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Predictions of large-scale coastal tendency: development and application of a qualitative behaviour-based methodology

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ABSTRACT

The prediction of coastal evolution is difficult due to the variety of spatial and temporal scales over which coastal changes occur, and the inter-dependence between different geomorphic features as components of the natural system. Despite these difficulties, it remains necessary to attempt to identify coastal geomorphic issues that are relevant over decades to centuries.

This paper describes the development of geomorphic tools to assist in gaining an improved understanding of coastal behaviour, based upon key controls, influences and linkages within the coastal system. These geomorphic tools are then applied to the coastline of central southern England in order to demonstrate their applicability.

ADDITIONALINDEXWORDS: *coastal evolution; geomorphology; qualitative; Futurecoast, England.*

INTRODUCTION

A comprehensive review of a series of coastal defence planning documents in England and Wales concluded that relatively little vision existed of how the coast is likely to evolve over a future timeframe of 50 to 100+ years (MAFF, 2000). In response, the UK Government initiated a research project named Futurecoast to improve understanding of the major natural influences upon evolution over the next century for the entire open coastline of England and Wales (BURGESS *et al*., 2001).

Unlike previous assessments of this coast, which focused upon contemporary hydrodynamic and sediment transport processes, the methodology adopted in the Futurecoast project involved a complementary geomorphological approach, aimed at an improved understanding of larger-scale coastal behaviour based upon key controls, influences and linkages. This approach involved the identification of different elements that make up the coastal structure and development of a qualitative understanding of how these elements interact at different spatial and temporal scales.

This paper describes the methods developed during the Futurecoast study and demonstrates their application through a case study from central southern England.

PREDICTIONS OF COASTAL EVOLUTION

Predictions (or estimates) of long-term future coastal evolutionary tendency are necessary in order to identify geomorphological issues that remain relevant beyond the design life of existing buildings or coastal defences and beyond the time horizon of existing coastal defence planning and land use planning documents. Coastal managers need to be aware of such issues now to enhance their ability to make coastal engineering and land use planning decisions that are sustainable in the long-term.

The estimation of coastal evolutionary tendency, however, is a difficult science due to the variety of spatial and temporal scales over which coastal changes occur, and the inter-dependence between different components of the coastal system.

For example, coastal change may occur within the timescale of:

- A few seconds (e.g. in response to turbulent fluctuations within a hydraulic flow);
- A few hours (e.g. during a storm or tidal cycle);
- A few months (e.g. seasonal variations in forcing climate);
- Several years to decades (e.g. in response to variations in the lunar tidal cycle);
- Decades to centuries (e.g. coastal re-orientation);
- Periods exceeding millennia (e.g. long-term coastal evolution controlled by geology).

Coastal change may also occur over a spatial scale of a hundredth of a millimetre (e.g. movement of a single mud grain) through to stretches of coast extending over several hundreds of kilometres (e.g. larger-scale coastal re-orientation).

In addition, the morphological, sedimentological and hydrodynamic elements of a coastal system coalesce in an infinite combination of frequencies and magnitudes to generate processes and coastal responses of varying, non-linear and often unpredictable natures. Furthermore, the evolution of one particular element of the coast is influenced by evolution in adjacent areas (e.g. supply of sediment from updrift, or interactions between cliff recession and beach volumes). Often these influences extend in a number of directions; thereby further complicating the task of predicting change.

These complications have previously led coastal geomorphologists to state that quantitative prediction of large-scale coastal behaviour (development of a stretch of coast some tens of kilometres in length over timescales of decades to centuries) is presently impossible (e.g. TERWINDT and BATTJES, 1990). Based upon qualitative tools described in this paper, the authors contend that it is possible to make a qualitative estimation of coastal evolutionary tendency over the next century using geomorphological interpretation and based upon understanding of the characteristic behaviour (response and inter-linkages) of landforms.

GENERIC COASTAL BEHAVIOUR

Despite the aforementioned complications, sufficient information is known about certain coastal features to enable statements to be made describing how they form and evolve. Based upon this information, it is also possible to identify theoretical responses of various coastal elements to changes in certain controlling parameters. In order to be able to state precise responses, however, it is necessary to quantify thresholds of change. This is not possible at the generic level, and remains extremely difficult at the site-specific level, due to the need for quantified data relating to all potential parameters which may influence change, and considerable historic information concerning previous coastal response to these parameters. Despite an inability to generically quantify the thresholds for change, it remains possible to generically determine relative sensitivities of different systems to changes in fundamental controlling factors. Gaining such an understanding can lead to identification of the potential for one (or more) of four generic behavioural responses: no change; net retreat; net advance; morphological change/breakdown (Table 1).

METHODOLOGY

The methodology adopted during the Futurecoast project reflected the need to study coastal evolution at a range of scales. It encapsulated the fact that initial understanding of coastal evolution must be gained at a large scale in order to determine the critical controls and influences on geomorphological evolution. For purposes of the Futurecoast study, this broad scale understanding was developed at a large scale using Coastal Behaviour Systems (CBSs): within which the sediments, morphology and forces of the offshore, nearshore, shoreline and backshore interact. Identification of CBS involved assessments of:

- Shoreline and offshore geology (e.g. lithology, sequencing, faulting and folding);
- Offshore features and their interactions with the shoreline;
- Hydrodynamic and sediment processes;
- Holocene evolution;
- Historic trends;
- Estuarine influences (e.g. tidal flushing, presence of deltas).

Within each CBS, a number of distinct smaller sections of coast can be identified whose plan-form evolution is apparently governed by these controls and influences, through a combination of different linkages. These smaller-scale units were described in the Futurecoast project as Shoreline Behaviour Units (SBUs), examples of which include:

- Embayments created by wave diffraction around headlands;
- Drift- and swash-aligned shorelines;
- Source-corridor-sink units;
- Barrier islands and tidal inlets
- Estuaries and tidal deltas.

In turn, each SBU comprises a number of geomorphological elements along its length, such as cliffs, beaches, barriers, coastal dunes, tidal flats and marshes, or shore platforms. Based upon the known differences in characteristic behaviour of different combinations of the elements, a series of Geomorphic Units (GUs) were defined.

The definition of one component (e.g. CBS, SBU or GU) of the coast is dependent upon the scale at which the coast is viewed. For example, a gravel barrier could arguably be defined as either a GU (sitting within a SBU) or as a SBU itself. In turn, the scale at which the coast is viewed depends upon the spatial and temporal extent of controls, influences and linkages. Consequently, it is not possible to be prescriptive about what constitutes a CBS, SBU or GU. Instead, it is necessary to recognise that there exists a need to consider controls, influences and linkages at large-, medium- and small-scales.

Table 1. Generic Geomorphic Response in Shoreline Position

Response	**Shoreline "State"**	**Dominant Processes and Landform Changes**	**Examples**	**Present Causative Scenarios**	**Future Causative Scenarios**
	Resistance	Landforms resistant to change due to their lithology and structure	• Hard rock cliff	• Resistance of geology > forces applied (i.e. strength of material > applied stress)	
No change	No net advance or retreat of shoreline	Cyclic changes with a balanced sediment budget	• Seasonal cut and fill cycles on a sandy beach; • Berm building and flattening on a static gravel beach.	• Sediment supply = demand	• Sediment supply < demand and reduction in forcing conditions • Sediment supply > demand and increase in forcing conditions (aggradation)
	No net advance or retreat because evolution is constrained	Static or restrained shoreline in which the landform(s) are reducing in mass and in their capacity to dissipate energy and protect the backshore.	• Erosion of debris/lowering of beach levels at a cliff base • Saltmarsh undergoing coastal squeeze due to a constraining backshore topography	• Sediment supply < demand and evolution is constrained by backshore topography / resistance	• Sediment supply = demand and increase in forcing conditions AND • Backshore constraint
Net Advance	Regression	Accreting shoreline; seaward migration of a shoreline	• Prograding saltmarsh; • Dune building resulting in the seaward movement of the shoreline; • Sediment accumulation updrift of a longshore transport "constraint" (e.g. inlet, structure, ness) or in areas exposed to low forcing conditions	• Sediment supply > demand	• Sediment supply ≤ demand and decrease in forcing conditions (erosional regression) • Sediment supply > demand (dominant process) and decrease/no change/ increase in forcing conditions (depositional regression)
Net Retreat	Transgression	Transgressing shoreline; landward migration of a shoreline which nevertheless maintains the characteristic form and function of its landforms	• Retreating cliff coast /beach-dune system; • Retreating barrier beach or spit; • Landward migrating saltmarsh or tidal flat.	• Sediment supply = demand and increase in water level OR • Sediment supply < demand and evolution is not constrained by backshore	• Sediment supply ≤ demand and increase in forcing conditions (erosional transgression) • Sediment supply > demand and (dominant) increase in forcing conditions (depositional transgression)
Break-down	Variable trend	Transient (short-lived) change towards a new characteristic form	• Reactivation of landsliding on a relic cliff or other major change in style and rate of cliff behaviour; • Breaching and/or fragmentation of a barrier or spit; • Deterioration or removal of a constraint leading to permanent tidal inundation of the backshore	• Sediment supply<<demand • Sediment supply>>demand • Significant change in sediment composition • Significant increase in forcing conditions which cannot be accommodated by existing morphology • Removal/breaching/ inundation of backshore constraint • Reduction in material shear strength due to other factors (e.g. increased groundwater pressure within a cliff, chemical pollution breaking biological cohesion in a mudflat)	• Sediment supply<<demand • Sediment supply>>demand • Significant change in sediment composition • Significant increase in forcing conditions which cannot be accommodated by existing morphology • Removal/breaching/ inundation of backshore constraint • Reduction in material shear strength due to other factors (e.g. increased groundwater pressure within a cliff, chemical pollution breaking biological cohesion in a mudflat)

Coastal Behaviour Systems

To assist with identification of CBS, key controls and linkages within the coastal zone were determined. This was followed by consideration of related geomorphological sub-features which may theoretically be expected, given certain controls and linkages. The presence or absence of these was then recognised and explained, assisting in the identification of SBUs. For example, if a hard rock headland was identified as a key control, it was likely that it would have an influence on wave energy distribution, particularly if the dominant wave approach angle was oblique to the headland. In such a case, it was expected that an embayment would form in the lee of the headland.

Shoreline Behaviour Units

Once SBUs were identified, it was necessary to concisely describe for each:

- Past evolution (both Holocene and more recent evolution);
- Controls and linkages;
- Behaviour and sensitivities; and
- Behaviour constraints.

Geomorphological interpretation of the critical elements, behaviour and sensitivity of the SBU enabled statements to be made concerning likely future tendency at the SBU scale; thereby identifying potential areas of increasing, decreasing, continuing, ceasing or commencing pressure within the SBU caused by predicted future tendencies. Such pressure often related to re-alignment of the coast at the SBU scale that was potentially influenced by:

- Changes in geological controls (e.g. emergence of headlands within eroding cliffs; recession of existing headlands; exacerbation of embayment curvature due to immaturity of development);
- Hydrodynamic forcing (e.g. wave diffraction processes around headlands);
- New hydrodynamic influences (e.g. interruption of littoral drift by newly created tidal inlets);
- Sediment transport (e.g. natural changes in the rate or direction of sediment transport);
- Changes in sediment budget (e.g. shorelines switching from drift- to swash-aligned tendencies due to exhaustion of relic sediment sources);
- Human intervention (e.g. cessation of sediment supply due to cliff protection; interruption due to the extraction of material).

Within many SBUs, this pressure first was identified as that applying to the foreshore because this often represented the link throughout the entire SBU, or a large part of the SBU. Many foreshores also acted as the primary conveyor of non-cohesive sediment transport within the SBU. Any changes in pressure to this conveyor may have resulting implications both alongshore and between the shoreline and backshore features. This, therefore, provided the primary link between behaviour at the SBU level, driven by controls and influences derived at CBS level, and response at the GU level.

An understanding of SBU behaviour and changes in pressures assisted in the conceptual qualitative estimation of future evolutionary tendency within the SBU. This conceptual exercise was undertaken using two scenarios, the first of which is presented later in the paper for a case study:

- he unconstrained "natural" response (i.e. an entirely hypothetical scenario assuming the instant removal of all anthropogenic intervention within the SBU); and
- the response resulting from constraints to the above response, as presented by continuation of present anthropogenic intervention throughout the SBU.

Geomorphic Unit Response

Mapping of supra-tidal and inter-tidal morphology, together with an understanding of lithology and topography, enabled the definition of Geomorphic Units based upon changes in the known presence of certain combinations of different geomorphological elements. For each GU, it was possible to derive generic information relating to its:

- Formation and evolution processes;
- Typical behaviour;
- Links with other GUs;
- Sensitivity; and
- Future behaviour tendency.

It was then necessary to combine this generic behaviour understanding with known detail about past behaviour and the information learned about SBU-scale pressures derived from earlier work. By taking each GU in turn, it was possible to collate the information derived from the above exercises and make descriptive comments concerning future tendencies and trends under a scenario of the anticipated "natural" response (i.e. without any management intervention within the SBU). The influence of anthropogenic constraints to this evolution was then described.

Of particular importance when assessing the possible natural response was the translation of SBU pressures to the GU response. In order to achieve this within each GU, it was usually necessary to first consider the foreshore response to SBU pressures. Foreshore response was then translated to a backshore response based upon an understanding of backshore vulnerability to foreshore changes.

The SBU pressure most often related to the foreshore sediment balance, as follows:

- A predicted increase in foreshore sediment volume;
- A predicted decrease in foreshore sediment volume; or
- No predicted change in foreshore shoreline sediment volume.

Different consequential impacts, in terms of backshore response, are associated with each of the above foreshore responses.

Feedback and Interactions

Whilst the methodology presented thus far provided a fair representation of the actual response within each GU in many cases, there remained situations where it did not. This was due to the inter-dependence between some adjacent (or even physically separated) GUs located within a SBU. For example, the rapid and large-scale re-activation of recession of sea cliffs within one GU may release significant quantities of beach-building sediment that could be transported to a downdrift GU. Such an influx of sediment at the downdrift GU may result in its accumulation and progradation of the shoreline. Depending on the quantities of sediment involved, this response could even occur in the face of a rising sea level; potentially contradicting the predicted response of the downdrift GU when considering it in isolation from this potential sediment source.

Consequently, there was a need to view the cumulative impacts and knock-on effects of the predicted SBU pressures and individual GU responses within a wider context. The obvious scale at which to achieve such a view was the SBU scale, within which the sediment audit and inter-linkages that exist between GUs was considered.

Once descriptions of future tendency were made at the GU level for the natural response scenario (i.e. without present anthropogenic intervention), a trend was identified by comparing predicted future with observed past rates or tendencies of evolution (both plan form shape and cross-shore response) and using professional judgement to identify whether there was the likelihood for:

- Continuation of past rates;
- Acceleration of past rates;
- Deceleration of past rates;
- Cessation of past rates;
- Re-commencement of past rates; and/or
- Complete change in morphological type (e.g. the breakdown of a spit or barrier and the creation of a new tidal inlet).

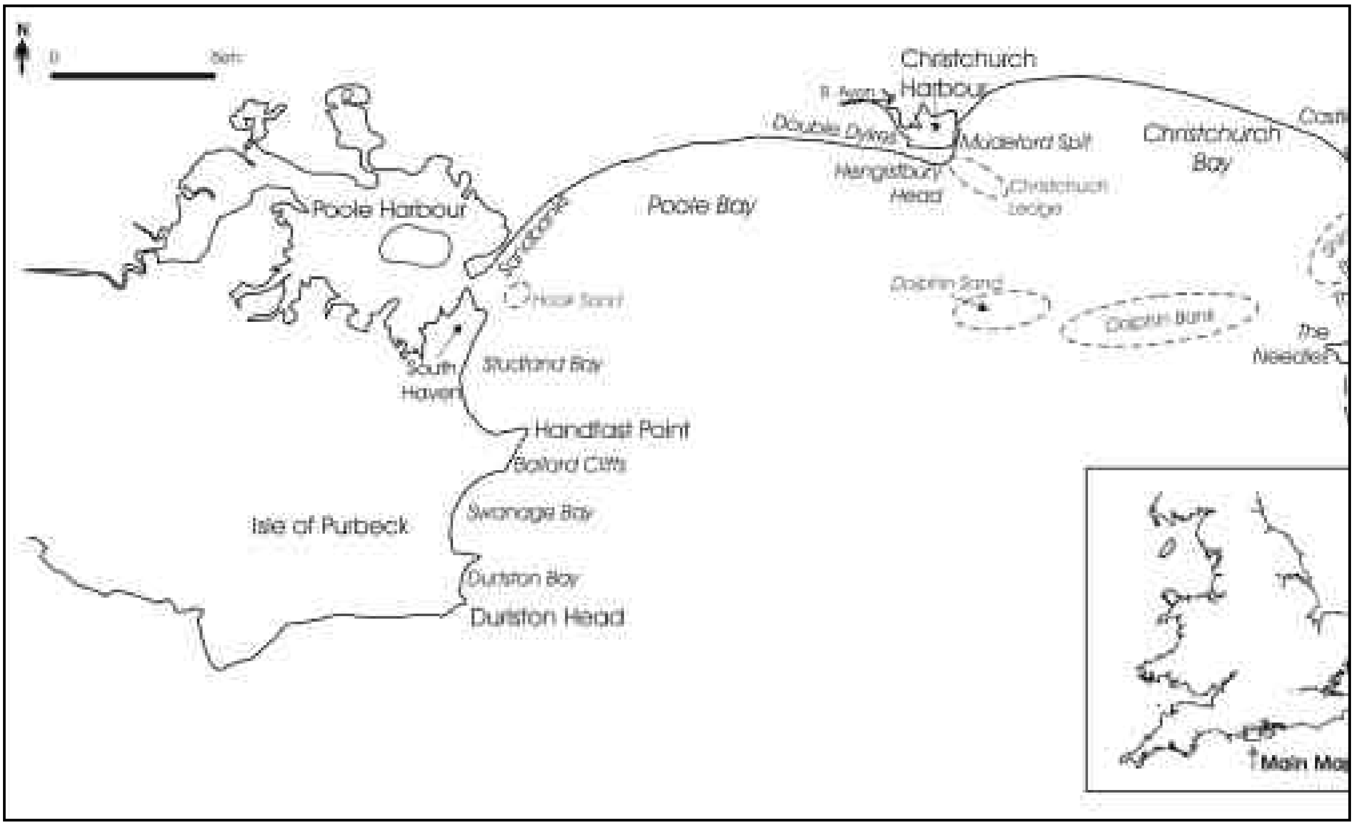

Figure 1. Case Study Area, Isle of Purbeck to Hurst Castle Spit

CASE STUDY: ISLE OF PURBECK TO HURST CASTLE SPIT

In order to demonstrate application of the methodology previously described, a case study from central southern England (Isle of Purbeck to Hurst Castle Spit: Figure 1) is presented below, using a series of numbered statements that collectively constitute the behavioural model. The case study first identifies the key controls and influences on coastal behaviour and describes the linkages that exist within the Coastal Behaviour System. It then presents the large-scale unconstrained (i.e. natural or quasi-natural) response, assuming the removal of all existing management intervention for three separate Shoreline Behaviour Units, namely:

(i) Durlston Head to Handfast Point;
(ii) Handfast Point to Hengistbury Head; and
(iii) Hengistbury Head to Hurst Castle Spit.

The sequence of statements presented below are supported by a number sources (ROBINSON, 1955; DYER, 1971; LACEY, 1985; NICHOLLS, 1985; HODDER, 1986; NICHOLLS and WEBBER, 1987; LELLIOT, 1989; MAY, 1990; BRAY *et al*., 1991; HARLOW and COOPER, 1996; HOOKE, 1998; VELEGRAKIS *et al*., 1999).

Coastal Behaviour System: Controls, Influences and Linkages

1. The Coastal Behaviour System extending between the Isle of Purbeck and Hurst Castle Spit is dominated by three major distinguishing components, each representing a Shoreline Behaviour Unit, namely: (i) the relatively hard rock headland of the Isle of Purbeck (Figure 2A); (ii) the soft Tertiary cliffs dominating the embayment of Poole Bay; and (iii) the soft Tertiary cliffs dominating the embayment of Christchurch Bay.

2. Due to the predominant eastward longshore drift, there is a degree of interconnectivity between these units.

3. Formerly, the Solent River ran eastwards through this CBS, draining into the present Solent. Its course was constrained to the south by a near-continuous Chalk ridge that once extended from Handfast Point (Isle of Purbeck) to The Needles (Isle of Wight). This ridge is believed to have occupied a relatively low and narrow profile and was dissected by initially small southward-orientated drainage channels.

4. These drainage channels progressively became exploited by rising post-glacial sea levels, resulting in the breaching of the Chalk ridge and the preferential southward flow of rivers in the Poole and Christchurch Bays catchment through the ridge rather than eastwards into the Solent.

Figure 2A). Chalk stacks and cliffs at Old Harry Rocks, Isle of Purbeck.

Figure 2B). Spits at the entrance to Christchurch Harbour

5. This led to the eventual removal of the Chalk ridge approximately 7,000 to 8,000 years ago; resulting in the separation of the Isle of Wight from the mainland, tidal inundation of the river basin, rapid erosion of soft material deposits and the establishment of the present day physical process regime.

6. During post-glacial rising sea level, coarse sand and gravel-sized sediment was transported landward from the seabed to form barriers of non-cohesive sediments (predominantly sand). With continued sea level rise, these barriers migrated further landward onto rising topography, whereupon rapid cliff recession occurred in the soft Tertiary sediments, forming the present Poole Bay and (the younger) Christchurch Bay.

7. Localised breaches of the predominantly sand barriers also led to the inundation of areas of low topography, creating Poole and Christchurch Harbours.

8. The present shape of the coastline is principally due to the presence of the Isle of Purbeck, whose general geological resistance against marine erosion has led to its development as a major headland. Modification of the predominant waves (approaching from the south-west) around the Isle of Purbeck headland has created the embayments to its east.

9. The presence of two smaller embayments between the Isle of Purbeck and Hurst Spit, rather than one larger continuous embayment, is due to the presence of Hengistbury Head, which acts as a secondary headland control.

10. Hengistbury Head provides an anchor for the development of Poole Bay and additionally a headland control on the development of Christchurch Bay. Its function as a secondary headland control within the CBS is due to the presence of ironstone nodules within its geological structure, which locally impart resistance to marine erosion.

11. These ironstone nodules were actively mined from coastal exposures and an inland quarry on Hengistbury Head during the 19th Century, resulting in its accelerated erosion. This significantly reduced the size of the headland, accelerating erosion in Christchurch Bay, although a degree of control is still exerted from seaward of the present shoreline through the presence of the nearshore Christchurch Ledge.

12. The Isle of Wight affords a degree of shelter to Christchurch Bay against waves approaching from the south and south-east (although this is not the predominant wave direction).

13. Reduction in contemporary sediment input to the CBS has occurred due to both exhaustion of the offshore Holocene sea bed supply and the artificial cliff protection throughout most of Poole Bay and much of Christchurch Bay. This has accelerated erosion of foreshore sediments and increased the need to input fresh sediment to the foreshore within many parts of the CBS through both sand and shingle replenishment activities.

14. The CBS comprises a number of depositional landforms, such as spits at the entrances to Poole and Christchurch Harbours, and Hurst Castle Spit (the latter is a feature which acts as a control on the development of the CBS to the east, by affording shelter to the tidal flat and marshes in its lee).

15. Offshore seabed sediments include the Dolphin Bank, Shingles Bank and North Head in Christchurch Bays. These features act as stores of sediment and serve to offer shelter to the shoreline against direct wave attack.

Large-scale Unconstrained Coastal Behaviour

Shoreline Behaviour Unit #1: Durlston Head to Handfast Point

1. This is principally a rocky sea cliff coastline which through differential erosion over geological timescales, has seen the formation of embayments between resistant headlands.

2. No future changes from the present behaviour are anticipated. Due to this, the principal control that this headland exerts over the development of adjacent frontages, extending eastwards to Hurst Castle Spit, will remain intact.

Shoreline Behaviour Unit #2: Handfast Point to Hengistbury Head

1. Poole Bay is a headland-controlled embayment in which natural cliff erosion from central frontages would supply sediment to beaches, with subsequent sediment transport predominantly eastwards towards, and beyond, Hengistbury Head.

2. The Bay appears to have partly re-orientated towards a greater degree of swash-alignment due to wave modification around the Isle of Purbeck. It still, however, experiences considerable drift along its length, indicating an immaturity of development.

3. This frontage exerts an influence on Christchurch Bay since a degree of sediment transport occurs around Hengistbury Head, and the presence of this headland affects wave diffraction to the east.

4. The interaction between longshore drift and tidal exchange at the entrance to Poole Harbour has created the associated spits and deltas which form an important component of the sediment transport system. These features also store volumes of material that would otherwise feed the adjacent shorelines.

5. Poole Bay is relatively young (in geological timescales) and is still adjusting, through erosion, in response to breaching of the former chalk ridge extending between the Isle of Purbeck and the Isle of Wight.

6. If a breach occurred at Double Dykes, the River Avon may change course to preferentially flow to the sea through the newly created breach. A circulatory flow may also occur through the existing Christchurch Harbour entrance and out from the newly created entrance (or vice versa). Alternatively, any new breach may be sealed relatively rapidly by material supplied from updrift sources through alongshore drift, although this will be dependent upon the volume of sediment available on the updrift beaches, or released from cliff recession.

7. The erosion of Hengistbury Head would have serious implications for both Poole Bay and Christchurch Bay. For example, one potential scenario is for the complete removal of Hengistbury Head and the creation of a larger-scale embayment between the Isle of Purbeck and Hurst Castle Spit. This scenario is unlikely to occur over the next century, however, because Hengistbury Head would, at least partly, remain and exert some degree of control. Furthermore the Christchurch Ledge would also remain and exert an influence on the downdrift frontage's evolution.

8. This would also be the case if a breach occurred at Double Dykes and the mouth of Christchurch Harbour switched position. (This would, however, result in a change in the wave penetration into Christchurch Harbour and alter its tidal regime; thereby enabling the creation of a new ebb-tide delta).

Shoreline Behaviour Unit #3: Hengistbury Head to Hurst Castle Spit

1. Christchurch Bay is a headland-controlled embayment, with material released from cliff erosion moving eastward along the shoreline to be deposited in the sink of Hurst Castle Spit and ultimately Shingles Bank.

2. The spit at Hurst historically has grown and rolled back with rising sea levels; a process that still dominates its contemporary and future development. It is, however, unlikely to completely breakdown and disappear over the next century due to the potential for increased sediment supply from eroding sea cliffs (under this unconstrained scenario) in central Poole Bay and central Christchurch Bay. Instead, the spit may breach, locally resulting in the creation of a new tidal inlet.

3. The presence of Christchurch Harbour (Figure 2B) has created the associated spits which form an important component of the sediment transport system and store volumes of material that may otherwise feed the shoreline. Mudeford spit typically experiences cycles of growth and breaching.

4. It is believed that because Christchurch Bay is relatively young in geological terms, it is still adjusting in response to breaching of the former Chalk ridge extending between the Isle of Purbeck and the Isle of Wight. Consequently, there is a tendency for continued erosion within the bay towards a more mature plan form development.

CONCLUSION

This study demonstrates that by adopting a geomorphic approach, together with a more commonly-adopted sediment transport process approach, to predicting future coastal evolution, it is possible to determine key controls and influences which govern large-scale coastal evolutionary tendency. Consideration of the linkages between different parts of the coastal system enables this large-scale behaviour to be combined with local-scale characteristics in order to describe future behavioural tendency of the coast at a range of scales. Such information is of assistance to coastal engineers and planners who must necessarily consider potential coastal changes extending beyond their conventional, short-term (in geological timescales), time horizons. The output from the Futurecoast study is being used in practice in England and Wales to contribute scientific information relating to future large-scale and long-term coastal changes in all coastal defence planning documents. This should be of assistance in ensuring that management decisions made now do not tie future generations into inappropriate, inflexible and perpetually increasingly expensive coastal defence options.

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