Hydrodynamics sediment transport and daily morphological development of a bar-beach system

Felix C.J. Wolf

Abstract

The hydrodynamics, the sediment transport and the morphologic development of an inner nearshore profile is examined. The data was collected during several field campaigns at the central Dutch coast. The hydrodynamic-, sediment transport- and morphologic processes examined can be related to an sequence of morphodynamic processes. This sequence is, in turn, related to the breaking of high-frequency wind-waves.

1 Introduction

Longshore breaker bars are present in the surf zone of the central part of the Dutch coast. These bars are expected to play an important role in the coastal development because they may reduce coastal erosion by acting as a natural breakwater. In addition, these bars incorporate large volumes of sand which can play a role in the natural recovery of the beach and nearshore zone after periods of coastal erosion. Despite numerous field- and laboratory studies, the behaviour of these bars is poorly understood and the main processes responsible for bar development have not been clearly identified. Several studies have related the migration and development of these bars to low-frequency waves but these studies are often theoretical and based on unrealistic boundary conditions. Most field studies have not been able to produce support for these theories. Another group of theories links the morphological development of bars to the breaking of high-frequency (wind-) waves. These theories hypothesise that sudden hydrodynamic changes occur when waves break, thereby inducing a convergence in the sediment transport that will lead to bar development. Despite the simplicity and attractiveness of this second group of theories, they have not been thoroughly validated in the field.

Within the framework of the Coastal Genesis programme of the National Institute for Coastal and Marine management (RIKZ) a study was started to reveal inner nearshore bar development on the short and medium scale and relate this development to hydrodynamic and sediment transport processes. The study concentrated on hydrodynamic and sediment transport processes associated with the shoaling and breaking of wind-waves. Two field experiments were executed near Egmond aan Zee (central Dutch coast) to collect the data needed for this study. Hydrodynamic, sediment transport and morphological processes were measured under a wide range of weather conditions in the autumn of 1991 and of 1992. The main results of this study are described hereafter.

2 Hydrodynamic processes of breaking and shoaling waves

The inner nearshore hydrodynamics of high-frequency waves shows a spatial cross-shore zonation ranging from non-breaking waves (seaward of the breakpoint) via breaking waves to swash (landward from the breakpoint). High-frequency motions (surface waves and orbital excursions) in these hydrodynamic zones dominate the spectra, although the contribution of low-frequency energy increases toward the coast. The hydrodynamic zones can be distinguished by the relative wave height parameter (H_s/h). Low relative wave heights indicate a non-breaking zone while high relative wave heights are observed in the swash zone. An increase in the relative wave height leads to a larger onshore and offshore peak velocity near the bed. Up to the breaker zone ($H_s/h \sim 0.55$), an increase in the relative wave height also results in more asymmetric waves and higher mean cross-shore currents near the bed (0-0.3 m). The waves typically have short and sharp-peaked crests and larger extended troughs with a smaller amplitude but large duration. The breaking of waves reduces the wave- and orbital excursion asymmetries, although waves and excursions remain asymmetric. The shape of the waves and orbital excursions can not be described using existing wave theories such as cnoidal and Stokes second order. Moreover, the mean cross-shore currents, which are offshore directed due to the undertow, can not predicted accurately by existing theories as well.

3 Sediment concentrations and sediment fluxes

The suspended sediment concentrations near the bed vary on time-scales of incident wave frequencies and lower frequencies. High-frequency oscillations dominate the velocity field and little correlation is, therefore, present between the instantaneous concentration and velocity. A large vertical diffusity exists in all hydrodynamic zones which implies that a higher time-averaged concentration near the bed is associated with a steeper and more uniform vertical concentration profile. The near bed concentration increases with the relative wave height and the highest concentrations are, therefore, found in the swash zone.

The mean suspended sediment transport dominates the sediment transport within 0 - 0.3 m of the bed, being about twice as large as the oscillating suspended sediment transport. Within the oscillating transport mode, the high frequency transport is about twice as large as the low-frequency oscillating transport. The total oscillating suspended sediment transport increases with an increasing relative wave height, while the mean suspended sediment transport depends on the strength of the mean cross-shore current. The highest time-averaged suspended sediment transports near the bed are found in the breaking wave zone as in this zone also the highest mean cross-shore currents were measured.

The time-averaged, depth-integrated, suspended sediment transport in the cross-shore direction was largely determined by the cross-shore mean currents. Hence, the time-averaged suspended sediment transports were all offshore directed and the largest quantities were found in the breaking wave zone. In general, the suspended sediment transport mode dominates the total net sediment transport, i.e. the sum of the suspended and bedload transports. There is, however, a great variation in the ratio between the depth-integrated suspended sediment transport and the bedload transport. The total onshore transport is likely to be generated by wave and orbital excursion asymmetry because no other transport mechanism is known that can generate the observed onshore transport quantities. Nonetheless, the wave asymmetry and the onshore sediment transport correlate poorly. The offshore sediment transport is steered by the mean cross-shore current.

The estimated sediment transports indicate that inner nearshore bar development does not always result from a convergence of sediment caused by opposing sediment transport vectors, as suggested by some bar generating theories. The inner nearshore bar developments may also be the result of gradients in a unidirectional sediment transport (either onshore or offshore).

4 Morphological response

The beach, shoreline and inner nearshore bar do not respond identically to every storm, because the response also depends on the antecedent cross-shore profile. Sediment from a berm, initially present at the upper beach, but eroded during the successive storms, is deposited near the shoreline, causing a prograding shoreline. After the berm is completely eroded by the first few storms, successive storms resulted in a retreat of the shoreline. An inter-tidal bar may act as a temporary barrier in the exchange of sediments between the

beach and the inner nearshore bar. However, the eroded beach sediments are eventually also transported farther offshore resulting in a build-up of the inner nearshore bar. During storms, the inner nearshore bar mostly migrates offshore while during non-storm periods this bar moves onshore. The offshore migration speed during storms is higher than the onshore migration speeds during non-storm conditions. Non-storm conditions occur, however, more frequent than storm conditions. Nonetheless, the integrated result of the inner bar development after several weeks is an onshore migration. The offshore migration distance of the inner bar increased during each successive storm, probably because the quantities of offshore transported beach sediment, replacing the offshore transported sediments at the bar, decreased with each storm. The response of the outer nearshore bar to storms was small, compared with the inner nearshore developments and varied along the field site.
The reaction and relaxation times of the inner nearshore during accretional stages were short. For instance, it was not uncommon that one or two days after the peak of the storm, for a new swash bar or inter-tidal bar to have emerged, and for the inner nearshore bar to have stopped its offshore migration (Figure 1). Despite such rapid response, it was not possible to establish quantitative relations between the inner nearshore developments and the offshore wave conditions.

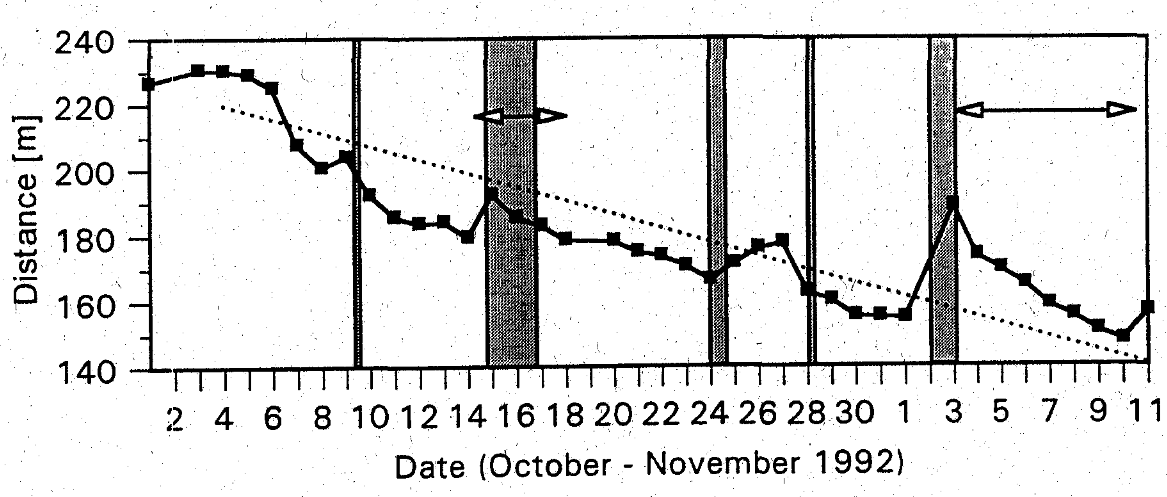

Figure 1 *Position of the crest of the inner nearshore bar and suggeted dynamic equilibrium (dotted line). Shaded areas indicate storms. Arrows indicate return time to equilibrium.*

5 Small and medium scale morphodynamic processes involved in the inner nearshore bar development

Morphological developments of the inner nearshore bar during storm and non-storm conditions are strongly influenced by high frequency wind-waves. The net sediment transport direction is determined by the balance between the orbital wave asymmetry (causing an onshore sediment transport) and the mean cross-shore current (causing an offshore transport). During lower wave conditions, the offshore directed mean cross-shore current induced by wave breaking (undertow) is not strong enough to dominate over the wave asymmetry and the local sediment transport direction is, therefore, onshore. During higher wave conditions, more waves will break and it is then that the undertow dominates the velocity field, resulting in an offshore sediment transport. Hence, the distribution of the net sediment transport direction over the inner nearshore zone is mainly related to the probability of breaking of the waves. The latter is largely determined by the bathymetry and the offshore wave height.

In all, an increase of the offshore wave height will result in the following sequence of inner nearshore processes (Figure 2):

- During periods of low offshore wave heights (H_s, offshore <0.5 m), waves do not break on the inner nearshore bar and the net sediment transport direction in the entire nearshore zone is directed onshore. This results in an onshore moving inner nearshore bar and a heightening and widening of the beach.
- If the offshore wave height increases (H_s, offshore = 0.5 - 1.5 m), waves will break on the inner nearshore bar, generating a (small) offshore sediment transport at the landward side of the inner nearshore bar, while the sediment transport at the seaward side is still onshore directed. As a result, the inner nearshore bar migrates onshore. Its onshore migration speed will strongly reduce, however, for higher waves because a larger offshore sediment transport at the landward side of the inner bar may be expected when the intensity of breaking increases. At the beach, the relative wave height will be larger than at the inner nearshore bar. Therefore, with increasing wave heights, the net sediment transport direction will reverse from onshore to offshore and erode the beach. The result is a retreating shoreline; however, in the case when enough sediment transported from the upper beach to the lower beach to resupply the beach face (erosion of a berm), the shoreline will be stable or may even prograde. It is unlikely, though, that eroded beach sediments largely contribute to the inner bar development, because the sediment transport direction in the trough between the inner nearshore bar and the beach may be still onshore.

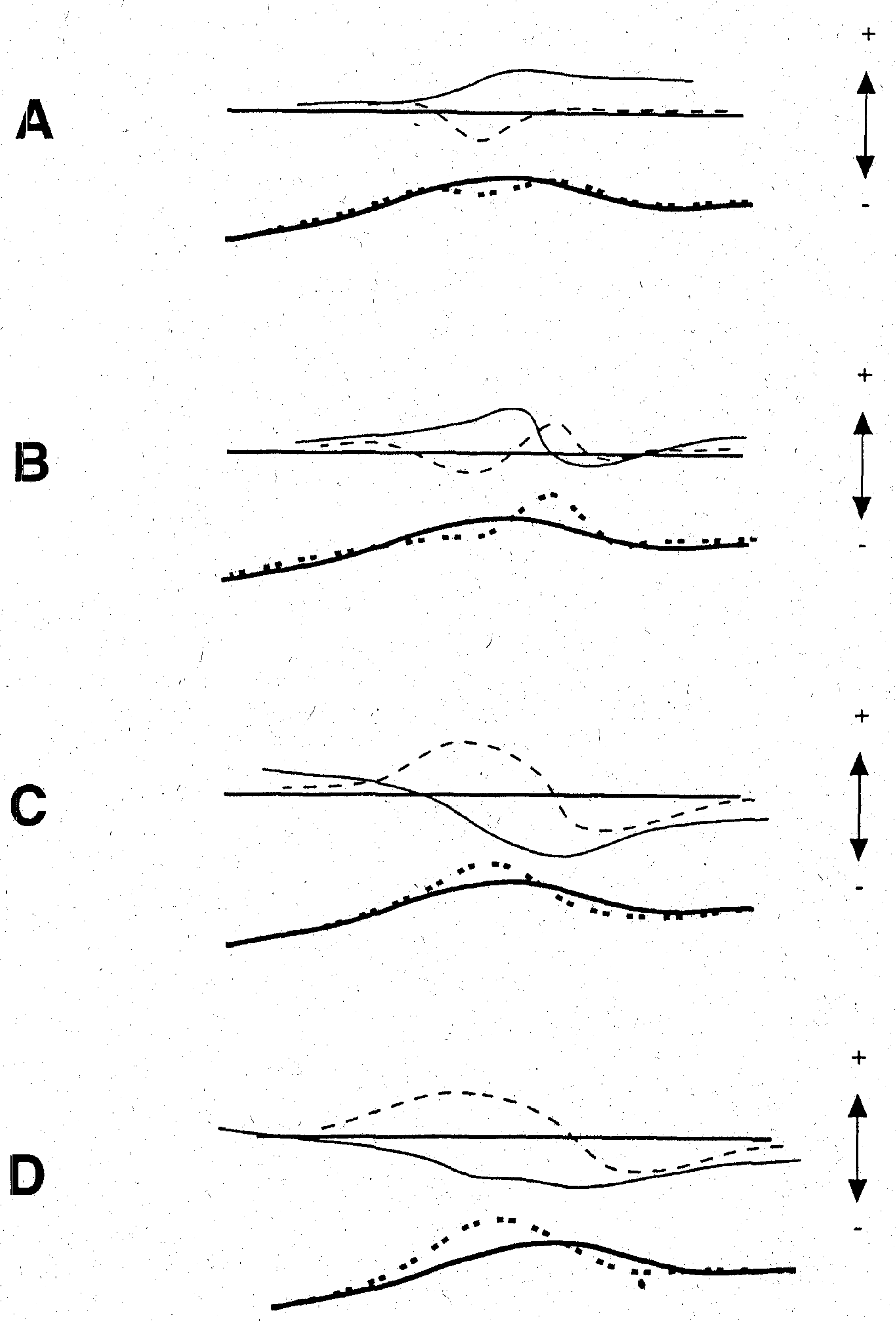

Figure 2 Sediment transport, sediment transport gradients at the inner nearshore bar during four different offshore wave height ranges. Plus means onshore sediment transport or gain sediment; minus means offshore sediment transport or loss of sediment.
The lines are: sediment transport (solid), sediment transport gradient (dashed), initial morphology (thick) and morphologic development (dotted). (A) $H_{s,offshore} < 0.5$ m; (B) $H_{s,offshore} \sim 0.5 - 1.5$ m; (C) $H_{s,offshore} \sim 1.5 - 2$ m; (D) $H_{s,offshore} > 2$ m.

Besides, an inter-tidal bar may act as a temporal blockade in the transport of sediment between the beach and inner nearshore bar.

- Offshore wave heights between 1.5 and 2 m will be large enough to generate an undertow in the inner nearshore zone that extends from the beach up to the crest of the inner nearshore bar. As a result, the sediment transport at the landward side of the crest of the inner nearshore bar is offshore directed and because onshore sediment transport only takes place at some distance seaward of the inner nearshore bar, the inner nearshore bar will migrate offshore. The beach will be eroded and the offshore transport of beach sediments will play an important role in the development of the inner nearshore bar because these sediments are likely to be transported towards and incorporated into the nearshore bar.
- Offshore wave heights larger than 2 m generate an offshore-directed sediment transport up to and over the inner nearshore bar, with high rates of offshore transport near the shore and lower rates in the direction of the inner nearshore bar. Hence, gradients in the offshore directed sediment transport will steer the inner nearshore bar developments. These sediment transports result in an offshore moving bar, in erosion of the beach and, if present, of the inter-tidal bar.

The above sequence of morphodynamic processes is based on a synthesis of field studies at Egmond aan Zee under particular offshore wave conditions and cross-shore profile configurations. In reality, the transformation from one group of processes to the next will vary with the shape and location of the nearshore bars and beach, and will occur gradually. The offshore wave heights at which one group of processes is being replaced by another must, therefore, be seen as indicative.

Nevertheless, these results make clear that, basically, inner nearshore bar movements are related to the breaking of high-frequency wind-waves, the so-called 'break point hypothesis'. However, this hypothesis explains bar development by using two opposing sediment transport vectors, i.e. an onshore movement of sediment at the seaward side of the bar and a landward sediment transport at the landward side of the bar. This study concludes that when there are very low ($H_{s,\ offshore}$ < 0.5 m) or very high ($H_{s,\ offshore}$ > 2 m) waves, the development of the inner nearshore bar is steered by gradients of unidirectional (onshore or offshore) sediment transport rather than by two opposing sediment transport fluxes. Only in the case of moderate offshore wave heights (between 0.5 and 2 m) the development of the inner nearshore bar could be explained by two opposing sediment transport vectors.

The presence and source of long waves were not studied because low frequency energy and low frequency oscillating sediment transport only formed a small part of the total sediment transport in the inner nearshore zone. In explaining inner nearshore bar behaviour these findings do not favour the infragravity theories.

6 Development of inner nearshore bar on a medium to large time scale

The integrated result of a sequence with storm events and non-storm periods is a net beach erosion. The swash bar or an inter-tidal bar is eroded by storms but reappears during the following non-storm conditions. Thus the beach displays cyclical behaviour (new swash bar, new inter-tidal bar) as well as unidirectional behaviour (lowering of beach) on a medium time-scale. The integrated result for the inner nearshore bar is an onshore migration, which is associated with an increase in volume. The entire sediment volume in the inner nearshore zone is, however, unaffected by the storm sequence.

On the medium time scale (days to weeks), the beach and an inner nearshore bar strive to achieve dynamic equilibrium. The non-storm processes, directed towards a low energy equilibrium occur more frequently, but are weaker compared to the storm processes directed towards high-energy equilibrium. Yet, non-storm periods dominate the inner nearshore bar development on the medium scale and the inner nearshore bar is part of a development that creates a 'fair-weather' beach state. The impact of a single storm varies and depends on the position of the inner nearshore bar at the onset of the storm; each successive storm has a stronger impact on the inner nearshore bar than its predecessor. At the same time, the onshore migration rates during non-storm periods remain the same. As the measurements were conducted in the autumn, and the occurrence of storms is higher in the winter season, the frequency of storms will also increase. Thus, at some point during the winter, the net migration direction on a medium time-scale will change from onshore to offshore and the net migration direction after the autumn and winter season (large time scale) will be offshore. The latter is clearly confirmed by studies analysing the yearly coastal surveys (JARKUS data base; e.g. Wijnberg, 1995).

This study has shown that the offshore transport of beach sediments plays an important role in the inner nearshore bar development. It is hypothesised, therefore, that the change in the net migration of the inner nearshore bar on the medium time scale is caused by a (temporal) decrease in offshore sediment transport from the beach to the inner nearshore bar. The first storm of every autumn erodes beach sediments which have been deposited during the summer. These sediments are eventually deposited on the inner nearshore bar. After a number of storms, the beach is in equilibrium with most storm conditions, i.e. only higher magnitude storms can erode greater quantities of sediment from the beach. At that condition, the offshore sediment transport at the inner nearshore bar during storms is no longer compensated by beach sediments, and the bar moves offshore (Figure 3). Storms with an equal magnitude are likely to have a smaller impact on the beach, if they occur at the end of a storm sequence, because by then the beach profile has adapted itself to the first few storms. Hence, bar dynamics not only depend on offshore wave conditions but also on the antecedent morphology, in particular the beach state and its associated sediment volume. As bar dynamics also determine the entire coastal profile development, it may also be concluded that the impact of a single storm on a coast over the medium time-scale depends on the shape of the coastal profile before the storm, i.e. the position of the storm in the sequence of storms. An identical conclusion can be drawn for the large time scale. The integrated impact of autumn/winter storms depends on the shape of the coastal profile at the end of the summer.

7 Summary

In short, the development of the inner nearshore bar is the result of two delicate balances, one present on the small scale, the other on the medium to large scale. The first is a balance between the onshore sediment transport induced by the wave asymmetry and the offshore sediment transport induced by the mean cross-shore current. This balance determines the local net sediment transport direction. The medium to large time scale distribution of the local net sediment transport direction is determined by the balance between non-storm and storm periods in relation to the antecedent morphology and sediment volumes. In other words, it is determined by the balance between the offshore transport of sediments in the inner nearshore and the supply of eroded beach sediments. This medium scale balance determines the development of the nearshore bars and, consequently, the development of nearshore profiles. The development of nearshore profiles determines, in turn, the development of the entire coast. To understand the development of the coast on a large time scale, it is of essential importance to know which knowledge about the small scale balance is important for the determination of the large scale developments. An identical scale problem is present regarding the two-dimensional approach of this study as it is not clear to what extent the results of this study may be extrapolated to three-dimensional situations.

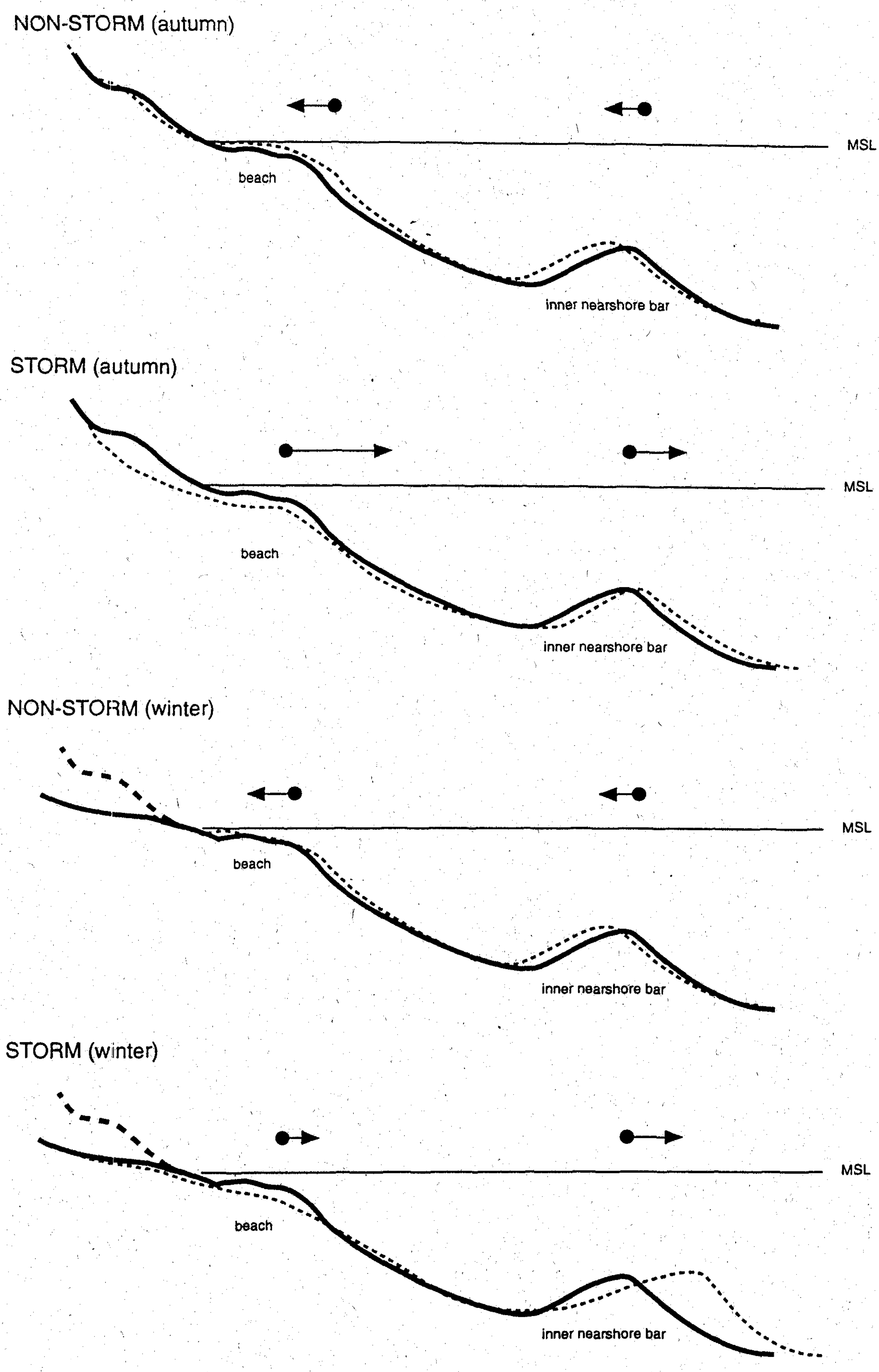

Figure 3 *Sediment transport vectors and the resulting morphologic development of the shoreline and inner nearshore bar during non-storm and storm-periods in the autumn and winter. Thick dotted lines indicate beach volume losses.*

References

Wijnberg, K.M., 1995. Morphologic behaviour of a barred coast over a period of decades, Ph. D. Thesis, Utrecht University.