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Conceptualising and mapping coupled estuary, coast and inner shelf sediment systems

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ABSTRACT

Whilst understanding and predicting the effects of coastal change are primarily modelling problems, it is essential that we have appropriate conceptual frameworks for (1) the formalisation of existing knowledge; (2) the formulation of relevant scientific questions and management issues; (3) the implementation and deployment of predictive models; and (4) meaningful engagement involvement of stakeholders. Important progress continues to be made on the modelling front, but our conceptual frameworks have not evolved at a similar pace. Accordingly, this paper presents a new approach that re-engages with formal systems analysis and provides a mesoscale geomorphological context within which the coastal management challenges of the 21st century can be more effectively addressed. Coastal and Estuarine System Mapping (CESM) is founded on an ontology of landforms and human interventions that is partly inspired by the coastal tract concept and its temporal hierarchy of sediment sharing systems, but places greater emphasis on a hierarchy of spatial scales. This extends from coastal regions, through landform complexes, to landforms, the morphological adjustment of which is constrained by diverse forms of human intervention. Crucially, CESM integrates open coastal environments with estuaries and relevant portions of the inner shelf that have previously been treated separately.

In contrast to the nesting of littoral cells that has hitherto framed shoreline management planning, CESM charts a complex web of interactions, of which a sub-set of mass transfer pathways defines the sediment budget, and a multitude of human interventions constrains natural landform behaviour. Conducted within a geospatial framework, CESM constitutes a form of knowledge formalisation in which disparate sources of information (published research, imagery, mapping, raw data etc.) are generalised into usable knowledge. The resulting system maps provide a framework for the development and application of predictive models and a repository for the outputs they generate (not least, flux estimates for the major sediment system pathways). They also permit comparative analyses of the relative abundance of landforms and the multi-scale interactions between them. Finally, they articulate scientific understanding of the structure and function of complex geomorphological systems in a way that is transparent and accessible to diverse stakeholder audiences. As our models of mesoscale landform evolution increase in sophistication, CESM provides a platform for a more participatory approach to their application to coastal and estuarine management.

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1. Introduction

Coastal and estuarine landforms mediate flood and erosion risks (Sayers et al., 2002; Narayan et al., 2012; Strauss et al., 2012; Batten et al., 2015) that are projected to increase significantly with climate change (Hinkel et al., 2014). Understanding and mitigating such risks is critically dependent on our ability to model landform evolution at a scale that is consistent with the requirements of strategic shoreline management planning (Nicholls et al., 2013). Whilst, this capability is partly delivered through the application of sediment dynamics models to coastal morphodynamic problems (Roelvink and Reniers, 2012), there is an increasing shift away from essentially reductionist models towards more synthesist approaches that more explicitly resolve coastal behaviour at mesoscales measured in decades to centuries and tens to hundreds of kilometres (Murray et al., 2008; French et al., 2015). Whatever the approach taken, generic principles must be translated into models that take account of the place-specific contexts wherein contemporary processes interact with antecedent geology, historical morphology and engineering interventions, and local landform dynamics are forced by tidal, wave and sediment supply boundary conditions at broader scales. This requires that we have frameworks for (1) the formalisation of existing knowledge; (2) formulation of relevant scientific questions and management issues; (3) the implementation and

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deployment of predictive models and (4) meaningful engagement with stakeholders. Despite technical progress on the modelling front (Van Maanen et al., 2016), conceptual frameworks for the analysis of coastal systems have arguably not evolved at a similar pace to accommodate our improving understanding and the challenges of coastal and estuarine management in the 21st century (Nicholls et al., 2012).

Since the pioneering work of Bowen and Inman (1966), the concept of the sediment budget has provided an overarching framework for countless analyses of coastal change under the influence of sediment transporting processes, sediment supply and human agency. Coastal sediment budgets are generally constructed with reference to more-or-less discrete littoral cells (Inman and Frautschy, 1966) or compartments (Davies, 1974). Cells are readily defined on compartmented coasts, where littoral sediment exchange between neighbouring cells is often assumed to be minimal, such that local changes can be attributed to specific factors such as seasonality in wave climate or human intervention in natural sediment transfer pathways (Shih and Komar, 1994; Storlazzi and Field, 2000; Komar, 2010; Barnard et al., 2012). Cell boundaries are harder to identify with any degree of objectivity on more open coasts, although estuaries and known divergences or convergences in transport pathways have also been used to infer the spatial organisation of littoral drift systems (Pierce, 1969; Stapor, 1973: Bray et al., 1995). At regional to national scales, hierarchies of cells provide a geomorphological basis for management planning that has clear advantages over schemes informed primarily by administrative boundaries (Komar, 1996; Cooper and Pontee, 2006; Stul et al., 2012). In the UK, for example, national mapping of major cells and sub-cells (Motyka and Brampton, 1993) provided the basis for a first generation of Shoreline Management Plans (SMPs) for England and Wales (Cooper et al., 2002). More recently, Eliot et al. (2011) devised a three-tier hierarchy of cells along the coast of Western Australia to provide a geomorphological framework for marine and coastal planning.

As shoreline management thinking has evolved, limitations of the cell concept have become apparent. One area of concern has been that littoral cells primarily reflect short-range transfers of non-cohesive 'beach-grade' material. As such, they are not well suited to handling broader scale linkages between estuarine, coastal and offshore systems (Cooper and Pontee, 2006), especially where longer-range suspended sediment transport fluxes are known to be important (e.g. Kirby, 1987; Dyer and Moffat, 1998; Keen and Slingerland, 2006). Cooper and Pontee (2006) also highlight concerns over the criteria used to delimit littoral cells, and the stability of cell boundaries, especially under significant changes in wave climate or sediment supply. Some of these issues were addressed in the FutureCoast project (Burgess et al., 2002). This embedded littoral cells within a spatial hierarchy of geomorphological units (effectively individual landforms), shoreline behaviour units (sub-systems, such as embayments and estuaries) and regional coastal behaviour systems, defined for the entire coast of England and Wales. Within these, existing scientific research was synthesised and formalised with reference to a behavioural systems approach (Burgess et al., 2004).

More generally, the demand for a greater degree of integration between the management of coastal, estuarine and offshore zones invites reappraisal of the role of the littoral cell and the potential for its incorporation into improved conceptual schemes capable of broader application at multiple scales. The concept of the coastal tract (Cowell et al., 2003a) represents a significant advance on this front. This envisages a broader scale sediment-sharing system that encompasses not only the upper shoreface of the open coast but also estuarine (backbarrier) environments and the lower shoreface. As a composite 'meta morphology' the tract constitutes the first order of a temporal hierarchy (or 'cascade') of sediment-sharing systems. Crucially, the tract is defined at a scale at which low-order progressive change can be disaggregated from higher-order variability and, moreover, resolves the interactions between estuarine, coastal and inner shelf morphodynamic behaviour that determine net shoreline trends. It thus provides a powerful basis for understanding and managing mesoscale coastal problems, especially when combined with a rigorous protocol for aggregating process understanding and data to match the dimensionality and scale of specific predictive models (Cowell et al., 2003b). Whilst the time scales of the tract hierarchy are explicit, the associated spatial scales are largely implied through the definition of morphological complexes, units and elements.

The need for an integrative systems-based perspective has become more pressing as the strategic application and evaluation of management and engineering options has evolved to address the broader time and space scales at which progressive shifts in shoreline position, and possibly overall coastal configuration, may be expected in the face of climate change and sea-level rise (French and Burningham, 2013). Application of the tract concept is complicated by the fact that cause-effect relationships are not as neatly hierarchical as often theorised (e.g. Fenster et al., 1993). Moreover, the spatial nesting of different sediment transfer pathways is clearly also important (see French et al., 2015), and the weaknesses of conventional littoral cell mapping are especially evident here.

Accordingly, this paper sets out a new approach to the conceptualisation of coupled coast and estuary systems based upon an ontology of component landforms and human interventions, nested hierarchically and interacting at multiple spatial scales. This ontology underpins a formal mapping protocol for Coastal and Estuarine System Mapping (CESM), which is implemented in a geospatial framework using open source software. The CESM concept and associated software implementation is offered as a means of formalising disparate sources of knowledge, informing the development and application of quantitative models, and also catalysing a more participatory approach to coastal management.

2. Integrating coastal, estuarine and inner shelf systems

Within the shoreline management paradigm that has prevailed in many countries (Mulder et al., 2011; Nicholls et al., 2013), open coasts and their associated geohazards (chiefly associated with erosion and shoreline retreat) have often been considered separately from estuaries, where risks associated with tidal and surge-related flooding are often of greater concern. Whilst the geohazards faced in open coastal and more enclosed estuarine settings are seemingly quite different, a divergent approach to their management has led to a lack of appreciation of the nature, extent and significance of the sedimentary and morphodynamic interactions between estuaries and the open coast, and indeed the wider shelf. This is well illustrated in the UK, where two generations of shoreline management plans have either neglected estuaries or else considered estuary–coast interaction in a very selective and inconsistent manner (Hunt et al., 2011).

Cowell et al. (2003a) argue that progressive changes present far more of a management challenge than the short-term variability that often dominates the observational record (see also Esteves et al., 2011). They also argue that such low-order coastal change needs to be evaluated within an expanded spatial scope that includes exchanges of sediment with the lower shoreface as well as interactions between open coast and backbarrier lagoonal and estuarine environments. The motivation for a broader scale conception of coastal problems stems partly from the observation that, as the time scale is extended, net cross-shelf exchanges of sediment accumulate and fluxes that are small in comparison with alongshore fluxes on the upper shoreface become increasingly significant contributors to coastal change, as do morphodynamic interactions between the three zones.

Somewhat contrary to the generally assumed correlation of time and space scales, it is clear that coupled estuary–coast–inner shelf behaviour at, say, a decadal scale, is characterised (and driven) by sediment exchanges at multiple nested spatial scales (Fig. 1). These scales are primarily related to the dynamic behaviour of different sediment size fractions (Keen and Slingerland, 2006; van der Kreeke and Hibma, 2005), although they also relate to different sets of forcings (especially anthropogenic versus natural; e.g. Fenster and Dolan, 1993; Hapke et al., 2013). Beach morphological evolution is typically driven by

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