MORPHOLOGY AND MORPHODYNAMICS OF SANDY BEACHES

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Contents

Summary

This article discusses the morphology and morphodynamics of sandy beach environments. Sandy beach morphology is characterized by a sloping profile with secondary morphological features superimposed, including nearshore bars, swash bars, rip channels, beach cusps. The existence of sandy beaches is influenced by the environmental boundary conditions (geology of the coastal area) and by the external hydrodynamic forcing (waves and tides). Sandy beach morphology is highly dynamic. Rapid adjustments occur under high-energy wave conditions, whereas morphological

changes under low-energy wave conditions are relatively slow. The changing morphologies can be coupled to the hydrodynamic forcings with the use of simple parameters for the energy conditions. These parameters are used to classify distinct morphological states in beach classification models. The management of sandy beaches is mainly concerned with protection of the coastline and the low-lying areas behind the coast against beach erosion. However, other functions like nature, recreation, tourism and sand mining are of growing interest to the coastal zone manager.

1. Introduction

A sandy beach can be defined as a wave-lain deposit of primarily sand-sized material found along marine, lacustrine and estuarine shorelines. In the vernacular, the beach relates to that part of the shore profile that extends from spring low tide level to some physiographic change such as a cliff or dune field, or to the point where permanent vegetation is established. From a morphological point of view, however, the part of the nearshore profile that is regularly affected by surf zone processes should be considered part of the beach.

Figure 1. World distribution of major dune and beach areas. The marked sections of coast mainly relate to the occurrence of long and straight beaches. Spatially-constrained embayed beaches are not indicated.

Source: van der Maarel. (ed.) 1993. "Dry Coastal Ecosystems: Polar Region and Europe". Elsevier, Amsterdam.

Sandy beaches are commonly found in association with coastal dunes and occur along approximately 20% of the world's coast (see Figure 1). Sandy beaches are found at all latitudes whenever there are waves, suitable sediments and a favourable basement relief. Along gentle continental shelves with an abundant sediment supply, long and straight beaches are generally found. In contrast, curved beaches within coastal embayments are more commonly associated with steep continental shelves and a limited sediment supply. Sandy beach environments vary greatly in size. Sheltered, microtidal estuarine and harbor beaches are often characterized by a cross-shore extent of only a few meters, whereas exposed, macrotidal beaches may be up to 1 kilometre wide. A bewildering array of morphological features can be found on sandy beaches, ranging from small ripple features to large nearshore bars. Despite the variety of sandy beach morphologies found in nature, they all share three common characteristics: (1) they consist of sandy sediments; (2) they are located at the interface of land and water; and (3) they are deposited primarily by the action of gravity waves.

Great advances have been made in recent decades regarding our understanding of sandy beach environments. Most of these have been made possible by embracing the morphodynamic approach. Morphodynamics can be defined in the context of sandy beaches as the mutual adjustment of beach morphology and nearshore hydrodynamics involving sediment transport (see *Waves and Sediment Transport in the Nearshore Zone* and *Episodic Processes*). Most importantly, the morphodynamic approach considers morphology and hydrodynamics intrinsically linked, indicating that they are both the result and the effect of each other. Consequently, they cannot be investigated successfully in isolation.

The purpose of this article is to give an overview of our present state of knowledge of the morphology of sandy beach environments. Section 2 indicates that sandy beach morphology comprises a primary beach profile on which secondary morphological features can be superimposed. Section 3 discusses the environmental boundary conditions and external hydrodynamic forcing of sandy beaches. Sandy beaches are highly dynamic and Section 4 demonstrates how beaches constantly adjust their morphology in response to changing hydrodynamic conditions. Combining beach morphology with a parameterization of the hydrodynamic forcings enables the formulation of beach classification schemes considered in Section 5. A brief discussion of the management of sandy beaches is given in Section 6 and some future trends and perspectives are suggested in Section 7.

2. Sandy beach morphology

The concept of scale is of fundamental importance in the investigation of sandy beach morphology. The behaviour of sandy beaches may be studied over a range of scales, both temporal and spatial, which vary from grain to grain interactions over seconds to the scale of shoreline evolution over centuries. Subsequently, the beach system may be seen to consist of a hierarchy of compartments, each with its own spatial and temporal scale. A compartment of higher order includes the compartments of lower order and therefore a higher order compartment has a larger spatial and temporal scale. A close coupling between the temporal and spatial scales at a certain compartment in a coastal system is generally assumed and this coupling is referred to as the primary scale relationship (see Figure 2). The morphodynamic concept further implies that the physical processes (waves, tides, currents and sediment transport) that control and are affected by the morphology are likely to occur on similar spatial and temporal scales as the morphological feature of interest.

2.1. Primary beach profile

The overall beach profile is referred to as the primary beach profile and consists of an approximately planar beachface and a concave-upward nearshore profile. The temporal and spatial scales associated with the primary beach profile are years and kilometres, respectively. Under the assumption that the beach is in equilibrium with the hydrodynamic conditions (mainly sea level) and that sufficient sediment is available to accomplish profile equilibrium, the concave-upward nearshore part can be described by a simple parabolic function:

$$h = Ay^{m} \tag{1}$$

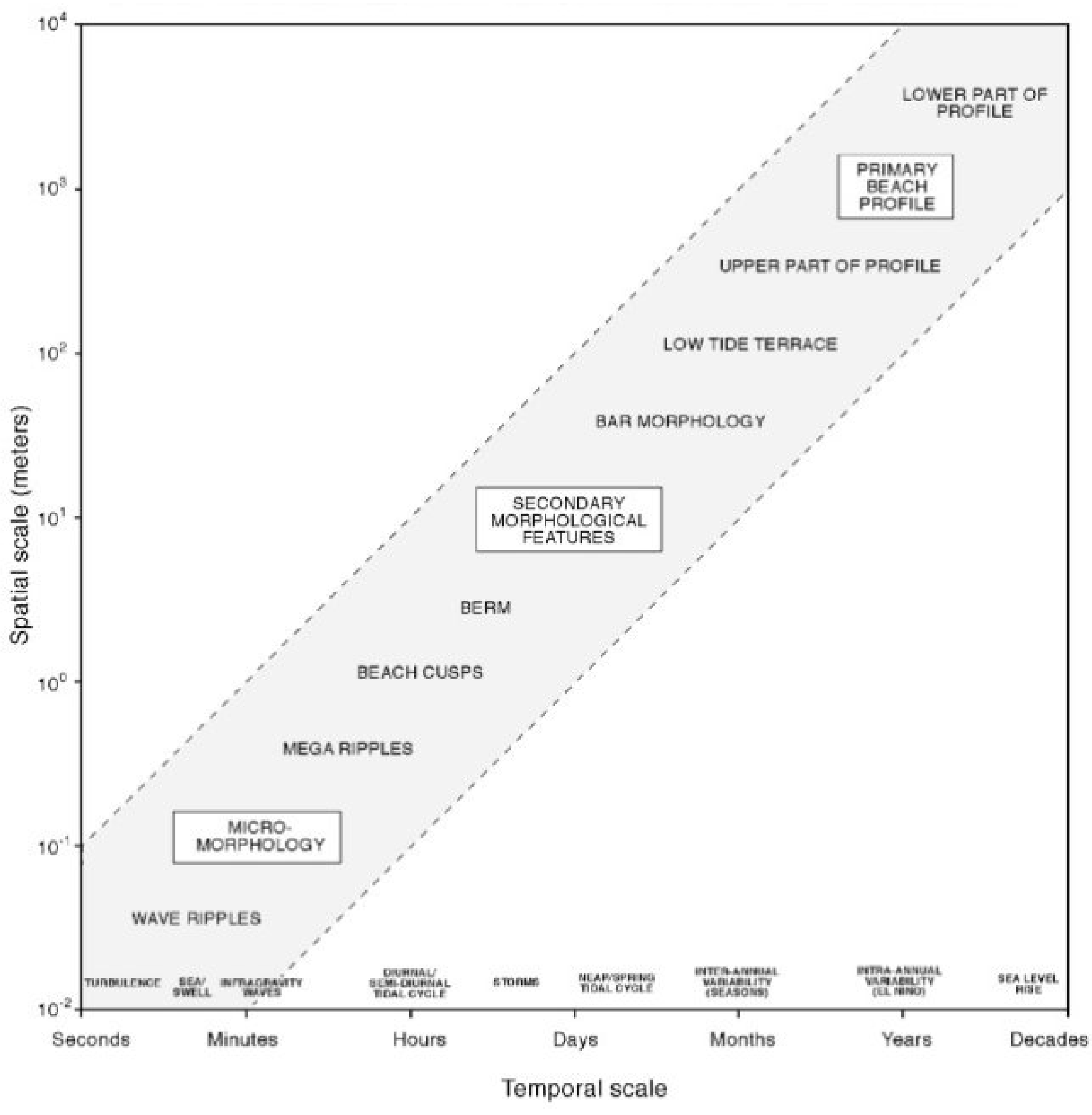

Figure 2. Relation between spatial and temporal scales of morphological features and fluid motions associated with sandy beaches.

where *h* is water depth, *A* is a dimensional parameter, *y* is cross-shore distance and *m* is a dimensionless exponent. Elaborate fitting of natural beach profiles to the equilibrium beach profile equation has suggested an average value of m = 2/3. The steepness of the resulting profile is controlled by A and increases with sediment size according to

$$A = 0.067 w_s^{0.44} \tag{2}$$

where w_s is the sediment fall velocity of the bed material. At present, the universality of the parameterizations of A and m is under considerable debate. In fact, the very notion that a beach can be in equilibrium with the hydrodynamic conditions is strongly questioned. Nevertheless, the equilibrium beach concept is the most widely used approach in predicting the effects of sea-level rise on sandy shorelines.

2.2. Secondary morphological features

Perturbations to the primary beach profile may occur in the form of smaller-scale secondary morphological features such as nearshore bar morphology. These secondary features occur on temporal scales of hours to a year and have spatial scales ranging from 10 to 1000 meters (the longshore length scale is usually larger than the cross-shore length scale). Figure 3 shows the most relevant secondary morphological features found on sandy beaches. It is unlikely that all these features are present at the same time on the same beach, but they may be present at different times on a beach.

The principal morphological features are as follows:

- **Bar**, **trough**. Bar/trough morphology can assume a large variety of configurations, including transverse bars, crescentic bars and longshore bars. In addition, multiple bars may be present on a beach. The mechanism of bar formation remains unresolved despite considerable research and modeling efforts. The most likely hypothesis is that nearshore bars form as a result of onshore sediment transport outside the surf zone due to the asymmetry of the waves and offshore transport in the surf zone by bed return flow. However, bar formation has also been attributed to the net sediment transport patterns associated with standing infra-gravity waves. Nearshore bar morphology is highly dynamic and tends to move onshore under calm conditions and offshore during storms.
- **Rip channel**. Rip currents are strong, narrow currents that flow seaward through the surf zone by means of rip channels. They return to the sea the water that was transported onshore by the waves and are an important mechanism of storm erosion on many beaches. They also provide a major hazard to swimmers. Rip occurrence and configuration are strongly linked to the bar morphology. Depending on the latter they may be skewed or perpendicular to the shoreline. The cross-shore length of rip channels ranges from meters (mini-rips associated with beach cusps) to kilometres (mega-rips occurring during extreme storm events). The formation of rip currents is poorly understood, although various mechanisms have been proposed, including self-organization and standing edge waves.
- **Low tide terrace**. On tidal beaches, a low-gradient, featureless terrace is generally found fronting the high tide beach. This feature is known as a low tide terrace and is often separated from the steeper upper part of the beach by a distinct break in slope and sometimes a small runnel. The beach groundwater table outcrops around this break in slope and the low tide terrace is saturated giving it a ‘glassy’ appearance. The formation of low tide terrace morphology may be related to interactions

between tide-induced beach groundwater table fluctuations and swash-induced sediment transport processes.

- **Swash bar**, **runnel**. Swash bars are low-amplitude bars located within the intertidal zone and are primarily controlled by swash processes. Runnels are generally found landward of swash bars. Longshore currents flow within the runnels and are fed through over-washing of the swash bars. On beaches subject to macrotidal ranges, numerous swash bars may be present on the intertidal profile and such morphology is referred to as ridge and runnel morphology. Swash bar morphology forms under calm, accretionary wave conditions and the bars generally migrate onshore as demonstrated by their asymmetrical cross-shore profile.

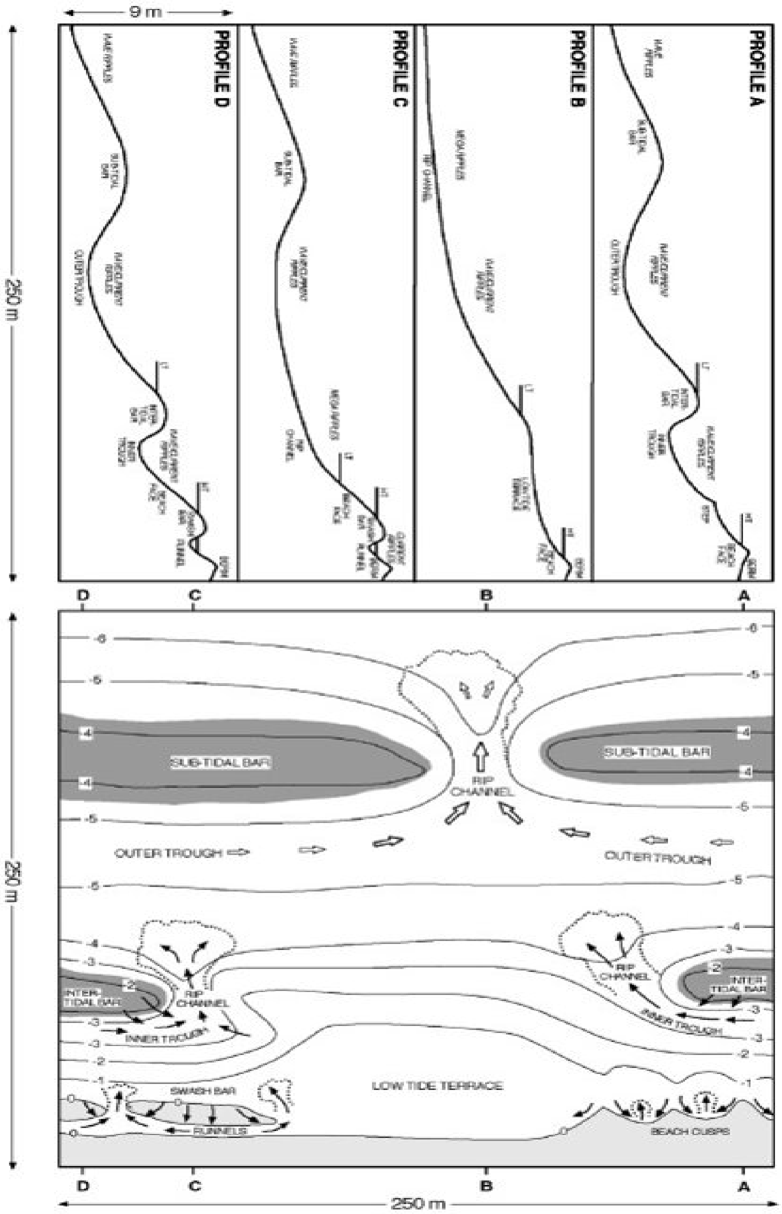

Figure 3. Schematic showing dominant morphological features on sandy beaches. High tide level on this beach is at an elevation of 0 meters and the tidal range is 2 m.

- **Beachface**, **berm**. At some stage an onshore-moving swash bar may weld to the beach and the runnel will fill up with sediments due to over-washing. The steep, seaward section of the swash bar is now referred to as the beachface and the quasi-planar back of the swash bar is known as the berm. The slope of the beachface increases with sediment size and the height of the berm generally reflects the maximum runup level attained during spring tides.
- **Beach step**. The beach step is the small, submerged scarp consisting of the coarsest available material formed at the seaward edge of the beachface. Its formation is associated with the backwash vortex and the size of the beach step is directly related to the height of the waves that break on the beachface. Beach steps generally do not develop on beaches with a large tidal range because they require relatively stationary water levels to develop.
- **Beach cusps**. Beach cusps are cuspate patterns in beach sediment formed by swash action and are characterized by steep-gradient horns and gentle-gradient embayments. Beach cusps have a pronounced longshore wavelength, referred to as cusp spacing, and are the most conspicuous example of rhythmic morphology found on sandy beaches. Their formation has been ascribed to standing edge waves and self-organization, but none of these mechanisms have yet been adequately proven.

2.3. Micro-morphology

Micro-morphology relates to morphological features that are characterized by a temporal scale of minutes and a spatial scale of less than 1 m. Such features primarily consist of bedforms such as wave and current ripples. Wave ripples are commonly found beyond the breaking waves outside the surf zone and on the seaward-facing sides of nearshore bars. Under the energetic action of breaking waves the sea bed is generally flat. Current ripples are present where strong unidirectional currents prevail, particularly rip currents. A mixture of wave and current ripples is found in troughs and runnels. The micro-morphology significantly affects sediment transport processes and boundary layer dynamics on sandy beaches. Suspended sediment fluxes over rippled beds are generally larger than over flat beds. Ripples also increase the bed friction experienced by shoaling waves and can significantly reduce the height of shoreward-propagating waves due to energy losses.

2.4. Scale and composite morphological features

The proposed time/space scale boundaries of the primary beach profile, secondary morphological features and micro-morphology are rather loose and may vary considerable between beaches. Generally, the boundaries move down towards shorter and smaller scales with decreasing energy levels. For example, on low-energy lacustrine beaches, the length scale of the primary beach profile may be the same as the scale of nearshore bar morphology on exposed ocean beaches. Nevertheless, the hierarchy of scales is characteristic of all sandy beach environments.

It should be emphasized that morphological features are rarely the result of a single process, but more commonly result from a spectrum of processes and are hence composite features. This notion is particularly relevant on tidal beaches where changing tide levels induce a lateral migration of different hydrodynamic zones across the intertidal profile. For example, a swash bar present around mid-tide level may be affected by breaking wave processes during spring high tide, subject to swash action during mid tide and under the influence of aeolian processes during low tide.

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Biographical Sketches

Gerd Masselink was an undergraduate student in the Department of Physical Geography, Utrecht University (The Netherlands), and graduated in 1990. He continued his studies at the Coastal Studies Unit, University of Sydney (Australia), where he completed his PhD in 1994. From 1995 to 1998 he was a post-doctoral researcher at the Centre for Water Research, University of Western Australia (Australia). Presently, he is a senior lecturer in the Geography Department, Loughborough University (UK). Gerd Masselink has conducted research on a wide range of beach environments and has published on a range of beach-related topics, including the effects of tides on beaches, surf zone hydrodynamics, sediment transport processes in the swash zone, beach cusp formation, the effect of sea breeze activity on nearshore dynamics and intertidal bar morphology.

Aart Kroon was an undergraduate student in the Department of Physical Geography, Utrecht University (The Netherlands) and graduated in 1987. He remained at the same university and completed his PhD in 1994. Presently, he is a lecturer at the Department of Physical Geography and works in the Institute for Marine and Atmospheric Research, Utrecht. Aart Kroon has conducted research on sandy beaches and published on the sediment transport processes occurring in the inter-tidal zone of beaches, nearshore bar dynamics and the behaviour of shoreface nourishments. He is also involved in research related to the morphodynamic behaviour of delta-lobes and fluvial geomorphology.