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Morphodynamic characteristics and classification of beaches in England and Wales

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ABSTRACT

The use of beach classification models has become widespread in literature in recent years. Beach classification models that recognise distinct modal beach states in response to environmental conditions are most widely used. These models were developed largely in high-energy, micro- to meso-tidal sandy environments and subsequent attention has focussed on extending their use into other beach environments. Here, the applicability of these traditional beach classification models to the highly diverse coastline of England and Wales was assessed through collection of detailed morphodynamic characteristics of 92 beaches, yielding a comprehensive multi-variate data set containing morphological, sedimentological and hydrodynamic information. The complex and diverse study region incorporates beach morphology covering the full spectrum from reflective to dissipative, and non-barred to multi-barred. Cluster analysis supplemented by MDS ordination resulted in the identification of 9 distinct beach types. Traditional morphodynamic indices Ω and RTR were found to be effective in discriminating between beach groups providing some support for the beach state models derived using information from Australian beaches. It was found that absolute wave energy (wave power) is important as well in controlling beach type. For intermediate beaches a wave energy flux P ($\propto H^2T$) value of 3 kW m^{-1} was found to differentiate between beaches with (P>3 kW m^{-1}) and without (P<3 kW m^{-1}) three-dimensional bar/rip morphology, a key component controlling recreational beach hazard levels. Observations presented here inform a beach classification model to be used as the basis for a national beach risk assessment programme. Beach classification models based on environmental parameters are, by necessity, simplifications and should be used as tools for understanding morphodynamic systems, rather than beach type prediction.

1. Introduction

Beach morphology varies in time with changing hydrodynamic forcing (waves and tides), while the modal beach morphology changes spatially in response to the geographical variability in environmental conditions (waves, tides, sediments, geology, etc.). This notion has resulted in the formulation of beach classification models that recognise the occurrence of distinct beach morphologies, or beach states/types, and link these to parameterisations of the key environmental conditions, namely wave climate, tidal regime and beach sediment characteristics. The most widely used of such models is the so-called Australian beach model, originally devised separately and independently by Chappell and Eliot (1979), Short (1979a) and Wright et al. (1979), and subsequently refined by Wright and Short (1984) and Wright et al. (1987).

The Australian beach model was based on the study of sandy beaches along the high-wave energy and microtidal (mean spring tidal range MSR<2 m) coastline of New South Wales, Australia. The key parameter in this model is the dimensionless fall velocity Ω given by H/w_sT, where H is the (breaking) wave height, w_s is the (high tide) sediment fall velocity and T is the (peak) wave period (Gourlay, 1968). Different classifications have been developed for other beach environments, for example the model of Hegge et al. (1996) developed for the microtidal and sheltered coastline of southwestern Western Australia, Short's (1991) model based on the macrotidal (4 m<MSR <8 m) beaches of central Queensland, Australia, and the classification of Jennings and Shulmeister (2002) based on a study of New Zealand gravel beaches. Masselink and Short (1993) used the Australian beach model as a starting point and extended it to account for the relative importance of tides and waves parameterised by the relative tide range RTR given by MSR/H, where MSR is the mean spring tide range. Based on the analysis of all 10,685 beach systems present in Australia, Short (2006) added a further two geologically-controlled and four low energy beach types to the combined models of Wright and Short (1984) and Masselink and Short (1993).

Beach classifications are useful in providing a conceptual framework within which beach and surf zone environments can be studied and understood, and the wide use of beach models for this purpose is demonstrated by the large amount of citations for beach classification papers (487 for Wright and Short, 1984; 70 for Short, 1991; 177 for Masselink and Short, 1993; 44 for Hegge et al., 1996; 27 for Jennings and Shulmeister, 2002; all based on Google Scholar checked on 6 June 2010). Because beach sedimentology and hydrodynamic processes are strongly correlated to beach fauna Defeo and McLachlan, (2005), beach classification models are also useful for providing the physical

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framework for beach ecologists. For example, both species' abundance and diversity are strongly linked to beach state and can be parameterised by similar parameters on which beach classification models are based (Rodil and Lastra, 2004). Finally, due to the link between beach morphology and surf hazards to bathers, beach classification models have also been used as the basis for beach risk assessment (Short, 1993,1999), with particular emphasis on the role of rip currents (Short and Hogan, 1994; Scott et al., 2009).

Beach classification models are generally based on a large amount of temporal and/or spatial observations, and are most applicable to the environment whence the observational data were collected. Application of a model outside the region for which it was developed can lead to general support (Sénéchal et al., 2009), modification (Costas et al., 2005) or outright rejection (Jackson et al., 2005) of the model. It is important to recognise that there is a fundamental difference between validation studies based on temporal data and those based on spatial data. In the former case, time series of beach state are used to investigate the morphological variability and beach state transitions on a single beach as a result of varying forcing conditions and often suggest that beach state is strongly reliant on the previous state (Costas et al., 2005; Jiménez et al., 2008; Ortega-Sánchez et al., 2008; Sénéchal et al., 2009). In the latter case, the modal beach state on a large number of beaches is linked to forcing factors and such studies tend to highlight the importance of factors specific to the study area, such as geology (Jackson et al., 2005) and wave height variability (Gómez-Pujol et al., 2007).

Two critical factors in the formulation and/or application of beach classification models are the objective characterisation of the beach state and correct parameterisation of the environmental factors (and whether the selected parameters are indeed appropriate; cf., Anthony, 1998). Early beach typologies were based on field sketches that captured the three-dimensionality of the morphology, supplemented with two-dimensional beach surveys (Chappell and Eliot, 1979; Short, 1979b). More sophisticated methods for characterising the beach morphology include three-dimensional beach surveys involving GPS (e.g., Sénéchal et al., 2009) and ARGUS video-monitoring (e.g., Ranasinghe et al., 2004). However, despite the sophistication of the methodology, in most studies the actual identification of the beach state is a manual process and therefore highly subjective. To avoid this problem, both Hegge et al. (1996) and Jennings and Shulmeister (2002) have deployed multivariate analytical techniques (cluster analysis and discriminant analysis, respectively) to help them objectively identify and classify the dominant beach types.

The problem with correctly parameterising the forcing conditions, in particular the inshore wave height and period, is potentially more significant. In temporal studies, the inshore wave field can be characterised using deep-water wave data, especially if a wave buoy is located immediately off the beach (e.g., Ortega-Sánchez et al., 2008; Sénéchal et al., 2009). However, in spatial studies, reliable inshore wave data are rarely available for all beaches in the data set and need to be estimated. Unless a numerical model is deployed to transform deep water wave conditions to the inshore for each of the beaches, breaker conditions are unlikely to be estimated correctly. As an example, in the study of Jackson et al. (2005), the average breaker conditions on 25 beaches were estimated by applying a simple shoaling equation to deep water wave data, without taking account of sheltering provided by headlands or consideration of the shoreline orientation relative to the dominant wave direction. As a result, the breaker conditions were considerably overestimated, with mean wave heights along the relatively low wave energy northeast coast of Ireland of c. 1.5 m. This, together with the use of the mean instead of the peak wave period, led to all but one of the north Irish beaches predicted to be ultra-dissipative, which as the study states, represents a poor characterisation of the actual beach morphology.

Jackson et al. (2005) highlight the role of site context within their dataset in constraining beach morphological change. They suggest that the complexity of beach morphological systems means that in many beach environments the morphological realisation of these dynamic forcing conditions (waves and currents) can, to varying extents, be constrained by the geological site context. On both a temporal and spatial scale, the geological framework within which a beach exists can impose important boundary conditions to the evolution of beach morphological state, affecting nearshore wave transformations, and sediment abundance and accommodation space (Jackson and Cooper, 2009; Short and Jackson, in press). Short and Jackson (in press) concede that much of the development of beach classification models and thinking on beach morphodynamics is dominated by consideration of unconstrained beach environments emphasising the importance of considering the role of geological site context when assessing the effectiveness of morphodynamic indices in the application of beach classification models outside of their region of development.

The aim of the present paper is to provide an overview of the spatial variability in beach morphology along the highly diverse coastline of England and Wales and synthesise the observations in a beach classification model that can be used as the basis for a national beach risk assessment programme. Previous work by Scott et al. (2009) identified the importance of rip currents and associated morphology in controlling recreational beach hazards in England and Wales. It was therefore important that a resulting classification model incorporated the presence/absence of rip morphology as well as representing the full spectrum of beach types and hazards likely to be encountered by bathers and therefore be of interest to beach safety managers. To this end, the database in this study comprises a broad cross-section of 92 beaches and, for each of these, beach type was classified objectively using cluster analysis based on morphology, sedimentology and hydrodynamics, with inshore wave conditions estimated using a combination of observational wave data and numerical modelling. In recognition of the site-specificity of coastal geomorphology, the classification approach adopted here is data-driven, but at the same time directed towards a purpose (i.e., national beach risk assessment programme). The outline of this paper is as follows. Section 2 presents an extensive description of the coastline of England and Wales, the prevailing environmental conditions and the data set used in this study. Section 3 describes the dominant beach morphologies and their grouping, while Section 4 explores the relation between beach type and morphodynamic indices. Section 5 introduces and discusses the final classification model and conclusions are presented in Section 6.

2. Study area and dataset

2.1. Boundary conditions along the coastline of England and Wales

The coast of England and Wales is one of the most diverse coastlines in the world and a large variety of coastal landforms are represented, including dunes, sand and gravel beaches, barriers and spits, various types of estuaries, tidal flats and salt marshes, rapidly eroding soft-rock cliffs and resistant hard-rock cliffs with shore platforms (e.g., Steers, 1946; May and Hansom, 2003). Accordingly, the setting of the many beaches also varies widely and the beach morphology covers the full spectrum from reflective to dissipative, and non-barred to multi-barred. The large variety in coastal settings and beach systems is mainly attributed to the along-coast variability in static and dynamic environmental factors, or boundary conditions, and the most important of these for beach morphology are geology, sediments and external forcing (wind, waves, storms and tides). The geographic variability in these boundary conditions is summarised in Fig. 1.

Long-term coastal evolution is largely driven by changes in (relative) sea level. At the end of the glacial maximum, around 18,000 years ago, global sea level started to rise rapidly from c. 120 m