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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.

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

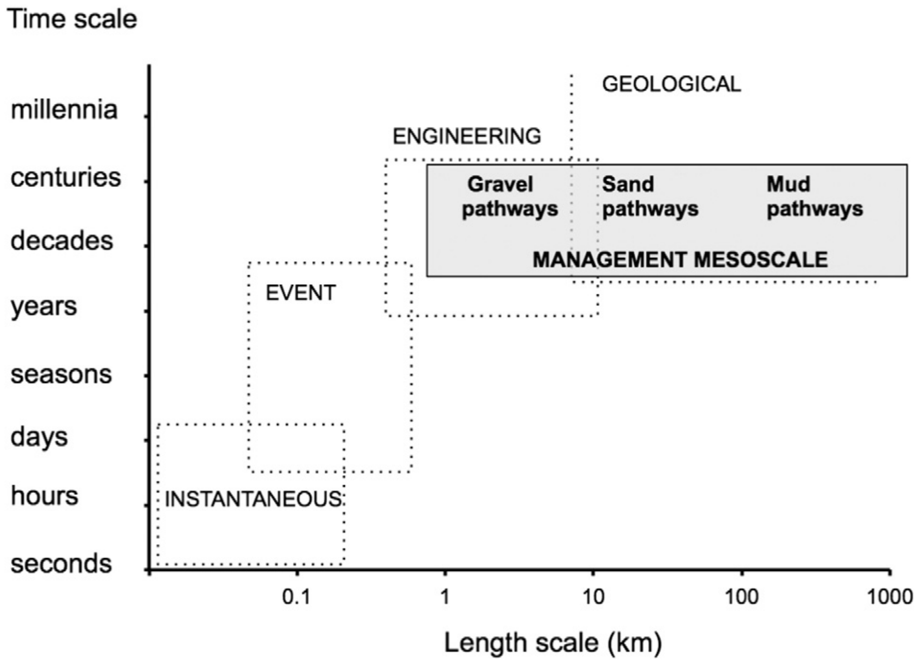

Fig. 1. A schematization of temporal and spatial scales of coastal behaviour (based on Cowell and Thom, 1994), with superimposed management mesoscale at which grainsize-dependent sediment system pathways transcend 'engineering' and 'geological' scales along the space axis.

short-range transfers of non-cohesive sand and gravel, often with proximal sources in eroding sea cliffs and/or coastal rivers (e.g. van Lancker et al., 2004; Komar, 2010). In contrast, fine cohesive sediments arising from either fluvial or coastal cliff sources can sustain intertidal deposition systems hundreds of kilometres from coastal or shelf sources (McCave, 1987; Dronkers et al., 1990; Gerritsen et al., 2000).

The nature of the coupling between estuary and adjacent coast varies substantially according to sediment regime, and different landform components exhibit quite different spatial inter-dependencies. The sand and gravel-dominated Suffolk coast of eastern England, for example, is punctuated by estuarine inlets that interact locally with the littoral drift system through the cyclical accumulation and bypassing of beach material via their tidal delta shoals (Burningham and French, 2006, 2007). At the same time, estuarine tidal flats and saltmarshes accrete through the accumulation of cohesive mud drawn from much longer-range fluxes within the southern North Sea (Dyer and Moffat, 1998; HR Wallingford, 2002), with much of this material in all likelihood originating from soft rock cliff recession and platform downwearing hundreds of kilometres to the north. Given that tidal delta sediment volumes have been observed to scale with estuary tidal prism (Walton and Adams, 1976; Powell et al., 2006), this implies a sensitivity of bypassing times (and therefore the local continuity of drift system at an estuary entrance) to various aspects of broader-scale coastal and estuarine behaviour (Gaudiano and Kana, 2001). These might include distant changes in cliff recession rates due to accelerated erosion followed by measures to protect the source cliffs. This has implications for the ability of the sediment sources to meet an increasing demand for sediment within estuarine sinks (Orford and Pethick, 2006); whether or not this demand is satisfied will influence the adjustment of estuary prism to sea-level rise (or to adaptive management strategies such as realignment of flood defences that have the potential to significantly change the tidal prism; e.g. French, 2008). Changes in prism, in turn, will potentially affect bypassing timescales and the local continuity of the littoral drift system. Long-range fluxes are hard to describe within existing coastal classification frameworks and, in the absence of sediment transport modelling at this scale, many of the linkages that underpin regional sediment budgets (e.g. McCave, 1987; HR Wallingford, 2002) have still not been adequately investigated in terms of either mechanisms or magnitudes.

Whilst estuary–coast interactions are readily approached through empirical studies or through modelling, the morphological evolution of many coasts is also constrained by exchanges of material with the inner shelf. These exchanges may be hard to identify, let alone quantify, but are perhaps most evident on shallow sloping, sand-dominated shorefaces where cross-shore transport drives correlated behaviour in upper shoreface and shoreline sedimentary systems (e.g. Aagaard et al., 2004; Anthony et al., 2006; Magar et al., 2012). Chronic nearshore sediment budget deficits are often explained by invoking 'offshore losses' that are rarely quantified or even corroborated (Brunel et al., 2014). In the absence of obvious fluvial or coastal sources, this may be a reasonable assumption, especially where supported by qualitative analysis of sediment pathways (e.g. from patterns in the alignment of tidal bedforms; Barnard, 2013). Volumetric estimations of large-scale seabed sediment sources have been attempted (e.g. southeast North Sea; Zeiler et al., 2000) and with advances in seismic survey capability, stratigraphic assessments can reveal strong spatial associations with shoreline morphodynamic behaviour (e.g. Gulf of Lions; Certain et al., 2005). More often, analyses focus on relative volumes associated with different shore-parallel, morphodynamic zones along cross-shore profiles, which might show more direct local connectivity (e.g. Hinton and Nicholls, 2007; Aagaard, 2011). It is nevertheless evident that our need to balance sediment budgets has often led to assumptions of connectivity that remain indeterminate or have been later shown to be non-existent (Shaw et al., 2008).

Whilst the focus so far has been very much on sediment-sharing between coupled landforms and complexes of landforms, other kinds of interaction also influence coastal behaviour. This is well illustrated at a broad scale by the role of shelf bank systems (e.g. Tucker et al., 1983; MacDonald and O'Connor, 1994; Park and Wells, 2005; Hequette et al., 2008; Hequette and Aernouts, 2010) and submarine channels (Browder and McNinch, 2006) in mediating wave energy at the coast. These systems often comprise significant sediment volumes and active internal transport, but have little or no direct sediment exchange with contemporary coastal systems (Antia, 1996). Tidal currents are also effective in the broader redistribution of (and control on the availability of) seabed sediments, particularly where currents can be deflected and enhanced by existing banks, leading to possible self-organisation of mobile sediment across the shoreface (van Landeghem et al., 2012).

3. Spatial ontology of estuary–coast–inner shelf system linkages

3.1. Hierarchical classification

As a first step towards articulating the vision outlined above, we here propose an idealised spatial ontology that provides a basis for mapping the configuration of coastal systems considered in the broadest sense to include estuaries and relevant portions of the inner shelf. The term ontology here refers to a formal specification of a conceptualisation (see Gruber, 1993), although we adopt a rather loose interpretation that encompasses a hierarchical classification of components and a set of permitted interactions between them. As outlined in Fig. 2, this scheme reflects some aspects of the coastal tract concept in that it envisages a hierarchy of morphologically-active sediment sharing landform systems. These are located within the geological context of a coastal shelf that can be considered time-invariant at the decadal to centennial timescales that are especially relevant to management (French and Burningham, 2013; French et al., 2015). In contrast to the primarily temporal tract hierarchy (Cowell et al., 2003a), our scheme emphasises the spatial nesting of discrete landform components within aggregate landform complexes, and explicitly represents varied human interventions and the way in which these constrain landform adjustment. These, in turn, are embedded within coastal behaviour systems at a broad regional scale (cf Burgess et al., 2002; Eliot et al., 2011).

3.2. Landform complexes

Estuarine, coastal and inner shelf complexes can be classified with reference to existing schemes and the range of landforms encountered in a given regional or shelf context. In any classification, there is a trade-off between workability and the need to resolve important differences. In the case of estuaries, varied attempts have been made to reduce the diversity in morphology and origin to a small set of subtypes. The Hume and Herdendorf (1988) classification, devised in a New Zealand context, identifies five major modes of estuarine basin formation, within which 16 estuary sub-types occur. A more elaborate scheme incorporating several distinct levels of controlling factors is presented by Hume et al. (2007). Other schemes, such as that by Roy et al. (2001) and Harris et al. (2002) in Australia, highlight variability in tide versus wave dominance as well as the interplay between marine and fluvial influence (to include systems that open only intermittently). Other schemes, such as the Davidson and Buck (1997) classification of British estuaries, are founded on a consideration of estuary origin and gross morphological characteristics. Fig. 3a presents a variation on this theme (based on ABPmer, 2008), in which the term 'inlet' is used to define systems in which fluvial influence is negligible and sediments are purely marine in origin; this corresponds to the lagoonal type of Boyd et al. (1992) and includes inlets that may be only intermittently active. Such a scheme has quite broad applicability within temperate zones (such as northwest Europe). Its relative simplicity is advantageous from a mapping perspective since it helps to reduce the operator variance that inevitably arises where classificatory judgements have to be made.

For open coasts, a similarly minimal scheme can be entertained. Following Cowell et al. (2003a), we adopt the idea of a mainland coast, but augment this (Fig. 3b) with headlands and bays for coasts that exhibit more obvious geological control. Cuspate forelands and spits are locally prominent and many are large enough to be afforded the status of a landform complex (e.g. Sanderson and Eliot, 1996; Park and Wells, 2007; Plater et al., 2009). It seems reasonable to include barrier islands (Hayes, 1979; Williams and Leatherman, 1994) as a landform complex in their own right and also to distinguish these from various forms of non-detached coastal barrier (e.g. Bray, 1997).

The inner shelf is less replete with obvious landforms, although the drowned palaeo-landscapes of the last glacial (Harris et al., 2013) and their potential interaction with modern shoreline dynamics (McNinch, 2004) are attracting increasing attention. However, many shallow shelf seas are characterised by distinctive bank systems that differ in

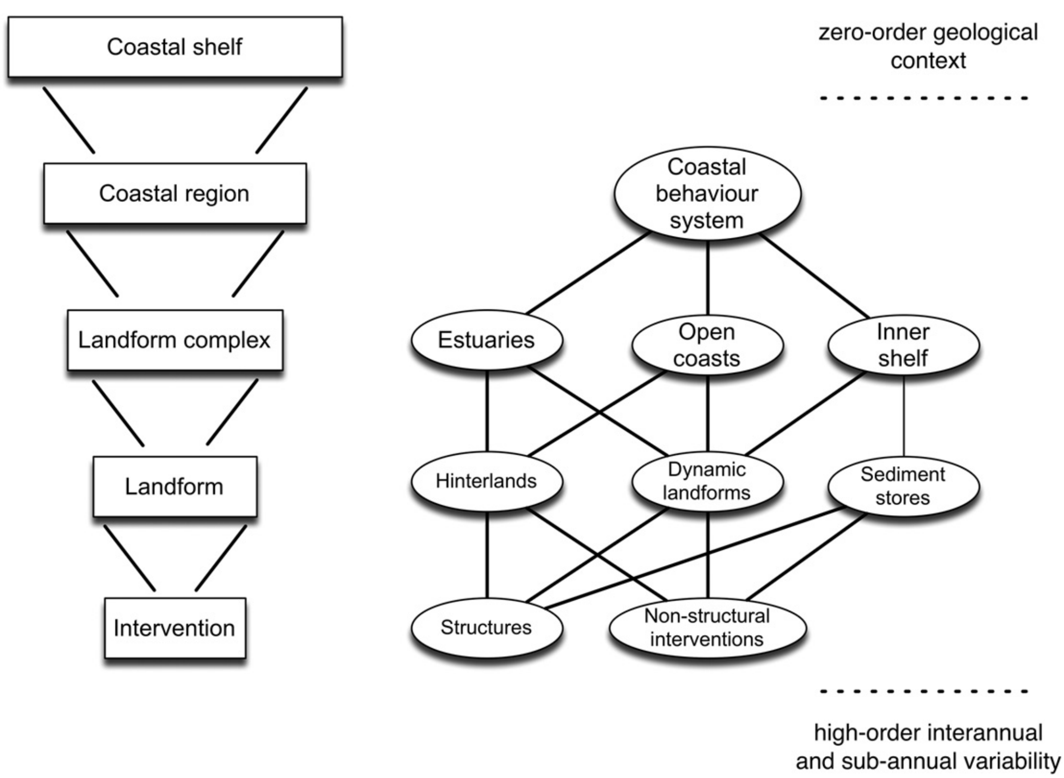

Fig. 2. Overview of spatial ontology of coupled estuary–coast–inner shelf geomorphic systems, showing nesting of landforms and landform complexes within broader-scale coastal regions. At decadal to centennial scales, the coastal behaviour system integrates the interaction of estuarine, open coastal and inner shelf morphodynamics, within a broader coastal shelf context that evolves only at much longer timescales. Interannual and sub-annual dynamics can generally be considered to be 'sub-grid' (cf. Cowell et al., 2003a) at times of decades and longer.

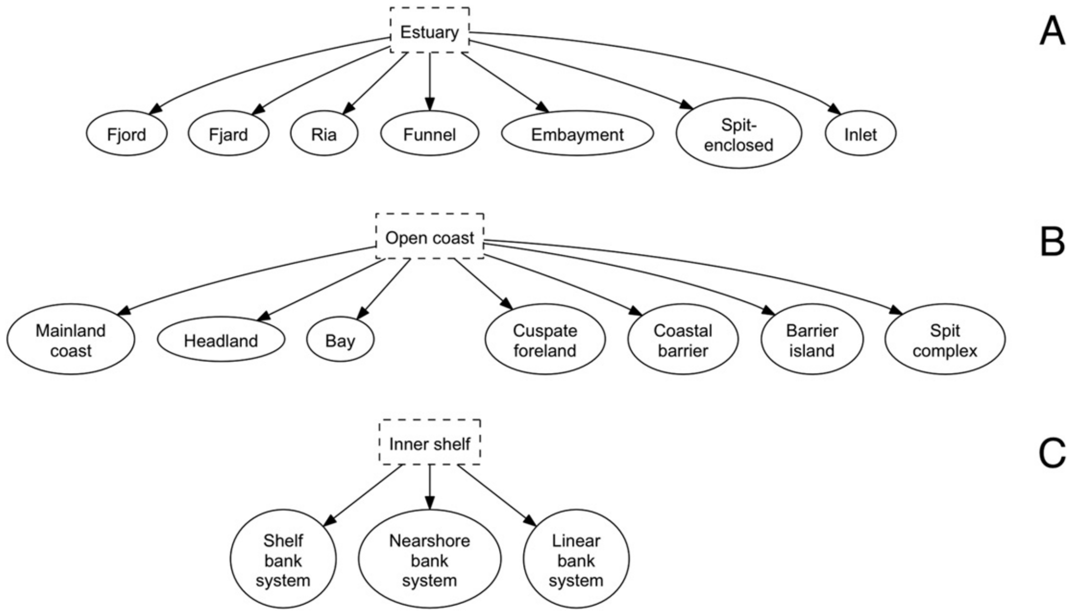

Fig. 3. Illustrative classification of estuary, coast and inner shelf landform complexes that might be suitable for application within a temperate (e.g. northwest European) context. The basic approach could readily be adapted to suit specific environments.

morphology, organization and origin (e.g. Swift and Field, 1981; Belderson, 1986; Hequette and Aernouts, 2010). A variety of styles of sand bank system are a prominent feature of the southern North Sea (Caston, 1972; Burningham and French, 2011). Some of these are known to exert a significant influence on contemporary shoreline behaviour, either through their role in modifying wave climate (Dolphin et al., 2007) or via their participation in coastal sediment pathways (Robinson, 1966; Chang and Evans, 1992). Our provisional classification of these features (Fig. 3c) distils the detailed analysis by Dyer and Huntley (1999) into three distinct types. Shelf Bank Systems correspond to Type I of Dyer and Huntley. These may or may not be morphologically active and, at decadal to centennial scales, chiefly act to modify coastal wave climate (e.g. Chini et al., 2010) and are associated with tidal interactions controlling broader bedload sediment transport pathways and residual currents influencing fine sediment transport (e.g. Dyer and Moffat, 1998). Linear Bank Systems are associated with larger meso- to macro-tidal estuaries (e.g. Burningham and French, 2011) and correspond to Type 2a. Nearshore Bank Systems include the various forms of headland-attached Type 3 ridge identified by Dyer and Huntley (1999) (e.g. Caston, 1972; Schmidt et al., 2007). It should be noted that ebb-tidal deltas, included as Type 2b estuary mouth banks by Dyer and Huntley (1999) are included here as discrete landforms rather than being aggregated into landform complexes (see also below).

3.3. Landforms

The estuarine, open coastal, and inner shelf complexes outlined above represent aggregations of landforms. Table 1 summarises a provisional set of landforms applicable to temperate settings, which includes 'textbook' features such as cliff, beach, tombolo and spit. The intention here is to think as generically as possible in terms of the functional differences between landform types. As such, the same landform type may occur within more than one type of landform complex (e.g. tidal flat, which can occur in both open coast and estuarine settings). Other landform types such as spits and ebb tidal deltas, occur at the interface between estuary and open coast and, as such, could be considered to be part of either complex. Spits are a special case in that larger examples can be mapped as a complex (with constituent dune, beach, beach ridge, saltmarsh etc.) whilst minor features can be considered as discrete landforms within another complex. This will necessarily involve a subjective judgement.

The set of morphologically active landforms is supplemented by a smaller set of hinterland types that are considered to exert a static boundary condition control. High ground is defined subjectively as terrain that rises well above current and projected future tide and surge elevations and which would be expected, in the absence of any protective works, to exhibit a predominantly erosional response to sea-level rise. Low ground, in contrast, is identified as being more susceptible to inundation, and this may constitute a more significant hazard (noting that erosion also leads to increased flood risk and that the two hazards are not independent). The distinction between high and low hinterland can be a subjective one or else could be quantified with reference to coastal slope (cf Applequist, 2012). Reclaimed areas are those that have been historically converted from the intertidal and subtidal zones and are protected from tidal action by fixed defences.

In addition to readily identifiable landforms, broad-scale sediment systems include distinct stores of sediment that can be locally important in mediating landform behaviour. Much of the shelf is veneered by patches of sediment, some of which are essentially inactive under current sea level, wave climate and tide regime, and some of which participate in sediment pathways that interact with coastal or estuarine environments. Seabed stores can be demarcated on the basis of grain size, with their inclusion or otherwise in the contemporary sediment system being informed by, inter alia, consideration of shelf sediment

Table 1
Shared set of landform components common to open coastal, estuarine and inner-shelf complexes. These comprise morphologically active landforms, as well as major sediments stores, and hinterlands that are not considered to evolve at the timescales of interest here.

Landform		Hinterland	Sediment store
Cliff	Inlet channel	High ground	Seabed gravel
Shore platform	Ebb delta	Low ground	Seabed sand
Beach	Flood delta	Reclaimed	Seabed mud
Beach ridge	Bank		Suspended mud
Tombolo	Channel		
Dune	Tidal flat		
Spit	Saltmarsh		
Rock outcrop	Brackish marsh		
Lagoon	River		

pathways (e.g. Poulos and Ballay, 2010), possibly augmented by sediment transport modelling (e.g. Whitehouse et al., 2003; Barnard, 2013).

3.4. Human interventions

Present-day coastal behaviour is strongly conditioned by, and indeed partly a consequence of, human interventions of various forms over a period of decades to centuries. The effects of coastal protection works are evident locally (Runyan and Griggs, 2003; Basco, 2006), regionally (Clayton, 1989; Dawson et al., 2009; Brown et al., 2011) and are discernible at national scales (Hapke et al., 2013). Historically, many of the most obvious interventions have been structural, with the aim of preventing erosion, facilitating reclamation or reducing the risk of flooding. Engineering practice has evolved significantly to incorporate varied local experiences and requirements, and this is reflected in a diverse nomenclature for types of intervention that perform the same basic function. Accordingly, we here present a minimal and highly generic classification of basic types of intervention according to function performed (Table 2). Most of these have the effect of arresting movement, for example through limiting erosional retreat or channel migration. Some, such as groyne fields, represent a direct intervention to retain or restore a sediment store and any associated littoral drift pathway. Non-structural interventions in coastal and estuarine sediment systems are also pervasive, not only through dredging and aggregate extraction (Hitchcock and Bell, 2004) but also through the adoption of 'softer' and more adaptive approaches to coastal management. Beneficial reworking of sediment (including various forms of nourishment or recharge) to restore known deficits and enhance the resilience of degraded environments is increasingly undertaken. Here too, the scale and scope of intervention is becoming increasingly ambitious (e.g. the Dutch Sand Engine — Stive et al., 2013; van Slobbe et al., 2013).

3.5. Interactions

Our provisional ontology includes about 60 components, distributed over four hierarchy levels. Some landform components are shared between open coast and estuary, although the human interventions are rather more selectively applicable to restricted sets of landforms. From a functional perspective, system components also influence each other and this complex web of interactions (illustrated for the set of landforms and human interventions in Fig. 4) is an important element of the ontology. Interactions in the broadest sense refer to any cause-effect relation between components; for example, a jetty exerts an effect on an inlet channel, stabilising its location and influencing its cross-sectional characteristics (e.g. through a constraint on width adjustment) and hydrodynamics (e.g. Fitzgerald et al., 2003; Seabergh et al., 2003). It is evident from Fig. 4 that some components (e.g. beach, inlet channel, channel) are far more connected than others (including the less common landforms and structural interventions). Some interactions are more obviously bidirectional, such as the interplay between a seawall and a beach (Dean and Jones, 1974; Kraus and McDougal, 1994; Basco, 2006). A sub-set of the interaction network involves transfers of mass and these sediment pathways, taken together, define the sediment budget (Bowen and Inman, 1966; Rosati, 2005). Some of the linkages may be simple unidirectional ones, for example where sequential beach units define a littoral drift system. Others may represent more complex causality: a cliff may source sediment to a fronting beach (mass transfer) and the beach may influence the cliff (via an influence through which beach morphology feeds back into the cliff recession rate; Walkden and Hall, 2011).

Consistency in the representation of system interactions is clearly important and can be achieved through careful tabulation of permitted interactions, their nature and directionality, and a supporting logic backed by references to the scientific literature. Table 3 presents an illustrative portion of an interaction matrix for the system as visualised in Fig. 4. There are essentially three types of interaction: (1) None — paired components exert no direct influence on each other; (2) Influence, where there is a process interaction, such as wave sheltering, but no direct sediment exchange; and (3) Sediment pathway — a direct exchange of sediment between components. In its entirety, this table specifies the way in which landforms can be assembled into complexes, the manner in which they interact, and the effect of various human interventions. Whilst there will invariably remain scope for disagreement over specific interactions, and local circumstances may require special provision, this a priori specification of system structure is essential to ensure consistency when system mapping is applied in practice.

4. Coastal and Estuarine System Mapping (CESM)

4.1. Knowledge formalisation

The CESM approach provides a means of synthesising and formalising our understanding of how open coasts, estuaries and inner shelf landforms interact. Its specific intention is to capture the configuration of the key morphological components, human interventions, and the sediment and other influence pathways that connect them, with a particular reference to the decadal to centennial scales. Accordingly, variability at seasonal and short interannual scales (such as event-driven changes in littoral transport or beach rotation associated with modes of atmospheric variability; Thomas et al., 2011) is excluded in favour of more persistent interactions. The result is a time-averaged 'snapshot' of system configuration as conditioned by present processes and human constraints. Behavioural dynamics are not resolved explicitly, although system maps may be used to identify potential changes in behaviour due to configurational state changes (cf Phillips, 2014, and see also below).

Table 2
Minimal classification of generic structural and non-structural interventions in estuary, coast and inner shelf sediment systems, with their indicative purpose.

Structural	(Indicative purpose)	Non-structural	(Indicative purpose)
Seawall	Erosion protection	Dredging	Navigation; mining
Revetment	Erosion protection	Dredge disposal	Spoil disposal
Bulkhead	Erosion protection	Sediment recharge	Restoration of sediment deficit (beach, intertidal)
Embankment	Flood protection	Sediment bypassing	Continuity of sediment pathway; navigation
Barrage[a]	Flood protection	Sediment recycling	Resilience (beach profiling)
Breakwater	Wave energy reduction		
Detached breakwater(s)	Wave energy reduction		
Groyne(s)	Sediment retention		
Training wall	Channel stabilisation/navigation		
Jetty	Varied		
Outfall	Drainage/dispersal		
Quay	Navigation/trade		
Dock	Navigation/trade		
Weir	Regulation of river gradient and/or tidal limit		

[a] In the current schema barrage and barrier are used interchangeably.

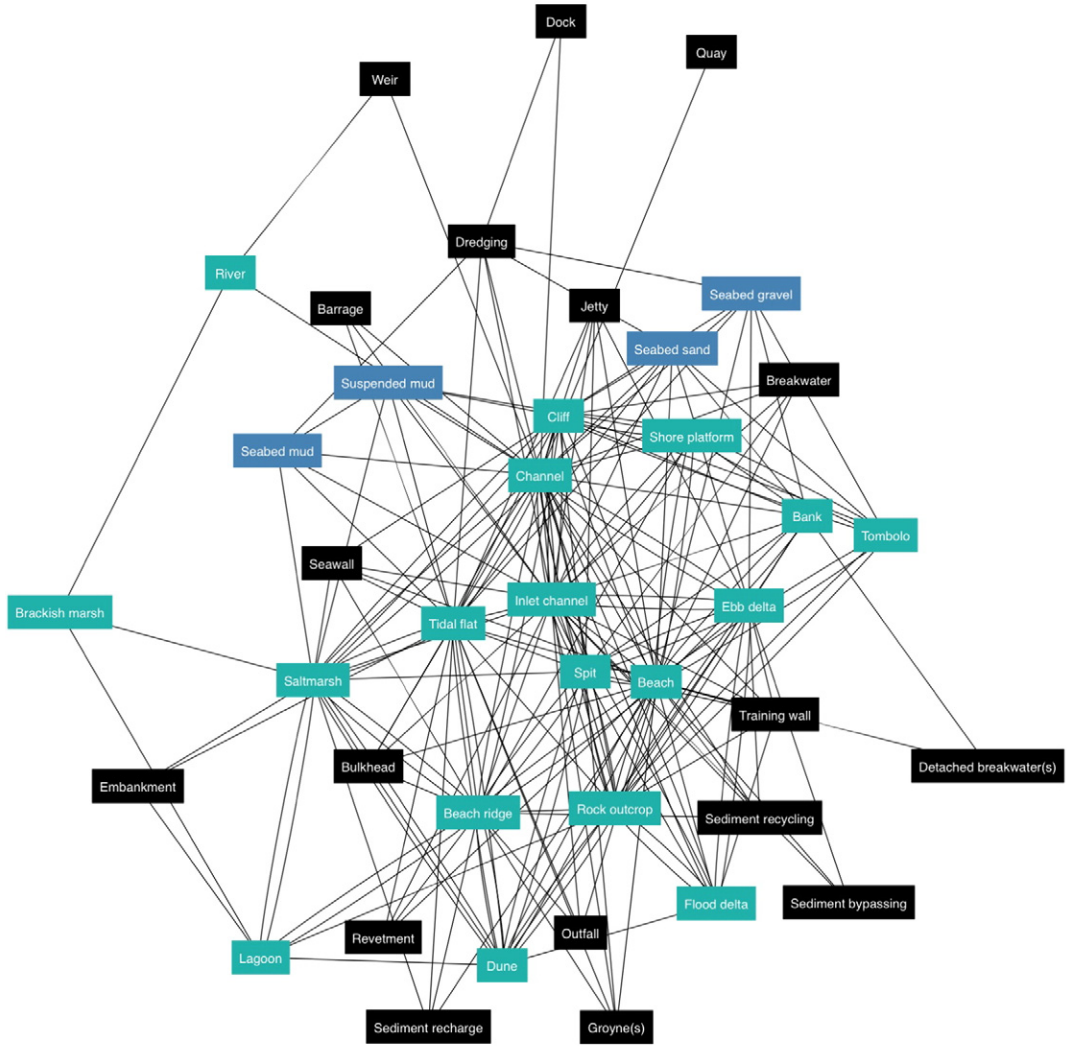

Fig. 4. Functional interactions between landforms and human interventions for components summarised in Tables 1 and 2 (hinterland omitted). Landforms are in green, human interventions in black and sediment stores in blue. Note that this diagram is not intended to be read in detail but conveys the complexity of the system as well as the sparsity of its interaction matrix (see text for further explanation).

Given the subjective nature of knowledge formalisation it is unrealistic to think in terms of a single system map that can be considered 'valid' for a particular location and application. Different experts will always interpret data and scientific literature in different ways, and in one sense, system mapping can thus provide a vehicle for the development of scientific consensus regarding the behaviour of a given coastal system. Comparison of maps (and conceptual models) produced in isolation by different experts can also reveal areas of consensus or robust understanding, and areas of disagreement or weak understanding. Both outcomes depend on mapping being undertaken in a logically consistent and rigorous manner. To this end, we first present a set of guiding principles and then describe a software tool that has been developed to implement these within a geospatial framework.

4.2. Formal protocol for mapping the connectivity of coupled coast and estuary systems

Earlier proof-of-concept work (Whitehouse et al., 2009) has been refined into a consistent CESM protocol, a workflow for which is summarised in Fig. 5. This commences with careful 'specification' of the problem at hand, for which a formal statement of the application is required. This will necessarily involve a judgement of the appropriate time-averaging period over which to characterise this system, the spatial resolution that is appropriate, as well as the geographical scope. The latter might vary from regional mapping to guide the preparation of a shoreline management plan, to more detailed representation of intertidal flat, saltmarsh and reclaimed flood compartments to provide

Table 3
Illustrative paired examples of system interaction rules for landforms and interventions.

From	To	Interaction	Logic (literature source)
Cliff	Beach	Sediment pathway (sand, gravel)	Cliff sources beach-grade sediment (mud typically lost offshore)
Beach	Cliff	Influence	Presence and morphology of beach feeds back into cliff recession rate (e.g. Walkden and Hall, 2011)
Seawall	Beach	Influence	Presence of seawall may cause lowering of beach (e.g. Basco, 2006)
Beach	Seawall	Influence	Beach protects toe of seawall and reduces wave energy on face
Jetty	Inlet channel	Influence	Jetty exerts stabilising influence on channel position and constrains width adjustment
Inlet channel	Jetty	none	No direct causal relation in this direction

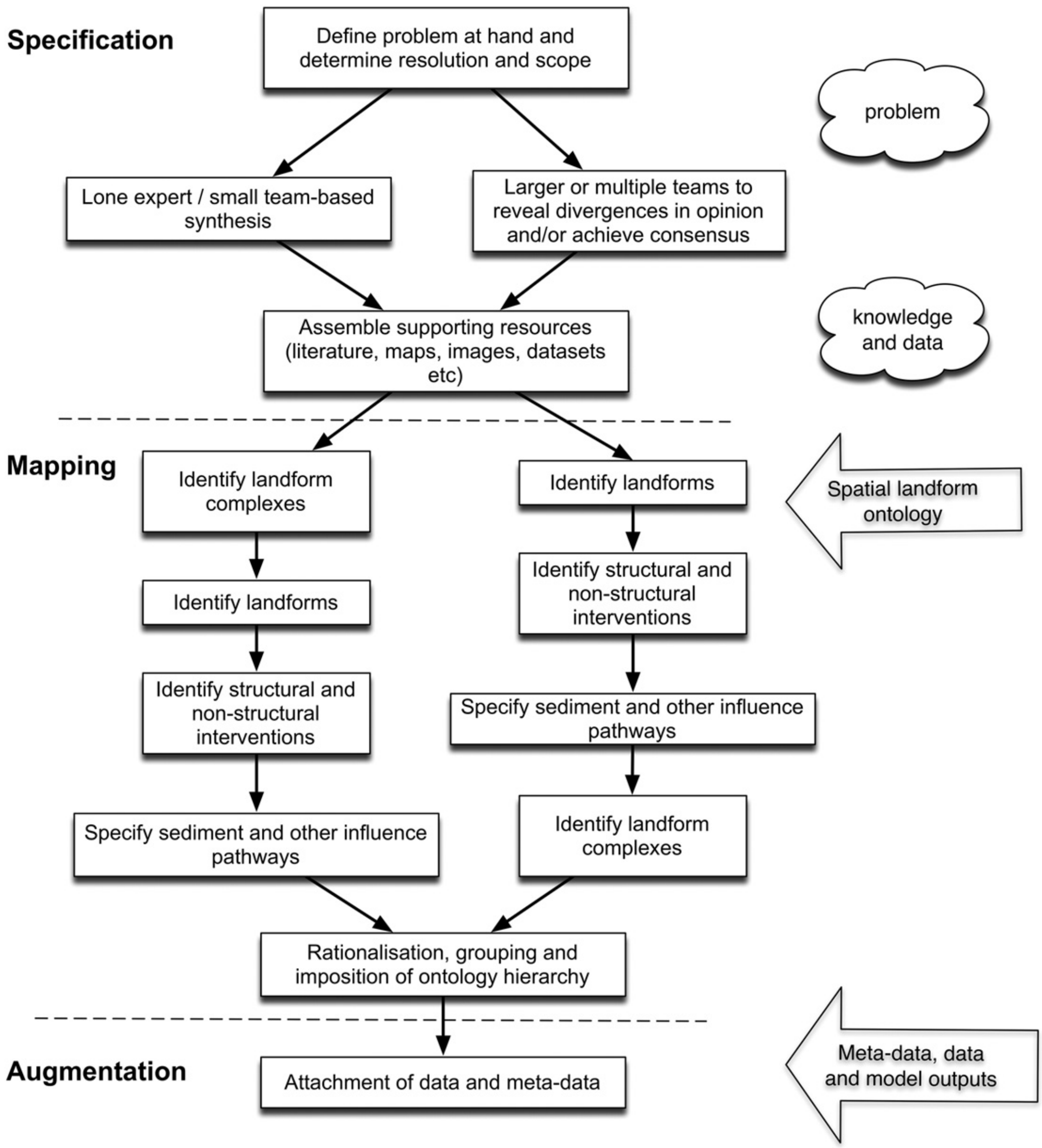

Fig. 5. Outline workflow for Coastal and Estuarine System Mapping. This involves three main stages: specification, in which the problem is defined and information assembled; mapping, in which the system is conceptualised in map form; and augmentation, in which data (such as quantitative sediment flux estimates), reports, images etc. are appended to create a spatial database.

context for a specific estuary flood defence realignment scheme. The next step is to determine the most effective route to formalising the current state of understanding. For well documented and/or understood systems, a lone expert or small team of experts may be able to achieve a relatively uncontentious synthesis of existing knowledge. Where the system is less well understood, CESM provides a starting point for the progression of a conceptual model and a larger team might be required to achieve a consensus. This might be done as a joint effort or through rival efforts that then reveal areas of divergent opinion; direct involvement of stakeholders may be beneficial. Finally, in the augmentation stage (Fig. 5), background knowledge (published papers, reports etc.) and datasets (aerial images, geological maps, bathymetry etc.) are drawn together to inform the mapping process.

System mapping is undertaken with reference to the hierarchical set of landforms and interventions defined in the ontology. It is emphasised that the generic ontology presented in this paper has been developed for application in temperate environments, and customization will usually be required to suit particular geographical contexts and applications. As indicated in Fig. 5, mapping may follow a 'top down' route, in which landform complexes are identified first and then populated with landform detail, or a 'bottom up' route whereby landforms and interventions are mapped in detail and then organised into broader-scale complexes. Irrespective of the route taken, open coastal and estuarine complexes require a consistent approach to the identification of discrete system components and the interactions between them. Our preferred approach is illustrated through a simple explanatory example.

Fig. 6 depicts an illustrative juxtaposition of open coastal and estuarine landform complexes. The key interaction at this scale is that between a small spit-enclosed estuary and an open coast comprising a predominantly sandy bay, bounded by two headlands of resistant geology. Mapping of the open coast proceeds by identifying distinct hinterland–backshore–nearshore sequences and any local constraints due to structures or known non-structural interventions (e.g. beach nourishment or sediment bypassing programmes). This is similar to the approach taken by Hanson et al. (2010), who set out a scheme for mapping barrier and non-barrier coasts based on sequential transitions in cross-shore profile type, as defined by a set of prescribed landform elements. Fig. 7a illustrates a portion of open coast, showing backshore to

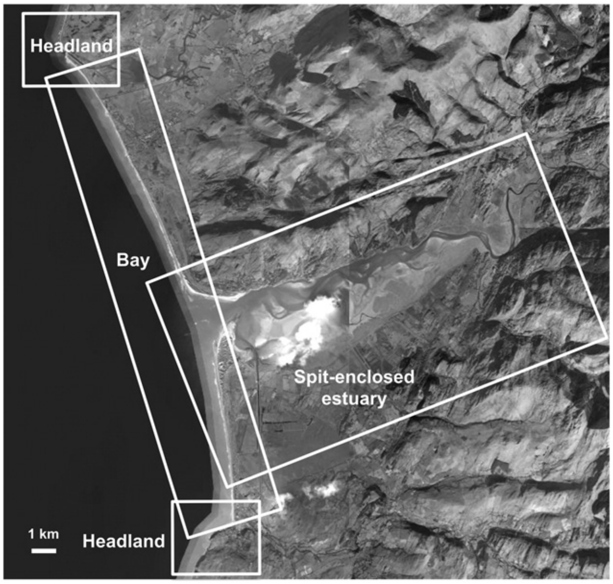

Fig. 6. Illustrative composition of open coast and estuary landform complexes (example is Aberdovey, Wales, UK, but mapping is purely illustrative).

hinterland sequences of landforms and significant interventions (all structural here, including a minor jetty and more extensive groynes, bulkhead and embankments), mapped at alongshore intervals that define a broadly coherent sequence that can be considered to function more-or-less as an integrated whole. Interaction pathways have been added, with the directionality of the sediment pathways indicated, and distinction made between these and 'influence only' interactions (e.g. those involving the various structures) that are not part of the sediment system. Sediment pathways will often have a preferred direction, but may also be bi-directional (as in Fig. 7a) where movements are uncertain or oscillatory.

Within the estuary, distinct subtidal–intertidal–hinterland transitions are similarly mapped with reference to the dominant axis of the estuary (in this case a sand-bed channel that includes a minor branch). This is illustrated for part of the outer estuary in Fig. 7b. This particular spit-enclosed estuary exhibits an asymmetric cross-sectional morphology, with a northern shore (left edge of figure) flanked by high ground and cliffs (partly protected by seawalls) and a southern shore with wide tidal flats, saltmarsh and embankments protecting reclaimed wetlands. The estuary exchanges sand with adjacent beaches via the paired spits, one of which is welded to the northern shore, and the tidal delta sand bodies. Sand dredged from the harbour channel is used to nourish dunes to the north.

Fig. 7 characterises open coast and estuary sets of components, connected by various forms of influence. This representation naturally leads to the consideration of the system as a network graph, from which perspective various forms of quantitative analysis are possible, ranging from simple inventories and interaction probabilities to more sophisticated inferences of overall system behaviour based on network topology (Phillips, 2012). All analyses of this kind exhibit a high degree of sensitivity to the way that a system is rendered in terms of discrete components (network nodes) and interactions (edges or links) and this process invariably involves subjective judgement, especially in the demarcation of discrete landforms in continuous landscapes. Moreover, the approach adopted in Fig. 7 generates multiple instances of landforms that are considered to participate in more than one distinctive nearshore (or estuarine subtidal) to hinterland sequence. Some form of network rationalisation is therefore needed to adjust the network topology to merge multiple instances of the same geomorphic feature. Fig. 8 shows how this can be achieved for the outer estuary. Note that duplicate landforms and interventions are merged wherever possible but some aspects of the graph require special treatment. For example, spatially extended channels or beaches may be associated with known convergences or divergences in sediment pathways, such that their disaggregation into multiple functional components is warranted. It should also be noted that our treatment of hinterland considers this to bound the active coastal and estuarine system rather than to functionally interact with it as a dynamic landscape component. Thus, whilst demarcation of discrete reclaimed flood compartments might be justified in estuaries, the depiction and labelling of low and high ground can be approached from a purely aesthetic perspective, and these components can be omitted from quantitative network-based analysis. Whilst map subjectivity can never be fully eliminated, adherence to a rigorous mapping protocol should at the very least ensure internal consistency and transferability of the results. System graphs rationalised in the manner outlined above are amenable to quantitative analysis of the abundance and connectivity of their components. This potential is considered further in the Discussion below.

The workflow in Fig. 5 incorporates a final 'augmentation' stage, in which the system map can be annotated to include metadata (e.g. references and active links to relevant research and datasets) as well as data (e.g. digital research documents, images, observational datasets and model outputs). In order to operationalize this geospatial database function, suitable software is required. The following section describes the implementation of the CESM approach as a Geographical Information System (GIS) plugin that allows all aspects of the workflow to be performed in a geospatial framework.

4.3. Implementation of CESM within an open-source GIS platform

Initial development of the CESM method (French and Burningham, 2009; Whitehouse et al., 2009) was accomplished using a variant of the workflow presented above in Fig. 5 in conjunction with concept mapping software (specifically, the CmapTools freeware; Cañas et al., 2005). However, this proof-of-concept implementation lacked the ability to produce georeferenced system maps or to directly utilise geospatial data resources. To provide this important functionality, we have developed a new software tool that operates within a GIS framework.

QGIS (http://www.qgis.org) was selected as a preferred geospatial platform on account of its maturity as an open source GIS, support for multiple operating systems and growing user base. QGIS is written in C++ and allows integration of software plug-ins coded in either C++ or Python. The CESM workflow has been implemented as a Python plugin that enables system components to be mapped interactively over one or more QGIS data layers. Whilst the GIS plugin approach imposes some constraints on the graphical capabilities of the software (chiefly through its dependence on the QGIS Application Program Interface), it avoids the need to code the various geospatial tools from scratch, which would have required far greater development effort.

The CESM plug-in architecture and workflow are summarised in Fig. 9. System mapping is performed with reference to a base layer that defines the projection and co-ordinate system. Possible layer types include digital mapping, Web Map Server-based layers (including Google Maps or Bing maps), or digital photography. The base layer can be supplemented by 'helper layers' that provide useful information to guide the identification of landform types and identify human interventions. Airborne LiDAR raster layers are especially useful, as are digital bathymetric charts and geological maps, and vector layers containing information on flood and coastal defence infrastructure. The plugin is designed such that the ontology is separate from the tool itself, and is described in an external file that can be edited independently of the code. This file is defined using a simple XML-like semantic markup language, which permits the inclusion of optional presentational markup to impose various label and line style settings. These can be overridden within the software, either manually, or via application of separate preferences settings. The available components (landforms, landform

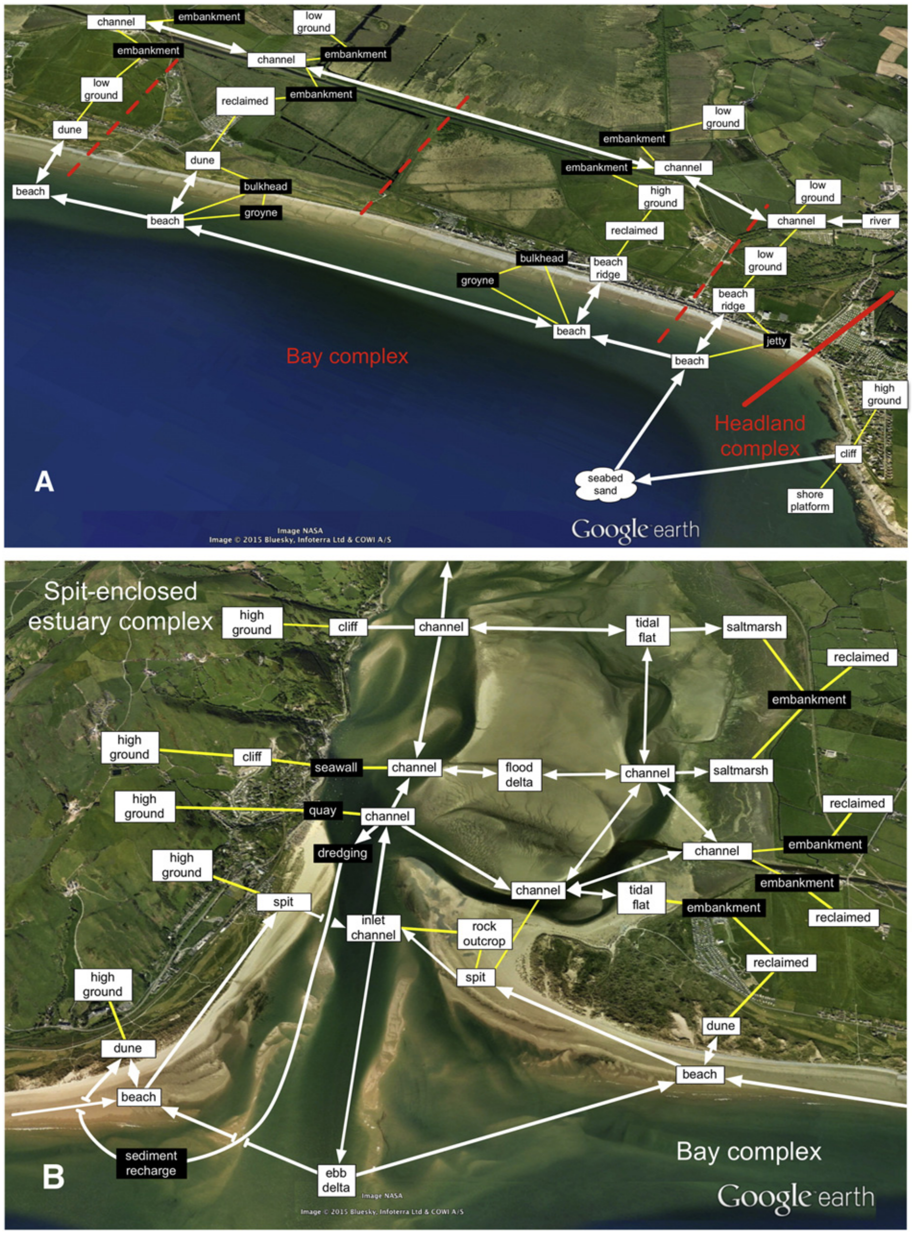

Fig. 7. A) illustrative open coast mapping for a portion of bay complex (about 3.5 km along the main beach) showing segmentation into distinct cross-shore transitions (demarcated with broken red lines), with directional sediment pathways (white) and 'influence only' interactions (yellow). Imagery of Aberdovey (Wales, UK) courtesy of Google Earth; B) equivalent mapping of outer estuary (about 3.5 km visible across estuary mouth), showing contrasting intertidal–backshore–hinterland sequences either side of central channel. Imagery of Aberdovey (Wales, UK) courtesy of Google Earth. System mapping is purely illustrative and not intended to be interpreted as a detailed case study.

complexes) are read from the ontology and used to guide on-the-fly creation of Graphical User Interface (GUI) palettes, which provide the user with a pre-determined set of system elements and impose constraints on how these can be combined. These extend to the hierarchical nesting of components as well as the functional interactions between them (Fig. 4). The plug-in also provides a means to define the linkages between the various components and specify the type and directionality of the connection (influence, sediment transfer), including the option to include numerical values for sediment transport where appropriate. The selection of a combination of landforms to be included as part of a specific landform complex can be accomplished using the software tool which will automatically provide a check that the grouping is permissible within the defined ontology; this maintains a base level of consistency between different users when producing coastal and estuary system maps. The resulting map (a point layer of components and a line layer of connections) is saved in ESRI shape file format, which can be read by a wide variety of other applications and thus provides a common platform for distribution of system maps to stakeholders.

4.4. Illustrative application — Suffolk coast, eastern England

The CESM approach and software are presently being used within the Integrating Coastal Sediment Systems (iCOASST) project (Nicholls et al., 2012) as a conceptual framework for modelling of coastal and estuarine morphological change at decadal to centennial and broad regional scales. In this context, system maps provide a basis for determining how best to break down a regional coastal behaviour system into a set of complexes within which landform morphological change can be simulated by a set of coastal and estuarine models linked through an external coupling interface (e.g. OpenMI; Gregersen et al., 2007). Identification of discrete landform components, interventions and interactions between them at a sub-complex scale then informs

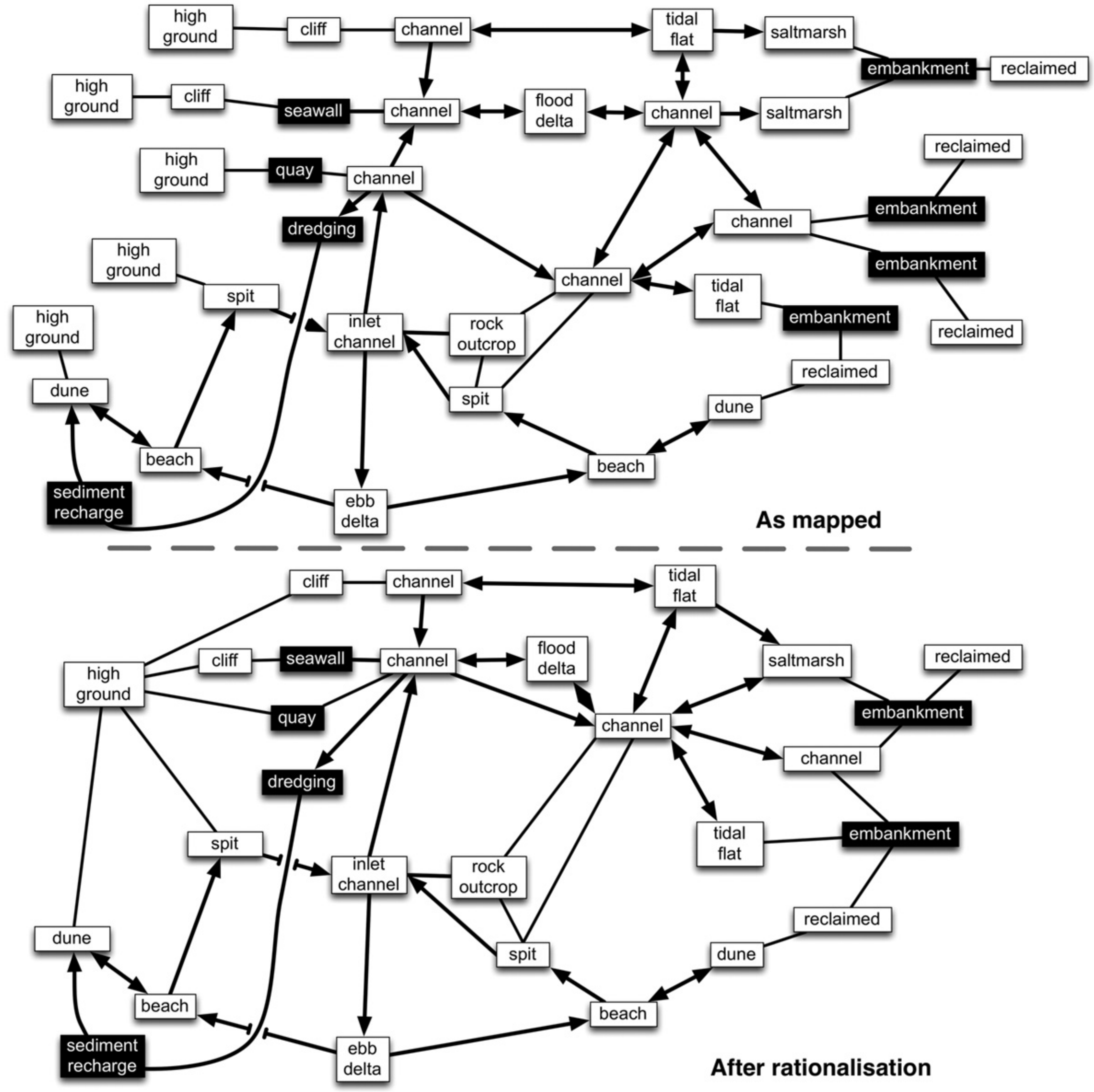

Fig. 8. Rationalisation of the network graph for the outer estuary (Fig. 7b; reproduced in the upper panel) to remove multiple instances of the same landform and intervention. This creates a more consistent topology (lower panel) that could potentially be analysed more quantitatively.

the development of specific model codes. The conceptual and predictive models developed within the iCOASST project are being evaluated via regional case studies of Liverpool Bay (northwest England) and Suffolk (eastern England). Selected aspects of CESM applied to Suffolk are presented here.

The Suffolk coast constitutes a coastal behaviour system that extends from Lowestoft in the north to Felixstowe in the south, an open coastal length of approximately 77 km. This system is readily segmented into a sequence of open coastal, estuarine and inner shelf landform complexes (Fig. 10). The mainland coast largely comprises stretches of cliff-backed sand and gravel beach (Burningham and French, 2015) interspersed with barrier-enclosed brackish lagoons (Pye and Blott, 2009; Spencer and Brooks, 2012). The soft rock cliffs exhibit high rates of erosion (up to 5 myr^{-1}; Brooks and Spencer, 2010) and release sand and gravel to the beach system (Burningham and French, 2015). The alongshore continuity of the open coast is punctuated by the Blyth, Alde/Ore and Deben estuaries, all of which are predominantly muddy with extensive intertidal flat and saltmarsh. These estuaries were extensively embanked and reclaimed for agriculture in the 18th and 19th centuries, and much of this reclaimed intertidal area is still protected by flood embankments. Muddy sedimentation within the estuaries is sustained by long range fluxes of mud within the southern North Sea (Dyer and Moffat, 1998; French et al., 2008), since local cliff retreat contributes virtually no muddy material (Burningham and French, 2015).

Each of the complexes can be unpacked to reveal interactions between individual landforms and the varied engineering structures (groyne fields, seawalls, inlet jetties and extensive estuary flood embankments) and other non-structural interventions (which here include beach nourishment, re-profiling of beach ridges and dredging). Fig. 11 illustrates some of the local interactions between estuary and adjacent open coast in the vicinity of the Deben estuary inlet. This includes naturally occurring cyclical sediment bypassing via the ebb tide delta shoals (Burningham and French, 2006), that has historically sustained the downdrift Felixstowe frontage. This figure also illustrates the use of a LiDAR-derived elevation raster layer, a bathymetry vector layer and Bing aerial imagery to assist the mapping process within the CESM software.

The analytical capabilities of the CESM software are currently being developed and will ultimately include various measures to capture the relative occurrence of the various system components and the nature and extent (including the spatial scale) of their interactions. In its simplest form, the map of components and interactions presents a highly

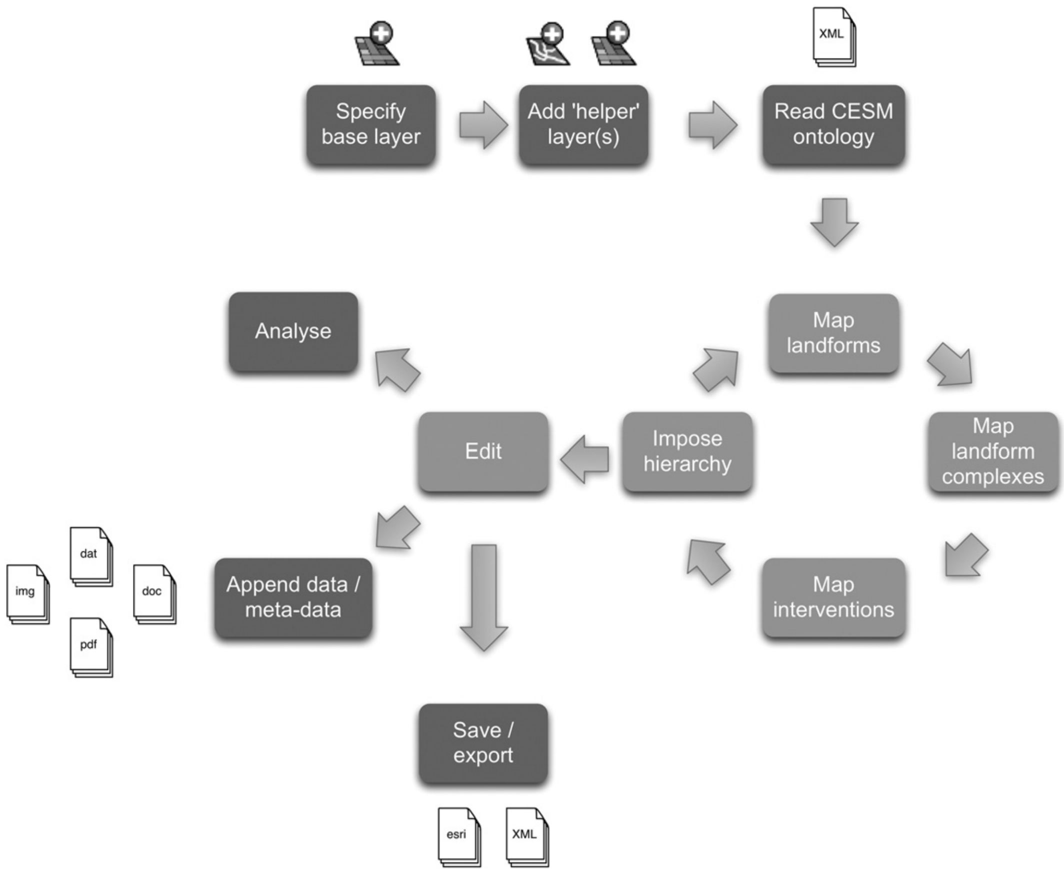

Fig. 9. CESM software (QGIS plug-in) architecture and workflow. At least one GIS base layer is required on which to interactively locate landforms, interventions and interactions. Helper layers (bathymetry, geology, flood defence lines etc.) can be used to inform the interpretation of the coastal and estuarine systems. Grouping into the landform complex hierarchy can then be carried out and the software will also support the appending of data or meta-data. Standard GIS and image output formats are supported.

accessible representation of the structure of the coastal and estuarine system. In the example above, landforms along the open coast are connected by a littoral sediment transport corridor that is intersected by the estuary inlets. Estuarine landforms are connected to more distant fine sediment sources through channel-open sea suspended sediment transport pathways. Whilst a multitude of network graph-based analyses are possible (see, for example, Phillips (2012)), more straightforward visualisations of the occurrence of the different landforms and interactions can be extremely effective as a means of communicating with stakeholders. For example, normalised interaction frequency matrices (Fig. 12) have generated considerable interest at stakeholder workshops conducted in the iCOASST project. This kind of diagram can be constructed in various ways. In Fig. 12, the direction of the interactions is neglected but bi-directional links are counted twice. Computed for the Suffolk coast, the interaction matrix illustrates the dominant sediment fluxes within the littoral (beach-beach/beach ridge) and estuarine (channel-channel/saltmarsh) subsystems. It also demonstrates the importance of embankments in exerting some control on estuarine landforms.

5. Discussion

5.1. Classification and knowledge formalisation

Conventionally, classifications have been widely employed within geomorphology to make sense of the diversity of coastal landforms and the contexts within which they emerge, and to provide a framework for both empirical and theoretical work (Finkl, 2004). The present work combines a spatial hierarchy of landform components and the functional interactions between them in an ontology that provides a rational basis for mapping the configuration of open coastal and estuarine geomorphological systems. These environments have hitherto largely been considered separately and this continues to be an area of weakness in shoreline management planning (Cooper and Pontee, 2006; Hunt et al., 2011).

CESM draws upon disparate sources of published research, data, and anecdotal knowledge to synthesise a qualitative understanding of the interdependencies between coastal and estuarine landform complexes that operate at decadal to centennial scales. A key aspect of this is the abstraction of geomorphological landscapes characterised by inherently ill-defined boundaries as discrete landform objects. Hanson et al. (2010) present a similarly generic scheme in which distinct cross-shore assemblages of landforms are identified, together with the constraining effect of defensive structures; the resulting alongshore matrix is then used to explore potential future changes, through application of a qualitative fuzzy-logic approach. The knowledge formalisation within CESM is less directly concerned with the potential for future change, but focuses instead on the elucidation of the complex web of interactions, nested at multiple spatial scales, that govern the aspects of coastal behaviour that contribute to progressive morphological change. These include the effect of a greater variety of engineered structures than considered by Hanson et al. (2010) as well as human interventions on the sediment budget. Identification of sediment pathways is not restricted to short-range fluxes of beach-grade material but also includes long-range fluxes of suspended mud. When mapping is extended to broad regional scales, the dependence of estuarine fine sediment sinks on distant coastal cliff sources can thus be resolved. In the form presented here, CESM is currently being applied within the iCOASST project (Nicholls et al., 2012) to identify potential mud transport pathways on the scale of the North Sea, which are being corroborated through shelf-scale coastal area

Fig. 10. Segmentation of Suffolk coastal behaviour system (approximately 77 km of coast between Lowestoft and Felixstowe, eastern England) into open coast, estuary and inner shelf complexes.

modelling. The coastal area modelling also highlights potential locations where exchange of sand between inner shelf and coast may be important; these can then be incorporated in the system maps and model-derived flux estimates for both mud and sand fractions appended to the associated geospatial database as attributes associated with the corresponding sediment pathways.

5.2. Insights into mesoscale behaviour as a prelude to process-based modelling

CESM endeavours to capture the spatial configuration of landform components and their interdependencies averaged over a 'management mesoscale' (Fig. 1; see also French et al., 2015) measured in decades to centuries. High order behaviour, including sub-annual (e.g. seasonal, event-driven, tidal and low-interannual (North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO)) variability is specifically excluded. This gives rise to a system description (in the sense of Robinson, 2011), which characterises those aspects of the real world that relate to a set of problems to be addressed. CESM also engages more directly with the modelling domain in that it can be used to identify aspects of real world behaviour that need to be included in model simulations. Most obviously, this includes the specification of landform behaviour models that aggregate morphological components and the processes that drive their evolution at scales appropriate to the investigation of low-order coastal change. Models at this scale tend to be synthesist rather than reductionist in nature (Paola, 2002; Murray et al., 2008). Exemplified by models such as SCAPE (Walkden and Hall, 2011) and ASMITA (Kragtwijk et al., 2004), they are readily applied at the scale of the landform complexes that constitute the intermediate level of aggregation in Fig. 2. As argued by Sutherland et al. (2015) and also Van Maanen et al. (2016), one of the most promising lines of activity now involves co-deployment of models via sophisticated external coupling interfaces.

Qualitative modelling, in its varied guises, can be extremely valuable as a precursor to quantitative modelling (Wolstenholme, 1999). At the scale of the landform complex, CESM provides a transparent basis for arriving at sensible model compositions. At the scale of landforms and human interventions, it also highlights critical components and linkages that need to be represented within any particular model. Payo et al. (2014) demonstrate the potential of Causal Loop Analysis (Forrester, 1968; Sanò et al., 2014) as an intermediate step that can provide valuable insights into the dynamics of a particular system configuration in terms of the most critical processes to include in a mechanistic model and also a priori insight into the qualitative behaviours (e.g. erosion or accretion; flood or ebb dominance) that can be expected.

As Phillips (2014) has argued, landform change is not manifest solely as incremental changes in position or rate but also occurs through qualitative changes in system state. Many of these are dynamic, in the sense that they relate to shifts in process regime, such as a transition from flood to ebb dominance or from import to export in terms of estuary hydrodynamics and sediment flux. Behaviour of this kind is generally well resolved by conventional sediment dynamics models. Such models tend to be discretised using fixed domains and computational grids and therefore struggle to accommodate gross changes in system configuration. Configuration state changes, such as the breaching of coastal barriers, are not especially prevalent at sub-annual to low inter-annual timescales but may be significant at decadal to centennial scales (e.g. Orford and Jennings, 2007). Phillips (2014) advances a convincing argument in favour of network representations of geomorphological systems as a basis for identifying and analysing historical contingency in landform evolution. We see similar potential in the application of CESM to identify alternative future states based on the formalisation of our knowledge of particular geographical contexts. By way of illustration, Fig. 13 shows the potential for locally divergent coastal futures on a stretch of the Suffolk coast that comprised alternating soft rock headlands punctuated by short sections of gravel barrier beach backed by shallow brackish lagoons (Spencer and Brooks, 2012). Here, system mapping (simplified for illustrative purposes) depicts a possible change in configuration at the landform scale resulting from a persistent breaching of one of the low gravel barriers, leading to the formation of a new tidal inlet complex. In modelling terms, this could be handled through an adaptive composition of coupled model codes, in which breaching is evaluated in terms of forcing and state parameters (e.g. using the Barrier Inertia Method; Obhrai et al., 2008). The likelihood of any barrier breach persisting could then be evaluated using an inlet stability analysis and, if necessary, a tidal inlet model invoked to accommodate the creation of a new complex of this type.

5.3. Towards a more participatory approach to coastal and estuarine management

The challenge of coastal and estuarine management is not simply one of devising models that can generate scientifically satisfying answers to questions generated by climate change science. Such efforts are clearly extremely important but, as in other areas of convergence between environmental science and policy, coastal problems increasingly require the combining of natural and social science perspectives and scientific and lay knowledges to achieve politically and socially acceptable solutions. A key aspect of this convergence has been the emergence of participatory modelling as a means of achieving meaningful engagement between scientists, policy makers and stakeholders (Voinov and Bousquet, 2010). There are several strands to this process. Communication is clearly of paramount importance as science has become almost wholly founded on models. Hall et al. (2014) draw parallels with climate science, where public understanding and confidence have been impaired by poor communication of the nature and purpose

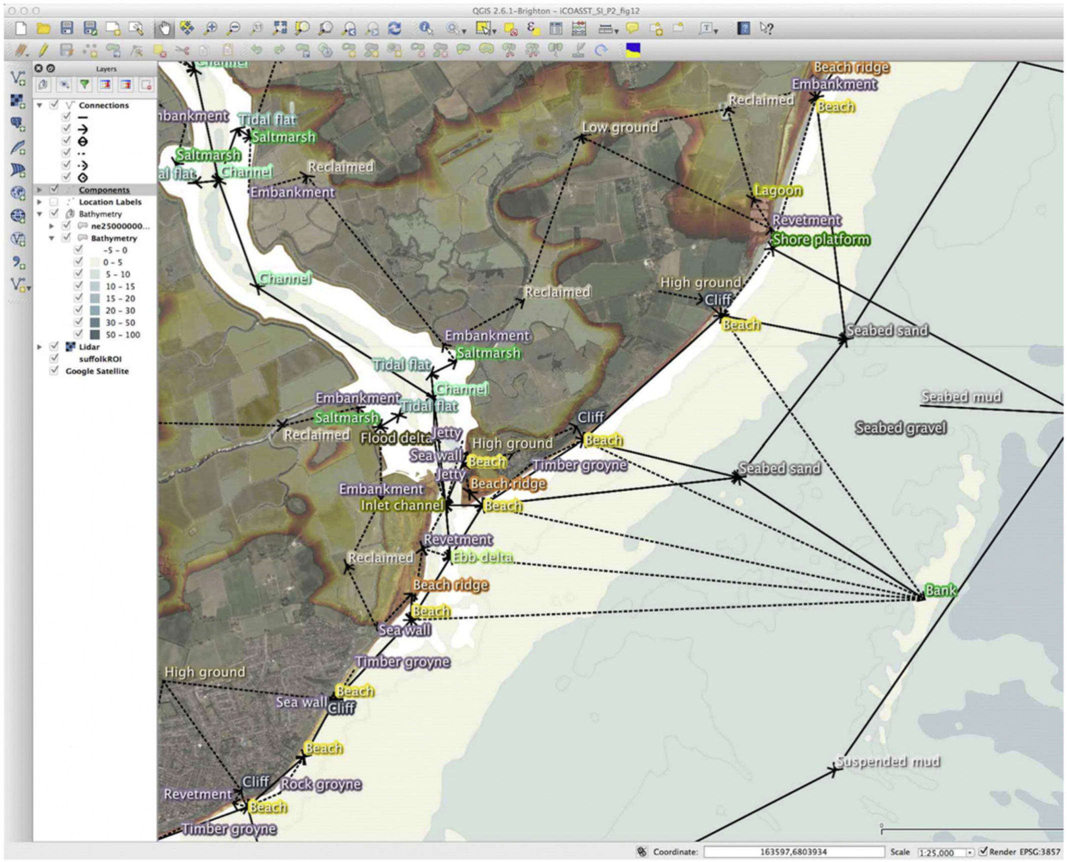

Fig. 11. Ilustrative screenshot of CESM QGIS plugin, showing interface between estuary and open coast complexes at the entrance of the Deben estuary. Background is a composite of aerial photography (source: InfoTerra) and intertidal LiDAR altimetry data (courtesy of the Environment Agency) and offshore bathymetry. Solid linkages represent sediment pathways and dashed pathways represent other influences (e.g. the sheltering effect of offshore banks on the beaches).

of simulation models. They further observe that it is not just articulation of the technical aspects of model formulation and application that are important, but also the provision of clear and unambiguous explanatory definitions for the basic concepts that underpin them. Qualitative modelling has a clear role here, especially as a means of arriving at shared understanding of the system being studied and the nature of the problems that need to be addressed. A plethora of approaches are pursued, in which systems thinking (Forrester, 1968) looms large. Some of these are especially well suited to the generation of consensus understanding, possibly among experts and more technically adept stakeholders. Casual Loop Analysis (Payo et al., 2014), for example, is a powerful tool for the model development community to tease out the most important qualitative behaviours that need to be resolved in system-level models. In simplified form, it can also be used to facilitate the prioritization of issues (e.g. Sanò et al., 2014).

As Hall et al. (2014) observe, it is equally important to achieve some fusion of scientific and lay conceptualisations of how the world works. From the perspective of post-normal science, a good model is not just one that best accords with theory and observation, it is one that also accounts for what citizens believe that they know about the place in which they live (Hall et al., 2012). The CESM approach that we have presented here is intended, at least in part, to engage with this challenge. It has the advantage of rendering the complexity of coastal and estuarine geomorphological systems as a fairly simple ontology of components and interactions, and depicting these in a visual form that provides a highly effective catalyst for discussion and debate between scientist, stakeholder agencies and organisations, and local citizens. Importantly, it also allows valuable local knowledge to be captured and incorporated into the formulation of a problem and the selection of appropriate modelling approaches – key elements of good modelling practise that have all too often been neglected (e.g. Schmolke et al., 2010).

CESM is transparent and accessible, partly through its implementation in open-source software; this counters one of the major shortcomings of the 'top down' approach to coastal planning that has historically been heavily reliant on proprietary closed-source model codes and GIS software available to the larger consultancies but not to local communities and smaller consultants. The open source paradigm of computer science is a good model here (Voinov and Gaddis, 2008), in that it demonstrates the benefits of genuine community effort, both in terms of transparency and assessibility and also in terms of legacy. It is very much hoped that CESM will facilitate consistency alongside stimulating a more participatory style of coastal and estuarine management. We also hope that the system maps that are generated will become openly accessible living products that evolve beyond individual project timelines through the continued involvement of a joint community of researchers and stakeholders.

6. Conclusions

Geomorphology is pivotal to understanding how coasts and estuaries, and their associated populations and infrastructures, will be impacted by climate change at decadal to centennial scales. Whilst our ability to predict such impacts is heavily dependent on quantitative models, we must also have conceptual frameworks that allow us to formulate management problems in a scientifically meaningful way. This problem is compounded by the pervasive influence of human agency on contemporary shorelines and the multitude of the stakeholders involved. Translation of research into policy thus requires frameworks that

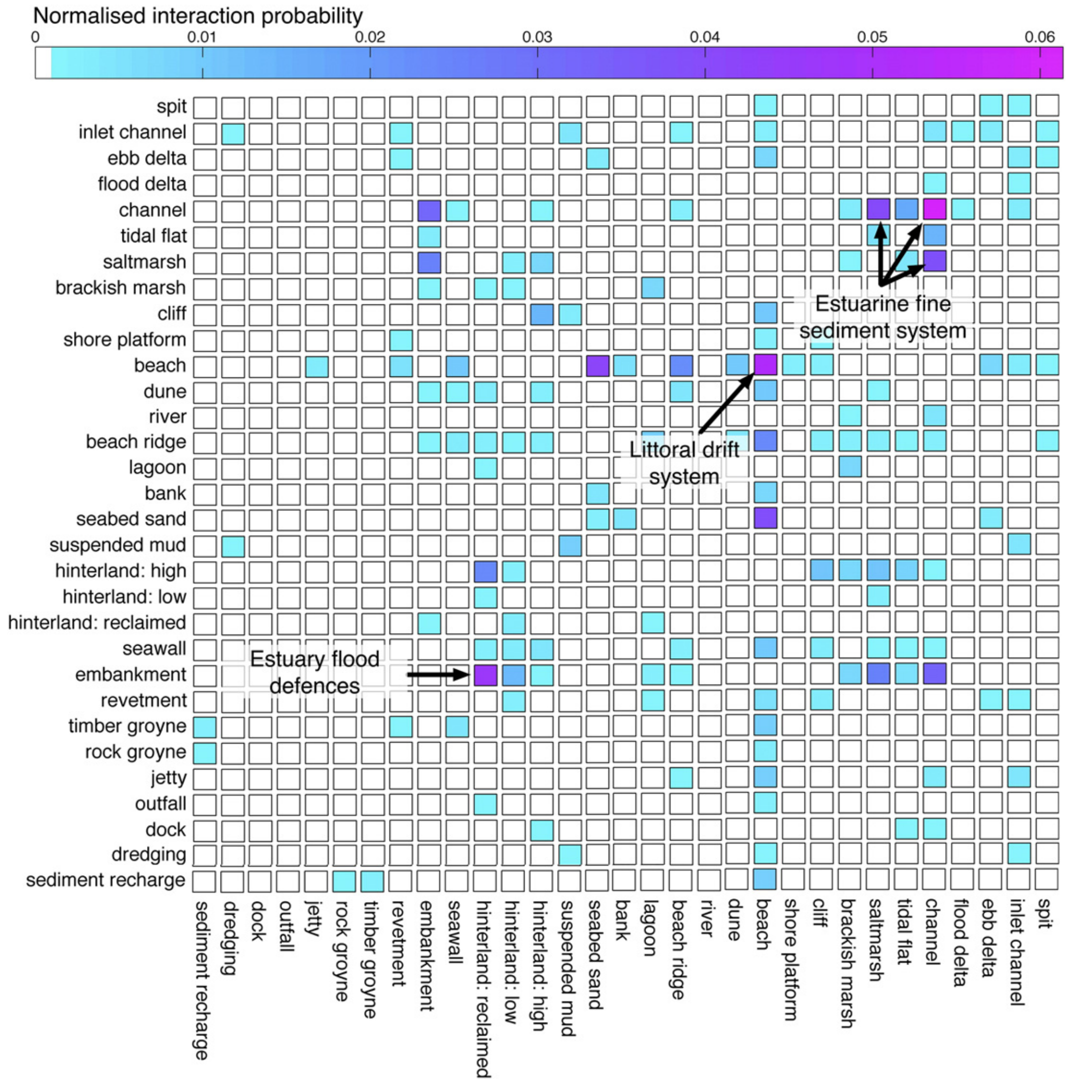

Fig. 12. Interaction frequency matrix (normalised against the total number of interactions) for landforms and human interventions within the whole the Suffolk coastal behaviour system (13 coastal, estuarine and shelf complexes; Fig. 10). White cells indicate interactions that do not occur in this system map, shaded cells show the varying probability of the interactions that do occur. As with the preceding figures, this is more about the concept than the detail. However, it should be noted that in, our mapping, ebb tidal deltas interact with inlet channels, rather than generic estuary channels (hence the lack of connection in the matrix; see also, Fig. 7b).

formalise scientific understanding of human–environment systems in a transparent and accessible way and also permit the assimilation of diverse lay knowledges as a basis for a more participatory approach to management planning.

Our approach to Coastal and Estuarine System Mapping (CESM) is intended to contribute to this interface between science, policy and management by offering a geomorphological framework that resolves a more complete web of interactions than the littoral cell-based segmentation that has hitherto been the basis for shoreline management planning. Although CESM remains a work in progress, its preliminary implementation as an open-source geospatial software tool demonstrates potential on several important fronts. Firstly, the use of a hierarchical landform ontology integrates estuary, coast and parts of the inner shelf in a coherent conceptual scheme that is able to accommodate multi-scale sediment sharing pathways and explicitly resolve the localized human interventions that constrain their natural operation. Secondly, the mapping process constitutes a form of knowledge formalisation in which disparate sources of information (published research, imagery, mapping, data etc.) are generalised into a conceptual model of geomorphological system configuration that can guide the development and application of predictive models. As a software product, the maps can also be converted into a geospatial database for both data and model outputs (not, least, estimated fluxes for the principal sediment pathways). Adoption of a rigorous mapping procedure should help with internal consistency and transferability of results, as well enabling meaningful intercomparisons to be made between contrasting systems. Thirdly, whilst configurational state changes (such as the creation of a new inlet following barrier breaching) are typically not handled well by reductionist hydrodynamic and sediment transport models, they could potentially be simulated using time-varying compositions of coupled coastal and estuarine models. Conceptualising the spatial structure of a geomorphological system in advance of model development and application allows for locally-divergent changes in configuration to be anticipated in the design of such model compositions, paving the way for broader-scale simulations of coastal behaviour that go beyond incremental changes in position and rate. Finally, CESM articulates 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 predictive models of mesoscale landform behaviour increase in ambition and sophistication, CESM provides a platform on which to build a more participatory approach to the conduct and communication of model-based coastal and estuarine science.

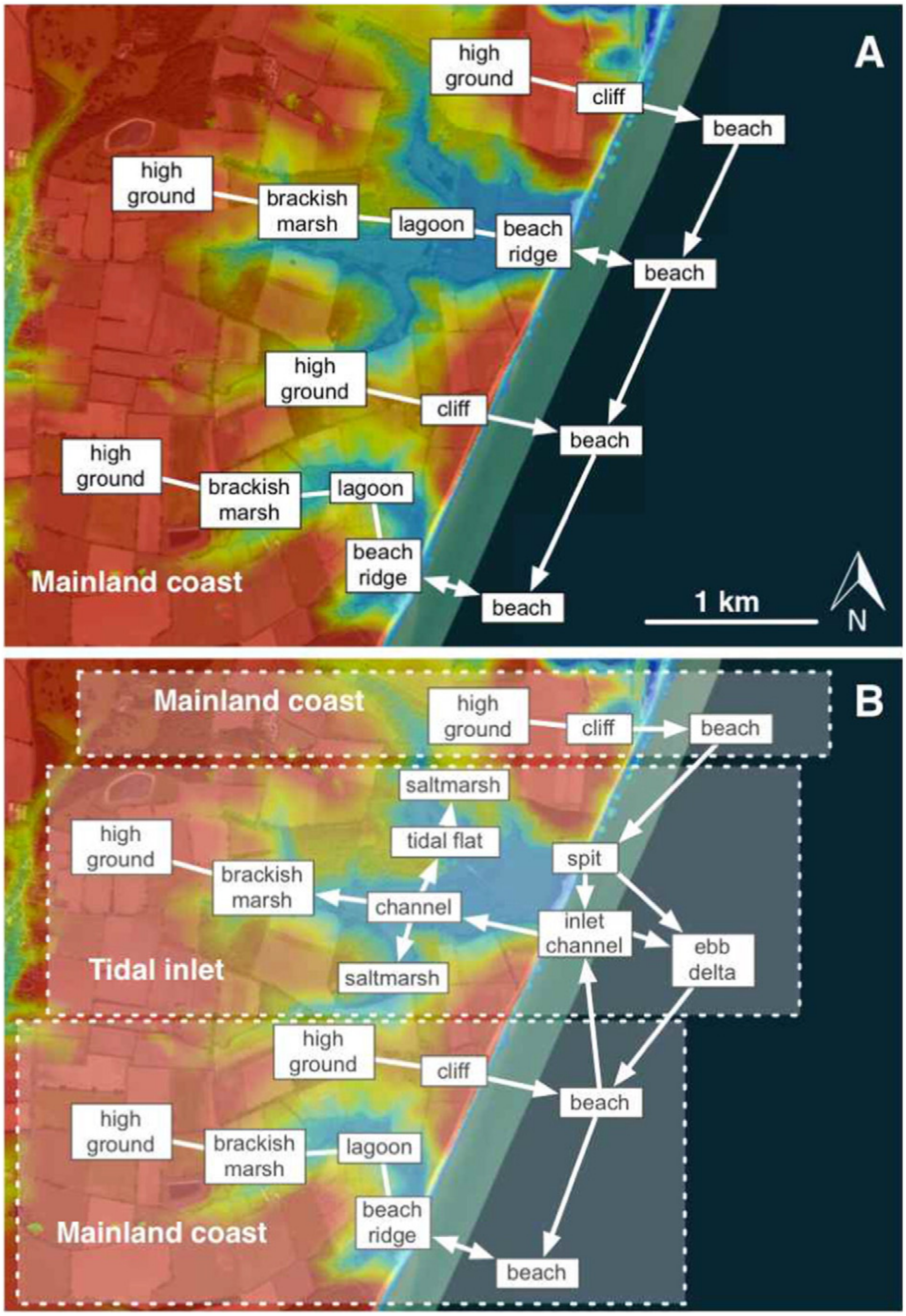

Fig. 13. Highly idealised mapping of a 5 km stretch of the Suffolk coast, eastern UK, illustrating A) the current mainland coast complex, dominated by a barrier beach backed by alternation of brackish lagoons and elevated cliff headlands; and B) a potential future configuration following hypothetical barrier breaching and the creation of a permanent tidal inlet.

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