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Concepts in gravel beach dynamics

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Abstract

The dominant processes in gravel beach dynamics are reviewed, highlighting some common themes which unify the various components of the gravel beach system, the repercussions of which impart on how gravel beach dynamics might be understood conceptually. In particular, gravel beach dynamics are thought to be highly dependent on the temporal and spatial variation in grain size, and the continual adjustments made by an active beach step, both of which act not only as the expression of changing morphodynamic conditions, but also as a controlling influence. Morphodynamics, the notion that the exchanges on beaches between the hydrodynamics, sediment transport, and morphological change takes the form of reciprocal relationships which are mediated through feedback mechanisms (in such a way that they cannot be thought of or studied independently) is not a new one. Yet it appears that for the gravel beach, morphodynamics must be re-defined to describe conditions where variations in sediment size are thought to deserve parity, rather than as merely a sequent entity or boundary condition. 'Morpho-sedimentary-dynamics' is a phrase coined to intuit such cause and effect, detailing the co-evolution of morphology, hydro-hydraulics and sediment properties whilst acknowledging causative pluralism, feedbacks and multiplier effects. This is the recommended conceptual framework within which to crystallise thought and organise further research for the gravel beach. Essentially, it increases the minimum number of parameters needed to describe the state of the gravel beach as a physical system. Therefore, it is advised that simplicity will be most expedient in our future modelling efforts, if complexity is to be adequately encapsulated.

Keywords: Coastal geomorphology; Gravel beaches; Nearshore sediment transport; Sedimentology

1. Introduction

Historically, our insights into shorter term gravel beach (Fig. 1) dynamics have lagged behind our understanding of littoral environments composed of finer sediments, mainly because of the logistical problems associated with laboratory or field experimentation. Recently, however, there has been some revival of interest in gravel beach dynamics, resulting in a spate of experimental and modelling efforts (e.g., Blewett et al., 2000; Van Wellen et al., 2000; Holmes et al., 2002, 2003; Clarke et al., 2003; Pedrozo-Acuna et al., 2006; Austin and Masselink, 2006). The intention of this paper is to review shorter-term, process-oriented gravel beach foreshore and beach face morphodynamics by highlighting the key aspects which most require further study. The aim is to stimulate sustained interest in gravel beach dynamics by acknowledging that most of these morphodynamic facets have in the past gone virtually unstudied, due to both conceptual and experimental difficulties, and emphasising the importance of redressing this fact. Indeed, although swash-dominated, gravel

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Fig. 1. A swash aligned gravel barrier beach (Slapton, UK). Top row, from left to right: panoramic view of the barrier beach; morphological surveying and sediment sampling; developing cusp formations and foreshore sediment zonation. Middle row, from left to right: waves breaking close to shore under calm conditions; rig preparation for a short term hydrodynamic experiment; storm waves imparting upon a sea-wall. Bottom row, from left to right: sediment heterogeneity; foreshore swash excursion measurement; and energetic storm surf zone waves.

beaches are scarcely mentioned in recent reviews of swash zone hydrodynamics and sediment transport (Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006), and various contemporary commentators have drawn attention to the discrepancy between recent advances made into the morphodynamics of sand beaches and the comparative lack of similar advances made into gravel beach dynamics (e.g., Van Wellen et al., 2000; Mason and Coates, 2001; Jennings and Shulmeister, 2002; Orford et al., 2002; Horn et al., 2003; Pontee et al., 2004). This situation has become increasingly untenable because the use of coarse grained sediment to replenish eroding beaches is on the ascent, since gravel is an efficient and hydraulically-rough (dissipative) form of sea defence (Van Wellen et al., 2000). Accurate monitoring of coastal gravel transport is therefore important in relation to gravel extraction, replenishment and sediment mobility (e.g., Voulgaris et al., 1999).

The collective noun under the Udden–Wentworth classification scheme for sediment with a *b*-axis diameter of between 2 and 60 mm is ‘gravel’, which has physical connotations understood not only by coastal scientists and engineers, but geomorphologists, geologists and ecologists (the alternative term, ‘shingle’ is not as inter-disciplinary or international; e.g., Carter and Orford, 1993; Van Wellen et al., 2000; Orford et al., 2002). A necessary distinction is made between gravel beaches so-classified and boulder beaches (e.g., Novak, 1972; Lorang, 2000; Johnston, 2001; Lorang, 2002), or beaches composed of coral gravel (e.g., Felton et al., 2000).

Gravel beach sediments have a characteristic size and shape heterogeneity (Zenkovich, 1967; King, 1972; Carter, 1988) since the physiographic context to the development of gravel beaches is glacial and mountain weathering. Therefore the geographic coverage is distinctly high-latitudinal, with long term sediment supply dominated by continental shelf reworking of gravels supplied by terrestrial weathering processes. Gravel beaches are particularly widespread on the wave-dominated coastlines of Northern Europe (especially Russia, UK and Ireland), Canada, USA, Japan, New Zealand, and Latin America.

Orford et al. (2002) have recently provided a comprehensive review of the modern thinking behind the long-term, large-scale geomorphology of gravel beaches and barriers. Gravel beaches within large regional settings are the subjects of Isla and Bujalesky (2000) and Anthony (2002). The structural sedimentology of gravel beaches, including the historical interpretation of internal beach structures/stratification (an enquiry which, incidentally, is almost wholly absent from the process-oriented gravel beach studies), is treated in detail by Bluck (1999). This paper reviews and discusses the dominant processes and concepts which affect up to entire beach faces or sections of beach faces on larger features such as spits and barriers compose entirely of gravel sediment, in tidal settings which are affected directly by wave action. This includes cliff-backed and pocket beaches, as well as barrier and spit fontages, but not back beach deltas (which are formed and stranded by storms), lateral deltas formed by permanent barrier breach, and sheltered sections of spit heads. Whilst many of the concepts and processes discussed here will be applicable to mixed sand and gravel (MSG) beaches or beach sections, the dynamics of such beaches are quite distinct (e.g., Kulkarni et al., 2004), and are the subject of review by Kirk (1980) and Mason and Coates (2001).

This paper explores a number of features which may be peculiar to beaches composed of gravel-sized sediment, predicting that further research will uncover a unifying theme common to all avenues of enquiry: the importance of spatial distributions in sediment size and shape. We shall introduce conceptual ideas that centre around the notion that the spatial heterogeneity of sediment properties are both an expression and a control on gravel beach morphodynamics. We conclude by making suggestions for analysing data and modelling the short-term changes which occur on gravel beaches.

2. Hydrodynamics and sediment transport

2.1. Hydrodynamics

The gravel beach is the classic reflective beach morphotype in the beach classification nomenclature (Carter and Orford, 1984, 1993; Jennings and Shulmeister, 2002). Nearshore hydrodynamics on gravel beaches are dominated by the swash zone. Short wave bores induce highly asymmetrical swash motions at incident wave frequencies as waves break close to the shoreline. Very narrow surf zones support just one relatively uniform breaker line, quasi-perpendicular to the beach face (Baldock et al., 1997; Baldock and Holmes, 1999). The rapidity of nearshore wave transformations dictate energy concentration at breakpoint, in close proximity to the shoreline, minimising the generation of broad-band infra-gravity oscillations, and maximising the importance of fluid motions at incident and subharmonic frequencies (Huntley and Bowen, 1975a; Mase, 1995; Miles and Russell, 2004). Significant wave grouping may remain at the shoreline (*cf.* Ivamy and Kench, 2006). The lack of breakpoint variability, dictating a spatial concentration of energy, means that critical thresholds for sediment transport are almost always exceeded (e.g., Carter and Orford, 1993). If and where the tidal frame dictates wave breaking over a shallow sand slope immediately seawards of the gravel bank, as on a ‘mixed’ beach, nearshore hydrodynamics are substantially different. The interested reader is referred to Jennings and Shulmeister (2002), Blanco (2002) and Pontee et al. (2004) for the most recent reviews into mixed beach dynamics, although a substantial deficit in mixed beach hydrodynamic research is apparent in the literature.

Pre- and post-breaker energy fluxes may have interesting and important consequences for the spatial decay of energy with wave transformation distance, and turbulence, both locally-generated and the contribution advected from bore collapse (e.g., Puleo and Holland, 2001; Longo et al., 2002; Jackson et al., 2004; Butt et al., 2004; Pritchard and Hogg, 2005). The potential importance of the advection of material convected by turbulent bore collapse into the swash zone, reported by numerous authors in recent years (and reviewed in Masselink and Puleo, 2006) appears particularly essential for swash-dominated gravel beach foreshores. The extent to which reflection is attenuated by the loss of fluid into highly permeable beach faces (*cf.* Powell, 1990) is at present unknown, as are undertow and set-up; and near-bed velocity profiles, which again are in need of much further scrutiny.

The nearshore hydrodynamic regime so-described allows bore theory (e.g., Peregrine, 1966) and the non-linear shallow water wave equations (NLSWE, or simply SWE; Shen and Meyer, 1963, reviewed in detail by Hughes, 1992, 1995; Peregrine and Williams, 2001), or the ‘ballistic model’ (Hughes and Baldock, 2004) to be particularly applicable. We may assume swash discretion (or uncurtailed individual events) with most validity on gravel foreshores where permeabilities (and therefore fluid loss) are high (Austin and Masselink, 2005). Although swash interaction has been shown to occur naturally (Austin and Masselink, 2006), steep slopes and high permeabilities gratify the assumption that individual swashes are 'launched' up the foreshore slope (Hughes and Baldock, 2004). When using the NLSWE, for the necessary formulations to hold, the fluid of the swash tip must maintain very shallow depths (Peregrine and Williams, 2001). Fluid loss through infiltration appears to be highest on the leading edge of the uprush during the latter stages of the uprush event (Horn et al., 2003), i.e. towards the top of the foreshore. Fluid exchanges on highly permeable substrates are possible to model using ballistic approaches (Clarke and Damgaard, 2002; Clarke et al., 2003). For all of these reasons, a more complicated approach, such as employment of the Boussinesq equations (e.g., Pedrozo-Acuna et al., 2006) may not be necessary to model swash motions. However, just like sand beach shorelines (Elfrink and Baldock, 2002; Masselink and Puleo, 2006), how swash zone hydrodynamics relate to sediment transport and morphological change is much more problematical.

2.2. Swash-groundwater hydraulic exchange and sediment transport

The transmission of fluids through granular interstices, and swash flow modification as a result of differential groundwater responses over the varying sediments of a gravel foreshore, have interesting and under-studied implications for sediment transport and morphological change on gravel beaches (*cf.* Masselink and Li, 2001; Austin and Masselink, 2005). Horn (2002) attributes the failure of various swash zone sediment transport models to the over-simplification of swash hydrodynamics with respect to swash groundwater flows (hydraulics, also Pedrozo-Acuna et al., 2006). On a gravel beach, permeabilities and hydraulic conductivities are generally high (Horn et al., 2003). Hydraulic conductivity shows a sensitive dependence on sediment size (see Fig. 2), so the spatial distribution of surface sediment size, and indeed the spatial variance in vertical size distributions, or the variation in sediment size with depth, are particularly significant on gravel beaches with respect to hydraulics.

The qualitative behaviour and importance/magnitude of these features may be peculiar to gravel beaches, and their study may be more difficult in the field for three crucial reasons. Firstly, the magnitude of swash-groundwater exchanges is greater (Holmes et al., 2002; Horn et al., 2003). Secondly, air encapsulation within groundwater–sediment matrices, hitherto considered ineffectual for sand beaches, may be important for porous gravel substrates (Horn, 2002). Thirdly, the high seepage

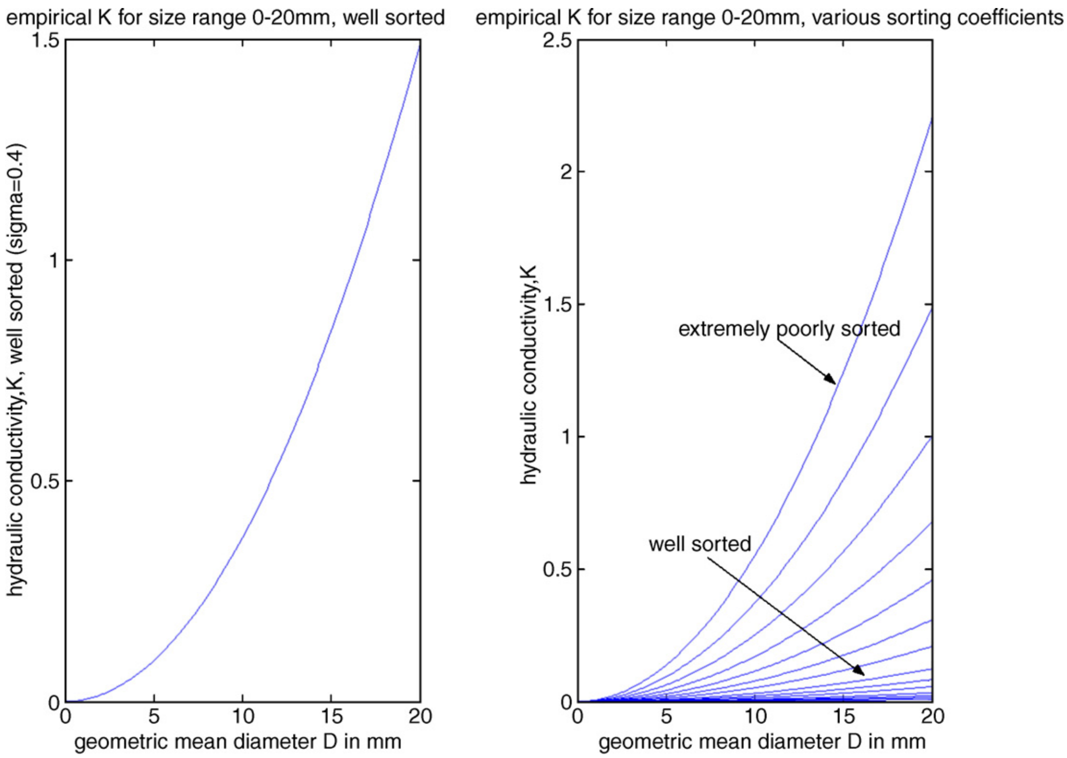


Fig. 2. Nonlinear sensitivity of hydraulic conductivity K (m s^{-1} to size), D (mm), derived from linear empirical formula (Krumbein and Monk, 1943). Horn (2002) notes that coarser and mixed size distributions may not show this linear dependence.

velocities under swash flows (reported by Holmes et al., 2002, and Horn et al., 2003.) implicates a non-Darcian flow regime, or a nonlinear groundwater (hydraulic) through-flow velocity dependence on hydrostatic pressure fields, explicating the sensitive nonlinear relationship between sediment size and hydraulic conductivity where permeability is high (a notion which has remained latent until very recently). Accordingly, instantaneous swash hydrodynamics–hydraulics (or simply their combinatorial, 'hydro-hydraulics') have taken on a new dimension and renewed impetus for gravel beach dynamics (*cf.* Masselink and Li, 2001; see also Clarke et al., 2003; Horn et al., 2003; Austin and Masselink, 2005; Isla and Bujalesky, 2005), where the hydrostatic forces of vertical water exchange are potentially so exacting. Numerical models for gravel profile development (Powell, 1990; Clarke and Damgaard, 2002; Clarke et al., 2003; Pedrozo-Acuna et al., 2006) acknowledge the importance of a rigorous groundwater module to account for infiltrational effects over highly porous media. The next stage will be to allow for a range of sediment sizes, and spatial variability in sediment size, as will be needed in gravel beach sediment transport calculations. Derivation of mean boundary shear stress used to describe the effect of bed roughness on swash flow characteristics may be obscured by the nonlinear interaction of stress inherited from wave breaking, boundary layer development and micro-topographically induced acceleration and deceleration. Grain mobility, roughness to flow and infiltration may be inherently stochastic, dependent on the statistical distribution of sediment size and shape (facies) through time and space. The bulk (porosity, permeability, hydraulic conductivity) and transport-specific (sediment effective weight, surface tension and fluid cohesion, in/ex-filtration) parameters are potentially a complex function of size, shape, packing, orientation and vertical/horizontal gradation. Assessing the importance of groundwater dynamics in swash zone sediment transport may involve quantification of boundary layer development, the contribution of fluid exchanges to 'friction'; stabilisation/destabilisation (e.g., Turner and Masselink, 1998; Butt et al., 2001; Nielsen, 2002); and measurement of the form of swash lens (e.g., Baldock et al., 2001; Horn et al., 2003; Baldock and Hughes, 2006). It must be noted that 'friction' is a term employed loosely for roughness or 'skin friction', but in reality additionally encapsulates the instantaneous dissipation of potential energy associated with turbulent structures, and the loss of fluid mass, both of which may be more important in gravel sediment transport and profile dynamics (Masselink and Li, 2001). Separation of the relative frictional and infiltrational contributions to shear stress for sediment transport formulations will be more difficult for gravel beaches than for sand (and perhaps most difficult for 'mixed' beaches).

On gravel beaches, permeability (which has a sensitive positive nonlinear relationship with sediment size) becomes more important (Fig. 2). Austin and Masselink (2005) show that watertable outcropping is highly dynamic on natural gravel foreshores, suggesting that infiltration at the swash limit contributes swash asymmetry, onshore sediment transport and berm formation. Berm building and onshore migration provides an additional mechanism for maintenance of beach face reflectivity. Duncan (1964) observed that larger foreshore sediments tend to move onshore, forming strand lines and berms, whilst fine material congregated further downslope. This seemed counter-intuitive since the velocity gradient (and therefore flow competency) decreases landwards. Duncan (1964) explained it thus: toward the limit of each uprush, velocity is insufficient to retain sediment in transport because water volumes undergo increasing diminution through infiltration. Larger material stranded at the landwards extent of run up lacks a mechanism for its removal since infiltrational losses have weakened backwash with respect to uprush, although some fine material is downcombed by backwash. In this way, a lens of sediment is pushed onshore over tidal cycles through cut-and-fill and berm building (Eriksen, 1970; Waddell, 1976; Horn et al., 2003; Austin and Masselink, 2005). Masselink and Li (2001) modelled the dependence of foreshore slope on swash infiltration, finding a critical sediment size of 1.5 mm beyond which infiltration-enhanced onshore flow asymmetry caused significant profile steepening. It would appear, therefore, that hydraulics is more important to gravel beach dynamics than sand beach dynamics.

2.3. Transport mode

Saltation, traction-bedload and sheetflow dominate the nearshore of gravel beaches. Transport mode will be a direct function of swash hydrodynamics and hydraulics, but individual clast motion will be dictated by a number of micro-mechanical factors attributable to size and shape variation over a heterogeneous bed. Transport mode may have direct influence on the gross nature of sediment sorting, sediment transport and morphodynamic feedbacks. Gravel is large, so occupies a greater proportion of the volume of swash flows relative to sand. Sheet flow is therefore likely to be important in gravel beach dynamics, especially on fluid-thin backwashes. Sheetflow is poorly defined, taken by some authors to mean any collision-dominated sediment slurry where fluid-momentum forces flow but sediment concentration is high (e.g., Savage, 1984). Others define it in terms of the Shields parameter (e.g., Wilson, 1987, defines sheet flow as $\theta \geq 0.8$); and others in particular reference to dispersive pressures which arise through grain collisions, resulting in inverse gradation or 'shear sorting' (dispersive pressures are greater on larger grains than small in the same horizon of flow, causing larger grains to migrate upwards, e.g., Bagnold, 1954; Inman et al., 1966; Clifton, 1969; Sallenger, 1979). Finally, it may be defined in specific reference to hindered settling effects. Baldock et al. (2004) demonstrated that particle settling velocity may reduce to 10% of clear water settling velocity within sheet flow. At present the nature of sheet flow in the nearshore (e.g., contact stresses, pressure dispersion, inter-particle collision and hindered settling) is poorly understood (Seminara, 1998; Drake and Calantoni, 2001), especially for coarse sediments.

3. Textural mosaics

3.1. Sorting and grading

Gravel is not only larger, but usually varies over several orders of magnitude greater than that for beach sands. In consequence, gravel beach sediments are spatially differentiated in terms of both size and shape to a greater degree (Bluck, 1967; Orford, 1975); therefore textural zonation is more obvious on gravel beaches than sand beaches (Orford, 1975), forming mosaics of relatively fine and coarse sediment (Fig. 3). The step, cusp horns, strands and berms are composed of larger sediment than foreshores, although a number of levels of textural zonation within this general case may be discernible as sediments are redistributed continually (the level at which sediment zonation becomes important in terms of the morphodynamics of the beach is conceptually interesting, and discussed further later in this paper).

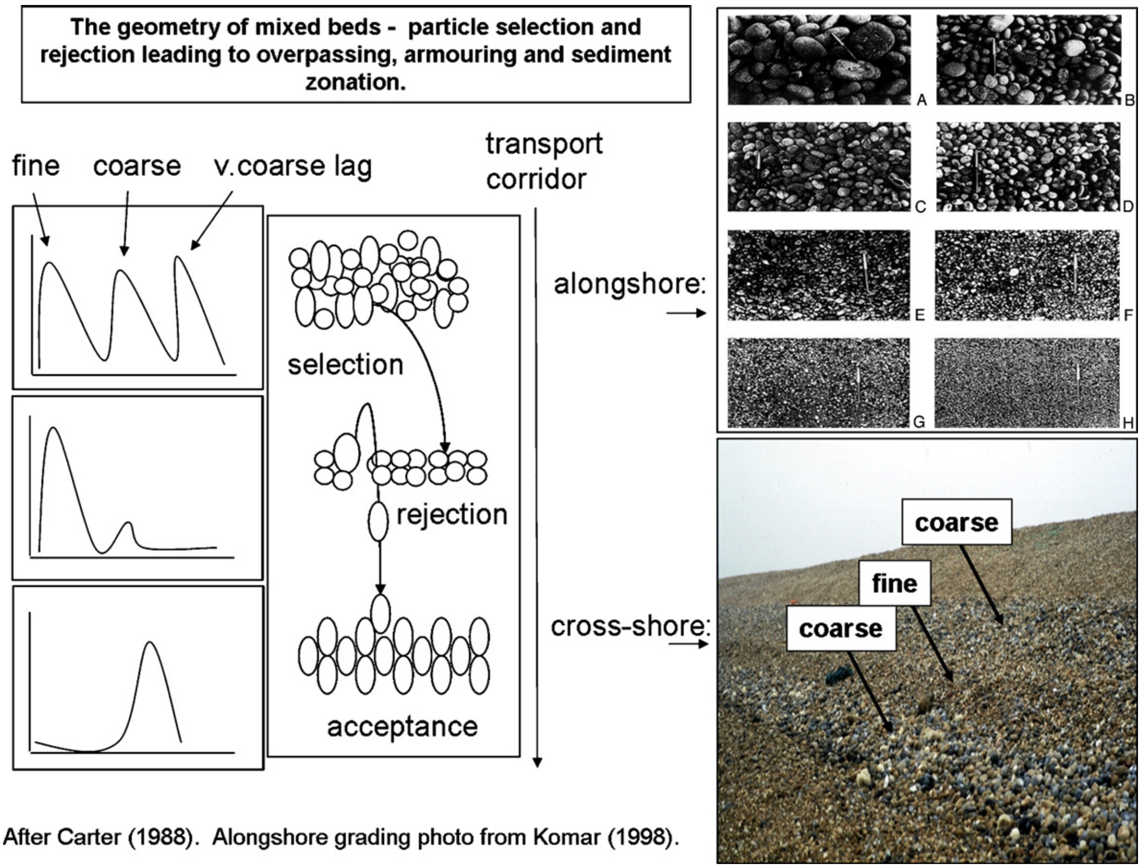


Fig. 3. Diagrammatic portrayal of selective overpassing and armouring phenomena, expressed in terms of transport stresses on individual grains in mixed-size beds (after Carter, 1988), where overpassing occurs in the longshore (e.g., Bird, 1996) and armouring occurs in both long- and cross-shore directions (e.g., Isla, 1993).

Sediments which are selectively entrained congregate as 'sediment structures' or 'assemblages' (Bluck, 1967, 1999; Fig. 3) whereby the difference between a sediment structure and a packing framework is the difference between a planimetric and an altimetric pattern (or horizontal and vertical grading) by virtue of their similarity in response to the prevalent hydro-hydraulic regime. In order to understand these processes, we require command over this notion of 'hydraulic equivalence' (Rittenhouse, 1943). This condition is manifest through a whole suite of 'emergent' sedimentary properties acquired through the mutual association of individual grains in a mixed population. In other words, individual grains acquire these properties only in context to 'background' populations of collections of grains. These emergent properties include packing arrangements (hence porosity, permeability and hydraulic conductivity); angle of pivot (hence relative flow protrusion, shadowing); shape-controlled imbrications and angular-interlocking; and angles of internal friction. Moss (1962, 1963) invoked the idea of particle rejection/acceptance to explain gradation phenomena through differential response to swash phase (Fig. 3). Particles smaller than background size filter into the interstices of the large (a process known as kinetic sieving); and large particles override the small (called 'overpassing', e.g., Carr, 1969; King, 1972; Bird, 1996).

That different cross-shore size–shape zonations exist on gravel beaches is verified by numerous authors (e.g., Flemming, 1964; Bluck, 1967; Orford, 1975; Williams and Caldwell, 1988; Petrov, 1989; Isla, 1993), although the relative importance of size and shape in sorting is yet to be resolved. Bluck (1967, 1999) postulated on the tendency of disc and blade-shaped particles to be preferentially transported upslope, acting like a hydrodynamic 'wing', and for spherical and roller shapes to be transported downslope (echoed by Wright et al., 1979; Williams and Caldwell, 1988; Petrov, 1989; but not supported by the findings of Carr, 1971; or Jackson and Nordstrom, 1993). It is not clear whether sorting by size, and sorting by shape, are achieved by two fundamentally different mechanisms; or what aspect of anisotropy is important ('shape' is, hydro-hydraulically, multi-faceted, e.g., Winkelmolen, 1982; Illenberger, 1991; Le Roux, 2002, so varying measures of two-dimensional sphericity, aspect ratio and elongation, and the axially less dominant third dimension, or *c*-axis, may produce different responses to flow, individually, and as part of mixed beds).

3.2. Longshore sediment transport

The principle of 'overpassing' (Fig. 3) has been used to explain the existence of both cross shore and alongshore grading, the latter perfectly illustrated by gravel barriers such as Chesil Beach in the UK, and Hawke Bay Beach, New Zealand (Carr, 1969; King, 1972; Bird, 1996). Overpassing is the process by which the large scale alongshore segregation of smaller and larger sediment occurs as a corollary of differential transport rates through acceptance or rejection into background material. A greater ratio between individual large grains and mixed beds increases the propensity for mobility since greater boundary layer flow projection is thought to concentrate fluid drag about the angle of pivot, causing the preferential selection and transport of larger grains and proximal–distal coarsening. In contrast, a diminished ratio between individual and background sediment would perhaps impede transportation through hiding effects (and inverse-grading, see Isla, 1993). Net or time-averaged grading may be viewed as a null point argument (Cornaglia, 1877; Bowen, 1980; reviewed by Miller and Ziegler, 1958; and extensively by Horn, 1992): for every grain size there exists a unique alongshore position where the coarse/fine ratio grades perfectly alongshore. Alongshore grading occurs within the swash, not as the result of longshore currents sensu stricto. The longshore movement of material in the swash of gravel beaches, termed swash 'grazing' (Sherman and Nordstrom, 1985) is the subject of a comprehensive review by Van Wellen et al. (2000), who imply that 50–70% of longshore sediment transport of material occurs in the swash, which has importance not only in terms of overpassing and grading but in the long term health of beach systems, sediment leakage, and planforms. Masselink and Puleo (2006) have recently suggested that the longshore component of cross-shore dominated swash flows may be more important than previously realised, although there are few published measurements of longshore sediment flux and hydrodynamics in the swash (Elfrink and Baldock, 2002). Van Wellen et al. (2000) note the particular shortage of high quality field data on longshore sediment transport/volumetric changes on gravel beaches and spits, especially during storms (*cf.* Chadwick et al., 2005), which has severely hampered progress in this area. According to Masselink and Puleo (2006), the same is also true of sand beaches.

3.3. Conventional sorting coefficients

Most sorting coefficients are measures of distributional spread, where 'well-sorted' means a small standard deviation. However, this definition of 'sorting' is really two separate properties, namely the evenness with which the total amount of material is distributed between arbitrary classes; and the spread of the distribution. Most sorting coefficients describe just the latter, not accounting for fluctuations within the distribution. Alternatives exist, however, for example the simple sorting coefficient of Sharp and Fan (1963), a univariate information statistic characterising the whole distributional form of the GSD, the value of which is independent of the position of the classes, and which expresses both the spread and the evenness of the entire distribution (standard deviations do not express the evenness of the distribution). These considerations become potentially more important in littoral environments where sediment size varies over orders of magnitude. A multi-size-fraction approach is required to model spatial sorting on coarse clastic beaches, such as taken by the sediment transport module of the numerical model developed by Lawrence et al. (2002) which includes a multiple size fraction sorting algorithm. The mean diameter of a sediment sample is more than a record of fluid power expenditure: it is a cumulative record of grain size filtering at successive positions along the sediment transport pathway. This is true both of sand and gravel beach sediments, but perhaps only on beaches composed of the larger clastic fractions does the material being transported exert positive feedback control over subsequent transport events, and hence morphological change. If so, even multiple size fraction sediment transport and sorting formulae will not be enough to describe and account for observed changes in morphologies. This notion is developed further in the discussion section of this paper.

4. Morphological features

4.1. Step and foreshore dynamics

The step is a relatively small and steep feature at the base of the foreshore, a submerged break of slope at the base of the swash zone which appears to adjust to nearshore hydrodynamic regime (e.g., Hughes and Cowell, 1987), characteristic of reflective sand and gravel beaches (Masselink and Hughes, 1998), and composed of sediment which is coarser than the sediment immediately landwards or seawards. Beach steps, which are relatively under-studied, have been reviewed by Bauer and Allen (1995). The step is distinct from the scarp (e.g., Sherman and Nordstrom, 1985) which is a subaerial (upper swash or tidally-stranded) feature. The steep seawards facing slope is of the order of 20° and 32° (Short, 1984; Larson and Sunamura, 1993). Wave-breaking is thought to be forced and modulated by the step, a morphodynamic relationship possibly related to wave height (Sunamura, 1984), or surf similarity parameter. Bores develop, shoal, and collapse immediately following breaking over the relatively shallow (slip-)face of the step at the base of the foreshore (Austin and Masselink, 2006).

Being permanently submerged, the step is technically not a feature of the swash zone, but initiation and maintenance is thought to have as much to do with swash processes as wave breaking, undergoing dimensional alteration in response to increases in wave height at breaking (therefore wave breaker type, Sunamura, 1984; Hughes and Cowell, 1987) and changes in swash regime (Larson and Sunamura, 1993). As such, steps serve to highlight the importance of the interdependence of the pre- and post-breakpoint fluid motions on steep beach dynamics. Matsunaga and Honji (1980, 1983) demonstrated that supercritical flow conditions arrived at by strong backwashes curtailing strongly asymmetrical incident bores can create a hydraulic jump and associated backwash vortex, under various wave breaker types, that could be responsible for the formation of the step. Takeda and Sunamara (1983) and Larson and Sunamura (1993) developed these ideas into a dynamical model for step hydro- and sediment-dynamics, postulating on the importance of the step in swash zone flows, slope development, sediment transport and sorting mechanisms. According to this interpretation, the step gradient is maintained by the upward stroke of a backwash vortex which impedes avalanching and allows for deposition on the crest. The coincidence of an unstable turbulent bore with an immediate antecedence of sediment entrained by a backwash vortex may cause advection of material onshore. This process may provide a mechanism for preferential slope building and supply the liberated coarse material for berms and cusp horns (Fig. 4).

The efficaciousness of step dynamics are likely to have consequence for swash zone sedimentation through convective–advective entrainment and transport on the uprush (see also the section on hydrodynamics and sediment transport) and foreshore adjustments. For example, a recent laboratory study (Lara et al., 2002) found that turbulence associated with breaking had a sensitive sediment-size dependency, where larger gravels induced an increase in the vertical velocity gradient and hence larger instantaneous shear stresses. This finding would suggest that sediment would be convected at the step (where very coarse grains tend to concentrate, e.g., Short, 1984), to be advected by onshore-asymmetrical bores shoaling over the relatively flat step crest. Austin and Masselink (2006) present a time-series of step dimensional adjustments on a gravel beach, showing the step to respond to wave height, and to migrate with the

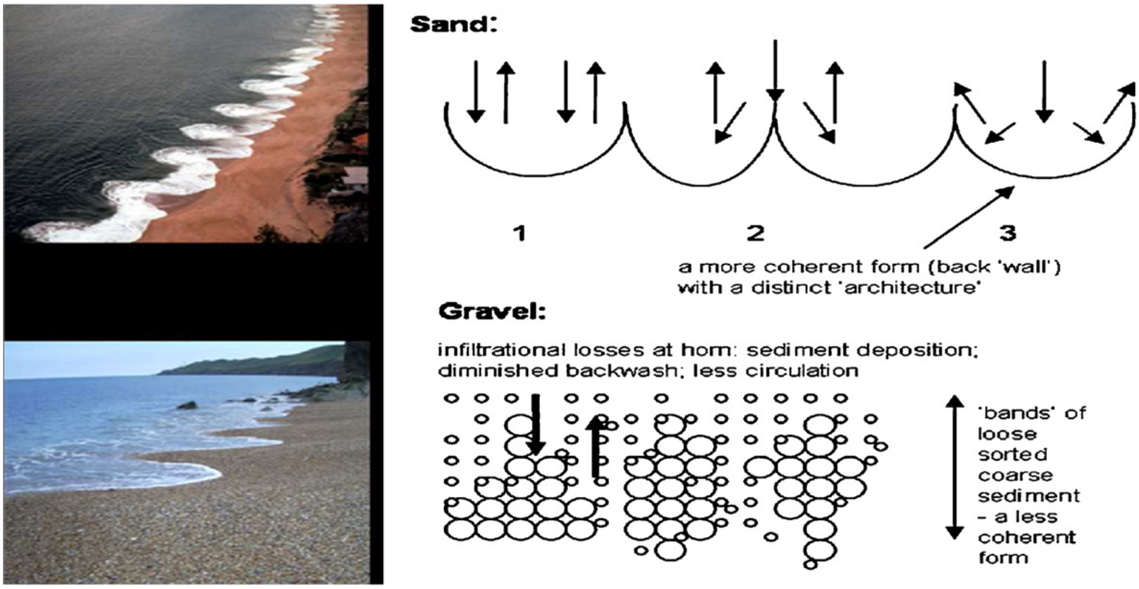


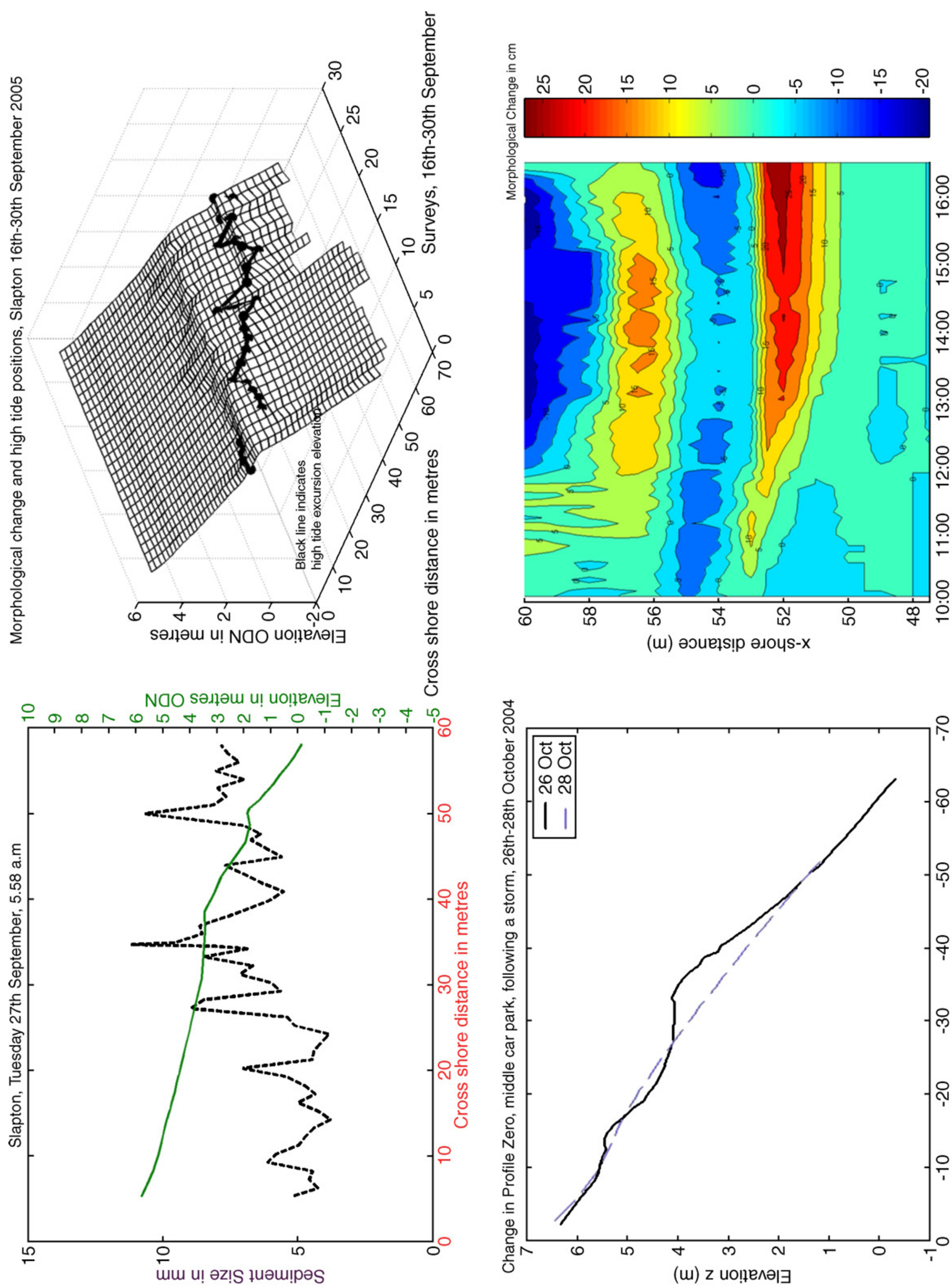
Fig. 4. The processes of cusp formation on gravel beaches illustrate the role sediment may have in the morphodynamics of those beaches, building and maintaining morphology through feedback mechanisms to an extent never matched by sediments comprising sand beaches. Sand cusp photo courtesy of Dr. Peter Cowell.

tide (see also Fig. 5, bottom right panel). Backwash vortices should be most energetic when resonance occurs between wave period and swash duration (*cf.* Kemp, 1975). Less clear is the requirement for backwash–uprush interaction at the base of the foreshore to force supercriticality. Beach steps may thereby be central to our understanding of the modulation of foreshore adjustments in response to swash–swash interaction and frequency-downshifting (Kemp, 1975; Mase, 1988, Mase, 1995; Baldock et al., 1997; Holland and Puleo, 2001; Erikson et al., 2005). Indeed, the role of the step appears crucial in gravel beach morphodynamics, being a dissipative feature perhaps analogous to a sand beach bar, and is discussed in detail later in this paper.

Gravel beaches commonly support slopes in excess of 10 degrees (Longuet-Higgins and Parkin, 1962; Williams and Caldwell, 1988; Austin and Masselink, 2006, also Fig. 5). The relative importance of nearshore hydrodynamics, sediment characteristics and beach face hydraulics, in the maintenance of reflectivity is unresolved. Hughes and Cowell (1987) emphasised the importance of the step in maintaining steep slopes, hypothesising that the morphodynamic adjustment of step dimensions to wave height acts in the same way, or has an analogous morphodynamic role, as a dissipative surf zone. Step maintenance allows waves continue to shoal in deep water close to the shoreline; the energy of wave breaking forced by the step face is spatially concentrated, providing the conditions for step maintenance and for reflective conditions to persist. Step height increases with wave height, so surging breakers would flatten the step, and plunging breakers steepen the step face. As wave heights increase, the dominance of uncurtailed backwashes would provide the backwash strength required for interaction further downslope (i.e. at the base of the foreshore), vorticity generation and step building. Swash zone asymmetries therefore appear to satisfactorily resolve both the Matsunaga and Honji (1980) hypothesis for step formation and the Hughes and Cowell (1987) hypothesis for beach face reflectivity. Bagnold (1940) famously stated that beach face angle depends only on the size of grains, and was independent of wave height. Kemp (1975) also thought that there was no relationship between wave energy and beach face grading. Under the Hughes and Cowell (1987) hypothesis, foreshore slopes become less sensitive to incident wave energy since the step forces energetic breaking and bore collapse (as stated previously, the step is therefore the morphodynamic equivalent to a sand bar). The wave energy independence stated by Kemp (1975), therefore, is a direct result of dimensional alteration in response to an increase in wave energy, up to a certain threshold.

4.2. Cusps

Cusps are small quasi-rhythmic crenulations formed at the shoreline by swash flows, composed of coarse



Slapton, Tuesday 27th September, 5.58 a.m
Sediment Size in mm
Cross shore distance in metres
Elevation in metres ODN
Morphological change and high tide positions, Slapton 16th-30th September 2005
Black line indicates high tide excursion elevation
Elevation ODN in metres
Cross shore distance in metres
Surveys, 16th-30th September
Change in Profile Zero, middle car park, following a storm, 26th-28th October 2004
26 Oct
28 Oct
Elevation z (m)
Cross shore x (m)
Morphological Change in cm
x-shore distance (m)
Time (hrs)

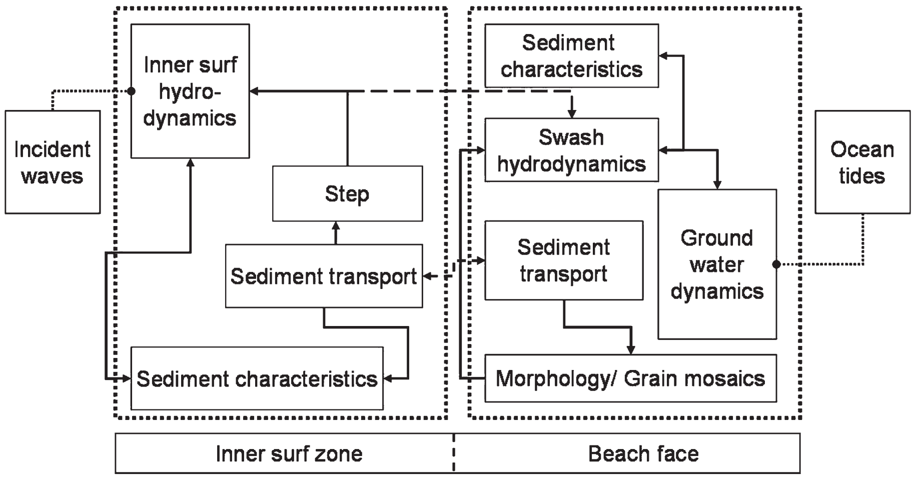


Fig. 6. Conceptual morpho-sedimentary-dynamics diagram for the gravel beach face (modified from Masselink and Puleo (2006, their Fig. 1), which should be used as a guide to illustrate the conceptual differences between the two morpho-types).

horns and fine bays (Fig. 4). They are a common ephemeral feature of steep beaches, signatory of a reflective morphodynamic state. Accordingly, cusps are a common occurrence on gravel beaches (e.g., Kuenen, 1948; Longuet-Higgins and Parkin, 1962; Bluck, 1967, Williams, 1973; Bluck, 1999; Nolan et al., 1999; Sunamura and Aoki, 2000), but gravel cusps differ from sand cusps in that they are less of a coherent morphological form, and more of a collection of loose sediment structures, more obviously sorted by size, and often forming 'bands' of material down the foreshore (Figs. 1 and 3). Bluck (1967, 1999) and Sherman et al. (1993) detail a wide range of potential couplings (facies) between shape and size and associated hydraulically-equivalent sediment structures which may exist in relation to gravel cusps. Since the size variation of beach gravels is in general greater, the differentiation of coarse horns and fine bays is even more noticeable.

Beach cusp formation hypotheses have been reviewed extensively elsewhere (e.g., Guza and Inman, 1975; Inman and Guza, 1982; Komar, 1998; Coco et al., 1999). The developments and discussion of the two dominant models, namely the edge wave (hydrodynamic template, e.g., Huntley and Bowen, 1975b; Komar, 1998) and the swash-circulation/self-organisation (Werner and Fink, 1993; Masselink et al., 1997; Masselink and Pattiaratchi, 1998a,b; Coco et al., 1999, 2001, 2003, Masselink et al., 2004; Coco et al., 2004) have proceeded almost without reference to gravel cusps. Huntley and Bowen (1975b) attribute the formation of cusps on a gravel beach to zero-mode edge waves; however, the importance of wave reflection and associated standing wave forms on gravel beaches requires much greater scrutiny. Masselink et al. (2004) has shown that the assumption of edge waves during (or at least to initiate) cusp formation may not be convincing: energy within the edge wave band for a particular wave frequency may be the product of a whole suite of nearshore processes (e.g., Baldock et al., 1997), and the only satisfactory method of edge wave detection involves an array of sensors measuring both the cross-shore and long shore vertical structures of the water column. One potentially interesting topic may be the formation and maintenance of cusps in the light of various swash-interaction modes and associated type spectral (e.g., Mase, 1995) or frequency-distribution signature. Fig. 4 shows the potential differences between gravel and sand cusp swash circulations: it is clear that gravel cusps pose numerous interesting and unstudied avenues of enquiry, which may shed light on the nature of selective sorting at the shoreline.

Fig. 5. Experimental morpho-sedimentary-dynamic data collection consists of concurrent morphological, sedimentological and hydrodynamic data. Here are some example plots of morphological data collected from Slapton gravel barrier beach. Top left: a morpho(green line)-sedimentary (black line) 'snap-shot' under fair weather conditions. Top right: A time-series of observed cross-shore morphological change over a spring–spring tidal cycle, showing multiple berm formation (black circles indicate position of high tide). Bottom left: cross-shore profile change associated with a major storm. Bottom right: morphological/bathymetric change over the nearshore region over 6 h (half-tidal cycle) around high tide, showing the development of dynamic step/berm morphology (relative to initial: accretion in red, erosion in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Storm beach

Swash-aligned gravel barrier beaches are thought to migrate onshore over time through a mechanism known as 'rollover' (e.g., Carter and Orford, 1993), whereby onshore sediment transport during storms throws material landwards to form a coarse storm-stranded lag, or storm beach (see Fig. 5, bottom left). The relative altitude of this storm beach to spring high water level is remarkable, and can only be explained by storm-induced set-up superimposed upon a high spring or high astronomical tide. The material is effectively lost from the active beach system, since it lacks a mechanism for removal (offshore transport) during calmer conditions. Elevated groundwater levels and bed fluidisation coincident with high energy plunging breakers is thought to cause seawards-directed transport, but the seemingly paradoxical nature of onshore storm sedimentation is far from resolved. Indeed, the mechanism for landwards sedimentation proposed by Orford (1977), invoking the formation of a breaker-bar to force wave-spilling at tidal extremities, remains the only interpretation forwarded thus far. Since analysis of high-magnitude storm events on gravel beaches is exceedingly rare (Sanders, 2000; Orford et al., 2003; Cooper et al., 2004), explanations are necessarily heuristic. The Orford (1977) hypothesis remains to be verified: indeed, the formation of a bar would require substantial resistance to planation (Orford et al., 2003). The periodicity and nature of storm sedimentation may be studied using the internal structure of storm beach sedimentation/spill-over features (e.g., Bluck, 1999), which have good preservation potential, although the magnitude of associated beach sediment removal offshore, and the effect of this on the long-term health of the beach, is much more difficult to determine.

5. Discussion

However well beach gravels are sorted, we must remember that in nature a continuum of sediment size always exists. Therefore, mean or median size (D_{50}) would tell us very little about the processes of sorting, since what is important here is relative, and not absolute, size (recalling that flow thresholds are almost always met by energetic swash). Considering awhile only the relative abundance of coarse and fine sediment, there may be conditions on the gravel beach where the principle of self-limitation may be invoked (e.g., Philips, 2003), whereby the depletion of a system component (in this case, sediment material) limits or truncates potential pathways. The development and growth of the step, berm or cusp horns, for example, requires a certain sequence of processes: the growth of a berm requires onshore sediment transport, a foreshore-advecting tidal regime; infiltrational losses at the landward extremities of run-up; perhaps a specific sequence or set of swash excursion distances (not too many large swashes which would 'overtop' and erode the berm; not too many small swashes which would not reach the berm). Yet these features also require a certain availability of coarse sediment, and a certain ratio of coarse to fine sediment in a mixed bed to instigate overpassing, which if lacking leads to truncated development. The conditions of truncated development, or the unfulfillment of potential which would otherwise be fulfilled, appears crucial in gravel beach dynamics. In other words, no variation in sediment size, and no clear secondary morphological features. The first step would be to demonstrate convincingly that both temporal and spatial variations in sediment size are strongly related to morphological change.

Sensitivity to spatial variations in sediment size is another dominant theme, with respect to, for example, vertical velocity profiles, morphological (step, cusp, berm: Fig. 5) and textural mosaic dimensions, kinetic sieving (acceptance), overpassing (rejection), and emergent sediment properties such as hydraulic conductivity and pivot angle. Larger sediment helps to dissipate and spatially concentrate energy at the step, forming a lag where infiltrational fluid losses are greatest. Carter and Orford (1993) state that the emergence of sorting patterns through selection, rejection and acceptance tend to create patterns which resist further movement. In other words, the formation of textural mosaics and morphologies would progressively have fewer configurational possibilities, which would limit further reorganisation. Therefore, gravel foreshores tend to become more organised, creating mosaics of sediment which have a distinct form (the sediment structures of Bluck, 1967, 1999), which are able to withstand and control transport (or limit work done – this notion is discussed in terms of 'entropy' by Carter and Orford, 1993). The wide range of size–shape structures reported in the literature (Bluck, 1967, 1999; Orford, 1975; Sherman et al., 1993) are interpreted as the product of this process, although it is far from clear which sediment assemblages represent periods of stability or order, and which assemblages are the cumulative product of periods of relative disorder, and indeed to what fine a scale must one measure.

Gravel morphological features would perhaps appear to control the flux of energy and matter through themselves. In other words, gravel beach architectures may act as mechanisms themselves which recycle sediment selectively (Evans, 1939; Longuet-Higgins and Parkin, 1962; Sherman et al., 1993; Bluck, 1999), so, effectively, sorting may beget sorting. Sherman et al. (1993) cogently argues that sediment structures, hetero-spatially, but not stochastically arranged, have a distinctive form which 'survives' or 'consistently appears' as distinct, irrespective of location, due to their propensity to either migrate in response to changing conditions (through hydraulic equivalence) or withstand or indeed even control local process variations and dynamics either through flow diversion or constraint, or spatially differentiated hydro-hydraulic properties.

The perfect example of such a relationship is a gravel cusp (Figs. 1 and 4). This potentially self-organised system is likely to be governed by internal (intrinsic) dynamics, and not exclusively on external hydrodynamic forcing: it remains dissipative (i.e. it requires continual energy transfer), but as it grows and becomes a more ordered, stable form. The formation of sediment structures may provide system 'memory', or templates for morphological change, as initial unpatterned (unordered) sediments form patterned (disordered) states. Time-lags between morphological adjustment (relatively long-term responses) and hydrodynamics (relatively short-term responses) in beach dynamics are common since sediment must be transported to invoke morphological change (e.g., Werner, 1999). Energetics-type models (Bailard, 1981) treat sediment transport as 'work done' by a hydrodynamic machine: these sediment transport models may have to be adapted in light of the previous discussion, since sorting implies the storage of energy which cannot be used to do work. Sediment sorting may either be progressive (i.e., occurs upon deposition) or instantaneous (i.e., occurs on entrainment and transport). The former may be related to mixed bed sediment geometry and the processes of selection and rejection, and the latter may be more related to flow competence and power. The challenge will be in the separation of the signals from the two components which are acting in concert to sort sediment.

5.1. Beach feature – analogues and 'bedform surrogacy'

On gravel beaches, why are coherent nearshore bedforms such as crescentic, longitudinal and transverse bars, and swash bars, absent? There may be several contributing factors. The hydrodynamic boundary conditions inhibit flow field instabilities (e.g., Dodd et al., 2003) associated with nearshore circulation, rips, shears and infra-gravity motions. Incident obliquity and longshore sediment flux, or bedload and sheetflow load dominance, obscures developing bedforms. Bedform initiation or maintenance requires low angles of internal friction.

One might speculate that perhaps sorting forms graded sediment structures, morphologies and mosaics of texture *instead* of bedforms. In other words, they draw physical resemblance to bedforms, or are bedform surrogates. The explication of scale–hierarchies between barely-perceptible and easily-perceptible sediment structures and packing frameworks, textural mosaics, and morphological features, could be interpreted as 'bedform surrogacy'. Beaches must absorb enormous quantities of energy to maintain their structure and characteristics – sedimentary and morphological reconfigurations and continual adjustments, through sediment transport, facilitate this energy dissipation. The features created are specific to available sediment size, and sediment size variation. For example, as reported earlier, as a dissipative feature forcing wave attenuation, the step may be analogous to a bar; sand and gravel cusps may be morphodynamically equi-final. Size-sorting in discrete mixed beds is a function of relative transportability, whereas sediment sorting on bedforms is controlled by the passage and recycling of sediment through the bedforms. Both coherent bedforms and gravel mosaics and sediment structures share in common a certain rhythmicity. Considering gravel features as surrogates for quasi-regular and coherent nearshore bedforms may uncover analogies for bedform spatial dimensions and wavelengths; migration rates and propensity; alignment; local flow and transport mode modification; and stability fields. Potentially, this idea has implications for the relative contribution of form drag to total shear stress (usually produced by the pressure field associated with flow over bedforms, but which may equally have a gravel analogue in the form of coarse sediment patches), and skin friction, produced by individual grains. Accordingly, textural mosaics may yield information on vectorial dispersal and spatial energy gradients over larger areas (the use of grain size characteristics is an approach common in coastal sedimentology, e.g., McLaren and Bowles, 1985; Gao and Collins, 1992). Equally, sediment structures may be non-repeating in time or space. The ephemeral nature and migration rates of bedform surrogates may aid the quantification of sedimento-morphological relaxation and inertia. Sediments must be transported to invoke morphological change, so sediment transport leading to the spatial distribution of sedimentary variables may provide the system 'memory' at the heart of many geophysical time-lags. Textural mosaics, morphologies and hydro-hydraulics may be developing over discordant time-scales. Werner (1999) describes this phenomenon as 'slaving', where fast variables are 'slaved' to slow variables, for example in the long-term motion of grains slaved to the migration of bedforms.

6. A conceptual framework for gravel beach research: Morpho-sedimentary dynamics

Gravel beaches have distinct dynamics, which may be explained not only through the mutual association between fluid flows and morphological change mediated through sediment transport, but extraneously on the particular controls sediment variations may exert on nearshore processes. It has become increasingly clear that the morphodynamic model first proposed by Wright and Thom (1977) can only partially explain gravel beach dynamics. Morphodynamics is a type of dyadic interaction, where a cluster of behaviours dominates the meaning of each member's behaviour. No single behaviour can be separated from the cluster for analysis without losing its meaning in the sequence. 'Morpho-sedimentary-dynamics' (*cf.* Carter and Orford, 1993) is defined as the mutual association and feedbacks in operation between flows (hydrodynamics and hydraulics), and forms (morphological architectures and textural mosaics), mediated through selective sediment transport mechanisms acting upon the mechanical, hydrodynamic and hydraulic properties of sediments (Figs. 3 and 6). It represents a modification of the morphodynamic domain, applicable where textural differences are so great that traditional morphodynamics are incapable of accounting for the apparently complex time series of beach geometries and morphological behaviours. A morpho-sedimentary-dynamics (MSD) approach treats sediments, and the spatial heterogeneity of sediment characteristics, not as a boundary condition (along with, for example, tidal range, offshore wave height and physical obstructions), but as a fundamental and integral aspect which permeates through morphodynamics, which may act as both an expression and control on gravel beach behaviour (Fig. 6). There are a number of extraneous interactions and feedbacks between system components, and more degrees of freedom (the number of parameters which may be independently varied). MSD therefore is about complexity, i.e. collective behaviour, and emergent behaviour through nonlinear interactions, although at this stage we may only postulate upon how MSD may be implemented within approaches specifically adapted to account for these interactions, especially over larger temporal and spatial scales, for example complex adaptive systems (e.g., Kingston et al., 2000); and hierarchical modelling (e.g., Stive and DeVriend, 1995; Werner, 1999).

7. Suggestions for further work

Soulsby (1997, pp. 20–22) lists the typical errors (uncertainties) associated with various sediment transport model input parameters: grain diameter has the largest uncertainty of any listed parameter, due to spatial and temporal variations in the distribution. Physics-based formulae for sediment transport must encompass the full spectrum of textural difference: the absolute value of median granular diameter may not be as important as the ratio between the fine and coarse tails of the distribution (e.g., Thaxton et al., 2001). Camenen and Larroude (2003) show that there are large discrepancies between the various nearshore sediment transport formulae when sediment size is considered, and that no formula satisfactorily describes transport behaviour with respect to size. The spatio-temporal coordinates of sediment size may, however, serve as a proxy for hydrodynamic roughness and hydraulic conductivity, as well as the micro-mechanical factors of preferential selection. It has become clear that in order to better understand the potential forcing sediment size may have on gravel beach morphodynamics, we have to seek better ways to measure and map sediment size, preferably in real time. Manual sampling and transportation to a lab for mechanical sieving may be too time-consuming and laborious for the required temporal and spatial resolution. In addition manual subaqueous sampling is intrusive insomuch as it removes sediment from the system and therefore potentially alters the very system-trajectories under scrutiny. Therefore remotely-sensed automated methodologies, such as the collection and processing of digital images of sediment, would appear to be more appropriate. These methodologies fall into two categories: algorithms which detect and measure individual particles (e.g., Butler et al., 2001; Graham et al., 2005) or the proportion of fine sediment to coarse (e.g., Carbonneau et al., 2005), and techniques which use the statistical properties of entire images to quantify sediment size (e.g., Rubin, 2004). Both types of techniques have their disadvantages and advantages (the reader is referred to individual referenced papers), but are generally rapid and robust measures of sediment size. Other sediment properties such as shape, imbrication and alignment may be quantifiable from digital images in a similar way, using geostatistical algorithms on the textural properties of images (e.g., Verdu et al., 2005). As well as utilizing optical signals, in situ sizing of subaqueous gravels may be possible using passive acoustics, detecting the noise of particle collisions, or self-generated noise (SGN):

Thorne (1986) showed that the peak frequency of the SGN spectrum is inversely related to sediment size.

The explanation of nearshore gravel motion will involve the adequate description of the kinematics of fluid–sediment flux under high shear stresses where sediment concentrations are so high; of rough, inhomogenous particles, the shape and size of which is variable, in fluid-thin, collision-dominated flows, where sensitivity to restitution and friction are largely unknown (e.g., Wilson, 1987; Seminara, 1998). Where underlying processes are thoroughly understood and well documented by observational and experimental data, it is possible to model beach dynamics using the classical approaches of mathematical physics: a quantitative expression for the phenomenon under scrutiny, expressed as a differential equation, which when integrated with a suitable boundary condition, becomes a deterministic parametric model which may be highly nonlinear and sensitive to initial conditions. However, on gravel beaches, where the underlying processes are poorly understood, it may not be possible to trace and evaluate the cause of every effect. The spatio-temporal sedimentary controls on morpho-sedimentary-dynamics constitute supplementary variables: the implication is that sophisticated techniques will not substitute a need to collect more data points in the field (e.g., Fig. 5) to define relationships (Philips, 2003). A full dynamical description of sediment-water flows based on first principles is a long way in the future, so at present, numerical models for morpho-sedimentary-dynamical systems (Fig. 5) seem an ambitious undertaking. A sensible and pragmatic approach would be to first document field observations and phenomena, then work 'backwards' into the underlying physics. But how are we to conceptually and analytically organise this observational and experimental information? Two possible approaches are:

7.1. Behavioural modelling

The physical impossibility of continuous measurement of every conceivable variable necessitates every discovery to begin with an imaginative preconception of what the truth may be, therefore process-inference requires Kantian thought experiments where logical judgement is made on the basis of circumstantial evidence or a priori knowledge, upon which to base further experimental observation and hypothesis testing. A phenomenological approach is a type of data analysis which tries to reveal the observed modes of behaviour that occurred during measurements (e.g., Southgate et al., 2003). Behavioural models employ a phenomenological approach to explore the possibility of accounting for minimal process-knowledge whilst replicating observations, describing general behaviour with simple numerical expressions and system rules without detailing the minutiae of the underlying physical processes. Simplicity is a key element, and is the pragmatic realisation of the inadequacy of fully-deterministic methods in modelling highly nonlinear complex systems. Behavioural models may find efficacy in guiding our thoughts on the mutual existence of various sediment patterns and morphological forms: we recommend this method to explore the idea of bedform surrogacy within a morpho-sedimentary-dynamical system. The behavioural approach (primarily using cellular automata and lattice-gas simulations) has been used to model and test theories to replicate and account for the behaviour of complex coastal morphologies, for example ripples (e.g., Pannell et al., 2002); cusps (e.g., Werner and Fink, 1993; Coco et al., 2003, 2004); crenulated and transverse bars (e.g., Falques et al., 2000; Caballeria et al., 2002); and intertidal bars (Masselink, 2004). Elsewhere is geomorphology, such a conceptual modelling approach has been employed to study, for example, braided streams (e.g., Murray and Paola, 1996) and aeolian dunes (e.g., Werner, 1995), encapsulating the physics of a system without detailing precise explanations of each individual component and their interactions with every other, useful for the exploration of ideas (e.g., Plant et al., 2001), and to generate simple expressions for complex sediment pathways and testable ideas for further research.

7.2. Probabilistic analysis

Sediment sorting is inherently episodic and probabilistic, and dominated by time-lagged variables. Sediment mechanics, morphological configurations and process chronologies within morpho-sedimentary-dynamic feedbacks may be difficult to account for, since new sedimentary structures and morphological architectures arise through the variation and recombination of antecedent ones. Signature retention quickly fades as sediments are continually redistributed. Methods of data analysis such as linear regression and spectral analysis may not be able to detect overall trends between morphological, sedimentological and hydrodynamic change. A sequence is stochastic if it can be characterized only by its statistical properties, i.e. it does not contain truly periodic components. Such systems are commonly analysed using time-series analysis based on the continuous spectrum or spectral density function of sequences. However, this is just one way of analysing a morphodynamic system: variance apportioned into frequency bands within a continuous spectrum is equivalent to a continuous probability distribution, where the features of time-series, such as ensembles, stationarity, homogeneity, and ergodicity, all have analogues within the probabilistic realm. The use of non-standard time-series analysis, using principles and techniques from probability theory, may be employed to define the statistical and stochastic properties of a morpho-sedimentary-dynamic system, using a family of statistical techniques focussing on system 'memory' or 'inheritance', and the distributional form of a variety of measured and derived variables. If there is a statistical tendency for certain states to be preferentially followed by others then there is a certain amount of conditional dependency of any given state on the previous state. A sequential approach has enormous potential for characterising the nature of morpho-sedimentary-dynamics, especially where information on the importance of antecedence and process chronologies (e.g., Southgate, 1995) is limited.

One common approach to deal with complex sequential information is the state- (phase-) plot, whereby an indicator of system state at time t is compared with that at time $t+1$. Such analysis may produce hysteresis loops, indicative of multiple dependent variables which force the independent variable under scrutiny (e.g., Murray and Paola, 1996; Sapozhinkov et al., 1998) in a relationship whereby state-pathways through time do not repeat. The dependent and independent variables must be assumed beforehand. However, in a morphodynamic or morpho-sedimentary-dynamic system, it is often unclear how to define independent and dependent variables beyond boundary conditions, because of process-interactions and feedbacks. The probabilistic statistics developed to quantify economic diminishing returns may be useful to model the threshold quantities (or fine/coarse availability ratio) required for the morphologies of truncated development through sediment unavailability. The use of sequential (probabilistic) statistics, which characterise the nature of systems through the probabilities of state-transition, may find particular use because, importantly, one need not specify what the independent variables are. Rather, we can test what the independent or dependent variables are, in an exploratory sense.

Carter and Orford (1991) explored the notion of assigning probabilities to the casual felicity of individual sediment transport events on a gravel beach, for example the acceptance or rejection of particles into background material, the nature of vectorial dispersion, and the spatio-temporal coordinates of grain size distributions. A transition probability is one kind of conditional probability, specifically one of target and given events occurring at different times (i.e., the probability that, given a type of 'state' has just occurred, there will be a type of 'fate' after a specified length of time). Transition probabilities can be very powerful in dynamic systems where sequences of events are important, acting as conditional probabilities through time-lags: simple probabilities may indicate no differences because different events may nonetheless be sequenced differently, which may or may not have bearing on the evolutionary trajectory of the system as a whole. Models built around transitional probabilities are known as Markov chains. Markov chains deal with sequences of information, specifically with transitions from one 'state' to another. Movement from one state to another may be within a spatial or temporal domain. The 'Markov property' is one where the future state depends only on the present state and not the past history, and in effect is a measure of system 'memory' (i.e., a system where statistical dependency exists between states and their immediate predecessor but not any state before that). A Markov chain is a conceptual and quantitative device for analysing and describing the nature of changes generated by movement and flux, by describing and modelling state successions (e.g., Anderson and Goodman, 1957; Bishop et al., 1975). Markov chains are an established technique in the earth sciences (e.g., Krumbein, 1968; Dacey and Lerman, 1983); ecology (e.g., Gibson et al., 1997; Hill et al., 2002); soil science (e.g., Li et al., 1997, 1999); shelf oceanography (e.g., Thompson et al., 2002); and fluid mechanics (e.g., Kirkbride and Ferguson, 1995; Wu and Yang, 2004).

8. Conclusion

The dominant themes and specific nature of gravel beach hydrodynamics, sediment transport and morphological change have been summarized and discussed. The spatial segregation of sediments through sorting mechanisms, and the natural propensity for morphological and textural pattern formation, mediated through a granular 'like-seek-like' principle, appears fundamental in our understanding of gravel beach dynamics. The organisation of gravel sediments into sediment-'structures' which have congregated by means of similar responses to the same forcing conditions, or a certain amount of hydraulic equivalence, may contain system 'memory', which, if detectable and quantifiable, would be crucial for our understanding of the geophysics of potential morphodynamical time-lags and phase-shifts. Antecedent sedimentary characteristics and structures may provide the conditions of prearrangement or 'templates' upon which successive states have derivation. Indeed, the potential importance of successional properties in both hydrodynamic and morpho-sedimentary properties of gravel beaches in their morphodynamics would suggest that sequential statistics based on chronologies and state transitions may be particularly applicable, especially since gravel beach dynamics are relatively poorly understood. The notion of bedform 'surrogacy' is introduced, whereby it is suggested that the absence of coherent nearshore morphological forms such as bars may be because these features, common on sandy beaches, draw parallel with the creation of mosaics of texture, and morphological forms which show acute dependence on the spatial and temporal selectively of sediment transport on the gravel beach. Implicatively, every feature found on a sand beach may have a gravel analogue. Finally, a conceptual framework is suggested, 'morpho-sedimentary-dynamics', to encapsulate these ideas. Understanding gravel beach morpho-sedimentary-dynamics, by exploring the largely unsubstantiated ideas presented here, requires a resolute experimental effort. We confidently predict that future field experimentation will highlight the importance of beach step dynamics in the morpho-sedimentary-dynamics of gravel foreshores.

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References

Anderson, T.W., Goodman, L.A., 1957. Statistical inference about Markov chains. Ann. Math. Stat. 28, 89–110.

Anthony, E.J., 2002. Long-term marine bedload segregation, and sandy versus gravely Holocene shorelines in the eastern English Channel. Mar. Geol. 187, 221–234.

Austin, M.J., Masselink, G., 2005. Infiltration and exfiltration in the swash zone of a steep gravel beach. Implications for morphological change. Coastal Dynamics '05, Barcelona.

Austin, M.J., Masselink, G., 2006. Observations of morphological change sediment transport on a steep gravel beach. Mar. Geol. 229, 59–77.

Bagnold, R.A., 1940. Beach formation; some model-experiments in a wave tank. J. Inst. Civ. Eng. 15, 27–52.

Bagnold, R.A., 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proc. R. Soc. Lond., A 225, 49–63.

Bailard, J.A., 1981. An energetics total load sediment transport model for a plane sloping beach. J. Geophys. Res. 86, 10,938–10,964.

Baldock, T.E., Holmes, P., 1999. Simulation and prediction of swash oscillations on a steep beach. Coast. Eng. 36, 219–242.

Baldock, T.E., Hughes, M.G., 2006. Field observations of instantaneous water slopes and horizontal pressure gradients in the swash zone. Cont. Shelf Res. 26, 574–588.

Baldock, T.E., Holmes, P., Horn, D.P., 1997. Low frequency swash motion induced by wave grouping. Coast. Eng. 32, 866–874.

Baldock, T.E., Baird, A.J., Horn, D.P., Mason, T., 2001. Measurements and modelling of swash-induced pressure gradients in the surface layers of a sand beach. J. Geophys. Res. 106 (C2), 2653–2666.

Baldock, T.E., Tomkins, M.R., Nielsen, P., Hughes, M.G., 2004. Settling velocity of sediments at high concentrations. Coast. Eng. 51, 91–100.

Bauer, B.O., Allen, J.R., 1995. Beach steps: an evolutionary perspective. Mar. Geol. 123, 143–166.

Bird, E.C.F., 1996. Lateral grading of beach sediments: a commentary. J. Coast. Res. 12 (3), 774–785.

Bishop, Y.M.M., Fienberg, S.E., Holland, P.W., 1975. Discrete Multivariate Analysis: Theory and Practice. The MIT Press, Cambridge, Mass.

Blanco, B., 2002. Experiments on gravel and mixed beaches: experimental procedure and data documentation. HR Wallingford Report TR, vol. 130.

Blewett, J.C., Holmes, P., Horn, D.P., 2000. Swash hydrodynamics on sand and shingle beaches. Proc. 27th Int. Conf. Coast. Eng. (ASCE), New York, pp. 597–609.

Bluck, B., 1967. Sedimentation of beach gravels: examples from South Wales. J. Sediment. Petrol. 37 (1), 128–156.

Bluck, B., 1999. Clast assembling, bed forms and structure in gravel beaches. Trans. Royal Soc. Edin: Earth Sci. 89, 291–323.

Bowen, 1980. Simple models of nearshore sedimentation: beach profiles and longshore bars. Geological Survey of Canada Paper, vol. 80–100, pp. 1–11. S.B.McCann.

Butler, J.B., Lane, S.N., Chandler, J.H., 2001. Automated extraction of grain size data from gravel surfaces using digital image processing for hydraulic research. J. Hydraul. Res. 39, 1–11.

Butt, T., Russell, P., 2000. Hydrodynamics and cross-shore sediment transport in the swash zone of natural beaches: a review. J. Coast. Res. 16 (2), 255–268.

Butt, T., Russell, P., Turner, I., 2001. The influence of swash infiltration–exfiltration on beach face sediment transport: onshore or offshore? Coast. Eng. 42, 35–52.

Butt, T., Russell, P., Puleo, J., Miles, J., Masselink, G., 2004. The influence of bore turbulence on sediment transport in the swash zone and inner surf zone. Cont. Shelf Res. 24, 757–771.

Caballeria, M., Coco, G., Falques, A., Huntley, D.A., 2002. Self-organisation mechanisms for the formation of nearshore crescentic and transverse bars. J. Fluid Mech. 465, 379–410.

Camenen, B., Larroude, P., 2003. Comparison of sediment transport formulae for the coastal environment. Coast. Eng. 48, 111–132.

Carbonneau, P.E., Bergeron, N.E., Lane, S.N., 2005. Texture based image segmentation applied to the quantification of superficial sand in salmonid river gravels. Earth Surf. Process. Landf. 30, 121–127.

Carr, A.P., 1969. Size grading along a pebble beach; chesil beach, England. J. Sediment. Res. 39, 297–311.

Carr, A.P., 1971. Experiments on longshore transport and sorting of pebbles: Chesil Beach, England. J. Sediment. Petrol. 41, 1084–1104.

Carter, R.W.G., 1988. Coastal Environments. Academic Press, London.

Carter, R.W.G., Orford, J.D., 1984. Coarse clastic barrier beaches: a discussion of the distinctive dynamic and morphosedimentary characteristics. Mar. Geol. 60, 377–389.

Carter, R.W.G., Orford, J.D., 1991. The sedimentary organisation and behaviour of drift-aligned gravel barriers. Coastal Sediments '91. ASCE, pp. 934–948.
Carter, R.W.G., Orford, J.D., 1993. The morphodynamics of coarse clastic beaches and barriers: a short term and long term perspective. J. Coast. Res. SI 15, 158–179.
Chadwick, A.J., Karunarathna, H., Gehrels, W.R., Massey, A.C., O'Brien, D., Dales, D., 2005. A new analysis of the Slapton barrier beach system, UK. Mar. Eng. 158, 147–161.
Clarke, S., Damgaard, J., 2002. Applications of a numerical model of swash zone flow on gravel beaches. Coast. Eng. ASCE.
Clarke, S., Dodd, N., Damgaard, J., 2003. Modeling flow in and above a porous beach. J. Waterw. Port Coast. Ocean Eng. 130 (5), 223–233.
Clifton, H.E., 1969. Beach lamination: nature and origin. Mar. Geol. 7, 553–559.
Coco, G., O'Hare, T., Huntley, D., 1999. Beach cusps: a comparison of data and theories for their formation. J. Coast. Res. 15, 741–749.
Coco, G., Huntley, D.A., O'Hare, T.J., 2001. Regularity and randomness in the formation of beach cusps. Mar. Geol. 178, 1–9.
Coco, G., Burnet, B.T., Werner, B.T, Elgar, S., 2003. Test of a self-organisation model for beach cusp development. J. Geophys. Res. 105, 21991–22002.
Coco, G., Burnet, B.T., Werner, B.T., 2004. The role of tides in beach cusp development. J. Geophys. Res. 109 (C04011). doi:10.1029/2003JC002154.
Cooper, J.A.G., Jackson, D.W.T., Navas, F., McKenna, J., Malvarez, G., 2004. Identifying storm impacts on an embayed, high-energy coastline: examples from western Ireland. Mar. Geol. 210 (1–4), 261–280.
Cornaglia, P. (1877) On Beaches, in Horn, D.P. (1992).
Dacey, M.F., Lerman, A., 1983. Sediment growth and aging as Markov chains. J. Geol. 91, 573–590.
Dodd, N., Blondeaux, P., Calvete, D., De Swart, H.E., Falques, A.G., Vittori, G., 2003. Understanding coastal morphodynamics using stability methods. J. Coast. Res. 19, 849–865.
Drake, T.G., Calantoni, J., 2001. Discrete particle model for sheet flow sediment transport in the nearshore. J. Geophys. Res. 106, 19859–19868.
Duncan, J.R., 1964. The effects of water table and tidal cycle on swash–backwash sediment distribution and beach profile development. Mar. Geol. 2, 186–197.
Elfrink, B., Baldock, T., 2002. Hydrodynamics and sediment transport in the swash zone: a review and perspectives. Coast. Eng. 45, 149–167.
Eriksen, N.J., 1970. Measurement of tide induced change to water table profiles in coarse and fine sand beaches along Pegasus Bay, Canterbury. Earth Sci. J. 4 (1), 24–31.
Erikson, L., Larson, M., Hanson, H., 2005. Prediction of swash motion and run-up including the effects of swash interaction. Coast. Eng. 52, 285–302.
Evans, O.F., 1939. Sorting and transportation of material in the swash and backwash. J. Sediment. Petrol. 9 (1), 28–31.
Falques, A., Coco, G., Huntley, D.A., 2000. A mechanism for the generation of wave-driven rhythmic patterns in the surf zone. J. Geophys. Res. 105, 24071–24088.
Felton, E.A., Crook, K.A.W., Keating, B.H., 2000. The Hulopoe Gravel, Lanai, Hawaii: New sedimentological data and their bearing on the Giant Wave (Mega-Tsunami) Emplacement Hypothesis. Pure Appl. Geophys. 157, 1257–1284.
Flemming, N.C., 1964. Tank experiments on the sorting of beach material during cusp formation. J. Sediment. Petrol. 34, 112–122.
Gao, S., Collins, M., 1992. Net sediment transport patterns inferred from grain-size trends, based upon definition of 'transport vectors'. Mar. Geol. 80, 47–60.
Gibson, D.J., Ely, J.S., Looney, P.B., 1997. A Markovian approach to modelling succession on a coastal barrier island following beach nourishment. J. Coast. Res. 13, 831–841.
Graham, D.J., Rice, S.P., Reid, I., 2005. A transferable method for the automated grain sizing of river gravels. Water Resour. Res. 41, W07020. doi:10.1029/2004WR003868.
Guza, R.T., Inman, D.L., 1975. Edge waves and beach cusps. J. Geophys. Res. 80, 2997–3012.
Hill, F.S., Witman, J.D., Caswell, H., 2002. Spatio-temporal variation in Markov chain models of subtidal community succession. Ecol. Lett. 5, 665–675.
Holland, K.T., Puleo, J.A., 2001. Variable swash motions associated with foreshore profile change. J. Geophys. Res. 106 (C3), 4613–4623.
Holmes, P., Horn, D., Blewett, J., Blanco, B., Peel-Yates, T., Shanehsaz-zadeh, A., 2002. Hydraulic gradients and bed level changes in the swash zone on sand and gravel beaches. 28th ICCE, Cardiff. ACSE, New York.
Horn, D.P., 1992. A review and experimental assessment of equilibrium grain size and the ideal wave-graded profile. Mar. Geol. 108, 161–174.
Horn, D.P., 2002. Beach groundwater dynamics. Geomorphology 48, 121–146.
Horn, D.P., Li, L., Holmes, P., 2003. Measurement and modelling of gravel beach groundwater response to wave run-up. Coastal Sediments '03. ASCE, New York.
Hughes, M.G., 1992. Application of a non-linear shallow water theory to swash following bore collapse on a sandy beach. J. Coast. Res. 8, 562–578.
Hughes, M.G., 1995. Friction factors for wave uprush. J. Coast. Res. 11 (4), 1089–1098.
Hughes, M.G., Baldock, T.E., 2004. Eulerian flow velocities in the swash zone: field data and model predictions. J. Geophys. Res.–Oceans 109 (C8) (art. no. C08009).
Hughes, M.G., Cowell, P.J., 1987. Adjustment of reflective beaches to waves. J. Coast. Res. 3 (2), 153–167.
Huntley, D.A., Bowen, A.J., 1975a. Field observation of edge waves and their effect on beach material. J. Geol. Soc. (London) 131, 69–81.
Huntley, D.A., Bowen, A.J., 1975b. Comparison of the hydrodynamics of steep and shallow beaches. In: Hails, J., Carr, A. (Eds.), Nearshore Sediment Dynamics and Sedimentation. Wiley, London, pp. 69–109.
Illenberger, W.K., 1991. Pebble shape (and size!). J. Sediment. Petrol. 61 (5), 756–767.
Inman, D.L., Guza, R.T., 1982. The origin of swash cusps on beaches. Mar. Geol. 49, 133–148.
Inman, D.L., Ewing, G.C., Corliss, J.B., 1966. Coastal sand dunes of Guerro Negro, Baja California, Mexico. Bull. Geol. Soc. Am. 77, 787–802.
Isla, F.I., 1993. Overpassing and armouring phenomena on gravel beaches. Mar. Geol. 110, 369–376.
Isla, F.I., Bujalesky, G.G., 2000. Cannibalisation of Holocene gravel beach-ridge plains, northern Tierra del Fuego, Argentina. Mar. Geol. 170, 105–122.
Isla, F.I., Bujalesky, G.G., 2005. Groundwater dynamics on macrotidal gravel beaches of Tierra del Fuego, Argentina. J. Coast. Res. 21 (1), 65–72.
Ivamy, M.C., Kench, P.S., 2006. Hydrodynamics and morphological adjustment of a mixed sand and gravel beach, Torere, Bay of Plenty, New Zealand. Mar. Geol. 228, 137–152.

Jackson, N.L., Nordstrom, K.F., 1993. Depth of activation of sediment by plunging breakers on a steep sand beach. Mar. Geol. 115, 143–151.

Jackson, N., Masselink, G., Nordstrom, K.F., 2004. The role of bore collapse and local shear stresses on the spatial distribution of sediment load in the uprush of an intermediate-state beach. Mar. Geol. 203, 109–118.

Jennings, R., Shulmeister, J., 2002. A field based classification scheme for gravel beaches. Mar. Geol. 186, 211–228.

Johnston, M.R., 2001. Nelson Boulder Bank, New Zealand. N.Z. J. Geol. Geophys. 44, 79–88.

Kemp, P.H., 1975. Wave asymmetry in the nearshore zone and breaker area. In: Hails, J., Carr, A. (Eds.), Nearshore Sediment Dynamics and Sedimentation. Wiley, London, pp. 47–67.

King, C.A.M., 1972. Beaches and Coasts. Arnold, London.

Kingston, K.S., Ruessink, B.G., Van Enckevort, I.M.J., Davidson, M.A., 2000. Artificial neural network correction of remotely sensed sandbar location. Mar. Geol. 169, 137–160.

Kirk, R.M., 1980. Mixed sand and gravel beaches: morphology, processes and sediments. Prog. Phys. Geogr. 4, 189–210.

Kirkbride, A., Ferguson, R., 1995. Turbulent flow structure in a gravel-bed river: Markov chain analysis of the fluctuating velocity profile. Earth Surf. Process. Landf. 20, 721–733.

Komar, P.D., 1998. Beach Processes and Sedimentation. Prentice Hall, NJ.

Krumbein, W.C., 1968. Statistical models in sedimentology. Sedimentology 10, 7–23.

Krumbein, W.C., Monk, G.D., 1943. Permeability as a function of the size parameters of unconsolidated sand. Trans. Am. Inst. Min. Metall. Eng.;
Bear, J. (Ed.), 1972. Dynamics of Fluids in Porous Media. Elsevier, New York. 764 pp.

Kuenen, Ph.H., 1948. The formation of beach cusps. J. Geol. 56, 34–40.

Kulkarni, C.D., Levoy, F., Monfort, O., Miles, J., 2004. Morphological variations of a mixed sediment beachface (Teignmouth, UK). Cont. Shelf Res. 24, 1203–1218.

Lara, J.L., Losada, I.J., Cowen, E.A., 2002. Large scale turbulence structures over an immobile gravel-bed inside the surf zone. Proc. Coast. Eng. 2002. ASCE, pp. 1050–1061.

Larson, M., Sunamura, T., 1993. Laboratory experiments on flow characteristics at a beach step. J. Sediment. Petrol. 63 (3), 495–500.

Lawrence, J., Karunarathna, H., Chadwick, A., Fleming, C., 2002. Cross-shore sediment transport on mixed and coarse grain sized beaches: modeling and measurements. Proc. Coastal Eng. 2002. ASCE, New York, pp. 2565–2577.

Le Roux, J.P., 2002. Shape entropy and settling velocity of natural grains. J. Sediment. Res. 72 (3), 363–366.

Li, W., Li, B., Shi, Y., Tang, D., 1997. Application of Markov chain theory to describe spatial distribution of textural layers. Soil Sci. 162, 672–683.

Li, W., Li, B., Shi, Y., 1999. Markov chain simulation of soil textural profiles. Geoderma 92, 37–53.

Longo, S., Petti, M., Losada, I.J., 2002. Turbulence in the swash and surf zones: a review. Coast. Eng. 45, 129–147.

Longuet-Higgins, M.S., Parkin, D.W., 1962. Sea waves and beach cusps. Geogr. J. 128, 194–201.

Lorang, M., 2000. Predicting threshold entrainment mass for a boulder beach J. Coast. Res. 16, 432–445.

Lorang, M., 2002. Predicting the crest height of a gravel beach. Geomorphology 48, 87–101.

Mase, H., 1988. Spectral characteristics of random wave run-up. Coast. Eng. 12, 175–189.

Mase, H., 1995. Frequency downshift of swash oscillations compared to incident waves. J. Hydraul. Res. 33 (3), 397–411.

Mason, T., Coates, T.T., 2001. Sediment transport processes on mixed beaches: a review for shoreline management. J. Coast. Res. 17 (3), 645–657.

Masselink, G., 2004. Formation and evolution of multiple bars on macrotidal beaches: application of a morphodynamic model. Coast. Eng. 51, 713–730.

Masselink, G., Hughes, M.G., 1998. Field investigation of sediment transport in the swash zone. Cont. Shelf Res. 18, 1179–1199.

Masselink, G., Li, L., 2001. The role of swash infiltration in determining the beachface gradient: a numerical study. Mar. Geol. 176, 139–156.

Masselink, G., Pattiaratchi, C.B., 1998a. Morphological evolution of beach cusp morphology and associated swash circulation patterns. Mar. Geol. 146, 93–113.

Masselink, G., Pattiaratchi, C.B., 1998b. Morphodynamic impact of sea breeze activity on a beach with beach cusp morphology. J. Coast. Res. 14 (2), 393–406.

Masselink, G., Puleo, J., 2006. Swash zone morphodynamics. Cont. Shelf Res. 26, 661–680.

Masselink, G., Hegge, B.J., Pattiaratchi, C.B., 1997. Beach cusp morphodynamics. Earth Surf. Process. Landf. 22, 1139–1155.

Masselink, G., Russell, P., Coco, G., Huntley, D.A., 2004. Test of edge wave forcing during formation of rhythmic beach morphology. J. Geophys. Res. 109 (C06003). doi:10.1029/20004JC002339.

Matsunaga, N., Honji, H., 1980. The backwash vortex. J. Fluid Mech. 99 (4), 813–815.

Matsunaga, N., Honji, H., 1983. The steady and unsteady backwash vortices. J. Fluid Mech. 135, 189–197.

McLaren, P., Bowles, D., 1985. The effects of sediment transport on grain size distributions. J. Sediment. Petrol. 55 (4), 0457–0470.

Miller, R.L., Ziegler, J.M., 1958. A model relating dynamics and sediment pattern in equilibrium in the region of shoaling waves, breaker zone, foreshore. J. Geol. 66, 417–441.

Miles, J.R., Russell, P.E., 2004. Dynamics of a reflective beach with a low tide terrace. Cont. Shelf Res. 24, 1219–1247.

Moss, A.J., 1962. The physical nature of common sandy and pebbly deposits: Part I. Am. J. Sci. 260, 337–373.

Moss, A.J., 1963. The physical nature of common sandy and pebbly deposits: Part II. Am. J. Sci. 261, 197–243.

Murray, A.B., Paola, C., 1996. A new quantitative test of Geomorphologic models, applied to a model of braided streams. Water Resour. Res. 32, 2579–2587.

Nielsen, P., 2002. Shear stress and sediment transport calculations for swash zone modelling. Coast. Eng. 45, 53–60.

Nolan, T.J., Kirk, R.M., Shulmeister, J., 1999. Beach cusp morphology on sand and mixed sand and gravel beaches, South Island, New Zealand. Mar. Geol. 157, 185–198.

Novak, I.D., 1972. Swash zone competency of gravel sized sediment. Mar. Geol. 13, 335–345.

Orford, J.D., 1975. Discrimination of particle zonation on a pebble beach. Sedimentology 22, 441–463.

Orford, J.D., 1977. A proposed mechanism for storm beach sedimentation. Earth Surf. Process. Landf. 2, 381–400.

Orford, J.D., Forbes, D.L., Jennings, S.C., 2002. Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. Geomorphology 48, 51–85.

Orford, J.D., Jennings, S.C., Pethick, J., 2003. Extreme storm effect on gravel-dominated barriers. Coastal Sediments '03. In: Davis, R.A. (Ed.), Proceedings of the International Conference on Coastal Sediments, 2003.

Pannell, M.A., O'Hare, T.J., Huntley, D.A., 2002. Modelling of sand ripple development by self-organization in unsteady flow conditions. Proc. 28th Int. Conf. on Coastal Eng., Cardiff. ASCE, New York, pp. 2837–2849.

Petrov, V.A., 1989. The differentiation of material on gravel beaches. Okeanologiya 29 (2), 279–284.

Pedrozo-Acuna, A., Simmonds, D., Otta, A.K., Chadwick, A.J., 2006. On the cross-shore profile change of gravel beaches. Coast. Eng. 53, 335–347.

Peregrine, D.H., 1966. Calculations of the development of an undular bore. J. Fluid Mech. 25, 321–330.

Peregrine, D.H., Wiliams, S.M., 2001. Swash overtopping a truncated plane beach. J. Fluid Mech. 440, 391–399.

Philips, J.D., 2003. Sources of nonlinearity and complexity in geomorphic systems. Prog. Phys. Geogr. 27 (1), 1–23.

Plant, N.G., Ruessink, B.G., Wijnberg, K.M., 2001. Morphologic properties derived from a simple cross-shore sediment transport model. J. Geophys. Res. 106 (C1), 945–958.

Pontee, N.I., Pye, K., Blott, S.J., 2004. Morphodynamic behaviour and sedimentary variation of mixed sand and gravel beaches, Suffolk, UK. J. Coast. Res. 20 (1), 256–276.

Powell, K.A., 1990. Predicting Short Term Profile Response for Shingle Beaches. Hydraulics Research Limited, Wallingford, Oxfordshire.

Pritchard, D., Hogg, A.J., 2005. On the transport of suspended sediment by a swash event on a plane beach. Coast. Eng. 52, 1–23.

Puleo, J.A., Holland, K.T., 2001. Estimating swash zone friction coefficients on a sandy beach. Coast. Eng. 43 (1), 25–40.

Rittenhouse, G., 1943. Transportation and deposition of heavy minerals. Bull. Geol. Soc. Am. 57, 651–674.

Rubin, D.M., 2004. A simple autocorrelation algorithm for determining grain size from digital images of sediment. J. Sediment. Res. 74, 160–165.

Sallenger, A.H., 1979. Beach cusp formation. Mar. Geol. 29, 23–37.

Sanders, D., 2000. Rocky Shore-gravelly beach transition, and storm/post-storm changes of a Holocene Gravelly Beach (Kos Island, Aegean Sea): stratigraphic significance. Facies 42, 44–47.

Sapozhinkov, V.B., Murray, A.B., Paola, C., Foufoula-Georgiou, E., 1998. Validation of braided-stream models: spatial state-space plots, self-affine scaling, and island shapes. Water Resour. Res. 34, 2353–2364.

Savage, S.B., 1984. The mechanics of rapid granular flow. Adv. Appl. Mech. 24, 289–366.

Seminara, G., 1998. Stability and morphodynamics. Meccanica 33, 59–99.

Sharp, W.E., Fan, P., 1963. A sorting index. J. Geol. 71, 76–84.

Shen, M., Meyer, R.E., 1963. Climb of a bore on a beach. J. Fluid Mech. 16, 108–125 (Part 3: run-up).

Sherman, D.J., Nordstrom, 1985. Beach scarps. Z. Geomorphol. NF. 29, 139–152.

Sherman, D.J., Orford, J.D., Carter, R.W.G., 1993. Development of cusp-related, gravel size and shape facies at Malin Head, Ireland. Sedimentology 40, 1139–1152.

Short, A.D., 1984. Temporal change in beach type resulting from a change in grain size. Search 15 (7–8), 228–230.

Soulsby, R., 1997. Dynamics of marine sands. HR Wallingford, Thomas Telford.

Southgate, H.N., 1995. The effects of wave chronology on medium and long term coastal morphology. Coast. Eng. 26, 251–270.

Southgate, H.N., Wijnberg, K.M., Larson, M., Capobianco, M., Jansen, H., 2003. Analysis of field data of coastal morphological evolution over yearly and decadal timescales: Part 2. Non-linear techniques. J. Coast. Res. 19 (4), 776–789.

Stive, M.J.F., DeVriend, H.J., 1995. Modelling shoreface profile evolution. Mar. Geol. 126, 235–248.

Sunamura, T., 1984. Quantitative predictions of beach-face slopes. Geol. Soc. Amer. Bull. 95, 242–245.

Sunamura, T., Aoki, H., 2000. A field experiment of cusp formation on a coarse clastic beach using a suspended video-camera system. Earth Surf. Process. Landf. 25, 329–333.

Takeda, I., Sunamara, T., 1983. A wave flume experiment of beach steps. Annual Report of the Institute of Geoscience, University of Tsukuba, vol. 9, pp. 45–48.

Thaxton, C.S., Calantoni, J., Drake, T.G., 2001. Can a single representative grain size describe bed load transport in the surf zone? EOS Trans., vol. 82 (47), p. 587 (AGU Fall Meeting).

Thompson, K.R., Dowd, M., Shen, Y., Greenberg, D.A., 2002. Probabilistic characterisation of tidal mixing in a coastal embayment: a Markov chain approach. Cont. Shelf Res. 22, 1603–1614.

Thorne, P.D., 1986. An intercomparison between visual and acoustic detection of seabed gravel movement. Mar. Geol. 72, 11–31.

Turner, I.L., Masselink, G., 1998. Swash infiltration–exfiltration and sediment transport. J. Geophys. Res. 103 (C13), 30813–30824.

VanWellen, E., Chadwick, A.J., Mason, T., 2000. A review and assessment of longshore sediment transport equations for coarse-grained beaches. Coast. Eng. 40, 243–275.

Verdu, J.M., Batalla, R.J., Martinez-Casanovas, J.A., 2005. High resolution grain size characterisation of gravel bars using imagery analysis and geo-statistics. Geomorphology 72, 73–93.

Voulgaris, G., Workman, M., Collins, M.B., 1999. Measurement techniques of shingle transport in the nearshore zone. J. Coast. Res. 15 (4), 1030–1039.

Waddell, E., 1976. Swash–groundwater–beach profile interactions. In: Davis Jr., R.A., Ethington, R.L. (Eds.), Beach and Nearshore Sedimentation: Tulsa, OK, Society of Economic Paleontologists and Mineralogists Special Publication, vol. 24, pp. 115–125. 187 pp.

Werner, B.T., 1995. Eolian dunes; computer simulations and attractor interpretation. Geology 23 (12), 1107–1110.

Werner, B.T., 1999. Complexity in natural landform patterns. Science 284, 102–104.

Werner, B.T., Fink, T.M., 1993. Beach cusps as self-organised patterns. Science 260, 968–970.

Williams, A.T., 1973. The problem of beach cusp development. J. Sediment. Petrol. 43, 857–866.

Williams, A.T., Caldwell, N., 1988. Particle size and shape in pebble beach sedimentation. Mar. Geol. 82, 199–215.

Wilson, K.C., 1987. Analysis of bed load motion at high shear stress. J. Hydraul. Eng. 113 (1), 97–103.

Winkelmolen, A.M., 1982. Critical remarks on grain parameters, with special emphasis on shape. Sedimentology 29, 255–265.

Wright, L.D., Thom, B.G., 1977. Coastal depositional landforms: a morphodynamic approach. Prog. Phys. Geogr. 1, 412–459.

Wright, L.D., Chappell, J., Thom, B.G., Bradshaw, M., Cowell, P., 1979. Morphodynamics of reflective and dissipative beach and inshore systems, southeastern Australia. Mar. Geol. 32, 105–140.

Wu, F.-C., Yang, K.-H., 2004. A stochastic partial transport model for mixed-size sediment: application to assessment of fractional mobility. Water Resour. Res. 40, WO4501.

Zenkovich, V.P., 1967. In: Steers, J.A. (Ed.), Processes of Coastal Development. Oliver and Boyd, London.