring model in their suspended sediment concentration computations at Duck. Interestingly, the computations are extremely sensitive to assumptions of using a single grain size, many grain size fractions and surface armouring (see figure 5). Their measurements were best reproduced when armouring was modelled as well. Unfortunately they did not study the effect of various sediment sorting, hiding-exposure and armouring models.

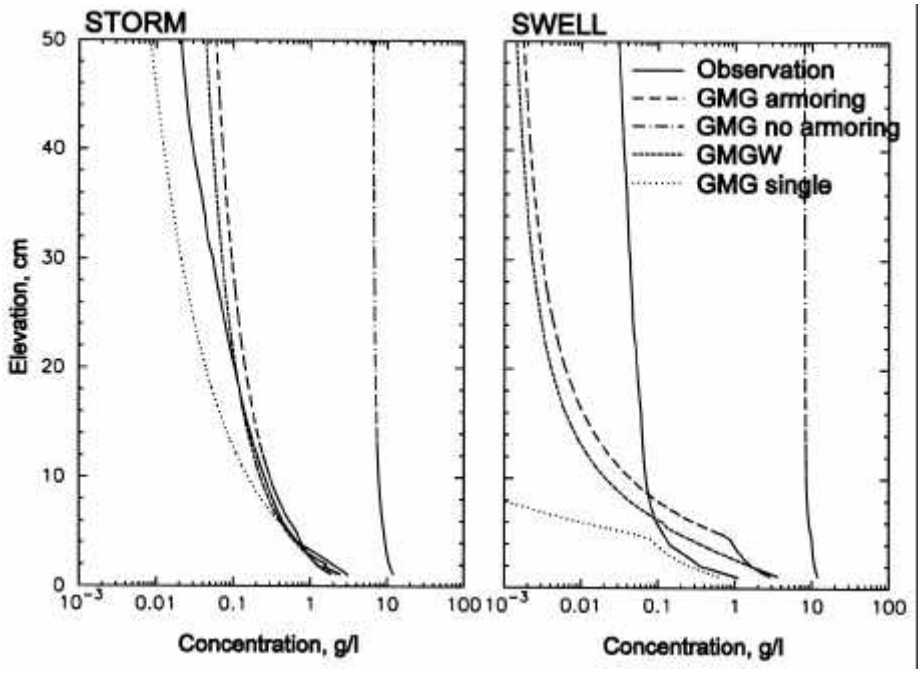

Figure 5. Observed and modelled concentration profiles with various models with graded sediment and armouring, one with a single grain size, and one without armouring (Lee et al. 2002, figure 13).

An extreme sorting pattern is found in New Zealand and Australia, where a band of coarse sediment is generated at a water depth of 30-40 m. Due to shoaling waves of 2-4 m height

and 9-12 s period, the ripple height is the largest in that water depth (Black and Oldman 1999). The increased roughness leads to increased winnowing of finer sediment. A positive feedback is that ripples become even larger for coarser sands, which was also found at the New Jersey site.

The transport of sand and silt in a deep tidal channel, on the other hand, were found to be decoupled completely. The suspended sand concentrations were found to be dependent solely on local flow and sediment characteristics, whereas the silt concentrations were related to silt concentration gradients in the whole estuary (Green et al. 2000). The decoupling may partly be explained by the bimodality of the mixture, which leads to different (dimensional) critical shear stresses, and partly by the segregation in suspension due to settling velocity differences.

In tidal-current dominated conditions over the 40 m high sand banks and ridges off Belgium (Vincent et al. 1998, Van Lancker et al. 2000) graded sediment is segregated due to size-selective advection of suspended sediment. However, storm waves still had a significant role in suspending the sediment and consequently the more wave-sheltered sides of the banks had finer sediment.

Off the Danish coast the grain size segregation seemed to be dominated by vertical sorting in bedforms (Anthony and Leth 2002). Along dunelike sandwaves, going from trough to crest the grain size decreased from 0.6 to 0.2 mm. Such a fining upward sorting strongly suggests dune migration by avalanching in bedload-dominated conditions (Kleinhans 2002). A less pronounced vertical sorting was observed on the tidal banks off Belgium by Van Lancker et al. (2000), where additional, horizontal sorting patterns were also obvious. This raises the question whether strong sorting in dunes can counteract horizontal sorting patterns.

Concluding, the grading of seabed sediment has a first order effect on the sediment transport directions, mostly because of grain size-selective suspended sediment transport (coarser sediment in bedload mode, finer sediment in suspended load which may be in a different direction). The bed state determines the rate of armouring to some extent (ripple height). In addition, there seems to be a strong effect of grain size on ripple size and sheet flow (discussed later), which leads to modification of the flow and consequently sediment transport magnitude.

2.6. Sediment exchange between shelf, shoreface and surfzone

These observations raise questions about the nature and importance of sediment exchange between shelf, shoreface and surfzone. On the one hand, the surfzone of sandy coasts seems to be largely decoupled from the shoreface and shelf on the annual time scale. Sediment transport rates on the shelf and shoreface (deeper waters) are orders of magnitudes smaller than in the surfzone. Most of the sediment transport in the surfzone is associated with sediment reworking and bar migration, while the exchange with the dune front or the shoreface is negligible except in strong upwelling or downwelling events (e.g. Duck) and in heavy storms and/or degrading coastal stretches (e.g. the Netherlands). Other indications of the annually insigificant exchange are the cross-shore grain-size sorting and the morphological (significant) depth of closure.

On the other hand, the balance between offshore and onshore transport components at the seaward surfzone boundary is delicate and may depend on small cross-shore fluxes and gradients in longshore transport. The cross-shore and longshore sediment transport in deeper waters may be small but is certainly not insignificant, especially not during storms. Sedimentary structures indicate depths of activity in the order of bedform heights, and the presence of sand waves and large current megaripples also indicate significant transport. From this activity it can be inferred that there may be significant gradients in cross-shore and longshore sediment transport for different grain sizes. Concluding, the exchange of sediment between surf zone, shoreface and

shelf may be important for coastal sediment budgets on longer time scales (decades), but virtually nothing is known on the order of magnitude and the direction of the net exchange (for different grain sizes).

2.7. Long-term sediment transport components

Like in many morphodynamic systems, neither the common nor the most extreme conditions cause the largest sediment transport events on a yearly average basis, but rather the more intermediate energetic conditions, as was found on the sandy Dutch shoreface. On the other hand, in the deep waters of the muddy mid-shelf off California it is the most extreme event (highest storm waves) that generates the largest sediment transport component on a yearly basis, whereas in the sheltered conditions of the Gulf of Mexico, fair weather transport seems to dominate. Thus it depends on specific characteristics of each site which conditions are the most important for long-term sediment transport, which demonstrates the need for field measurements at the site of interest.

Four approaches for long-term integration of sediment transport were found:

1. The first is to employ measured or simulated time series of flow conditions in combination with sediment transport measurements or a sediment transport model (e.g. Wiberg and Harris 1997, Harris and Coleman 1998).
2. The second is to combine the yearly wave and flow statistics from time series with sediment transport measurements in various conditions (e.g. Ruessink 1998) or with a sediment transport model (e.g. Harris and Wiberg 1997, Xu 1999). Joint probability distributions for flow and sediment transport can be computed for several components of the sediment transport, for instance the gravity and infragravity transport and currents.
3. The third approach would be long-term mathematical modelling, but even when some elements of the model are calibrated with measurements this approach comes with a host of uncertainties from the model parts (discussed above) as well as from error propagation (e.g. De Vriend 1997).
4. The last is the determination of net transports from long-term morphological mapping of the seabed. Van Rijn (1997) combined this with a mathematical model sensitivity study to determine some constraints on the directions of the sediment transport (which are difficult to infer from morphological changes) and on the contributions of various components.

Wiberg and Harris (C8, 1997) compared the first two methods for the Californian site in deep water and found that the probabilistic approach is more useful than the time-series approach over time scales longer than the available record, but tends to underestimate the net transport because it does not capture the episodic nature of transport events at that site. The time-series approach is more reliable because it preserves cross-correlations between the wave and current time series and auto-correlations within each time series, but has the disadvantage that the data must have been collected continuously throughout the years, or (parts of) time series must be simulated, usually with the additional disadvantage that current and wave velocities must be assumed independent.

Van Rijn (1997) and Wijnberg (1995) indicate the basic problems with method 4: a long-term dataset must be available, and the resolution and accuracy of positions and depths morphological maps are very limited and vary in time. In the surfzone, morphological changes may be large, but outside the surfzone and beyond the depth of closure, the changes are negligible and cannot be significantly determined. However, an alternative morphological method has

successfully been applied in rivers and estuaries: dunetracking. The migration of dunes (or other bedforms) is then used for the determination of net bedload sediment transport (see Wilbers in prep. for an overview). This method has been tried with ripples on the shelf and in the intertidal zone (e.g. Amos et al. 1999, Traykovski et al. 1999, Hoekstra et al. in press) and with the slowly migrating megaripples (NITG in prep.) in the North Sea. Problems are that only the net bedload component is determined whereas the suspended load remains unknown, and at the onset of saltation sediment may pass over ripples but contribute to the megaripple migration. It is unknown how the ripple and megaripple migration relate to each other and to the true bedload transport (e.g. sampled with well-calibrated bedload samplers). The assumption that bedload transport by ripples is equal to that by megaripples is flawed because of overpassing sediment and various problems with superposition of bedforms (Kleinhans 2002). An advantage of using the slow megaripples over the small wave ripples or current ripples may be that the slow megaripples need not be mapped frequently and can easily be mapped over large regions. So the megaripple mapping may facilitate the spatial extrapolation of the probabilistic method which is usually done at a few points only. However, a practical problem may be the frequent obliteration of the bedforms by fishers.

Concluding, the time-series approach seems to be the most reliable in environments with 'episodic' transport events, for instance in very deep waters and on coasts with hurricanes or tropical cyclones, but is problematic when long-term records are unavailable. In environments that are not very 'episodic' but where the fair or more intermediate energetic conditions are responsible for the annually largest sediment transports, the probabilistic approach may be more appropriate for long-term integration and does not require the very long records necessary for the time-series approach. For an extrapolation of the results at the measurement location to a larger area (e.g. to determine transport gradients), a combination with mathematical models and long-term meteorological data would be appropriate, whereas a modelling study that is unconditioned by the transport measurements would be less reliable. The method of dunetracking deserves further development as it may provide complementary information on bedload transport and larger spatial scales.

2.8. Effect of marine benthos on sediment dynamics

Murray et al. (2002) provide an overview of the implications of microscale interactions between marine benthos and the sediment dynamics and consequent morphodynamics. Their conclusions indicate that the effects can be considerable and even dominant. Not only the vertebrates and smaller animals play significant roles, but also marine meiofauna with sizes of 0.05-1 mm. These are very abundant from intertidal to deep-sea environments and may have larger effects worldwide than other burrowing animals by sheer abundance.

Below the reviewed effects of benthos on the sediment dynamics and morphodynamics are summarised in order of decreasing importance for the upper North Sea shelf off the Netherlands. At this specific site the fishing intensity with nets that disturb the seabed is impressive; the bed at every point is disturbed at least twice a year and the megaripples are often completely obliterated. This obviously increases the dynamics of this environment to the point where certain species no longer occur and where significant changes of the seabed structure by organisms are precluded by the raking of the bed by fisher nets. The summary in order of decreasing importance as far as known, is:

- *sediment mixing*: burrowing, digging and deposit feeding of animals mixes the sediment and inhibits armouring. This mixing can also produce winnowed deposits as fine

sediment is continuously brought to the surface to be eroded, leading to coarse depressions in the seabed

- *bed surface armouring*: mussel and oyster beds of hundreds of meters may cover the bed sediment. Although the shells are not very dense, the mussels fix themselves to other mussels, rock and gravel with byssus threads with impressive tensile strengths (~10^7 N/m^2)
- *biodeposition*: filter- and suspension-feeding benthic animals deposit faeces in and on the sediment, which reduces the concentration of fines and the suspended concentrations dramatically
- *sediment stabilisation*: worms and crustaceans may stabilise sediment and may lead to mud banks (> 50 m)
- *sediment compaction*: the vertical and horizontal movement of invertebrates generates considerable pressure within the sediment, which can lead to differential compaction, diurnal and seasonal changes in sediment consistency

Of no importance for the North Sea environment (but considerable importance elsewhere) are:

- *sediment disruption*: feeding and mating activities of large vertebrates (tile fish, otters, whales, turtles) involve disruption, excavation and burrowing of the sediment in the order of meters of width and depth
- *slope failure*: animals may produce mucus (biologic polymeres) that may inhibit slopes to avalanche; bioturbation reduces the magnitude of small discontinuities (e.g. lamination) that are potential initial failure surfaces; the morphology of failure structures may be determined by the nature of the biological communities

In addition, biogenic bottom features and organics production may lead to significant changes in the near-bed wave and current boundary layers:

- *feacal mounts and protruding tubes*: patchy erosion around tubes in low tube abundance because of vortex generation behind the structures (whereas the structures are stable due to cementation), and stabilisation in high tube abundance by hydraulic sheltering of the bed by the tubes
- *mucus (extracellular polymeric material)*: mucus is produced by fauna for their own biomechanical functions but may lead to both sediment deflocculation and flocculation, polymer drag reduction and suppression of turbulence of 50% at low concentrations, pore blockage and reduction of permeability of the sediment, cementation of sediment; all have considerable effects on sediment suspension and deposition, ripple mobility and mass failures.

As geomorphological processes are dependent on the delicate balance between driving and resisting forces in the sediment, the forces added by biological processes may be significant on short and long time scales. By biomechanical action, the chemical energy stored in the tissues of organisms becomes available to do sedimentological work. Neither the local nor the global impacts are mapped (let alone understood), however.

2.9. General conclusions on sediment transport on the shoreface

The balance of cross-shore and longshore transport components on the shoreface depends on a large number of processes, such as bedform formation and migration, armouring, infragravity waves, density-induced currents, wave-current interaction in the near-bed boundary layer as well as wind-water interaction in the water surface boundary layer, and potentially biological processes. The shear stresses generated by different combinations of hydrodynamic forcings are not well understood, which is illustrated by the finding of Houwman and Van Rijn (1999) that a constant roughness value represents the roughness better than the existing models in all conditions. Indeed, Xu and Wright (1995) ventured to remark that "of the three components of bed roughness, the grain roughness is one about which there is the most agreement". Considering the uncertainty in this grain roughness of at least a factor three in uniform sediment, and much more in sediment mixtures (e.g. Van Rijn 1993), it must be asserted that a principal problem in the sediment transport process is still unsolved. There is some scope for long-term sediment transport determination by measurements and the probabilistic integration combined with extensive large bedform mapping and mathematical modelling. Furthermore, interdisciplinary work is needed to incorporate the biological effects into sediment dynamics studies.

The fact that the shear stresses generated by different combinations of hydrodynamic forcings are not well understood, indicates that a comparison between various environments is problematic. On the one hand, shelf environments over the world have different forcings. It follows from the review that different physical phenomena become important under different forcings, which complicates generic modelling. On the other hand, a comparison between the surfzone and the upper shelf in the same environment would also show a different set of dominant physical processes, notably significant wave breaking in but not beyond the surfzone. Both approaches may be useful to follow, but neither need be conclusive.

3. A global framework for nearshore shelf environments?

Ideally, the knowledge summarised above would be applicable generically to comparable coasts. The question is then how to compare various coastal settings, and whether such comparable coasts exist at all. A few possibilities for global frameworks are discussed below.

3.1. Enigmatic shelves

The origin and genesis of shelves is not well known. Shelves are the margins of continents (see figure 6) that were probably created by super mantle plumes and plate tectonics in early Earth's history. Shelves are often divided into active margin and trailing edge shelves for collision-facing and spreading sides of the continents, respectively. The original continental margins attenuated and spread out because of loss of lateral support, and were reshaped by tectonic processes at active margins and by erosional or depositional processes at active and passive margins. At passive margins, sediments from the hinterland may accumulate to such thicknesses that the basal crust has been depressed (e.g. in the Gulf of Mexico), leading to further crustal thinning and subsidence (e.g. North Sea basin). However, the main processes shaping the inner shelf surfaces seem to be of a smaller scale, and only the top 0.5-1 m of the sediment is relevant for sediment dynamics on a time scale of a few decades.

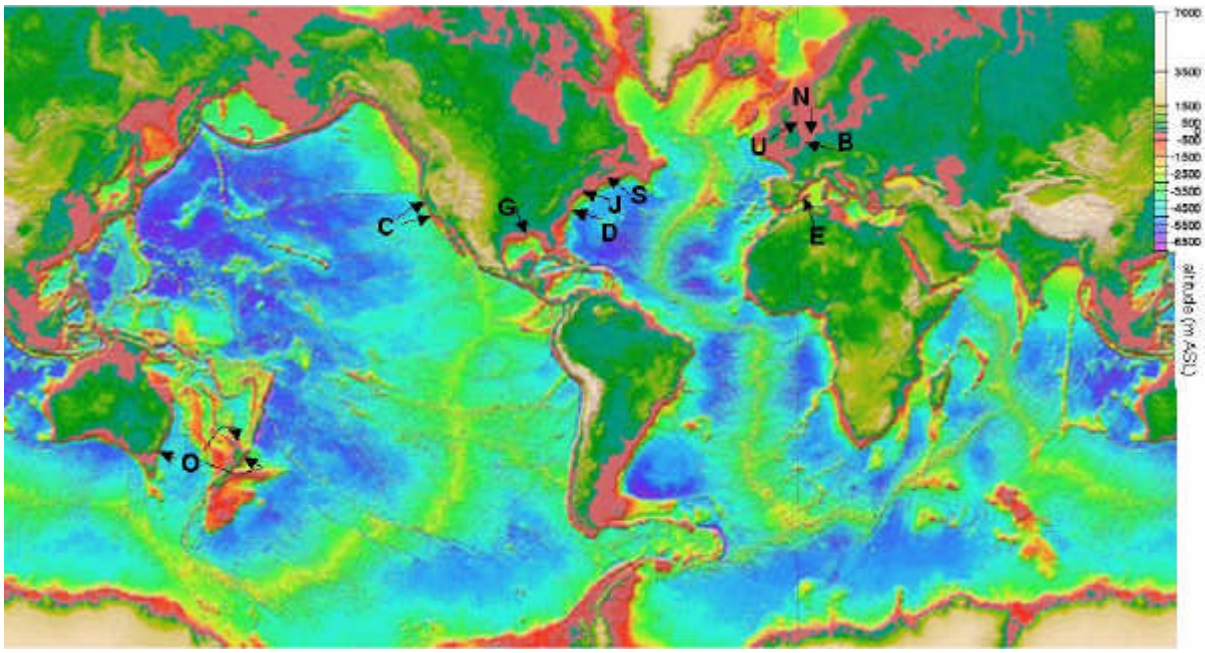

Figure 6. Bathymetric and topographic map of the world from satellite altimetry and ship depth soundings (Smith and Sandwell 1997). The color scheme is such that shelf regions stand out in red colours. The arrows and lettering refer to field sites of datasets discussed in this review.

For an overview of large scale morphological boundary conditions, the classification of Inman and Nordstrom (1971) might be useful here to characterise the environments that are relevant to the SANDPIT project. They classify coasts in a tectonic sense as collisional coasts, trailing-edge coasts and marginal seas. In Europe, 1/3 of the coastline (length) is marginal sea

coast (North Sea), 1/2 is trailing-edge coast and 1/6 is collisional.

For second-order features, Inman and Nordstrom classified coasts on the dominant environmental aspects: wave erosion and deposition, river deposition (delta's), wind deposition, glaciated and biogenous (e.g. reefs). In Europe, biogenous and wind deposition are irrelevant, but more than 1/3 is dominated by wave erosion and less than 1/3 has been glaciated. The remainer is dominated by wave and river deposition. Compared to the rest of the world, there is less wave erosion and more wave and river deposition in Europe.

Finally, a number of morphological classes were identified: mountainous, narrow or wide shelf with hilly coast, narrow or wide shelf with plains coast, deltaic, reef and glaciated coasts. A comparison between the first-order, tectonic classification with the second-order, environmental and with the morphological classifications reveals considerable overlap, for instance 97 % of the mountenous coasts are also collision coasts, which are dominated by wave erosion. For trailing-edge and marginal sea coasts, wind- and river deposition and wide shelfs occur most frequently together. The sediments on continental shelves vary with latitude (see figure 7). Sand occurs the most frequent of all sediments and occurs at all latitudes, whereas mud and coral is limited mostly to latitudes below 20°. Rock and gravel increases strongly to the north.

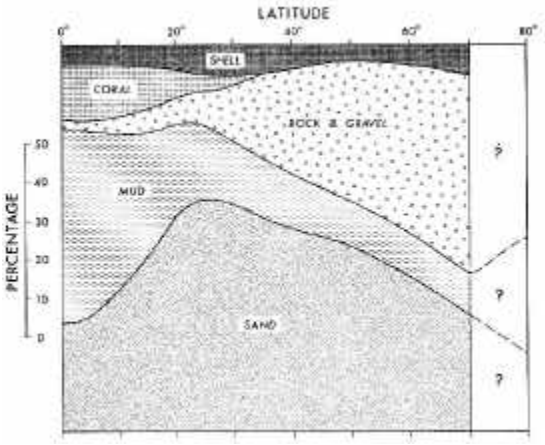

Figure 7. Variation of sediment type with latitude on shelves of the world (Davies 1972).

Although the shelves over the world share many characteristics at a large arm-waving scale, it is clear that the many permutations of combinations of environments and boundary conditions and the small number of realisations leads to a certain uniqueness of most shelves. For instance, the North Sea shelf may contain mostly sand like the Duck shelf does, but the forcings for sediment transport on the North Sea are tidal currents and sea waves, while at Duck swell waves and tropical cyclones play a major role instead. Also a comparison between the Eel river shelf off California and the Ebro delta shelf in the Mediterranean gives limited insight: although the episodic nature of fine sediment suspension due to the relatively large water depth is comparable, the Californian environment is much more dominated by currents and long-period swell than the Mediterranean Sea. Moreover, the Californian shelf is also exposed to much more energetic waves due to limited wave dissipation over the narrow shelf. A comparison between the deltaic coasts of Europe is not very useful either, because the largest, the Rhine, Rhone, Ebro and Po deltas, are not only formed by the rivers themselves but also by the antecedent coastal morphology, the tides, waves, etc.

Apart from the various combinations of forcings, there is a confusing variety of smaller

scale local conditions on many shelves (e.g. outcrops, drowned rivers, (fossil) coral reefs, etc.). There may well be combinations of environments and conditions that existed in the past but not on the present-day Earth. Moreover, it seems far from straightforward to employ the observed processes at one type of coast for a prediction of sand mining effects on another type of coast. At a world-wide scale a classification of coasts may give insight, but the environments at the local scales of the datasets discussed herein are only linked to a limited extent with the large-scale features. It is therefore not attempted to couple the present-day processes important for the SANDPIT project to the history and processes at geological time scales.

3.2. The Big Picture

A comparison of the various environments under present-day forcings has been done by Davies (1972), Kelletat (1995) and others, who produced maps of tidal ranges, wave attack, water temperatures, sediment properties and biological phenomena. As said before, these large-scale maps will be difficult to couple to the much more local conditions relevant for the SANDPIT project, but they are useful as a comprehensive background for the interpretation of the datasets discussed in this review. Based on these maps (figures 8-10), the following general remarks about the European coasts can be made:

i. There are wide shelves off north-western Europe except some parts of Ireland and Norway, whereas the southern French, Spanish, Portugese shelfs are narrow. Also the shelves in the Mediterranean are narrow, except in the Adriatic sea and south of Sicily.
ii. The Atlantic coast at southern France, north Spain and Portugal have large macrotidal ranges, which decrease to the north to mesotidal. The Mediterranean has a microtidal range.
iii. The west coasts of Ireland, the UK and Norway experience the largest storm waves (> 5 m for 3% of the time), while the Mediterranean coasts have the lowest. Although the southern North Sea-coasts are sheltered, the Netherlands and Denmark may have waves as large as those off the UK for North-western storms.
iv. Most of the environments in Europe have storm waves, only Portugal receives some swell from the Atlantic ocean.
v. Pebble beaches occur along the coasts of the UK and Ireland, and less frequently at some locations on the French, Portugese, Italian and Greek coast. Other coasts have mostly sandy beaches, and rock in some cases.
vi. Most of the coasts of Europe are artificial in the sense that there are protective structures against natural hazards and in some cases land reclamations, except off Spain, Portugal, Ireland and Norway.

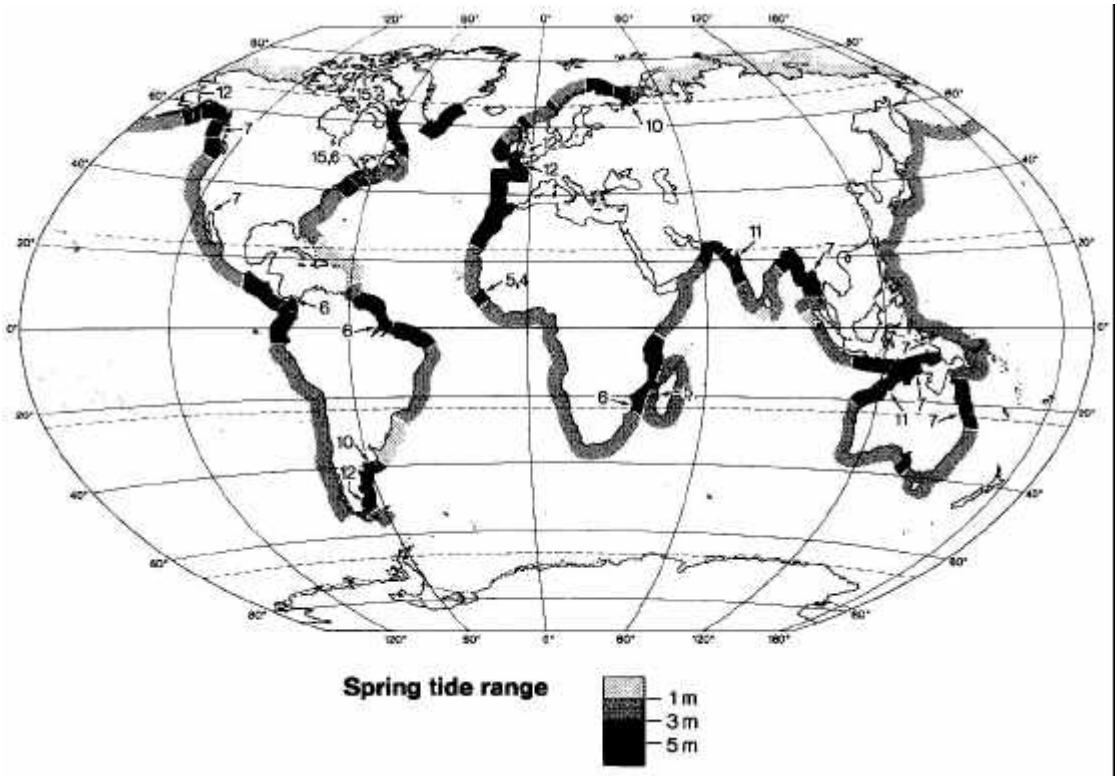

Figure 8. Spring-tide range along the coastline of the world (Kelletat 1995).

The applicability of the existing datasets on sand transport on shelfs and shorefaces to European coasts can now roughly be assessed. It is tempting to extrapolate the datasets of Duck, Sandbridge and Nova Scotia to the North Sea, of the Gulf of Mexico to the Mediterranean and the west coast of the USA to Spain and Portugal. These comparisons would be based on comparable large-scale morphologies of the shelves and comparable sediments.

Unfortunately, the wave and current climates are very different. This is not to say that the knowledge of very locally observed phenomena like wave-current interaction and ripple behaviour of sandy seabeds in various environments cannot be extrapolated to other environments. However, the knowledge of annual wave and current climate and sediment dynamics is limited to the environments in which they were determined because of the large number and variety of factors involved. The west coast of the USA experiences frequent tropical storms with higher waves and strong wind-driven down- or upwelling, which is not representative for the North Sea. The east coast of the USA receives large, long-period swell waves from the Pacific (apart from tropical storms), which is certainly not representative for the coast of Portugal and Spain. The Australian and New Zealand coasts also receive much more high ocean swell than European sites. The Gulf of Mexico has either very low energy or tropical hurricanes, which does not characterise the more moderate wave climate of the Mediterranean Sea. The Nova Scotia site may be more comparable to the North sea in tidal and wave climate, but has more complicated morphology of the shelf and coastline with rock platforms and cliffs and muddy bars in deeper water.

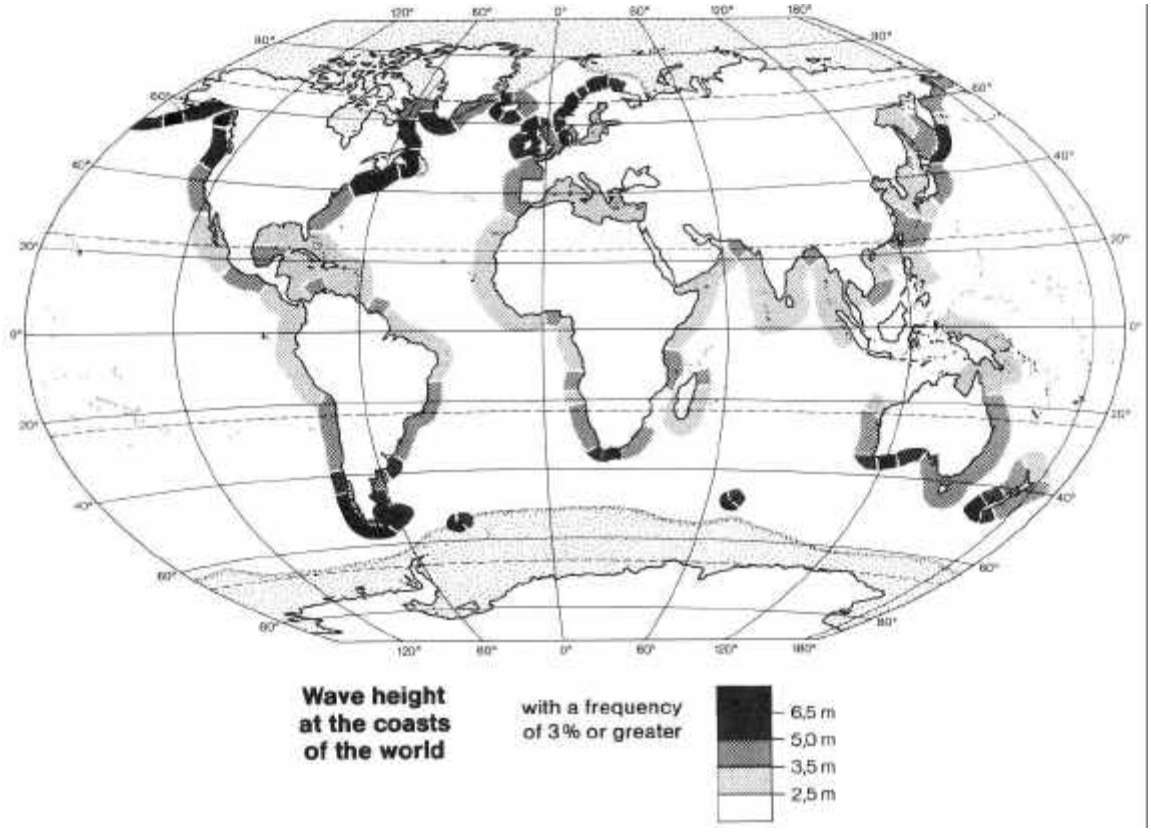

Figure 9. Average significant wave heights along the world's coastline (Davies 1972).

Concluding, an extrapolation of the annual wave, current and sediment dynamics from sites around the world to (unstudied) European coasts is far from straightforward. In the comparison between various environments we must distinguish between three aspects: geologic long-term at large length scales, annual/decadal climate at shorter length scales, and short-term localised aspects at the positions of measurements. Only knowledge of the first and the third may be applicable to other coasts at the same large and small scales respectively, but the second (climate) is not due to the various combinations of factors and boundary conditions summarised in this and the previous section. For these, local measurements are essential. In short, the global picture is of very limited use in the local environments of interest. However, the knowledge of short-term and short length scale phenomena from many sites can be integrated in quantitative models that have the potential for applicability in other environments. This is also the reason for the planned extensive field measurements and combined modelling studies in the SANDPIT project.

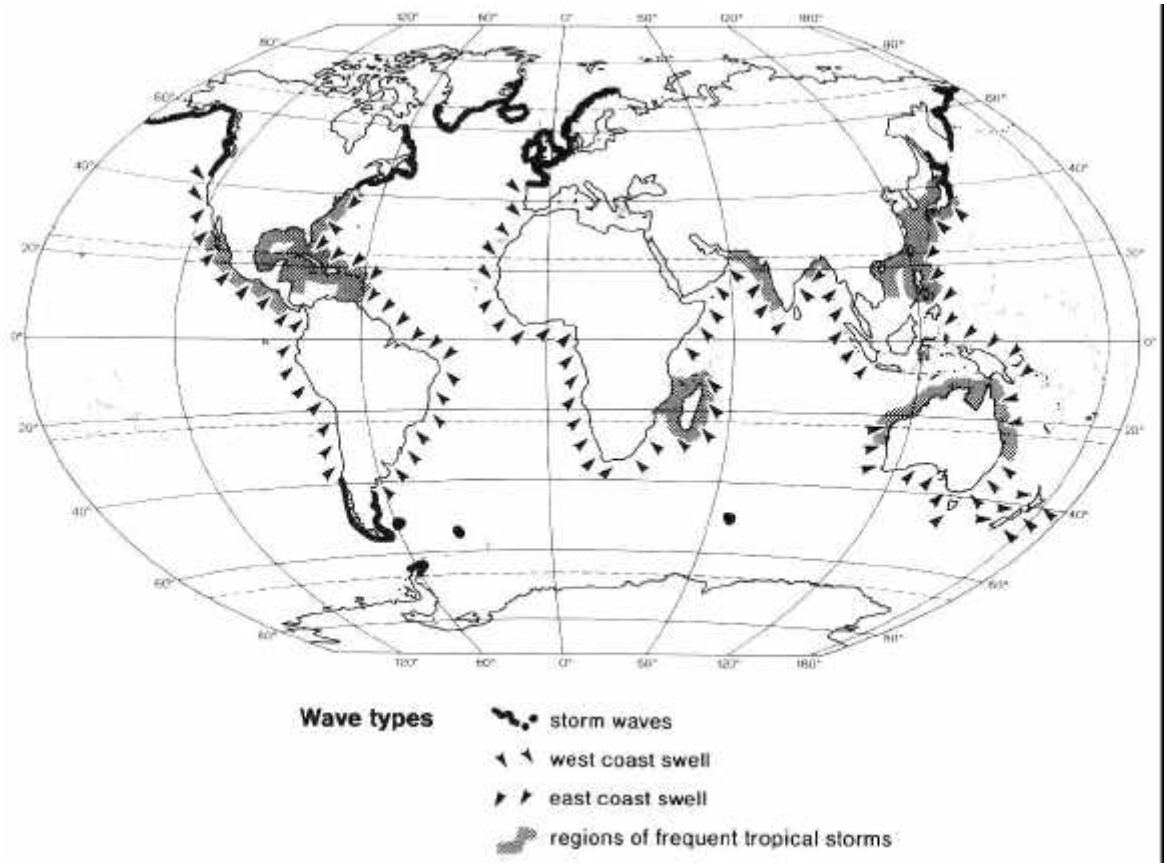

Figure 10. Wave types along the coastline of the world (Davies 1972).

4. Models ‘off the shelf’

The discussion of models in earth science is usually after the discussion of various empirical results. However, in the present case, models are involved already in the stage of data processing. In fact, certain shear stress and hydraulic roughness models necessarily must be combined with the measured flow parameters to yield separate shear stress components, because these cannot directly be derived from the measurements. The shear stresses are necessary for further modelling of bed states and sediment transport. The fact that models are so deeply intertwined with measurements leads to serious epistemic problems. If sediment transport models give results that do not agree with measured sediment transports, then the mismatch might be caused by the shear stress model or the bedform model or the sediment transport model or all of them, apart from systematic measurement errors. In addition, for a single dataset the transport model outcome could be the same for a range of parameter choices and contributions from the different model components (called morphological convergence, als equifinality in hydrology and underdetermination in philosophy). Consequently there is much latitude of choice as to what model components can be evaluated in the light of a single dataset (Quine 1953). So, comparisons between various shear stress models and various datasets might indicate present shortcomings. It is important to discuss these before the bedform and sediment transport data and model studies are discussed, because the latter not only depend on measurements and bedform and transport model components but also on the shear stress models (although obviously the bedforms and morphological changes feed back to the flow).

4.1. Hydraulic roughness and shear stress models

There are a small number of models that predict different components of the hydraulic roughness and shear stress such as grain roughness, bedform roughness, apparent roughness from wave-current interaction and bedload roughness. These models can be implemented in a combined wave-current boundary layer model. One of the objectives is to solve for the grain-related shear stress that is necessary for the prediction of bedload transport and reference concentrations. Another objective is to solve for the average and instantaneous velocity profiles, for instance to combine with the suspended sediment concentration profiles for computation of the sediment transport.

The best-known models are Smith and McLean (1977), Grant and Madsen (1979, 1982), Nielsen (1981, 1983, 1992), Van Rijn (1993) and Xu and Wright (1995). The bedform roughness is computed from bedform dimensions, which are often predicted with Nielsen (1981), Grant and Madsen (1982), Van Rijn (1993), Madsen et al. (1993) and Li et al. (1996).

Based on the extensive Terschelling data, Houwman (2000) and Houwman and Van Rijn (1999) validated 18 different combinations of these roughness models with grain roughness, wave-current interaction, bedform roughness and in some cases bedload roughness in a wide range of fair-weather, storm, neap-tide and spring-tide conditions at a water depth of 8 m (seaward boundary of the surfzone). They concluded that the apparent total roughness is best represented by a constant value of the roughness length of 0.1 m for all conditions, instead of predicting variations by more sophisticated models.

Xu and Wright (1995) tested four bottom roughness models with data from Duck, and specifically tested the roughness associated with bedload transport in transitional and sheet flow regimes. The bedload-related roughness was found to be at least an order of magnitude smaller than the bedform-related roughness, and the first thus becomes dominant only in sheet flow

conditions. They found that all four models overestimate the sediment transport roughness under sheet flow conditions, whereas the roughness of rippled beds was quite well predicted with the Nielsen (1983) model. They related the discrepancies to defects in the ripple dimension and roughness predictors as well as in the bedload roughness predictor, assuming that the grain roughness is well represented. Based on their data, Xu and Wright proposed a refined roughness model that combines Nielsen's ripple roughness and a modified bedload roughness component.

Li et al. (1997) determined the roughness of the bedload from a combination of the Grant and Madsen model with the observed threshold for suspension and sheet flow at the Nova Scotia site. Li and Amos (1998) used Nova Scotia data to show that both the Nielsen (1992) and the Li et al. (1997) bedload roughness algorithms gave reasonable predictions under combined current and waves. Furthermore, they tested the ripple roughness predictors of Grant and Madsen (1982) and Nielsen (1981), which were both found to overpredict the ripple roughness. Thus, Li and Amos (1998) proposed a new ripple predictor for combined flows and (the transition between) rippled bed and sheet flow. The shear velocity and apparent bottom roughness were well predicted with Grant and Madsen (1982), but underpredicted with Nielsen (1992). Li and Amos finally proposed an adapted roughness model (somewhat different from the Xu and Wright (1995) model).

Black and Vincent (2001) observed and modelled opposite instantaneous flow directions in high resolution in the lowest 2 cm of the water column which were caused by asymmetry of shoaling waves just seaward of the surfzone. As a result, two (instead of one) suspension peaks were observed during one wave period. This study was unfortunately limited to low-energy swell conditions and a single point. Yet, opposite flow directions in the lowest 2 cm were demonstrated to have a strong effect on reference concentrations, and supposedly may affect bedload transport in the same strong manner. If this structure prevails in many conditions and locations with asymmetric waves, then the shear stress models discussed before may be seriously defective. However, no other studies on this flow structure on the shoreface were found, partly because most studies did not have their 5 mm vertical resolution of velocity and concentrations in the lowest near-bed 120 mm.

Smyth et al. (2002) measured turbulence in detail from which the friction velocities could be derived for various bed states and hydrodynamic conditions at a water depth of 4 m in fine sand off Nova Scotia. A comparison with friction factor predictors of de Swart (1974) and Tolman (1994) revealed that the latter gave much better results, which was contributed to Tolman's use of a more recent ripple roughness predictor by Madsen et al. (1990), which incorporates the effect that irregular waves result in a hydrodynamically smoother bed than regular waves for the same ripple dimensions, and the use of the newer sheet flow roughness relation from Wilson (1989). From a comparison of wave friction factors with the predictors of de Swart (1974), Grant and Madsen (1982), Nielsen (1992) and Tolman (1994), the last predicted the measurements the best, whereas Grant and Madsen overpredicted, and de Swart and Nielsen predicted more or less constant values for all bed states which was inconsistent with the measurements.

Myrhaug et al. (2001) experimentally found that irregular, random waves have higher friction factors than regular waves. This seems to contradict the notion that wave ripples, which are the most significant contributors to the roughness, are smoother in irregular waves than in regular waves. However, the friction predictors of de Swart (1974) and others agreed rather well with the data.

Concluding, the evaluations of shear stress and roughness models in literature are somewhat conflicting, and one study suggests that an important (velocity-reversing) mechanism in asymmetric waves is missing in these models. For two different sites (Duck and Nova Scotia),

two different roughness predictors are found that were based on roughly comparable assumptions and calibrated (in the Li et al. case corrected) ripple predictors. At both sites, the bedload roughness was found to be less important than the ripple roughness except in sheet flow conditions. At a third site (Terschelling), surprisingly, the roughness is best represented by a constant value, while the dataset encompasses conditions of both rippled bed and upper plane bed which likely have highly different hydraulic roughnesses. This might be explained with the greater importance of currents at the Terschelling site, leading to a dominance of the wave-current interaction over the ripple and bedload roughness. In view of the underdetermination problems, it might be worth-while to combine the three datasets and analyse these together in the same manner and with various models, and possibly also analyse the combined set with neural networks (Kroon pers. comm.).

4.2. Deep-water tests of sediment transport models

There exists a large variety of sediment transport models and different combinations between model components. Most, however, have only been tested on laboratory and surfzone datasets, which is outside the scope of this paper (see Davies et al. 2002 for a review). Below, the model evaluations and discrepancies with deep-water datasets are summarised. Deep water is here understood to be outside the surfzone up to 60 m depth.

Vincent et al. (1991) evaluated the Smith and McLean (1977) reference concentration function with measurements combined with the Grant and Madsen model for wave-current interaction. Rather worrying differences between the model and observations were found, which were ascribed to the lack of a spectral representation (using one representative wave height and period instead), an unrealistic eddy diffusivity profile, and the sensitivity of the model to ripple height predictors (here Grant and Madsen, and Nielsen).

Li et al. (1997) tested bedload transport models and thresholds for several sediment transport states and modes. They found that the Shields criterion is applicable in combined wave-current flows if the Nielsen (1986) method is followed to obtain the ripple-enhanced shear velocity at the ripple crest. However, the suspension and sheetflow thresholds were more difficult to explain with existing thresholds of Bagnold (1956) and Komar and Miller (1975), respectively. After constructing a new empirical bedload roughness predictor, however, the shear velocity related to the sum of grain and bedload roughness was comparable to the threshold shear velocities for suspension and sheet flow. Of the transport predictors, the total-load Engelund-Hansen and Yalin bedload methods did not perform well, whereas the Einstein-Brown and Bagnold methods were found to give reasonable predictions of the bedload and total load, respectively.

In purely tidal conditions in a deep tidal channel, Green et al. (2000) compared the performance of Engelund and Fredsøe (1976), Smith and McLean (1977) and van Rijn (1984) reference concentration predictors to their data, and found that the first did not represent the observations well, but the latter two did although they both overpredicted the concentration with a factor 10. This is not encouraging, considering that the reference concentration predictors were developed for such currents. One reason may be that the bedrock was exposed at a number of positions, leading to sand flushing and subsequent limited supply of sediment in the bed. Indeed, Rose and Thorne (2001) tested the same van Rijn predictor and found reasonable agreement within a factor 2 for a tidal estuary with sand bed in the UK. They were able to derive a new empirical expression for the ratio of sediment diffusivity and eddy viscosity for the van Rijn predictor.

There seems to be no concensus concerning the effect of suspended sediment stratification. It was neglected by Xu and Wright (1995) but was incorporated by Vincent et al. (1991) following Glenn and Grant (1983). Vincent et al. used the combined Grant, Madsen and Glenn model in combination with a suspension model to compare the near-bed concentrations, with the aim to validate the suspension model. It was assumed that the wave-current interaction and other roughness components in the model were correct, although the importance of predicting the right ripple dimensions was emphasized in the sensitivity analysis. In Xu and Wright on the other hand, the other roughness components were under scrutiny. Guillén et al. (2002) and Jiménez et al. (2002), following a comparable approach to that of Vincent et al., found that the bed roughness according to the Wiberg and Harris (1984) and Grant and Madsen (1986) models could only be attained when the stratification correction was included in the model.

Concluding, very few tests of sediment transport predictors exist for deep waters. Moreover, the predictors critically depend on the shear stress computation, which is quite uncertain due to the largely unknown wave-current interactions and the lack of knowledge on bedload and ripple roughness.

5. Synthesis of bedforms and other bed states

Bedforms are a primary cause of hydraulic roughness of flows over sediment beds and may thoroughly modify flow fields. In waves or currents, wave ripples or dunes, respectively, play significant roles in the suspension of bed sediments. The bedform height determines the active layer thickness at the bed surface, which is important for transport and morphological computations over sediment mixtures. Moreover, the presence of ripples may lead to large phase differences between sediment suspension in vortex shedding from the ripples and orbital wave motion, which may invert the sediment transport direction. Certain bedform types occur only in a limited range of flow conditions and sediment sizes. Inversely, the presence of certain (relict) bedform types or their deposits may indicate the flow conditions during their creation. These relations with hydraulics, sediment transport and therefore morphological changes justify an extensive study of bedform occurrence and behaviour.

5.1. Definitions

Despite a number of concerted attempts to find concensus in bedform classification (e.g. Ashley 1990, Reineck et al. 1971), there is still a wide range of terminology for bedforms in use. In addition, terminology for bars, ridges and banks is often mixed with those for bedforms, while there are many indications that the formation mechanisms of these larger-scale features are fundamentally different from those of bedforms. Below it is attempted to summarise for which forms there is concensus and for which there is not (in order of decreasing length scale). Riverine bedforms are also given attention because their formation and stability may demonstrate comparable mechanisms in current-dominated conditions offshore.

The nomenclature for bedforms, roughly classified here according to concensus, includes both descriptive and genetic terms (e.g. upper plane bed versus sheet flow regime) (Allen 1984, Ashley 1990):

class name	other names	appropriate scaling
flat bed	upper plane bed or lower plane bed, sheetflow regime	grains
ripples	current (dominant) ripples, wave (dominant) ripples, short wave(length) ripples (SWR) or long wave(length) ripples (LWR), short- or long crested ripples, rolling-grain ripples, vortex ripples, orbital-, suborbital or anorbital ripples, megaripples, bedload sheets	grains, orbital amplitude
dunes	megaripples, bedload sheets, sand waves, bars	water depth
bars	banks, sand waves, sand sheets, riffles	>> water depth, channel width
banks	sand waves, bars, ridges	>> water depth

Ripples and dunes in unidirectional flows are distinguished by their scales and suggested maintenance mechanisms: ripples scale with the laminar sublayer and with grain size, whereas dunes are maintained by self-generated turbulent structures and scale with the water depth. As megaripples are also maintained by the self-generated turbulent structures, these are often classified as dunes. Bedload sheets mostly occur in non-uniform sediment, and scale with grain

size but plot in the dune regime in bedform stability diagrams, suggesting they are incipient dunes (Kleinhans et al. 2002).

Various banks, bars and ridges scale with the width of channels and are therefore often classified as distinct from bedforms. The nature of sand waves is enigmatic and the terminology is confusing. Large dunes in tidal channels and rivers have been called sand waves, as well as much larger features in the North Sea and elsewhere. Their dimensions are comparable to bars and large dunes, but some studies indicate that they are formed by the same mechanism as ridges and banks (Hulscher and van den Brink 2001).

Orbital ripples form under short waves and are directly related to the near-bed orbital amplitude and, to lesser extend, to grain size (increasing with both). Anorbital ripples form under very long waves and are independent of orbital amplitudes but increase in length for increasing grain size. Suborbital ripples form a transitional class with decreasing length for increasing orbital amplitude, and, like all classes, increasing length for increasing grain size.

It is obvious that some bedform types are ambivalent, as they fall in different classes among workers. For instance, megaripples, sand waves and dunes have been observed to grade into each other and might be argued to be one species (dunes) instead of three different bedform types (e.g. Allen 1984, p. I:335, Belderson et al. 1982, Davis et al. 1993). The confusion arises partly because: bedforms are often observed in superposition (discussed later); mathematical stability analyses of bedforms tend to aggragate several types (e.g. sand waves and tidal ridges); there exist transitional forms between many bedform types (e.g. dunes and sand waves, long ripples and megaripples, dunes and bars, bedload sheets and dunes). Ashley (1990) proposed to employ only descriptive terms, but even this appears to be problematic. The word ripple is used for small triangular bedforms in both current and waves, but current ripples and anorbital ripples are generated by inherent instabilities in water shearing over a mobile granular material, while wave (orbital and suborbital) ripples are often generated in the near-bed orbital motion caused by surface waves. In a later section, bedform stability diagrams are discussed, which classify (or map) bedforms in genetic terms of sediment mobility (based on wave orbital velocity or current velocity) and grain size.

5.2. Additional observations

Bedform occurrence and development depends on two factors: the nature and magnitude of the near-bed shear stress (e.g. waves, current or a combination) and on the composition of the sediment. To start with observations on the relation between bedforms and shear stress:

- For the application of the Shields curve, ripple predictors and sheet flow thresholds in wave-dominated conditions, the enhanced combined shear stress (of waves plus currents and of shear stress at the ripple tops, and of combined bedload and grain shear) has to be applied (Li et al. 1997). This may contrast with the fluvial situation where the grain-related shear stress is predictive of the bed state (Van den Berg and Van Gelder 1993). It is, however, not unlikely that the bedload-related shear stress in rivers is usually very low due to the absence of thick sheet flow layers, but that it should in fact have been added to the grain-related shear stress. A clear difference is that the spatially averaged grain- and bedload-related shear stress should be applied in fluvial conditions, while in wave-dominated conditions the shear stress at the bedform tops should be applied, which is in the order of a factor 2 higher.
- The transition from bedload to (saltating) suspended load transport was found by Amos et al. (1999) to be equal to the point where saltating grains start to bypass the ripple lee

faces. This suggests that beyond that point the ripple migration is no longer representative for bedload transport.

- Superposition of bedforms in rivers has been attributed to hysteresis in changing conditions, suggesting that the primary features are relicts of a previous state (Allen and Collinson 1974). However, many instances have also been reported were several scales of river dunes are co-existing or ripples exist on dunes (e.g. Harbor 1998, Kleinhans 2002), which suggests that the modified shear stress field over primary features promotes the secondary features. In wave-dominated conditions, superposition has also been observed (e.g. Hanes et al. 2001, Van Lancker and Jacobs 2000). Hanes et al. (2001, D1) found two populations of bedforms with small ripples superimposed on large wavelength ripples, although it is debatable whether the two populations are statistically significantly different (Grasmeijer in prep.). The small wavelength ripples had dimensions in the same order as was observed on other sites and predicted by models. The long ripples, on the other hand, were almost always present but could not be predicted with models. Flow and turbulence simulations indicate that the amount of flow separation of small ripples superimposed on long ripples is larger than over either one of the ripple types on its own. From these and other considerations, it is speculated that the long wavelength ripples are low-relief orbital ripples. Interestingly, the same long wave ripples were also found by Boyd et al. (1988) and Li and Amos (1999a).
- Ripple dimension predictors have been developed for regular and irregular waves. Ripples in irregular waves attain smaller heights and larger lengths than in regular waves. For these predictors, however, the measure of irregularity of the waves is undefined. It is not known how the ripple dimensions change in regular waves to slighty irregular to irregular (say, Jonswap spectrum) to extremely irregular (various wave fields mixed, e.g. swell and sea waves from the same and different directions). Usually the information on wave irregularity is not specified in the datasets, and a convenient parameter seems unavailable.
- Large bedforms like the long ripples take a longer time to be formed. Li and Amos (1999a) found that the long ripples were formed only in one of three storms, namely the storm with the slow build-up. Alternatively, the presence of strong currents prevented their formation.
- When bedforms have grown large, their reaction to changing conditions becomes tardy because the sediment volume involved in bedform reshaping likewise increased. As a result, hysteresis of their dimensions can be observed, which has consequences for the hydraulic roughness etc. In rivers, hysteresis during a discharge event may even lead to dune stalling and the emergence of superimposed secondary dunes (Allen and Collinson 1974, Kleinhans 2002). In the nearshore and shelf regions, hysteresis of bedforms has been observed by Boyd et al. (1988), Li and Amos (1999a) and Traykovski et al. (1999). Consequently, bedform types were observed to be out of phase with the concurrent flow conditions, especially in waning storm. Traykovski et al. observed ripples whose reaction to decreasing orbital diameter seemed to be one day.
- History effects are arbitrarily distinguished from hysteresis effects by the time scale: whereas hysteresis effects occur during a single storm event, history effects refer to (relict) bedforms inherited from a previous event. For instance, Traykovski et al. (1999) and Li and Amos (1999b) found rounded relict ripples from a strong storm of one week prior to the deployment period.
- The megaripple is a troublesome class of bedforms. In current-dominated conditions,

megaripples would be classified as dunes in most bedform stability diagrams, but usually they are much steeper than dunes. In wave conditions, lunate megaripples have been observed under asymmetric shallow-water waves (e.g. Van Rijn 1993). In reversing currents, current-generated megaripples may resemble sand waves because the reversing current displaces the brink point forwards and backwards on its crest, leading to more symmetric forms than would be the case in steady currents. However, sand waves generally have slopes that are far too low for avalanching to occur at the lee side. This suggests that they are genetically akin to a recently identified alluvial bedform type called low-angle dune (see Wilbers in prep. for a review on alluvial dunes). The relation between the latter and former types is by no means clear yet.

The composition of sediment also plays an important role:

- Wave ripples become larger with increasing grain size (Nova Scotia, New Jersey), while current dunes become smaller with increasing grain size. Seemingly conflicting evidence is reported by Van Lanker and Jacobs (2000), where megaripples were larger in areas with coarser sediment. However, this was caused by larger current velocities above the coarser areas, which caused both the coarsening of the sediment and the increased bedform dimensions.
- In both Belgian and Californian (deep) waters, ripples were absent in areas with more silt and clay in the bed. This indicates that the presence silt inhibits ripple formation. In the North sea (U1), on the other hand, ripples were found in the presence of as much as 44% silt and clay. It could be (but is unknown) that the silt and clay in the latter case was pelletised whereas it was not in the former cases.
- Current ripples are not generated in sediments coarser than about 0.7 mm (Southard and Boguchwal 1990).
- In badly sorted sediments, the bedforms do not necessarily behave conform their median or average grain size. For instance, fine-sand ripples may form superimposed on larger gravelly features (Kleinhans et al. 2002). Presence of much silt in the bed tends to prohibit ripple formation. Wave ripples in sediment mixtures are larger than expected on basis of their D50 because the presence of coarser sand in the bed (New Jersey). When sandy bedforms migrate over a resistant substrate, e.g. bedrock, clay or gravel armour layers, their morphology may be affected by the limited availability of sand, leading to forms like sand ribbons and barchans (e.g. Belderson et al. 1982). In the latter cases, the bedforms are best predicted from the bedload sediment instead of the bed sediment (Kleinhans et al. 2002). However, in the case of wave ripples (increasing dimensions with grain size) it is not clear what sediment is representative.

5.3. Regimes and bed state stability

In 1990, Southard and Boguchwal presented bedform stability diagrams for currents which summarised the insights of previous diagrams and investigations (by Simons and Richardson 1965, Allen 1984, etc.). The classification was based on the parameters flow velocity, grain size and water depth. The bedform classes were lower plane bed, ripples, dunes, antidunes and upper plane bed (in order of increasing velocity). The transition from ripples to higher-energy bed states was abrupt, the others were more gradual. This diagram was criticised in 1993 by Van den Berg and Van Gelder, who argued that the flow velocity and water depth were dependent parameters because of the hydraulic roughness by bedforms. They proposed to use the grain-

related shear stress instead of the flow velocity and the water depth. In addition, they found that the transition to upper plane bed in the Southard and Boguchwal was mostly related to the transition from subcritical to supercritical flow in the (mostly based on laboratory) data, instead of the true transition to upper plane bed, and therefore must be interpreted with care.

Allen (1984) presents a wave ripple diagram with maximum orbital velocity and grain size as principal parameters. There are only three bed states: lower plane bed, wave ripples and upper plane bed. Li and Amos (1999a) did not explicitly construct a bedform stability diagram for waves, but tested predictors for the onset of sheet flow (upper plane bed) and ripple height, which could be drawn in a diagram like that of Allen.

Arnott and Southard (1990) presented a bedform stability diagram for combined currents and waves, based on the current velocity and the oscillatory velocity (see figure 11). A number of 2D and 3D ripple classes could be distinguished. However, the diagram is only valid for one grain size, and for currents in the same direction as the waves. Furthermore, the disadvantage of using the flow velocity instead of an appropriate shear stress remains problematic. Finally, the diagram was constructed from flume experimental data and contained no field data.

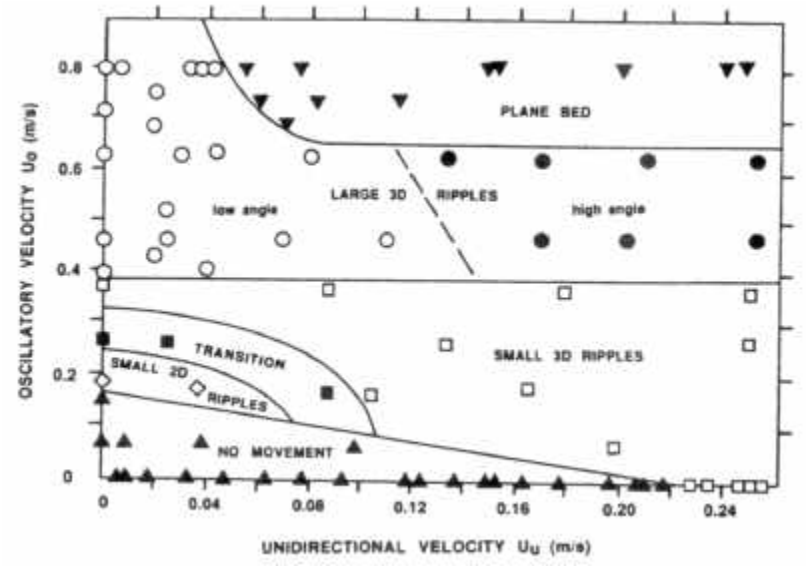

Figure 11. Experimental results of Arnott and Southard (1990).

A basic problem with wave bedform diagrams is the determination of the appropriate sediment mobility or shear stress parameter (as elaborated in a previous section). In conditions of combined waves and currents, this problem will be slightly more inhibitive. Apart from this, the lack of many more bedform stability diagrams (as for rivers or currents) indicates that other parameters and other bedform generation mechanisms are necessary to understand the variety of forms (like sediment sorting was necessary to explain various bedform types in rivers with sediment mixtures (Kleinhans et al. 2002)).

Most of the variation is related to three-dimensionality of the bedforms:

- *intrinsic three-dimensionality*: bedforms can be 2D or 3D (or, arbitrarily, transitional). There are several reasons for this. Current ripples probably have 3D equilibrium forms and are only 2D in incipient stadia. Current dunes are still under discussion; some hold that their equilibrium forms are also 3D but difficult to obtain in short flumes and unequilibrium field conditions (e.g. Michael Church, pers. comm.), while others hold that dune three-dimensionality emerges for increasing flow energy (e.g. Southard and

Boguchwal 1990). Wave ripples become more 3D with increasing wave energy (e.g. Boyd et al. 1988, Southard et al. 1990, Van Rijn 1993, Traykovski et al. 1999). However, there are various 3D forms, described as regular, bifurcated, chaotic, sinuous, serpentine, terminated, etc. (see Allen 1984, Boyd et al. 1988, Traykovski et a. 1999). It is not entirely clear which forms are stable in certain energy levels, and which forms are transitional between others. Boyd et al. found straight, long-crested short wave ripples in low energy and similar, long wave ripples in high energy conditions, with more irregular forms as transitions.

- *broad directional wave spectrum*: when waves come from various directions at the same time, ripples tend to be more 3D or chaotic (e.g. Boyd et al. 1988). Also when waves change direction, they may become 3D in transition to their new equilibrium (e.g. Traykovski et al. 1999).
- *superposition of currents and waves*: currents that are oblique to dominant waves may cause 3D ripples (e.g. Van Rijn 1993), but may also create current ripples in their own right (e.g. Li and Amos 1999b, Osborne and Vincent 1993) superimposed on wave ripples. Depending on the relative dominance of currents and waves, bedforms related to one may dominate with bedforms related to the other superimposed on them. In strong tidal currents megaripples may be formed (e.g. Van Lancker and Jacobs 2000) with wave ripples on top during tidal slackening.
- *Orbital, suborbital and anorbital formation of ripples*: orbital ripples form under short waves and are directly related to the near-bed orbital amplitude and, to lesser extend, to grain size (increasing with both). Anorbital ripples form under very long waves and are independent of orbital amplitudes but increase in length for increasing grain size. Suborbital ripples form a transitional class with decreasing length for increasing orbital amplitude, and, like all classes, increasing length for increasing grain size. Thus ripples first increase with increasing orbital amplitude, then decrease and become independent. This explanation (as used in most ripple dimension and roughness predictors) conflicts with the observations of superimposition and especially of long wave ripples (LWR), for it is not clear how one orbital amplitude can cause a bimodal ripple pattern.

To summarise, current bedform stability diagrams for waves cluster most ripple types in one bedform class, neglecting the variation of forms due to various processes. For unidirectional steady flows the stability of various bed states is rather well described in bedform stability diagrams. Most of the processes causing the three-dimensionality of bedforms are related to non-equilibrium conditions and omniconfusing flow (superposition of currents and waves), indicating that the bedform stability diagrams based on a small number of parameters can at least be improved. Unfortunately, the construction of such a diagram is hampered by the lack of knowledge on the fraction of shear stress that actually moulds the bedforms from the bed. On the other hand, a diagram that is successful in separating various bed states (if it can be found at all) may indicate which parameters are best for bedform dimension predictors as well. A new diagram might nevertheless shed light on the definitions of bedform types, and possibly on the coexistence of bedforms like ripples and megaripples (also see next section).

5.4. Tell-tale sedimentary structures

Sedimentary structures near the sea-bed surface may provide complementary process information. The structures may be interpreted as relicts of certain bedforms or bed states, which

indicates the prevalent conditions during their formation, and certain sequences of deposits may indicate a sequence of processes (e.g. Johnson and Baldwin 1996). Unfortunately, often the sedimentary record is ambivalent in the sense that certain structures point to a range of conditions or even various conditions. In addition, most of the record consists of (time-) hiates, especially in eroding conditions. However, when some additional parameters are known, such as water depth, tides and wave climate, the interpretations can be constrained with ripple predictors and transport threshold predictors (e.g. Wiberg and Harris 1994).

Some structures are rather straightforward to interpret, for instance (from Van de Meene 1994) cross-lamination by wave ripples (indicating wave-dominance), cross-bedding by megaripples (Nio et al. 1983), dunes and bars (indicating current-dominance), planar lamination by sheet flow upper plane bed conditions and mud drapes by tidal slacks. Van de Meene (1994) and Van de Meene et al. (1996) found an upward fining trend in the top 10-50 cm of the North Sea bed, with structures indicating a decrease of energy as well from high-angle cross-stratification or hummocky cross-stratification or planar bedding to wave ripples. The upper part of the bed often was bioturbated.

One sedimentary structure type that evoked a lot of discussion is the hummocky cross-stratification (HCS) (e.g. Arnott and Southard 1990, Southard et al. 1990, Van de Meene 1994, see figure 12), which also frequently occurs on the North Sea shoreface off the Netherlands. Due to its large scale, it is difficult to recognise in cores or box-cores. HCS is considered to be characteristic for combined current-wave conditions near the transition to upper plane bed (sheet flow). Southard et al. (1990) found in laboratory experiments that HCS was formed during sediment fall-out from strong purely oscillatory flows with large periods in waning storm, when 3D ripples develop from the planar bed. In this case, no dominant dip-direction was found in the HCS. However, when currents are present and become more important, one dip-direction of the cross-stratification becomes dominant (e.g. Van de Meene 1994). Li and Amos (1999a) remarked that long wave ripples often occurred in between short wave ripples and upper plane bed, which indicates that the LWR may be involved in depositing the low-angle HCS. The long wave ripples resembled hummocky megaripples, suggesting that these are the same, while hummocky megaripples (mixed wave- and current origin) are known to produce HCS (e.g. Li and Amos 1999a). Both Van de Meene (1994) and Li and Amos (1999a) found HCS in medium sands, whereas Southard et al. and Arnott and Southard experimented with fine sand.

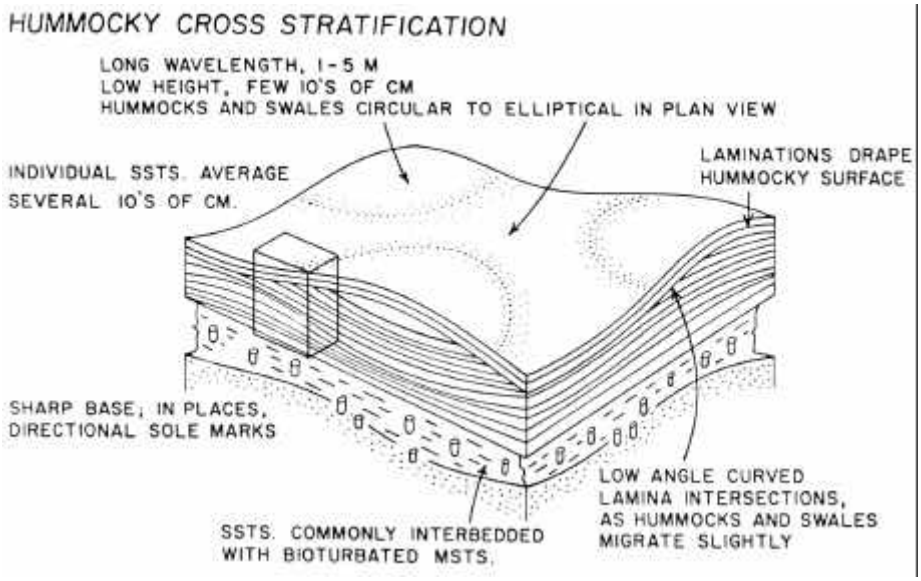

Figure 12. Hummocky cross-stratification. Note the box-core, drawn to scale (Swift et al. 1983).

Southard et al. (1990) hypothesise that formation of hummocky megaripples (and thus HCS) is favoured in high near-bed suspension concentrations. The presence of currents leads to more sediment diffusion above the wave boundary layer, and therefore reduces the opportunity for HCS formation. Thus, HCS is formed in wave-dominant conditions, possibly with relatively weak currents. This was confirmed by Li et al. (1997) and Li and Amos (1999a) who found that long wave ripples were not formed when currents are more important. On the other hand, the combination of a certain current with waves increases the bed shear stress and therefore sooner leads to the transition to upper plane bed than would be the case without a current. It is not clear what the implications of the latter point are, what the transitional bedforms to e.g. current megaripples are in that case.

6. SANDPIT: to boldly deploy where few have deployed before

The would-be exploiter of the ocean will do well to remember the words of the old Newfoundland skipper, "We don't be takin' nothin' from the sea. We has to sneak up on what we wants and wiggle it away."

K. O. Emery, Scientific American September 1969

The SANDPIT measurements of undisturbed seabed conditions will take place for a full year at a transect orthogonal to the coast at Noordwijk (near Leiden, see fig. 13). The water depths of interest are between 9 m (1.5 km off the coastline) and 20 m (20 km off the coastline). This ranges from the most seaward boundary of the surfzone to the lower shoreface. Storm waves may annually exceed 4 m height and decadally 6 m height (with periods up to 13 s), tidal currents are in the order of 0.5-0.7 m/s and wind-driven currents are in the same order of magnitude (see also dataset descriptions in the appendix). The grain size of the bed sediment is 0.15-0.20 mm (moderately sorted) between 8-12 m depth and 0.25-0.30 mm (well sorted) at greater depths. Three types of bedforms have been identified and classified by Delft Cluster (2002): ripples, with heights of 0.003-0.06 m and lengths of 0.04-0.6 m, megaripples of 0.06-1.5 m high and 0.6-30 m long, and sand waves of 1.5-15 m high and 30-1000 m long.

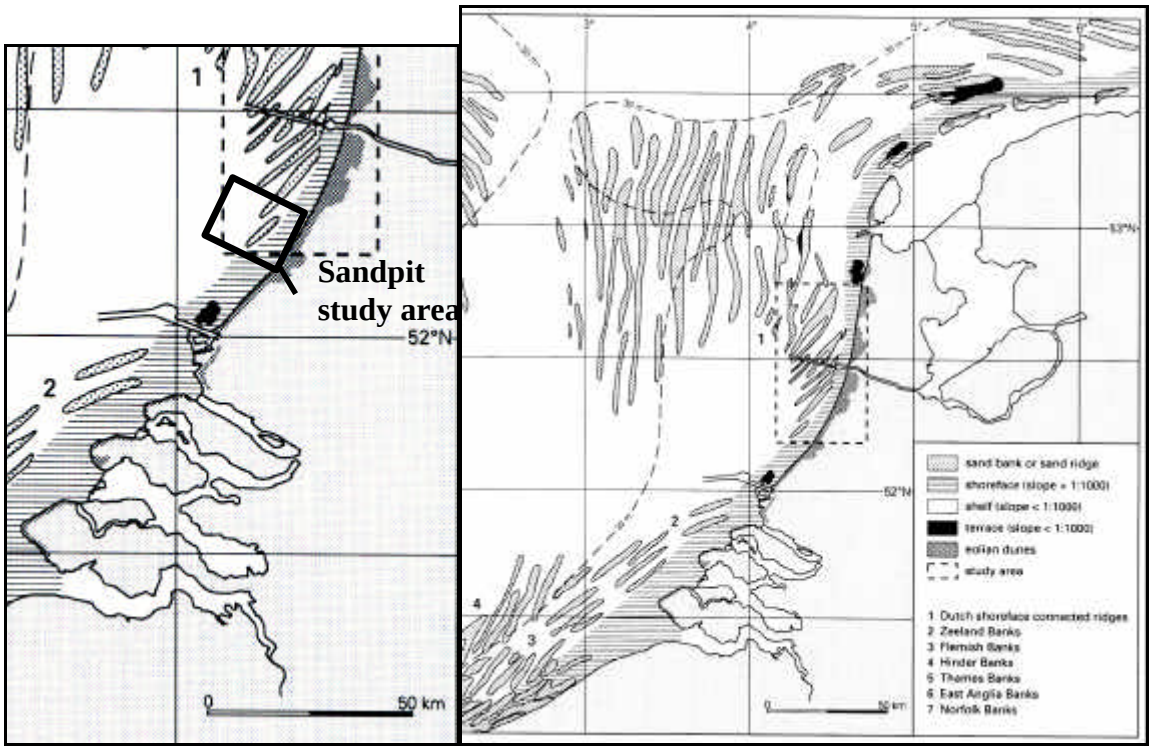

Figure 13. Sandpit study area near the coast of Noordwijk and location of tidal sandbanks and sand waves in the North Sea. After Van de Meene (1994). The two artificial jetties and channels are the Rotterdam (lower) and IJmuiden (upper) navigation channels.

The number of sediment transport studies at the Dutch shoreface may be large, but most are modelling studies; the number of measurements is rather small. There is one recent dataset at the exact SANDPIT location (CEFAS data with suspended sand, mud and flow measurements) but it has not been processed, analysed and interpreted yet. Apart from this there is a large number of ADCP measurements, bathymetry measurements and bed sediment samplings (Delft Cluster 2002 Ecomorf project). Delft Cluster also studied the benthic communities, which might

be needed to assess biological effects on sediment dynamics.

Herein, only a small number of datasets and one combined observation and modelling study is used to estimate the order of magnitude of the sediment transport (see table 2). The modelling study is by Van Rijn (1997), who combined a model with observations of migrating dredging pits and ridges, and a limited dataset of bedload transport in large waterdepth are by Van de Meene (1994, also Van de Meene and Van Rijn 2000). The net annual cross-shore transport (also including pores) computed by Van Rijn (1997) was 10 ± 10 m^2/year at 20 m depth, and 0 ± 10 m^2/year at 8 m depth. The Van de Meene data is only available parallel to the current, which is the shore-parallel net transport for half a tidal cycle.

The bed sediment data and bathymetric mappings at the Holland coast and off Terschelling (see appendix) strongly suggest that the sediment activity tapers off between highly active at the surfzone boundary to episodical suspension by storm waves at large waterdepths. This tapering off is at a much slower rate than the seaward decline of morphological activity. This is confirmed by the sedimentary structures and bedform observations.

Table 2. Published datasets of sediment transport off Holland.

Dataset	depth, bed	flow conditions	suspended load	bedload	author
15 aug 1991 Nile Sampler Noordwijk	14m, megaripples	u=0.2-0.42m/s H=0.3-0.8m	0.5-2 g/s/m = ~20 m^3/m/y (momentaneous...	0.5-2.5g/s/m = ~20 m^3/m/y ...in tidal cycle)	Van de Meene and Van Rijn 2000
model	8 m 20 m	yearly yearly	total longshore transport:	85 ± 45 m^3/m/y 35 ± 15 m^3/m/y	Van Rijn 1997

Based on this review and the data and observations on the Dutch shorefaces, the following working hypotheses for sediment dynamics at the SANDPIT site are formulated in addition to the more general hypotheses given by Wright et al. (1991, see introduction):

1. The North Sea has only small swell waves and is storm-wave dominated. Furthermore tide- and wind-driven currents occur throughout the year. Density-driven currents play a secondary role off the Dutch coast. Consequently:
    a. wave-current interactions (with wave direction usually orthogonal to current direction) will play an important role throughout the year;
    b. wave groupiness occurs frequently on the North Sea (Van de Meene 1994, Ruessink 1998) and may affect the sediment suspension;
    c. near the 10 m waterdepth, intermediate and storm waves dominate the sediment dynamics, whereas near the 20 m waterdepth, tidal and wind-driven currents dominate the sediment dynamics;
    d. at 10 m waterdepth, waves of moderate height will suspend sediment and contribute significantly to the annual transport; at 20 m waterdepth, only very large waves (say, recurrence once a year) will suspend sediment;
    e. consequently, the bottom orbital velocity climate at 20 m depth will have a more episodic nature, and will have dominant northwest and southwest directions, whereas at 10 m depth the other directions and smaller storms dominate the bottom climate;
    f. the approximate morphological depth of closure at a time scale of 50 years is approximately at 10 m depth; the approximate sediment transport depth of closure (above which significant exchange take place between the upper shelf and

surfzone) at the time scale of 50 years is unknown but probably between 10-20 m depth.

2. The net annual suspended sediment transport will be in the offshore direction, while the bedload will be onshore. The net annual longshore sediment transport rate is an order of magnitude larger than the cross-shore sediment transport rate.
3. Density-driven currents from freshwater outflow of the river Rhine is significant for cross-shore sediment transport. The tidal excursion is 11-16 km per tidal period which means that a freshwater lense may pass the measurement site twice during a tidal cycle. As the residual tidal excursion is 2-2.5 km per tidal period in the longshore direction, the transport of freshwater to the north is not very fast so the discharge peaks of the river Rhine will be attenuated by mixing along the coast.
4. At locations between 10 and 20 m depth, various wave- and current-generated bed states can be expected. The vertical sediment sorting and the active layer thickness of the bed are related to these bed states. Furthermore, biological and fishing activities will affect the bed state and the vertical sorting:
    a. lower plane bed (sediment almost immobile), various ripple types, and upper plane bed (sheet flow), although the latter is not expected more than once a year at a waterdepth of 20 m. At the 20 m waterdepth, current-driven bedforms are expected to dominate (ripples, megaripples and sandwaves), and during heavier storms also mixed flow bedform types;
    b. Effects of sediment mixtures are significant for the suspended sediment fluxes, but will probably not vary very much in the long-shore direction and slightly more in the cross-shore direction. The bed sediment fines upward in the upper 0.1-0.2 m, which is the active layer during storms;
    c. active burrowing, digging and deposit feeding by animals will mix the sediment and potentially secure mud to the bed in fecal pellets. Moreover, bed surface armouring by shells and shell fragments may be important;
    d. the bedforms on the seabed will be obliterated frequently by fishing activities, and the sediment will be vertically mixed to a depth of 0.1-0.2 m.

7. General conclusions and recommendations

- The determination of the shear stress component that causes bedload transport and bedform formation is highly uncertain, especially in superimposed currents and waves. The wave-current interaction is not well understood, especially not its effect in the wave boundary layer (where bedload transport occurs) and where currents and waves are not colinear. So far, field tests of certain shear stress components were done under the bold assumption that the other components were correctly modelled, leading to a heavy underdetermination of the whole theory by a single dataset. Due to uncertainty in the shear stress computations, the prediction of bedload transport and of reference concentrations in field conditions is highly uncertain. It might be worthwhile to perform the same model tests with a number of datasets with much more variation in parameters and the relative importance of currents and waves.
- The exchange of sediment between surf zone, shoreface and shelf is not well known nor understood but may be important for coastal sediment budgets on longer time scales (years-decades). Usually, the bedload transport (with preference for coarser grades) outside the surfzone is directed towards the coast while the suspended load transport (prefering finer grades) is directed towards the sea. At the seaward boundary of the surfzone, the balance between cross-shore sediment transport components is delicate and the net cross-shore transport is near-zero. Nevertheless, the net cross-shore transport may be relevant for sediment exchange between shelf, shoreface and surfzone on a decadal time scale.
- Density stratification due to fresh-water outflow from rivers into the shoreface waters may significantly affect the (coastward) cross-shore sediment transport rates, although the effect has not been quantified in measurements yet. The effect is to a certain extent comparable to downwelling and upwelling patterns.
- Biological effects by benthic fauna are numerous and diverse and are neither well mapped nor well understood.
- There are few datasets on wave and flow dynamics, sediment transport and bedforms in deep water (>10 m) outside the surfzone. Yet, because of the less dynamic and rough conditions, and the lack of breaking and heavily dissipating waves, this seems to be the place to start measurements for the understanding of shear stress computation, wave-current interaction, bedform dynamics and sediment transport.
- Although a number of ripple dimension and roughness predictors have already been developed, there is no satisfactory bedform stability diagram yet for waves and waves plus currents. In specific, the transitions between wave and current ripples and between wave and current megaripples (and long wave ripples) have not been clarified. Also the effects of highly irregular or bimodal wave spectra are unknown. Such a diagram, however, would probably depend on the same shear stress component as successful bedform dimension predictors, while it also would predict other bed states than ripples. It would seem logical to develop such a diagram from the existing (field) data as a first step. This might clarify many issues in bedform nomenclature, though not of bedform hysteresis and history effects. Furthermore a diagram would be helpful in the hydrodynamic interpretation of sedimentary structures.
- The effects of sediment mixtures on ripple dimensions, grain roughness and sediment transport in various conditions are not well known. Yet a fining upward storm sequence is often observed. Some understanding comes from river settings, but data in deep water

and omniconfusing flow is very limited.

- The use of ‘representative-wave’ parameters is questionable in the presence of coupled infragravity waves (wave groups), because the sediment concentration may be larger in wave groups. Also in the presence of two different wave fields (e.g. local sea waves and swell from a different direction) the suspended concentrations seem to differ from those in a ‘standard’ random wave field.
- To compare datasets from (and apply these to) different environments over the world, three aspects must be distinguished: the large-scale tectonic, morphological and geological setting and genesis of the shelf, the intermediate-scale of annual/decadal wave and current climate and concurrent sediment dynamics, and the local ‘measurement’ scale at short time scales (seconds-days). At the intermediate scale, there is an impressive variety of conditions, and a large number of possible combinations between the forcings. Consequently, the various settings are unique and the knowledge of these settings cannot be applied to others. This effectively decouples the largest (integrative, geological) scales from the local (generic, process-) scales and transforms the former into boundary conditions instead of forcings. The knowledge of local processes in various environments, however, can be integrated in quantitative process-models, with the inputs based on the intermediate (climate) scale characteristics and the boundary conditions on the geologic and general setting.
- The best method for the integration of sediment transport over years and decades is by use of a combination of a probabilistic method based on measured time series with mathematical modelling.
- The SANDPIT site is located between the wave-dominated surfzone and the (tidal) current-dominated shelf, and consequently experiences both storm-wave driven, tidal-current driven and combined flow-driven sediment transport with concurrent low-to-high energy bed states. Datasets in these conditions are rare. In addition, the pulsed fresh-water outflow from the Rhine may induce a highly variable density-driven sediment transport component. The shallower SANDPIT site may experience significant sediment exchange between surfzone and shoreface. The seabed sediment is non-uniform so various graded-sediment effects can be expected. Application of the dunetracking method for bedload transport determination may be useful to extend the point measurements to a larger area, although bed disturbance by fishing activities is far from negligible.
- Wave ripple migration might be used to determine the bedload transport in storm conditions with the dunetracking method, whereas in calm conditions a bedload sediment sampler may be used. If megaripple (0.2-0.3 m high, 10 m long) migration is determined solely by bedload transport, then based on the Van de Meene transport rates a migration celerity might be expected of about 40 m/year, which should easily be detectable with the planned bathymetry mappings. This method would be applicable to the whole mapped area which is useful for extending the point measurements of the frames to a larger portion of the shoreface.

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10. Appendix: datasets

Table 1 (at the back of the report) provides a summary of combined wave, flow, sediment suspension, bedform and bedload transport datasets (at the back of the report). The locations are given on figure 6.

10.1. California

Off California a large number of measurements have been done at water depths of 12 to 90 m, mostly in the framework of stratigraphic studies of shelf sedimentation. The active margin of the American continent is characterised by mountains dipping steeply into the ocean. Very nearshore there are sandy patches and beaches, but further offshore the bed is composed of mud, organic fluff material and grains of fecal pellets. Strong northern hemisphere swell is generated in winter by cyclones in the North Pacific and Gulf of Alaska and can reach wave heights of 8 m. Southern hemisphere swell with long periods (>20 s) is generated by storms off New Zealand, Micronesia or Central America during summer. Sea waves from local storms are generated in both winter and summer, and are generally higher to the north (off Canada) (Davies 1972, Kelletat 1995). Shore-parallel winds in the spring drive the strong upwelling common to central California. The tide is mixed diurnal and semidiurnal with a tidal range between 1 and 2.5 m.

C1 Storlazzi and Jaffe (2002) measured fluid flow and sediment fluxes at and just outside the surfzone in a pocket beach at a water depth of 12 m, offshore of a sand-filled paleo-stream channel flanked by bedrock extending beyond the surfzone. The sediment was 0.13 mm and contained dense aggradations of dendrasters (sand dollars; bioturbation structures). They collected data using an electromagnetic and backscatter sensor and a sonar altimeter and a wave buoy in June-July 1998, in moderate storms with deep-water wave heights just above 3 m but nearshore waves below 2 m in shore-parallel winds. The wave- and winddriven currents were below 3 cm/s. Near-bed sediment suspension events were mostly caused by waves, which is common for the whole shelf. The direction of the local wind and current seemed to be forced onshore through the incised paleo-stream channel and led to a downwelling net offshore current. The suspended sediment flux was onshore for large particles and offshore for small particles. This mechanism is probably partly responsible for the formation of the mid-shelf mud belt observed on this shelf (and possibly many others).

C2 Long term bed shear stress characteristics were derived from the local wave climate by Xu (1999) for two locations in the Monterey bay, one more exposed to the south and one more exposed to the north. The northern site, receiving the intense winter swell, had a 20-40 times higher probability for sheet flow conditions (depending on the sediment size) at a water depth of 13-15 m.

C3 Xu et al. (2002) studied the suspended sediment transport in much deeper water (32-120 m), where the bed consists mostly of mud, organic material and has some very fine sand. Three instruments were deployed north of the Monterey bay at water depths of 32, 50 and 120 m and had transmissometers, sediment traps, current meters and temperature and salinity sensors. The instruments were deployed for one year starting in August 1996. They measured consistent poleward flows near the bed, although this is in the opposite direction of the equatorial winds. The mid-shelf mud belt (described in C1) is derived from the Russion river (south), the Eel river, the Columbia river (north) and coastal cliff erosion. The sediment transport at the inner- and mid-shelf (<50 m) was dominantly northward, especially in the storm-driven flows of winter, but at

the outer shelf was equatorward. The hydraulic roughness was strongly dependent on the mud coverage (with some bioturbation and small-scale bedforms) of the hardrock shelf bottom.

C4 Further to the north, on the Eel river shelf, Cacchione et al. (1999) measured suspended sediment fluxes and bedform activity at a water depth of 50 m over a 4-month period in 1995-1996. The equipment consisted of a rotating sector-scanning sonar, a laser particle sizer, acoustic backscattering system, and current and transmissivity meters at various depths. The mean sediment diameter was 0.07 mm, but the mode was between 0.125 and 0.25 mm which represented 22-46% of the surface sediment. Significant near-bed wave orbital velocities were often above 20 cm/s (during storms >50 cm/s), which was the threshold for mobilisation of the sandy sediment, which moved mostly as bedload. Net bottom flows were predominantly seaward, and northward during heavy storms. Patchy occurrences of low-amplitude bedforms with wavelengths of 5-10 m were observed with side-scan sonar in the area, and 10 cm wavelength sediment ripples were observed at the surface. Boxcores revealed wavy ripple lamination and cross-bedding in the upper 3 cm. Bed-level changes of 5-10 cm were associated with migrating bedform fields. Using a model and the measurements, the peak discharge from the Eel river (2000-4000 m^3/s) was correlated with high suspended sediment concentrations, probably of muddy sediment advected from the river.

C5 Ogston and Sternberg (1999) worked together with Cacchione et al. (1999) at a water depth of 60 m, which was the landward edge of the mid-shelf mud deposit. They found a highly bioturbated bed, with ephemeral wave ripples in the winter. Again, orbital velocities of high waves were highly correlated with the suspended sediment fluxes, accounting for 72% of the net along-shelf transport. However, the storm events only accounted for 10% of the net across-shelf transport. This net transport is mainly caused by less energetic tidal currents, low-frequency and mean currents (not wave-driven) and river discharge.

C6 To the south, off the Palos Verdes peninsula in southern California, Wiberg et al. (2002) measured and modelled sediment tranport over a decadal time scale. Current and light attenuation meters were deployed and pump samples collected in December 1992 - March 1993 and the wave conditions were less energetic than in C4 and C5. The water depth was 63 m and the surface sediment consisted of 34% sand-sized fecal pellets, silt and clay. The orbital velocity magnitude was highly correlated with the suspension events. The suspension by waves lead to current-driven suspended sediment fluxes in the northward direction, which agreed with the observation that the mud belt seemed to be derived from the south, and the mean currents were not related to waves.

C7 Off the Russian River north of San Francisco, north California, Lynch et al. (1997) measured the same characteristics related to the mud belt at 90 m depth derived from this specific river. They deployed two acoustic backscatter systems and a current meter in the winter of 1990-91. Biogenic roughness elements caused suspension of fines above the wave boundary layer, which were then advected by the mean currents.

C8 Harris and Wiberg (1997) attempted to quantify the long-term sediment transport at the same site as C7. They considered several methods, including determination from long time series and probabilistic approaches. Interestingly, they used an active-layer model for the computation of sediment exchange between transport and bed of different size fractions of fecal pellets, silt and clay.

Summarising, the western coast of the United States is rocky and only partly covered by unconsolidated sediment, which is derived from small rivers. The coarser sand has been transported mostly as bedload to the coast and partly stored in beaches, whereas the finer fractions and organic material (insofar it has not been produced locally) has been transported in suspension to deeper water. In deeper water (20-100 m), the net current transports the fines as a

mud belt covering the rocky shelf. High waves of storms or swell are able to cause suspension events of the mud at that depth, and exceed the bedload threshold of sand to form ripples in the local fine sand patches within the mud belt.

10.2. Gulf of Mexico

The inner shelf of Louisiana in the northern Gulf of Mexico has very fine sand near the shore and mud in deeper waters. The sites described below are situated east of the youngest lobe of the Mississippi delta. The inner shelf is rapidly accumulating fine sediments from the Mississippi river and many smaller rivers flowing into the Gulf. Due to its low exposure, the hydrodynamic energy is much lower than on open ocean shores. Hurricanes occur mostly in September-October. The diurnal tides have an amplitude of 0.4 m and tidal currents are weak (< 5 cm/s).

G1 Pepper and Stone (2002) measured flow velocities with acoustic Doppler velocimeters and computed sediment transports at the seaward and landward side of a shoal at a water depth of 8.5 and 6.5 m, respectively. They deployed their instruments during the winter of 1998-1999 with heavy extratropical storms, weak storms and fair weather. The mean bottom currents during storms (>10 cm/s) were more than twice as large as during fair weather, and the computed sediment transport was directed offshore. Despite the expected limited wave action on a shelf of low exposure, weak storm and fair-weather resuspension and shoreward transport was found to be significant. Interestingly, the near-bottom currents during fair weather and weak storms flowed in the same direction as the prevailing wind. To satisfy continuity, a horizontal return current is expected but this was not measured nor remarked on. During storms, the wind- and wave driven currents were relatively more important than wave oscillations compared to fair weather.
G2 At water depths of 15.5 and 20.5 m, Wright et al. (1997) measured fair-weather bottom boundary layer processes and mud suspension with four Marsh McBirney electromagnetic current meters, five optical backscatter sensors and a sonar altimeter. The instruments were deployed in April 1992 at the 15.5 m site and in May-July 1993 at the 20.5 m site. Additional information at the latter site was obtained with side-scan sonar and sub-bottom profile surveys. It was found that a weakly consolidated mud layer of 5-10 cm thick covered the muddy fine sand at the 15.5 m site, and a thinner layer (1-2 cm) of mud covered a hard-packed layer of very fine sand at the 20.5 m site. During the deployment period, more mud accumulated and the roughness was mainly biogenic. In low wave energy, the hydraulic roughness was extremely low, but in moderate energy became over an order of magnitude higher due to wave-current interaction and suspended sediment stratification. The currents in low wave energy were alone not strong enough to suspend energy.

Summarising, despite the low hydrodynamic energy, the waves and currents in interaction are strong enough to cause shoreward sand transport in fair weather and weak storms, and seaward sediment transport during storms.

10.3. Ebro delta

The Ebro delta is situated in the Mediterranean at the north-east coast of Spain, where the tidal range is small. The river discharges 300-600 m^3/s on average with peaks up to 10000 m^3/s

of freshwater into the basin. At present, a very low sediment load is delivered to the Ebro delta because of river engineering and management works, which leads to a marine reworking of the delta (Jiménez et al. 1997). There is a river-derived mid-shelf mud belt at depths between 20-80 m, in between the sandy inner shelf and the relict transgressive sand deposits on the outer shelf. Between July and September there is strong thermal stratification whereas the water is fully homogenised between January and March. There is a net current towards the southwest, but winds may modify the currents. The winds are strongest in fall and winter and are in the northwestern (Mistral) or northeastern (Gregal) directions. The spring tidal range is only 0.25 m, so the coast is wave-dominated with two-thirds of the time sea waves and one-third swell, while long-period swell is absent. Mean water-level variations due to meteorological tides play a limited role as well because these increase the amount of incoming energy and because these extend the domain for wave action (Jiménez et al. 1997).

E1 In the period of November 1996 – November 1997 a series of measurements was done for a total duration of 3 months and at water depths of 8.5, 12.5, 60 and 100 m (Jiménez et al. 1999, 2002, Puig et al. 2001, Guillén et al. 2002, Palanques et al. 2002). The mentioned papers are all about (parts of) the same dataset and there is some overlap between the papers, so they are here discussed as one dataset. The tripods were equiped with up to three electromagnetic current meters and optical backscatter sensors, and a wave buoy was deployed for the period. A Region Of Fresh water Influence (ROFI) of the Ebro river occurred only to some extent with landward directed winds in winter, when the river discharge was high (Jiménez et al. 1999), but the effects on bed shear stress or sediment transport have not been quantified. The suspension of bed sediment was mostly associated with storm wave activity: the tidal currents were hardly strong enough to suspend the mud and not strong enough to suspend the sand. The longshore current was mostly wind-driven and occurred in eastern winds, when the waves were also large. Boundary layer modification by wave friction and sediment stratification accounted for a significant part of the longshore current drag; thus wave-current interaction was important.
Once mud was suspended it could remain suspended by current action only. The cross-shore gradients in wave-induced shear stresses is governed by the depth decrease with increasing wave action, and the shoreward increase of grain size from 60 m up. Longshore transport rates were an order of magnitude larger than cross-shore transports, partly due to wind-driven currents. The net cross-shore flux was offshore at 12.5 m depth but onshore at 8.5 m depth due to differences in the direction of the tidal and wind-driven current. Mud was advected seaward from the inner site and caused time lag effects in observed concentrations. Thus the cross-shore gradients in sediment size and wave action were important, but also the longshore current.
The sand of the inner shelf and foreshore was frequently suspended (30% of the time) whereas the mud at the mid shelf and the sand at the outer shelf were almost never suspended. The current shear stress at the outer shelf was larger than at the mid shelf, preventing the extension of the midshelf mud belt. The general conditions differ from those at the Californian and other shelves, where stronger tidal currents and longer-period (swell) waves are present and the resuspension by waves reach the outer shelf and the cross- and longshore sediment fluxes on the shelf have the same order of magnitude.

10.4. Duck

The Duck and Sandbridge sites of the US Army Corps of Engineers Field Research Facility are located off North Carolina in the Middle Atlantic Bight at the east-coast of the USA.

Many field studies have been done here in the past twenty years in the surfzone and at greater depths. The bed is stirred primarily by swell waves and sea waves generated in northeasterly storms and tropical cyclones. The sediment is fine to very fine sand with an increasing silt and clay content (up to 20%) outside the surfzone. The tides are semi-diurnal with a mean spring-tide range of 1.2 m.

D1 Hanes et al. (2001) studied wave-formed ripples at water depths inside and just outside the surfzone. A Multiple Transducer Array, a rotating scanning sonar and an underwater video camera were used for mapping the dimensions of the ripples. In addition, an acoustic backscatter system and an optical backscatter sensor for suspended sediment concentrations were deployed, and two acoustic Doppler velocimeters and a pressure sensor for waves and currents. Continuous measurements were done for a few months in 1995, 1996 and 1997 (latter at both Duck and Sandbridge) during fair weather conditions with 0.5-2.7 m high swell waves. They found that both short and long ripples (superimposed) migrated landwards in and just outside the surfzone with celerities of 0.5-1 cm min^{-1}.

D2 Wright et al. (1991) measured suspended sediment concentration profiles (five-element miniature optical backscatter sensor) and velocities (Marsh-McBirney current sensors) to determine the cross-shore fluxes. In addition the bed level was monitored from the tripods (using sonar altimeters) and suspended sediment was trapped at several heights above the bed. The measurements were done in fair weather in 1985 and 1987 at depths of 8 and 17 m respectively, in moderate energy at Sandbridge and in swell-dominated conditions at Duck in 1988 (depth 7.3 m), and in storm in 1985 (depth 8 m). Except in storm conditions, the net sand flux was directed shoreward. They found that a fairly common northeasterly storm is capable of transporting more sand offshore in an hour than fair weather in two or more days. The mean flow was found to determine the direction of sediment flux, with incident waves causing the sediment suspension, while low frequency waves caused measurable but not dominant cross-shore sediment fluxes.

D3 Li et al. (1996) measured flow, suspended sediment concentration profiles and some ripple dimensions in conditions with both waves and currents in 1985 and 1988 at depths of 8 and 7.3 m respectively. The data is a subset of D2. Conditions with ripples and washed-out bed (sheet flow) were taken into account. Over rippled beds, the sediment concentrations were found to increase with increasing shear stress, while the reverse was found for sheet flow. Armouring of the sediment, which decreased the reference concentrations, was suspected in some cases.

D4 Xu and Wright (1995) tested bed roughness models using Duck data from 1991 and 1992 at depths of 13 and 14 m respectively, at which the bed consisted of 80% fine to very fine sand and 20% silt. The instrumentation was the same as in D2. Bedform photographs were taken during deployment and recovery of the tripods, and the bed was found to be covered with ripples in fair weather and moderate sea conditions. Current shear velocities and apparent roughnesses were determined from burst-averaged current profiles, assuming the law of the wall. From the measurements and models, they found that the sediment transport roughness was an order of magnitude smaller than the ripple roughness, and became dominant only in sheet flow conditions (upper plane bed).

D5 Lee et al. (2002) deployed one tripod with six electromagnetic current meters and three profiling ABS at a water depth of 13 m and measured in storm and swell conditions. They found that the sediment concentrations during storm were higher within the wave boundary layer than in swell, but lower above the boundary layer than in swell. They argued that in swell conditions the vortex shedding over low ripples extended the eddy viscosity associated with waves to above the boundary layer, whereas during storm the strong currents prevented the penetration of vortices above the wave boundary layer. This remains speculative to some extent because the

modelled wave boundary layer thickness could not be constrained enough in the low vertical resolution of the current meters. Yet, no model on wave-current interaction considered the enhanced vertical exchange by shedding vortices above the wave boundary layer and the slow decay of concentration with height above the bed in weak currents, while this may prevail in various swell conditions. Another factor of large importance for the prediction of suspended sediment concentrations was the consideration of various grain size fractions. The predicted concentrations varied widely between application of single grain sizes, grain size fractions and the bed surface armouring. Lee et al. only used the model of Wiberg et al. (1994) for modelling armouring.

D6 Kim et al. (1997) deployed tetrapods (with comparable instrumentation as in D2) at 12 m and 20 m depth simultaneously to study bed shear stresses and suspended sediment concentrations in fair weather and storm conditions in October 1994. The measurements indicated that northeaster anticyclonic winds at the large synoptic length scale, causing downwelling near-bottom flows, caused an order of magnitude lower bed shear stresses and sediment suspension than the subsequent local-scale winds from a compact cyclone that was superimposed on the synoptic-scale winds. From results of shear stress model testing it could be inferred that the wave-current interactions in these conditions were rather important.

D7 The effect of wind climate and fresh-water input on the cross-shelf circulation was studied by Cudaback and Largier (2001) with three moored tripods with current meters and temperature and salinity sensors and with shipboard ADCP and CTD along seven transects. There are both seasonal and synoptical patterns. Winter storms drive downwelling circulation. The winter rains increase the fresh-water runoff and the winter wind pattern allows release of low-salinity water from Chesapeake bay. The autumn storms break down the thermal stratification, leading to a decrease of upwelling effects on temporal variability out of the upwelling season. Two patterns at the synoptic scale emerged from the data. Winds in the area reverse every few days, driving the cross-shore upwelling and downwelling circulation and the temperature variability alternately. The buoyancy current is primarily responsible for the along-shore circulation and the salinity patterns. The cross-shore currents developed within a few hours of the sudden onset of along-shore winds, and the along-shore currents developed after 10 hours (half an inertial period). Upwelling caused the buoyant (low-saline) plume to move offshore.

(Summary of Duck taken together with New Jersey, see below.)

10.5. New Jersey

J1 At a site northward of Duck and Sandbridge, Traykovski et al. (1999) studied wave orbital ripples in medium to coarse sand of a sand ridge on top of a holocene lagoonal mud between the ridges. The water depth at the deployment site was 11 m, and several tropical hurricanes passed the site during the measurement period. Benthic acoustic stress sensor current meters and electromagnetic current meters were used to measure profiles of water velocities, and an acoustic backscattering was used to measure concentration profiles. Visibility was very low (less than a meter) and biofouling became a problem in the two weeks deployment in August-September 1995. The bedforms were mapped with a sector scanning sonar. Current ripples in the longshore directions were found to be superimposed on orbital wave ripples, both on the crests and in the troughs, which were in the cross-shore direction. It was found that wave ripple migration was predominantly onshore, while suspended sediment fluxes were too small to force the ripple migration, and were in the opposite direction to ripple migration. The ripple migration

was used for determining bedload transport, which was an order of magnitude larger than the suspended load transport. The differences between orbital and anorbital ripples, and between two-dimensional and three-dimensional ripples were studied. For most of the year, the waveheight and period were such that the near-bed conditions at this depth were around incipient motion of the sand and below the transition from orbital to anorbital (suborbital) ripples. Hysteresis was observed in the temporal evolution of the wave ripples that were relict from a pre-deployment storm. Due to the non-uniformity of the sediment, the ripple dimensions could not well be scaled using the median grain size. As ripple dimensions are related to grain size, the ripples could grow larger than was predicted with several models because of the presence of larger grains.

Summarising, in the middle (Duck and Sandbridge) and northern (New Jersey) Atlantic Bight the bedload (inferred from wave ripple migration) and suspended transport outside the surf zone is shoreward except in storms, when sheet flow prevails, and when the downwelling is strong in northeaster storms, in which case the shoreward currents are counteracted and wave-current interaction is important. To the north (off New Jersey) the sand is coarser and consequently the bedload transport is more important than to the south, and more frequently near incipient motion. Wave-current interactions are important in almost all conditions: during storm, in swell and with prevailing downwelling and upwelling.

10.6. Nova Scotia

The Atlantic coast of Nova Scotia (Canada) has been studied at depths of 2.4 to 39 m water depth. The sediment ranges from 0.11-0.17 mm in shallow water to 0.23-0.34 mm in deep water. The semidiurnal tidal range is between 1 and 1.9 m with peak tidal flows of less than 0.35 m/s at deep water, roughly parallel to the coast. The wave climate is characterised by frequent winter storms, mostly from the southwest, and strong seasonality, with wave heights up to 8 m and peak periods of 2-18 s. The well-sorted sand on the shelf has been moulded into a series of shoreface-connected ridges.

S1 The effect on ripple migration of storm waves combined with swell was recently studied by Crawford and Hay (2001). In 1995 they measured during single-storm event of one day in autumn at the seaward boundary of the surf zone, where at best 23% of the waves were breaking. The location was Queensland Beach, a pocket beach at which Vincent et al. (1991) also measured. The water depth was between 2.4 and 4.1 m and the sediment ranged from 0.12 to 0.32 mm (D16-D84). Flow measurements were done with a dual-beam coherent Doppler profiler, and bedform information was collected with an acoustic rotary sidescan fanbeam, a rotary pencil-beam acoustic profiler and a laser-video bed profile imaging system with millimeter resolution. The ripple migration was found to be offshore during storm growth, and onshore during storm decay, which was strongly correlated with nearbed wave orbital velocity skewness (net flow direction). During the growth, incident swell waves interacted with the sea waves, leading to a bimodal velocity spectrum with negative (offshore) velocity skewness. Crawford and Hay assume this pattern during storm growth and decay to be representative for yearly conditions at this site.
S2 On the same site, Vincent et al. (1991) in their benchmark paper reported suspended sediment concentrations and reported the strong effect of bed roughness by ripples on the concentrations. In October 1987 they deployed a tripod at a water depth of 4-6 m with an acoustic concentration meter and two electromagnetic current meters. The reliability of the measured

concentration is not well known as a layer of fine organic material was observed to float close to the sea bed. In addition to the measurements, models of ripple dimensions and wave, current and apparent roughness were used. The modelled sediment transport due to the net current was found to be twice as small as those when the wave-current interaction was ignored and a simple logarithmic current profile was assumed.

S3 Boyd et al. (1988) used time-lapse film and a hydrodynamic tripod at a water depth of 10 m to study bedform dynamics in low to moderate wave heights (<1.7 m) during summer conditions with three small storms. Flow and orbital velocities, pressure and light attenuation were measured from the frame. The mean near-bed flows usually were much less than 0.1 m/s and wave asymmetry was low. The observed ripple geometry and crest orientation responded quickly to changes in the wave direction. The ripple migration (certainly without aliasing) was predominantly onshore but offshore during the highest waves of two of the three storms. This offshore migration was loosely attributed to wind-driven or tidal motions but not analysed further. It is not known whether the ripples might have migrated against the flow by suspension fall-out at the upstream side of the ripples.

S4 At a much larger water depth of 39 m, Li et al. (1997) measured waves, currents and ripple migration rates during the winter of 1992/1993. The grain size at the measurement site was 0.34 mm. The tripod was equipped with two acoustic current meters, a pressure transducer, two uncalibrated light attenuation sensors for qualitative suspended concentration measurements and a super-8 movie camera with a flash. A shadow bar was employed to derive ripple dimensions. The clarity of the photographs in combination with the observed ripple migration was used to classify dominant transport conditions into immobile, bedload, saltation/suspension and upper plane bed sheet flow. Ripples were almost always present; only in heavy storm conditions sheet flow was observed. The ripple dimensions and celerity were used for the determination of bedload transport which compared favourably with several bedload transport predictors combined with a shear stress/ roughness model. The wave-current interaction lead to a skin friction increase of 20% for roughly parallel waves and currents.

S5 Li and Amos (1998) report the measurements of three storms with wave heights larger than 2 m and wave periods up to 14 seconds during the next winter (1993/94) done at the same site with the same instrumentation. Measured shear velocities for waves, currents and combined flow were used to construct a new empirical total bed roughness model, incorporating a new empirical ripple predictor and the roughness due to bedload transport.

S6 Working on the same data as S5, Li and Amos (1999a) further studied the transition from wave ripples to sheet flow conditions. They found three-dimensional large ripples with regular small ripples superimposed on them. The large ripples were interpreted as hummocky megaripples that were formed under storm waves combined with some tidal, wind- and wave driven currents, although strong currents prohibited their formation. The hummocky megaripples are supposed to be transitional features from ripples to upper plane bed. They only occurred in storm growth when the growth was rather slow, but occurred in all three waning storm conditions. Sheet flow (upper plane bed) occurred only during the highest wave heights. Interestingly, the sheetflow conditions in these wave-current combined flows occurred already for Shields parameters that were only half those predicted with empirical (lab-based) sheetflow onset predictors for waves.

S7 From a slightly finer sediment at a water depth of 56 m on a site somewhat to the east of S5 and S6, Li and Amos (1999b) analysed flow, suspended sediment concentrations at various depths and ripple data from storms in the period Februari-March 1993. A certain sequence of bedforms was observed: 1) relict wave ripples with worm tubes, 2) irregular sinuous current or current-wave ripples (low angle between waves and current), 3) wave dominant ripples with

significant suspension, 4) sheet flow at the peak of the storm, 5) lunate megaripples and 6) transitory ripples in quasi-sheet flow conditions.

S8 Based on an old dataset from 1982 with a current meter and a time-lapse camera at 22 m water depth, Amos (1999) determined bed states and sediment transport thresholds in combined currents and waves of various magnitudes, as well as bedload transport from ripple migration. The bedload transport was in the shoreward direction both in storms and calm weather. Expressions for the onset of sediment motion and the onset of saltation in orthogonal flow and waves were derived from the data. The latter was close to the breakoff Shields parameter of Grant and Madsen (1982) between low (bedload dominated) and high (suspended load) transport regimes.

Summarising, interactions of swell and seawaves prevail in storm growth and cause a seaward bedload transport (inferred from ripple migration) just outside the surfzone, whereas seawaves alone are more prevalent in storm decay, leading to shoreward bedload transport. This mechanism has not yet been investigated at other swell-dominated coasts. In much larger water depths (~40-60 m) only the heaviest storm waves and (interacting) currents are able to form sheet flow, although the existing predictors for the threshold of sheet flow in waves were not yet exceeded, which indicates the importance of wave-current interactions.

10.7. Oceania

The measurements on the nearshore and shelf regions in Oceania are summarised together as they share some important features. The first site (actually two locations) is off southeast Australia (O1, Black et al. 1995, O4, Black and Oldman 1999), the second on the east coast of the North Island of New Zealand (O2, Black and Vincent 2001), and the third is at the northern coast of the North Island (O3, Green and Black 1999, O4, Black and Oldman 1999). The first and third site have more or less similar wave climate and weather patterns of large exposure and strong swell.

O1 Black et al. (1995) measured suspended sediment transport just outside the surfzone at a water depth of 1.11 m with incoming low-energy swell waves and with sediment of 0.33 mm. Two acoustic current meters and three optical backscatter sensors and a video monitoring suspended sediment clouds were deployed in Februari 1992. Mean offshore and longshore currents were in the order of 6 cm/s. Sustained periods of high sediment concentrations were associated with clouds of sediment arriving from the shoreward direction, rather than being entrained locally which happened in much shorter periods. Because the sediment clouds moved seaward at a location just seaward of the surfzone, they were hypothesised to be advected seaward from the breaking waves at the seaward boundary of the surfzone by infragravity motions.

O2 In a slightly larger water depth of 1.75 m, 5-10 m seaward of the breaker zone, Black and Vincent (2001) measured the same parameters with a three-frequency acoustic backscatter sensor (ABS) and an acoustic Doppler velocimeter (ADV). In addition they used a video system looking to the seabed. The sediment was 0.2 mm and the swell waves had a height of 0.42 m and a period of 10.3 s during the analysed runs of November 1997. They observed and modelled opposite instantaneous flow directions in the lowest 2 cm of the water column caused by wave asymmetry. As a result, multiple suspension peaks were observed during a wave period.

O3 The relation between suspended-sediment reference concentrations and bedforms under waves was studied by Green and Black (1999) on the shoreface at water depths of 7 and 12 m off

the northern coast of New Zealand with sediment of 0.23 mm mean diameter. An array of Marsh-McBirney electromagnetic current meters, a three-frequency acoustic backscatter sensor and a video system for bedform observations were deployed in Februari-March 1996. Various bedform types from ripples and hummocky bed to transitional to sheet flow were observed. Contrary to the hummocky bed and sheet flow bed states, the presence of ripples lead to strongly increased near-bed suspended concentrations.

O4 A band with significantly increased grain size and ripple dimensions was observed centred on 35 m depth on the shelf off southeastern Australia and northeastern New Zealand (Black and Oldman 1999). From the shore to the band the grain size increases from 0.3 to 0.9 mm and seaward of the band decreases again. Black and Oldman offer a mechanism for the initiation and sustainment of the band. From a combined wave shoaling, ripple dimension and bed roughness model, they predict that the maximum ripple height occurs at a water depth of 20-45 m on the shelf. This leads to increased roughness and corresponding sediment suspension, which leads to winnowing of fines. Once the winnowing begins, the positive relation between grain size and ripple dimensions enhances the sediment mobility and sorting effects, creating and sustaining the pattern over a long-term. A negative feedback is the decreased mobility of coarser sediment.

Summarising, just seaward of the surfzone suspended sediment transport is seaward. For lack of ripple observations and the complex near-bed flow pattern leading to the double suspension peak, it is difficult to conclude on the direction of bedload transport. On the shoreface (7-12 m) various ripple types are present whereas transitions to sheet flow conditions occur only in high-energy waves. In much deeper water (35 m), a sand belt is found that is created and maintained by interaction of sediment sorting, ripple dimensions depending on grain size, and ripple roughness and sediment size affecting the sediment mobility.

10.8. North Sea basin

U1 On the British North Sea shelf, off the river Tyne in Central England, Green et al. (1995) measured wave heights, currents and suspended sediment fluxes during a severe storm (significant wave heights above 6 m) at a water depth of 25 m. The semi-diurnal tide has a spring-range amplitude of above 4 m and tidal currents of 0.25-0.40 m/s to the south during flood and to the north during ebb, although during this storm it was >0.60 m/s during flood tide because of the additional wind-driven component. They used transmissometers, an acoustic backscatter sensor, Marsh-McBirney current meters and infra-red optical backscatter sensors at various heights above the bed in December 1990 until January 1991. The bed sediment was bimodal with modes at 0.1 mm (56% sand) and 0.025 mm (44% mud), and the seabed is typically covered with symmetrical wave-generated ripples of 10 cm long. The mean near-bed flow was retarded by the sum of the bed roughness and the apparent roughness due to wave-current interaction in the wave boundary layer. The observed bed roughness was consistent with large scale bedforms, although most bed state predictors already indicated upper plane bed conditions. The sediment flux was directed offshore and to the south. Despite the extremely high energy, the erosion depth required for the suspended sediment was <1 cm, indicating that larger sedimentary structures and stratigraphic contributions must be rare. (For a summary see the Netherlands.)

10.9. Belgium

The coastal waters off Belgium are dominated by flood flows and the Flemish coastal banks. The semidiurnal tidal amplitude is 2.9-5.4 m with current velocities of 0.86 m/s (ebb) to 1.32 m/s (flood). During storms, wave-induced currents and orbital velocities also become important. Most research in this area focussed on the Flemish banks, which are up to 40 m high relict features.

B1 Sediment transport and bedform behaviour on the Flemish banks was studied by Van Lancker et al. (2000) and Van Lancker and Jacobs (2000) in water depths of 0-15 m. The spring-tidal flood current alone can transport sediment of 0.42 mm at least, but larger when the sediment is stirred by waves as well. The coarsest sediments (up to 0.5 mm) with the best sorting are found on the tops of the banks. In general, medium-sand areas with better sorting were believed to have been subject to winnowing of finer sediment, which allowed the direction of sediment transport to be derived. The major controls on bedform formation were the flood current and the available sediment. The largest dunes (up to 3 m height) were found in the shallower areas (water depth <9m, depending on the current velocity) with medium sands, while areas with more silt in the bed had almost no bedforms. An additional dune height-limiting process is wave-stirring, especially in shallower areas. Smaller bedforms (also dunes?) were superimposed on the large dunes. The crest-lines of the dunes were all perpendicular to the flood current. Due to the orientation and fetch of the area, the persistence of hydro-meteorological conditions is more important than its strength.

B2 The sediment suspension and transport under waves and currents was studied in more detail by Vincent et al. (1998). In the winters of 1994 and 1995, they deployed a tripod at the northern steep side of the Middelkerke Bank at a water depth of 10 m, and at the less steep southern side of the bank in 11 m deep water. The tripod had two electromagnetic current meters and optical backscatter sensors, and an acoustic backscatter system. The wave heights were 1-4.3 m, and were observed to increase the suspension but have no effect on the transport direction. The sediment at their site was poorly sorted and location-dependent, and the suspended sediment fluxes were calibrated and computed fractionwise. The southern side of the bank appeared to be more wave-sheltered, which explains the lower suspended concentrations in part. The suspended sediment at the exposed northern side consisted mostly of 0.1-0.14 mm, which did not occur in significant portions in the bed material, indicating that it was advected by upstream wave- and current action.

B3 Williams et al. (1999) measured both suspended and bedload transport (from ripple tracking) at the northern side of the Middelkerke bank (median grain size in the bed 0.45 mm). They deployed a pressure sensor, a two-frequency acoustic backscatter system, electromagnetic current meters and an acoustic ripple profiler at a water depth of 20 m during calm weather and a storm in Februari 1993. They also conducted side-scan sonar surveys in the area. From the data they derived a semi-empirical equation for computing the suspended sediment transport in conditions with waves, currents and both.

B4 Williams and Rose (2001) analysed a subset of the previous dataset of one day in Februari 1993, and found agreement of the data with some transport predictors.

Summarising, the coastal waters off Belgium are dominated by tidal currents although the limited water depth allows strong action of storm waves on the tops of the Flemish Banks as well. The bedforms and grain sizes are spatially highly variable due to the large Flemish banks. The currents generate various (sometimes superimposed) classes of dunes, whose slow reaction to

changing hydrodynamic forcing (hysteresis due to the large volumes of the bedforms) may explain the absence of upper plane bed observations during storms.

10.10. The Netherlands

The compound coast of the Netherlands has barrier islands in the north (e.g. Terschelling), a closed barrier coast in the middle ('Holland coast') and estuaries and tidal basins in the south (e.g. Westerschelde and Oosterschelde). A large number of studies have been done in the past 20 years, which were mostly concentrated on the surfzone in the northern and middle zones, on bar and bedform dynamics in the estuaries, on ebb-tidal deltas off the estuaries and barrier islands and on ridges, sand waves and banks at deeper water. The semidiurnal tide has an amplitude of 1.5-2.1 m (neap-spring), with flood-dominated currents of 0.2-0.5 m/s near the bed. The average significant wave height is 1.1 m, and exceeds heights of 5 m during heavy northwestern or soutwestern storms, whereas swell waves are relatively small and unimportant due to the sheltered condition of the Dutch coast in the North Sea basin. The sediment is sand of 0.15-0.5 mm with small amounts of silt and clay and shell fragments. Off the Holland coast, a significant residual water motion outside the surfzone is driven by wind and density differences of water discharged from the Rhine that is drifting to the north.

N1 During campaigns to measure hydrodynamics and sediment transport in the surfzone off Terschelling, Ruessink (1998), Houwman (2000) and Ruessink et al. (1998, 1999) also deployed instruments at a water depth of 9 m at the seaward boundary of the surfzone. This region is dominated by suspended sediment transport by shoaling and breaking waves, and by wind-, wave- and tide-driven currents (mostly in the longshore direction). They used electromagnetic flow meters, optical backscatter sensors and pressure sensors.
It was found that the net cross-shore sediment flux is the result of a delicate balance with large fluxes in both offshore and onshore directions. Important components of this balance are upslope transport by wave asymmetry and the undertow. Consequently, the loss or gain of sediment from a coastal or foreshore stretch depends more on gradients in the longshore sediment transport within that zone than on the net cross-shore transport (Ruessink 1998, Ruessink et al. 1998).
The largest contribution to yearly cross-shore sediment transport (50-60%) is by (breaking) waves with a local significant height of 3.5-4.5 m, which occur only for 0.9% of the time. In these conditions the wave group-induced infragravity transport component is much more important than the high-frequency or mean current-induced transport. Fair-weather transports are very small and more energetic conditions are very rare (Ruessink 1998, Ruessink et al. 1999).
The longshore tidal currents at a water depth of 9 m are dominant in the flood (north-east) direction, but in strong winds the tide may be outbalanced by the wind-driven currents. The wind-induced longshore flows are an order of magnitude smaller and seaward directed near the bed for landward directed winds (Houwman 2000).
N2 In addition, the sea bed sediment off Terschelling was sampled in a large region from 0-15 m water depth and described by Guillén and Hoekstra (1996, 1997), Hoekstra and Houwman (1997), and Hoekstra et al. (1999). The cross-shore variation of sea-bed grain-size indicates that selective sediment transport processes are active. The maximum grain size (median of 0.26 mm) is found at the waterline, rapidly decreasing through the surfzone to 0.14 mm at a water depth of 8 m, and then slowly increasing until a water depth of 10 m (Hoekstra and Houwman 1997, Guillén and Hoekstra 1996, 1997). At the Holland coast, Van de Meene (1994) and Van de Meene (1996 et al.) also found a transition of sediment composition at a water depth of 10 m: in

shallower water the sediment was fine grey sand, whereas in deeper water is was medium brown sand. Guillén and Hoekstra (1996) relate the zones to their hydrodynamic activity and the consequent size-selective winnowing and sediment transport. The deepest coarse sand has been suggested to be a relict deposit of lower sealevels. The coarsest sediment on the beach, fining towards the sea, reflects the action of shoaling and breaking waves. They explained this pattern with a yearly mean onshore bedload transport of coarser sand due to wave asymmetry and streaming and an offshore suspended load transport of finer sand due to undertow. The minimum at a water depth of 8-10 m is the seaward boundary of the surfzone, which agrees with the morphologically significant depth of closure (9 m). It was hypothesised (Hoekstra et al. 1999) that the fine-sediment zone between 6-9 m reflects the suspended sediment fall-out by undertows and possibly rip-currents during storms. This would mean a decoupling between the upper and lower shoreface, which contrasts with the Duck site in the Middle Atlantic Bight off the eastern US, where upwelling and downwelling events play a role in the exchange of sediment.

N3 Based on a long-term morphological dataset (JARKUS, 1964-1992) and model computations and sensitivity analyses, Van Rijn (1997) analysed the sediment transport and sand budget of the coastal zone (Holland coast) in water depths of 8 and 20 m. The cross-shore transport was dominated by tide- and wind-induced currents and density-driven currents (from Rhine water), with the waves stirring the sediment. At 8 m water depth, the components of wave velocity asymmetry, bound long waves, Longuet-Higgins streaming and undertow dominated, whereas at the 20 m water depth, the density-driven current dominated the cross-shore sediment transport. About 60% of the longshore sediment transport takes place in the inner (200 m) surfzone. The wave-induced currents are dominant, but the tidal current also is a major component in sediment transport, especially in the north where the tidal asymmetry is larger.

N4 In relation to the shoreface-connected ridges off the Holland coast, sediment dynamics were studied at a water depth of 10-20 m by Van de Meene (1994), Van de Meene et al. (1996) and Van de Meene and Van Rijn (2000). Current velocities were measured with a ship-based acoustic Doppler current profiler and bedload sediment transport was measured with a basket-type sampler as used in rivers (the Delft Nile Sampler). An acoustic current meter, optical backscatter sensors and a pressure sensor were deployed in 1989-1991 in fair weather and storm. The wind- and density-driven currents added significantly to the tidal currents, especially for low tidal current velocities. In offshore winds, the wind-induced currents cause upwelling circulation in the cross-shore direction, although this upwelling is counteracted in moderate winds by the density-driven cross-shore currents.

In fair weather, the current-driven bedload transport is dominant and low, whereas in storm, the waves stir up the sediment and the sediment transport is dominantly in the suspended mode, driven by the mean currents. Infragravity wave-driven (wave-groups) transport is small.

From 250 box-cores and lacquer profiles, echo soundings and side-scan sonar surveys, it could be concluded that the sea bed is reworked by both currents and waves to a depth in the bed of 0.1-0.2 m. The grain size of the bed sediment is 0.15-0.20 mm (moderately sorted) between 8-12 m depth and 0.25-0.30 mm (well sorted) at greater depths. Sedimentary structures of megaripples, wave ripples, combined wave-current ripples and transitions to upper plane bed were found, with wave action generally increasing with decreasing water depth. Megaripples were observed in the sounding profiles and sonar images. Bioturbation is rather scarce and shell-fragment lags are often found at depths of 0.1-0.2 m below the sea-bed surface, indicating that the sedimentary structures have been formed recently and reflect the current dynamics. The sediment on top of the sand ridges is coarser and better sorted due to wave action (winnowing of fines).

N5 Density-stratification and density-driven currents off the Holland coast were studied by Van der Giessen et al. (1990) and De Ruijter et al. (1992, 1997) in the so-called Region Of

Freshwater Influence (ROFI) of the river Rhine. They used ship-based current meters, a temperature and salinity probe in 1985-1986 and in 1990 and 1992. The findings presented here agree with those of Van de Meene (1994). The fresh water plume is mostly confined in a band within 20 km off the coast. The density-driven currents have a significant onshore-directed component of about 3 cm/s, up to 10 cm/s for extreme river discharges. The wind speed and direction affected the density-driven currents mostly by stirring, which reduces the salinity gradients. The tidal modulation of the river discharge leads to a pulsed discharge of fresh water and consequently a train of fresh water lenses. One such pulse may remain recognisable for a week in the absence of wind and in neap tide. A literature survey indicated that the Rhine is extraordinary in this sense: most rivers do not have halted discharges due to the tide and therefore do not form these pulses.

N6 One of the first attempts to measure bedload by ripple tracking on the shelf is reported by Huntley et al. (1991). They deployed a camera with a flash light and shadow bars at a water depth of 29 m off the north-western coast of the Netherlands, and measured current velocities with an acoustic Doppler current profiler from a ship in fair weather in Februari 1989. The bed sediment was well-sorted sand of 0.29 mm with some shell fragments. The deployment site was within a region of sand waves of 3 m height and 200 m length. No suspension of sediment was observed, and observed bed states were lower plane bed and straight-crested ripples. The dataset is very limited due to aliasing problems and the short time of deployment.

Summarising, the northern coast of the Netherlands (barrier islands) is more exposed to waves than the western coast (Holland coast), whereas the western coast is affected by the density-driven currents from riverine fresh water outflow. Both coasts have surfzone and upper shoreface sediments that are significantly finer than the middle shoreface sediment, suggesting decoupled zones. The former are generated by contemporary suspended offshore transport and onshore bedload transport, whereas the latter are probably relicts. Nevertheless there are current-driven dunes and ripples as well as wave ripples and sheet flow conditions during storms in the deeper waters (~20 m), and a net longshore bedload transport. The latter is the result of the flood-dominated tidal currents, although these can be counteracted temporarily by strong wave- and wind driven currents in storms. The same bed states are found further to the northwest at a water depth of 25-30 m, although in dataset U1 the upper plane bed condition has not been observed despite the extreme storm energy and the presence of 44% silt in the bed, which tended to inhibit ripple formation in Belgian and Californian waters.

10.11. Experiments

Although this review focusses on field data from large water depths outside the surfzone, it is fruitful to include some recent laboratory experiments done in large facilities with large water depths and unbreaking, irregular waves. See also the literature review by van der Werf (in prep.). Below some studies are given that were not included in the SEDMOC database.

Lab 1 Thorne et al. (2002) applied irregular waves to a medium, badly sorted sand in a large flume (Delta Flume of Delft Hydraulics) at water depths of 4.5 m. The suspended concentrations were measured with ABS and pumps. The Nielsen models for time-averaged reference concentrations and concentration profiles were tested on the data to compare the applicability of diffusion, convection and the combination. It was found that pure diffusion represented the measurements the best in the lowest layer of twice the ripple height, whereas above a combined

convection-diffusion approach gave better results. The suggested reason was that the lower layer was dominated by near-bed vortices shed from the ripples, while the upper layer exhibited break-down of the vortices into random turbulence, although a full verification can only be obtained with non-time-averaged modelling.

Lab 2 Vincent and Hanes (2002) studied intrawave suspension in regular and irregular waves and wave groups. In repeated experiments, the variation in suspended sand concentrations was found to be 30%, which indicates that this variation may even be larger in field conditions where lag and history effects of bedforms are present. The settling velocity of the sediment appeared to be decreased significantly by the near-bed turbulence. It was found that waves are continuously 'pumping up' sediment, which did not settle back to the bed before the next wave arrives because of the low settling velocity. So intrawave suspension models should include the sediment suspension by antecedent waves to predict the correct suspended concentrations, otherwise the concentrations are underestimated. This lag effect in suspension was especially apparent in wave groups, where the highest concentrations were measured towards the end of the wave group, where the gravity waves rapidly decreased in height.

Set	year campaign	water depth (m)	grain size (mm)	wave height (range m)	wave period (s) sea/swell	tidal range (m)	max tidal velocity (m/s)	authors
Duck								
D1	95, 96, Sandyduck97	1.4 – 7	0.12 – 0.21	0.2 – 2.7	4 – 16			Hanes et al. 2001
D2	85, 87, 88, Sandbridge88	7 – 17	0.09, 0.125	0.6 – 4	9 – 14	~0.8		Wright et al. 1991
D3	85, 88	6.3 – 9.9	0.13	0.24 – 1.5	6 – 12	~0.5		Li et al. 1996
D4	91, 92	13 – 14	very fine s	0.9 – 2.6	sea 7 – 12	<1.2	0.1 – 0.2	Xu and Wright 1995
D5	96	13	0.12	-	both 6-12		0.2 – 0.5	Lee et al. 2002
D6	94 (1 year)	20	0.1	-	7 – 14		0.2	Kim et al. 1997
D7	94	8 – 30	0.1	-	-			Cudaback and Largier 2001
Nova Scotia								
S1	95	2.4 – 4.1	0.17	0.6 – 1	4 – 9	<2		Crawford and Hay 2001
S2	87	4 – 6	0.14	-	4.3 – 6.4			Vincent et al. 1991
S3	83	10.5	0.11	<1.7	5 – 11		1 – 1.9	Boyd et al. 1988
S4	93	39	0.34	0.4 – 4	8 – 15	0.5 – 1.5	0.2 – 0.35	Li et al. 1997
S5	93	39	0.34	0.4 – 4	10 – 13	0.5 – 1.5	0.2 – 0.35	Li and Amos 1998
S6	93	39	0.34	3	12 – 14	0.5 – 1.5	0.25 – 0.35	Li and Amos 1999a
S7	93	39	0.34	1 – 7	13 – 16	0.5 – 1.5	0.25 – 0.35	Li and Amos 1999b
S8	82	22	0.23	<1.5	sea 8 – 10	0.5 – 1.5	0.25 – 0.35	Amos et al. 1999
New Jersey								
J1	95	11	0.4	<2	5 – 18		0.1 – 0.2	Traykovski et al. 1999
California								
C1	98	13	0.13	1 – 4	swell 5 – 20	1 – 2.5	0.3 – 1.7	Storlazzi and Jaffe 2002
C2	90-95 (5 years)	13-15	0.2 – 0.5	0.5 – 2.5	swell 5 – 20			Xu 1999
C3	96	32, (70, 120)	mud / sand	0.5 – 6	swell 5 – 20		0.1 – 0.25	Xu et al. 2002
C4	95, 96	50	0.07 – 0.18	2 – 8	swell 10 – 20			Cacchione et al. 1999
C5	95, 96 (1 year)	60	0.02 (fecal)	<9.5	swell 5 – 30	0.1	0.35	Ogston and Sternberg 1999
C6	92, 93	63	mud / sand	<4				Wiberg et al. 2002
C7	91	90	0.04 (fecal)	-				Lynch et al. 1997
C8	91	90	0.04 (fecal)	-				Harris and Wiberg 1997
Northern Gulf of Mexico								
G1	98, 99	6.5, 8.5	0.12	0 – 2				Pepper and Stone 2002
G2	92, 93	15.5, 20.5	5cm biomud	-	8	0.3 – 0.5	0.05 – 0.15	Wright et al. 1997

Oceania								
O1 Aus	1992	1.11	0.34	-	12			Black et al. 1995
O2 NZ	97	1.75	0.19	0.42	10			Black and Vincent 2001
O3 NZ	96	7, 12	0.23	0.5 – 2	swell 6 – 11	1 – 2	0.1 – 0.15	Green and Black 1999
O4 Aus +NZ	- (3 years)	10 – 60	0.3 – 0.9	<4	6-12			Black and Oldman 1999
United Kingdom								
U1	90, 91	25	0.025, 0.10	0.5 – 8	6 – 10	< 4	0.25 – 0.4	Green et al. 1995
Belgium								
B1	95-99	3 – 15	0.15 – 0.5	-		2.9 – 5.4	0.86 – 1.32	Van Lancker et al. 2000, V.Lancker and Jacobs 2000
B2	94, 95	10 – 11	0.1 – 0.5	3.6 – 4.3	6.6 – 7.6	<5	0.75 – 0.99	Vincent et al. 1998
B3	93	20	0.45	1.9 – 2.9	6.2 – 10.8	2.7 – 4.5	0.3 – 1.0	Williams et al. 1999
B4	93	21	0.45	2.5		2.7 – 4.5	<1.0	Williams and Rose 2001
Ebro Delta								
E1	96 - 97	8.5, 12.5, 60, 100	0.008 – 0.15	0.5 – 4.5	2 – 12	<0.25		see text
The Netherlands								
N1	94, 95	3 – 9	0.16	0.5 – 5	sea 4 – 13	1.2 – 2.8		Ruessink 1998, Houwman 2000, Ruess. et al. 1998,99
N2	94, 95	3 – 9	0.14 – 0.25	-				Guillén and Hoekstra 1996,97
N3	64-92 (yearly)	8, 20	-	-				Van Rijn 1997
N4	90	15 – 25	0.25 – 0.30	-			0.3 – 0.7	Van de Meene 1994, Van de Meene et al. 1996, VdM and Van Rijn 2000a
N5	85, 90, 92	5 – 25	0.25	-			0.7 – 1.1	Van der Giessen et al. 1990 De Ruiter et al. 1992, 97 Simpson and Souza 1995
N6	89	29	0.29	-				Huntley et al. 1991

Set	UC profs*, grased	emphasis of study (WC=waves and currents)	burst-avg. data avail.?	authors
Duck				
D1		ripples	ripples	Hanes et al. 2001
D2		cross-shore energy contributors	-	Wright et al. 1991
D3	UC	ripple roughness and resuspension	no	Li et al. 1996
D4	U	bed roughness	no	Xu and Wright 1995
D5	UC grased	suspension in swell and sea, diffusion vs. advection WC	no	Lee et al. 2002
D6		weather types and wave conditions	no	Kim et al. 1997
D7	U	weather types, upwelling and buoyancy	no	Cudaback and Largier 2001
Nova Scotia				
S1		ripple types	-	Crawford and Hay 2001
S2		roughness and concentrations WC	-	Vincent et al. 1991
S3		ripple types and ripple stratification	ripples	Boyd et al. 1988
S4		bound layers, sed transp and ripples WC	no	Li et al. 1997
S5		ripple and roughness predictors WC	ripples	Li and Amos 1998
S6		ripple-sheet flow transitions WC	ripples	Li and Amos 1999a
S7	UC	ripples/sheetflow in WC	ripples	Li and Amos 1999b
S8		ripples and transport thresholds in WC	-	Amos 1999
New Jersey				
J1	UC grased	ripple types, dimensions, sed transp WC	ripples	Traykovski et al. 1999
California				
C1	grased	sediment suspension events	-	Storlazzi and Jaffe 2002
C2		wave climate and bed shear stress	-	Xu 1999
C3		sediment suspension events in storms	-	Xu et al. 2002
C4		Eel river mud, susp sed and bedforms	-	Cacchione et al. 1999
C5		Eel river mud, susp sed and bedforms	-	Ogston and Sternberg 1999
C6		sediment suspension events WC	-	Wiberg et al. 2002
C7	(U)C	sediment suspension events (SSE)	-	Lynch et al. 1997
C8	C grased	long-term modelling from SSE data	-	Harris and Wiberg 1997
Northern Gulf of Mexico				
G1		fair / storm SSE	-	Pepper and Stone 2002
G2	UC	WC boundary layers and SSE	-	Wright et al. 1997

Oceania				
O1 Aus	UC	sed advection from breakerzone to shelf	-	Black et al. 1995
O2 NZ	UC nearbed	suspension and sheet flow	-	Black and Vincent 2001
O3 NZ	UC	reference concentr measured+predicted	-	Green and Black 1999
O4 Aus +NZ	grased	35m-depth sand belt explanation	-	Black and Oldman 1999
United Kingdom				
U1	UC	storm sed transp, concentrat, roughness	-	Green et al. 1995
Belgium				
B1	grased	bedforms on banks, current-dominated	no	Van Lancker et al. 2000, V.Lancker and Jacobs 2000
B2	grased	suspended sed transp WC over banks	susp. transp.	Vincent et al. 1998
B3	UC	WC stress and susp on banks, model	no	Williams et al. 1999
B4	UC	sed transp meas+predict in storms	ripples and bedl. transp.	Williams and Rose 2001
Ebro Delta				
E1	UC grased	sed transp gradients	no	see text
The Netherlands				
N1		sed transp components + directions in and just outside surfzone	susp. transp.	Ruessink 1998, Houwman 2000, Ruess. et al. 1998,99
N2	grased	grain size sorting patterns in/out surfz.	-	Guillén and Hoekstra 1996,97
N3		modelling of long-term sand budgets	-	Van Rijn 1997
N4	U	fair-weather currents, sed transp and bedforms on shoreface-connected ridges	bedl. transp.	Van de Meene 1994, Van de Meene et al. 1996, VdM and Van Rijn 2000a
N5		currents from tide, waves and density-diff of Rhine fresh water	-	Van der Giessen et al. 1990 De Ruiter et al. 1992, 97 Simpson and Souza 1995
N6		bedload transp (also Nova Scotia)	-	Huntley et al. 1991

* This column denotes whether current profiles and/or concentration profiles were measured, and whether graded sediment occurs at the location and is considered in the publication.

Set	burst-avg. data avail.?	water depth (m)	grain size (mm)	wave height (range m)	wave period (s)	current velocity (m/s)	UC profs, grad sed	authors
Lab 1	yes	4.5	0.33	0.5 – 1.2 (only irreg.)	5 (only irreg.)	0	UC grased	Thorne et al. 2002
Lab2	yes	4	0.24	0.5 – 1.6	6.5 (reg, irreg, groups)	0	UC grased	Vincent and Hanes 2002

(Apart from the SEDMOC database)