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CoastalME version 1.0: a Coastal Modelling Environment for simulating decadal to centennial morphological changes

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Abstract. Modelling coastal morphological changes at decadal to centennial time scales is required to support sustainable coastal management world-wide. One approach involves coupling of landform-specific components (e.g. cliff, beach, dunes, estuaries, etc.) that have been independently developed. An alternative, and novel approach explored in this paper is to capture the essential characteristics of the landform-specific models using a common spatial representation within an appropriate software-environment. In the proposed Coastal Modelling Environment (CoastalME), change in coastal morphology is formulated by means of dynamically linked raster and geometrical objects. A grid of raster cells provides the data structure for representing quasi-3D spatial heterogeneity and sediment conservation. Other geometrical objects (lines, areas and volumes) that are consistent with, and derived from, the raster structure represent a library of coastal elements (e.g. shoreline, beach profiles and estuary volumes) as required by different landform-specific models. As a proof-of-concept, we illustrate the potential capabilities of CoastalME by integrating a cliff-beach model. We verify that CoastalME can reproduce behaviours of each individual landform-specific model. Their integration within the framework of CoastalME reveals behaviours that emerge from landforms interaction and which have not previously been captured, such as the influence of the regional bathymetry on the local alongshore sediment transport gradient. This is the first step of the framework development, which provides an alternative to directly coupling existing models.

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1 Introduction

Coastal managers worldwide are planning for decadal to centennial time horizons (e.g. Nicholls et al., 2012) and assessing longer-term adaptation measures (Brown et al., 2014; Hall et al., 2012). However, quantitative prediction of morphological coastal changes at meso-scales (decades to centuries and 10s to 100s of km) is scientifically challenging. Reductionist models that integrate small-scale processes have proven to be of limited use, both because of the accumulation of small errors over long timescales and because of the omission of processes that govern long-term change (de Vriend et al., 1993; Murray, 2007; Werner, 2003). Faced with these limitations of bottom-up physics-based models, coastal geomorphologists have begun to adopt simpler behaviourally-based approaches. These seek to represent the main physical governing processes at appropriate time and space scales (e.g. Cowell et al., 1995; French et al., 2016b; Murray, 2013). Central to these approaches has been selective, even reductionist, characterisation of the coastline: thus we have seen the development of models which simulate the temporal evolution of a range of individual elements of coastal morphology, such as coastal profiles, shorelines or estuary volumes. But modelling of complex coastlines involving multiple landforms (for examples beaches and tidal inlets) require consideration of interactions between the component landforms, subject to the principles of mass conservation. This is difficult and modelling these interactions is still not commonplace.

One possible way forward is the development of model interfaces; software wrappers that allow coupling of models that have been developed independently (Moore and Hughes, 2016; Sutherland et al., 2014). Significant effort has been expended in this direction during the last decade, in particular by theOpen Modelling Interface (OpenMI) and Community Surface Dynamics Modelling System (CSDMS). OpenMI emerged from the water sector as a way to link existing stand-alone models that were not originally designed to work together (Gregersen et al., 2005), while CSDMS draws on a large pool of open-access models well understood models (Hutton et al., 2014). The promise of OpenMI and CSDMS is to provide a unified system in which various models can be linked to explore broader system behaviour. However, a range of challenges exist when linking component models in this way, including non-trivial technical issues concerning variable names and units (Peckham et al., 2013), and difficulties associated with fully accounting for the cumulative effect of various assumptions and uncertainties in the constituent models. Furthermore, software-coupling frameworks are themselves completely agnostic with regard to the spatial structures of component models. This creates a significant challenge, due to notable inconsistencies in the conceptualisations of geometries, volumes and locations of sediment between existing Large Scale Coastal Behavioural (LSCB) models (Terwindt and Battjes, 1990). For example, the Soft Cliff and Platform Evolution (SCAPE) model assumes a beach of finite thickness perched at the top of the bedrock shore profile, while one-line approaches assume infinite beach thickness (Payo et al., 2015).

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Integrated modelling of complex coastal behavioural systems should, ideally, enable and encourage consistent treatment of the entities that are being modelled. Thus integrated modelling must go beyond the software coupling issues that have been the focus of OpenMI and CSDMS and deal more directly with the semantics of the various entities being modelled. We propose that one fruitful way to address this is by a modular, object-oriented framework in which these entities are the primary constructs. In other words, the objects which interact within the framework should correspond to the main constructs considered -- individually, so far -- by modellers of coastal behaviour. Of course, such an approach is dependent on an agreed ontology. Here, we have adopted the ontology suggested by French et al. (2016a), which includes both human interventions (structural and non-structural) and natural landform components (Table 1).

CoastalME (Coastal Modelling Environment) is a new approach to model integration which is conceptually consistent with existing LSCB models and which is flexible enough to incorporate multiple coastal landform complexes. Our aim is to achieve tight dynamic model coupling by capturing, within an appropriate modular framework, the essential characteristics of several models that have a long history of stand-alone use. These 'essential characteristics' are encoded within CoastalME as behavioural rules derived from these existing models. This approach circumvents difficulties associated with passing variable information between stand-alone models as discussed above by ensuring that the behavioural rules that represent the constituent models are consistently coupled with a clearly-defined spatial domain, exchanging information at the timestep invoked by CoastalME. The modularity of the approach also provides flexibility with regard to which behavioural rules are implemented, as long as the rules are implemented on an explicitly defined and consistent geometry and are subject to waves and Still Water Level (SWL) forcing from the model boundaries.

In this paper, we provide a detailed description of the CoastalME framework and we illustrate a proof-of-concept of its integrative capacity by unifying independently developed cliff and beach models. Validation of the geomorphological outcomes of model runs against real-world data will be the subject of a future study.

1.1 Determinants of large scale coastal behaviour

The dynamic behaviour observed in coastal geomorphology is the result of complex feedback relationships linking hydrology, sediment transport and resulting bed evolution, driven by time-variant or stationary boundary conditions and modulated by the underlying geology (e.g. Cowell et al., 2003). While coastal scientists do not have a full understanding of the key processes

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that control the dynamics of coastal morphology as observed at meso-scales, there are a number of processes that have consistently been identified as important during many years of research:

- Gradients in wave-driven alongshore transport related to coastline shape provide the alongshore connectivity between different landform specific models(Murray et al., 2013; Werner, 2003).
- Sediment sources and sinks in the nearshore system generate an alongshore-propagating curvature and shoreline change signal. Sources and sinks include human manipulations (localized sources or sinks), river mouths (sources), eroding cliffs, spits that grow into bay or estuary mouths, and to sediment fluxes to or from the continental shelf (e.g. Woodroffe, 2002).
- Wave-shadowing effects from protruding coastline features such as headlands, which tend to create a down-drift zone of diverging alongshore flux and associated shoreline response (e.g. Ells and Murray, 2012). Emergent coastline features such as cuspate capes and spits (Ashton et al., 2001; Ashton and Murray, 2006), which contribute autogenic wave-shadowing effects and result in shoreline undulations.
- Underlying lithology and coastline topography effects, which exert significant influence on shoreline change rates, in combination with both alongshore transport gradients and sea-level rise (Carpenter et al., 2015; Valvo et al., 2006; Walkden and Hall, 2011).
- Beach-cliff interactions, which influence the local cliff and shore platform erosion rate and provide as a significant sediment source (Payo et al., 2014; Walkden and Dickson, 2008).
- Estuaries and tidal inlets are net sediment importers and/or exporters from/to the open coast (de Swart and Zimmerman, 2009) and controlled by a number of ecological processes (Friedrichs and Perry, 2001)

1.2 Lessons from existing LSCB models

A commonality of most LSCB models is the use of simple geometries to represent complex real-world 3D coastal geomorphology. Profile models, coastline models and volumetric models are the three most prominent approaches used to formulate the meso-escale coastal morphodynamics. Coastal profile models simplify the coastal system to a 2D system (with elevation and cross-shore distance being the two dimensions) which assumes longshore uniformity. In coastline models, the sand beach morphology is represented by a single contour, and such models are therefore often referred to as “one-line” models. Volumetric model represents the different landforms as sediment sharing entities. Examples include: COVE by Hurst et al. (2015), SCAPE by Walkden and Hall (2005), and ASMITA by Stive et al. (1997). These three models are selected because of the breadth of landforms represented (sandy coast, cliffed coast, and estuaries, respectively). More comprehensive reviews of LSCB modelling approaches are available elsewhere (e.g. de Vriend et al., 1993; Fagherazzi and Overeem, 2007; Hanson et al., 2003).

The Coastal One-line Vector Evolution (COVE) model is a special case of a 'one-line' model designed to handle complex coastline geometries, with high planform curvature shorelines (Hurst et al., 2015). COVE is inspired on the Coastal Evolution Model of Ashton et al. (2001) but including wave refraction around headlands. The shoreline is represented by a single line (or contour) that advances or retreats depending on the gradient of alongshore sediment flux. One-line models make a number of simplifying assumptions to conceptualise the coastline in a way that is consistent with this single-line representation:

- The beach profile is thus assumed to maintain a constant time-averaged form. This implies that depth contours are shore-parallel, and allows the coast to be represented by a single contour line.
- Short-term cross-shore variations due to storms or rip currents are considered to be temporary perturbations of the long-term trajectory of coastal change (i.e. the shoreface recovers rapidly from storm-driven and tidal-driven cross-shore transport).
- Wave action is considered to be the main driver of alongshore sediment transport within the surf zone, and this may be represented by the height and angle of incidence of breaking waves. Gradients in alongshore transport therefore dictate whether the shoreline advances or retreats, and whether depositional landforms diffuse, migrate or grow.

A key innovation of COVE is that it uses a local, rather than global, coordinate scheme, requiring that coastal cells take on a variety of polygonal shapes such as triangles and trapezoids (Fig. 1). The coastline is represented as a series of nodes, each of which is associated with a single polygonal cell; between-cell boundaries are created by projecting cell boundaries perpendicular to the local shoreline orientation. Bulk alongshore sediment flux is driven by the height and incidence angle of breaking waves. Offshore waves are transformed according to linear wave theory, assuming shore-parallel depth contours.

The Soft-Cliff and Platform Erosion (SCAPE) model was introduced by Walkden and Hall (2005) and has subsequently been used to explore (i) the plan-shape evolution of soft-rock cliffs over relatively broad scales under varied climate and management scenarios (Dickson et al., 2007; Walkden and Hall, 2011), (ii) the impacts of sea level rise on cliff recession rates (Walkden and Dickson, 2008); and (iii) the effects of rock heterogeneity on rates of coastal cliff retreat (Carpenter et al., 2015; Carpenter et al., 2014) and (iv) the interactions of cliff units separated by low-lying topography (Walkden et al., 2015). SCAPE is a time-stepping model of soft-shore recession and morphological change on a profile which is normal to the coastline. It includes both process descriptions and behaviour-oriented representations. Beach sediment volume are quantified and conserved, although fine-grained sediments are assumed to be lost from the system. Sediment is released to the beach through

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rock erosion and is then moved across and alongshore. The beach form is assumed to be in a morphological steady state, which is consistent with a one-line model, since its profile is unchanging in time, whilst being translated landward or seaward during the simulation (Fig. 2). Alongshore variations in beach volume are captured by the representation of a series of shore-normal profiles. Beach volumes at each shore-normal profile are increased or decreased at each time step by the amount released from the rock to the beach system, and by gradients in alongshore sediment flux, including transport across the littoral boundaries. Alongshore sediment flux is determined using either the CERC equation provided in the Shore Protection Manual (CERC, 1984) or the expression provided by van Rijn (2014). Rock erosion rates are calculated using a modified version of the expression provided Kamphuis (1987).

The Aggregated Scale Morphological Interaction between Inlets and Adjacent Coast (ASMITA) model is a behaviour-oriented model that describes the evolution of a tidal inlet towards an equilibrium which is forced by external conditions and constrains by geometric interventions (Stive et al., 1997; Townend et al., 2016). The ASMITA concept has been applied to simulate the effects of the closure of tidal basins, dredging and dumping of sediment, and sea-level rise, on both hypothetical and real tidal basins (Rossington et al., 2011; Van Goor et al., 2003). ASMITA conceptualizes the estuary as a highly schematised representation of morphological geometric elements, for example the ebb-tidal delta, sub-tidal channel, and intertidal flats (as found on barrier island coasts such as the Wadden Sea. The most important assumption underpinning the ASMITA conceptualisation is that a morphological equilibrium for each estuary element is a function of the controlling hydrodynamic (e.g. tidal prism, tidal range) and on morphometric conditions (e.g. basin area). The tidal system can thus be schematised (Fig. 3**)** as one, two or three sediment-sharing elements involving the ebb-tidal delta, channel and tidal flat. Ebb-tidal deltas are important sediment reservoirs that may supply the tidal system with sediment, unless the delta is sediment-starved, in which case the system may demand sediments from the adjacent coast. The volume of an ebb-tidal delta can be defined assuming the coast is undisturbed by a coastal inlet, and therefore its bathymetry is assumed equal to that of the adjacent barrier coast. Thus in ASMITA, the volume of the ebb-tidal delta is equal to the volume above this virtual no-inlet coast.

1.3 Rationale

The LSCB models outlined above each have different sediment conservation and morphological updating principles, each operate on a different abstraction of coastal geometry, and each use different sediment accounting structures. However, they also have some salient attributes which potentially provide a basis for a shared generic geometric and sediment budget modelling framework. In particular, we observe that:

- All of the mesoscale models under consideration conserve sediment volume/mass.
- Sediment is storage as deposited material (gravel, sand, mud) or suspended sediment.
- All LSCB models typically involve some characterisation of hydrodynamic forcing (e.g breaking wave height and direction, 1D estuary water levels and tidal flows, fetch-limited estuary waves heights). Calculation of these forcing parameters is carried out in one of two ways: either based on a coastal geometry (e.g. a shore profile, estuary bathymetry), or by means of hydrodynamic forcing (e.g. wave and tide fields) imported from a 2D hydrodynamic model;
- The most general form of sediment accounting is on a two dimensional horizontal grid (2DH) (e.g. TIN, regular, curvilinear, quad-tree, raster); 1D geometries (e.g. shore profiles or a one-line model) may be represented with a 2DH;
- Behavioural models operate on some abstraction of a full 3D topography/bathymetry (e.g. shorelines, shore profiles, sandbank/delta volumes, estuary volumes/cross sections, estuary channel networks, mudflat areas), and appropriately make some classification of the modelled landforms (e.g. one-line models apply to curving sandy rich coastlines, SCAPE models apply to shore profiles);

Thus we suggest that these existing LSCB models have, along with other existing LSCB models, the potential to be integrated within a generic modelling framework, which emphasizes the above-listed salient attributes. In the next section we describe the initial implementation of such a framework.

2 Description of the CoastalME generalised concept

2.1 The model’s spatio-temporal domain

CoastalME’s representation of space, and of the changes occurring within its spatial domain, involves both raster (i.e. grid) and vector (i.e. line) representations of spatial objects. The novelty is that the data are routinely and regularly transformed between these two representations during a simulation.

A coast is an approximately linear boundary between sea and land: hence (and unsurprisingly) coastal modelling has a strong historical emphasis on linear – i.e. vector – models (see the discussion of LSCB models above). It was clear from the outset that CoastalME would build upon this tradition and so would use 2D vector representations of coastal features.

However, a raster grid – comprised of multiple cells, usually square or rectangular – is a widely-used alternative approach to representing 2D space. Raster grids have several attractive features when used for the acquisition, storage, and manipulation of spatial data (e.g. Densmore et al., 1998). Data such as topography are readily available in grid form and linkage with other environmental models is facilitated, since such models often output their results as raster grids. Cellular Automaton (CA) models, for example, operate upon regular grids and have taught us much regarding the spatial patterns produced by emergent behaviour (e.g. Dearing et al., 2006; Favis-Mortlock, 2013; Murray et al., 2014). The desirability of using raster grids for CoastalME's data input, storage, and output became obvious at an early stage in CoastalME's design. Thus linear objects would be used to describe morphological change, but sediment exchange, which represents the key source of information exchange within the framework, would occur on a raster grid, thereby providing consistent sediment accounting across the coastal domain (Fig. 4).

But a raster grid also has a number of disadvantages. The first is the creation of axially-aligned spatial artefacts: it is not trivial to ensure that cell-to-cell movement is uninfluenced by the alignment of the grid's axes. To achieve this invariably involves some computational expense. More seriously, there is also the problem of spatial precision and computational needs. The cell is the smallest spatial unit of the grid, so small spatial features can only be adequately captured by using small grid cells. Similar reasoning applies when there is a need to represent cell-to-cell flows that are fast-moving relative to cell size: then the requirements of the Courant-Friedrichs-LewyCondition -the time step must be kept small enough so that information has enough time to propagate through the space discretization Weisstein (2016)- also necessitate the use of small cells. A third consideration regarding cell size results from the tendency of the dominant geomorphological process to change with change in spatio-temporal focus (Schumm and Lichty, 1965). But as raster cells shrink and grid sizes grow, computational requirements increase non-linearly. If the majority of grid cells are involved in computation during most of the simulation, the increase in computational requirements may be roughly the square of the ratio of decrease in cell side, or even worse (Favis-Mortlock, 2013).

However, coastal modelling – with its strongly line-oriented focus – does not require an egalitarian treatment of grid cells. The computational focus is on a subset of grid cells, with much less happening, computationally-wise, on the remainder of the grid. So during early planning of CoastalME, we reasoned that despite our need for small cells (since we would be dealing with small features, and sometimes with fast-moving fluxes) and hence a large grid, only relatively few cells within that grid – those on or near the coastline – would be computationally expensive. This was reassuring, as there would of course be a computational overhead associated with conversion of spatial features between vector and raster representations.

In summary, CoastalME's hybrid raster-vector structure involves a trade-off between increased complexity (due to the need to transform between raster and vector representations) and parsimonious spatial structure (because the majority of computation involves only cells on or near the coast). By contrast, the model's treatment of simulated time is conventional. There is a fixed timestep which can, in principle, be of any duration. In practice, however, there are constraints on timestep duration due to cell size and the Courant-Friedrichs-Lewy condition.

2.2 Inputs and outputs

Input parameters for a model run consist of a set of raster files, and a text file containing configuration parameters, together with optional text-format time series files. Model output of the model consists of GIS layer snapshots. These include both raster layers such as Digital Elevation Models (DEMs) and sediment thickness, and vector layers such as the coastline. Optionally, there is also the ability to output snapshots of individual geometrical objects such as the shore profile.

As a minimum, two raster input files are required. These are (i) a basement file giving the elevation of non-erodible rock that underlies (ii) a single sediment layer giving the thickness of a single sediment size fraction, either consolidated or unconsolidated. More sediment layers, representing other sediment size fractions (both consolidated and unconsolidated) may be specified if desired. Non-consolidated layers are implicitly assumed to lie above non-consolidated sediment layers. Unlike other LSCB models, such as one-contour models, CoastalME does not require the user to define the shoreline location at the initial time step: this is done by the model, from layer elevations and from the initial SWL (specified in the configuration file), both at the beginning of the simulation and subsequently.

Figure 5 illustrates the model's conceptualization of sediment layers. Whilst the basement is a non-erodible layer, consolidated and unconsolidated sediment layers may increase or decrease their thickness during a simulation. Each of these sediment layers comprises fines, sand and coarse sediment. Any of these size fractions may be omitted for some or all raster cells, in which case the model will assume zero thickness of this size fraction for that raster cell. The size fractions within a layer are assumed to be well mixed. Here, consolidated sediments are considered to be essentially solid rock comprised of materials that have been metamorphosed or cemented together such as sedimentary rocks, including conglomerate, sandstone, siltstone, shale, limestone, and coal. Unconsolidated sediments are considered to be loose materials, ranging from clay to sand to gravel (sediment grain sizes are user-defined in the model's configuration file).

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The sediment mass transferability between these six different types of sediment (three sediment size fractions and two consolidation states) is hard-coded within CoastalME. Consolidated coarse and sand sediment fractions, when eroded, are assumed to become part of the unconsolidated coarse and sand material. In the present version of the model, eroded fine material is simply assumed (as in SCAPE) to become part of a global suspended sediment fraction.

In CoastalME, the framework convention for wave direction is the 'true north-based azimuthal system'. This is the oceanographic convention in which zero indicates that the waves are propagating towards the north, and 90 degrees indicates that waves are propagating towards the east. Shoreline orientation is also measured clockwise relative to the azimuth following the convention shown in Fig. 6, with shoreline orientation being 0 degrees when oriented S-N and 90 degrees when oriented W-E.

2.3 Within-timestep data flow and operations

Figure 7 illustrates the raster-to-vector transformations which take place during a single CoastalME time step. Vector coastlines and estuarine thalwegs are traced upon the raster grid. Vector lines are then generated which are normal to the coastline and which extend in a seaward direction. Vector polygons are created by joining (as needed) these coastline normals at their seaward ends. These vector objects are then used to calculate sediment erosion, movement, and deposition during the time step. The resulting changes in sediment thickness are stored in the raster grid, and all vector objects are destroyed. The cycle is repeated until the end of simulation period is reached.

Model operations during a single timestep as envisaged in the complete CoastalME are summarised below. Section 3 of this paper describes some of these operations in greater detail.

1. Any change in human intervention (i.e. construction of seawalls, beach nourishment, dredging…) is read.
2. Any changes to the external forcing are also read in: here, ‘external forcing’ values affect both the SWL, which is defined as the elevation of the sea surface in the absence of wind waves and tides; and the deep-water properties of incoming waves (wave height, peak period and direction) i.e. as unaffected by shallow-water refraction, shoaling and shadowing. SWL can be fixed or assumed to change linearly every time step so at the end of the simulated period the user defined sea level change is achieved.

3. The shoreline is traced on the raster grid as the intersection of the ground elevation and the current SWL. We use the wall-follower algorithm (Wikipedia, 2016) for this. The inevitable angularity of raster-traced 'lines' means that smoothing of the coastline is necessary. For this, the user may choose to use either a simple moving average or Savitzky-Golay smoothing – smoothing by fitting successive sub-sets of adjacent data points with a low-degree polynomial by the method of linear least squares, Savitzky and Golay (1964)-.
4. Estuaries appear as interruptions of the shoreline. Estuary morphodynamics are mostly driven by processes along the main channels, which can be described in terms of the thalweg -- the line of lowest elevation within the estuarine valley – rather than the normal to the shoreline (see below).
5. The model classifies coastal landforms, using a series of behavioural rules.
6. Coastline-normal profiles are now generated, with the elevations of these normals taken from the centroids of cells in the raster grid. The along-coast spacing of these coastline-normal profiles is at present approximately specified by the user, however this spacing is modulated both by coastline curvature and (optionally) by a random factor. The seaward length of the coastline-normal profiles is currently a user-specified value. As with the coastline, some smoothing of the elevation profiles is necessary. Where coastlines meet the edges of the raster grid, extra profiles are added which follow the grid edge but which are not usually normal to the coastline.
7. Check whether, in plan-view, any two coastline-normal profiles intersect. If so, both profiles must be merged seaward of the point of intersection. This is necessary because the coastline-normal profiles also serve as boundaries between coastal polygons (see below). The process is repeated until no two coastline-normal profiles cross.
8. Coastal polygons are generated. These are broadly similar to the coastal polygons of COVE.
9. Moving coastwards along the coastline-normal profiles, we next calculate wave attributes as in COVE. This enables us to identify the depth of breaking and the extent of the active zone for every coastline-normal profile. Values for wave attributes are then interpolated to the near-coast cells of the raster grid, using a distance-weighted average of values from the up-coast and down-coast coastline-normal profiles.
10. Consolidated cliff and shore platform morphology changes more slowly and is calculated before changes in unconsolidated topography. We use an implementation of SCAPE (see details below) for this. Values for potential platform erosion (i.e. not considering the availability of sediment) are calculated along the coastline-normal profiles. We interpolate these potential platform erosion values to the near-coast raster cells, again using a distance-weighted average of values from the up-coast and down-coast coastline-normal profiles. The actual (i.e. supply-limited) values for platform erosion are calculated along the profiles. The relative erodibility of each of the three sediment size classes is specified in the user configuration file. These values for actual platform erosion are then interpolated to the near-

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coast raster cells by creating a series of temporary elevation profiles each of which is parallel (in plan view) to the up-coast or the down-coast coastline-normal profile. Sand- and coarse-sized consolidated sediment eroded on each cell is added to the unconsolidated sediment on that cell (as with SCAPE, we currently just accumulate eroded fine sediment in a global total). Protection of the shore platform by overlying unconsolidated sediment is handled as in SCAPE.

11. Cliff collapse is represented in a way that is broadly similar to SCAPE's approach. However our need to use raster blocks means that we must represent this as a change in elevation rather than a change in coast-normal length, which is SCAPE's representation. This necessitates a slightly different algorithm, which is explained in detail in the next section. Collapsed material is distributed as talus on the cells seaward of the point of collapse by iteratively fitting a Dean profile to the talus (see next section).
12. The alongshore unconsolidated sediment transport budget between all sediment-sharing polygons along the coast object is calculated. First, potential erosion for each polygon is quantified using bulk alongshore sediment fluxes equations, and the direction of unconsolidated sediment movement (up-coast or down-coast) between adjacent polygons is determined. This enables us to construct a net potential unconsolidated sediment budget for each polygon
13. For polygons that experience net potential erosion, we calculate the actual (supply-limited) unconsolidated sediment erosion. We then use this value to calculate actual deposition of sand- and coarse-sized unconsolidated sediment (again: at present, eroded fine sediment is just accumulated) on polygons which experience net deposition. To determine change in unconsolidated sediment thickness for all cells within each polygon, we iteratively fit Dean profiles (see next section).
14. Revised elevation profiles and sediment thicknesses are then translated to the raster grid object. Some smoothing of the raster grid is carried out.
15. The model outputs (if desired) spatial patterns as GIS raster or vector layers. It also outputs totals for this timestep.
16. Finally, the updated raster grid becomes the initial raster grid for the next timestep. This loop is repeated until the end of the simulation is reached.

2.4 Modularity, implementation and design

Modularity is a fundamental requirement of the design of CoastalME. In order to facilitate capture of the 'essential characteristics' of component models as discussed above, it must be relatively easy for a model user to 'exchange' some part of the CoastalME framework with another software component that provides the same within-model functionality. At its

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simplest, this might involve replacing the code for alongshore bulk sediment transport equation, or less trivial such as replacing the current wave routing approach with a different approach.

To achieve this kind of plug-in modularity, CoastalME adopts the object-oriented architecture design and programming paradigm (e.g. Rumbaugh et al., 1991). Conceptually, the modelling framework comprises software objects, which are instances of software classes. The inputs and outputs of each software object are clearly specified: this enables one software object to be replaced with another, provided that both offer identical inputs and outputs. Thus a software object that supplies an equivalent functionality within CoastalME (e.g. computation of shore platform erosion) may straightforwardly be swapped for another, provided that the replacement software object offers equivalent functionality (as defined by its inputs and outputs).

The model framework (currently about 17000 lines of c++) uses only standard c++ libraries to maximize portability, with one exception: GDAL (Geospatial Data Abstraction Library: Open Source Geospatial Foundation, 2016) which is used to read and write the GIS outputs. Thanks to the functionality of GDAL, CoastalME is highly flexible regarding the raster input formats which it can read, and the raster and vector output formats which it can output. The user-preferred raster input/output format is defined, among others, in the configuration parameter file (code availability).

The main software classes, with some of their key attributes, methods and interdependencies are shown in Fig. 8. The simulation class runs CoastalME and has a bidirectional association with the classes RasterGrid, Coast, Landform and Intervention classes. The RasterGrid class comprises multiple Cell objects, each of which contains information about topography and stratigraphy at a point within the model's spatial domain. The Coast class represents not only the vector shoreline but also the vector shoreline-normal profiles. The Landform class is a generic representation of the different types of coastal landforms that can be found in the coastal zone, such as a cliff or estuary. Specific coastal landform classes inherit the attributes and methods of the generic Landform class but each one adds some landform-specific attributes and methods: e.g., an estuary has attributes such as an area at high and low tide and a tidal prism, while a cliff has information relating to incised notches. In addition to these classes, CoastalME contains a reduced set of geometrical classes such as Line, CoastalPolygon, 2DPoint and 2DShape that are used to construct the attributes of the above mentioned main classes and provide the user with a set of useful tools for building new classes, attributes and methods. To operate with both raster and geometrical objects, the Simulation class has available several GIS utilities e.g. for reading/writing data. A full list of software classes included in CoastalME is found in the online documentation of the model (see code availability).

3 Example application of CoastalME: integrating a one-line model with a cliff-beach model

In this section we illustrate how SCAPE and COVE behaviour can be reproduced within CoastalME. By integrating these two models, we obtain a simulation model that is able to reproduce cliff-beach-shore platform interaction for very irregular coastlines in a conceptually coherent framework. The generic model activities has been outlined above and the details on how these cliff and beach model has been integrated is explained in detail in this section.

3.1 Generation of coastline, profile normal and sediment sharing polygons

At the beginning of each time step the external forcings (SWL and waves) are updated from the user-defined inputs and assumed constant during each individual time step. The shoreline is located by intersecting the current DEM and the SWL using a locate-coastline algorithm which first marks all raster cells belonging to the shoreline and then generates a coastline geometrical object. A coastline geometrical object is equivalent to the idea of a coastline and is a line made up of a set of consecutive nodes, where each node has an associated location (x, y, z=SWL+ tide) in the global reference system but also holds local attributes such as curvature and orientation relative to the azimuth.

A set of profiles normal to the coastline, with an approximately user-defined along-coastline spacing, are also created. In addition, the user may specify a random component to profile spacing, so that profiles shift somewhat from timestep to timestep; this aims to reduce the impact of any artefacts arising from profile location. The model also preferentially locates coastline-normal profiles on 'capes' (portions of the coastline with maximal convex curvature), and preferentially does not locate profiles in small and tight bays (portions of the coastline with maximally concave curvature). There is a constraint on the user-defined profile spacing: if this is too small relative to the raster cell size, profiles will very frequently intersect. To avoid this issue, we require the user-defined profile spacing to be more than ten times the cell size. For a typical raster cell size of 5 m, the minimum distance allotted between profiles will be 50 m (which is similar to the smallest distance recommended for COVE).

A coastline-normal profile object is equivalent to a shore-normal elevation profile. It is a line made up of a set of consecutive nodes where each node has an associated location (x, y, z) in the global reference system, but also local attributes such as landward-marching slope (i.e. the slope of the profile as we move from the seaward limit towards the landward limit) and local (x', y') coordinates relative to the local origin (0,0), which is the landward limit of the profile. The landward limit is the centroid location of the actual cell that is marked as a coastline cell where the profile elevation intersects the SWL. The seaward limit of the profile is currently a user-defined value: it must, however, exceed the depth of closure (i.e. the sea depth beyond which no significant erosional change to unconsolidated sediments is expected). The depth of closure (d_L) is calculated using the empirical expression (1) proposed by Hallermeier (1978) where H_{sx} is the nearshore storm wave height that is exceeded only 12 hours each year and T_{sx} is the associated wave period. For each time step, changes of the unconsolidated profile are assumed to occur between the landward and seaward profile limits.

$$d_L = 2.28H_{sx} - 68.5\frac{H_{sx}^2}{T_{sx}^2} \quad (1)$$

The coastline-normal profiles are then used to calculate the sediment sharing polygons along the coastline that will later on be used for the alongshore sediment transport algorithm. The algorithm used in the model to calculate the location of sediment sharing polygons is similar to the one used by Hurst et al. (2015) but with some minor differences. As in COVE, coastal cells are built from the coastline profiles starting with the most concave coastline node. The CoastalME polygon generation algorithm differs from that used in COVE in the way the coastline curvatures are calculated. Instead of using the line that connects a given polygon's centroid with the upward and downward centroids to calculate the boundaries normal projections, CoastalME uses a smoothed coastline to project the coastline profiles.

All pairs of coastline-normal profiles are then checked for intersection. If profiles intersect then they are merged seaward of the point of intersection, with an orientation which is the mean of the two profile orientations. Fig. 9 shows the resulting sediment sharing polygons for different DEMs. If the coastline is rectilinear and oriented following the *y* global coordinate, all polygons are rectangles of equal size (assuming no randomness in between-profile spacing). If the coastline is rectilinear but tilted relative to *y* global coordinate the polygons are mostly of trapezoidal type but not all of equal size due to small step changes in the location of the coastline cells. If the coastline follows a Gaussian-shape then most polygons are still trapezoidal, but some triangular polygons are also created. Finally, if the coastline follows a Bay-shaped geometry an alternation of concave and convex trapezoidal and triangular polygons are generated.

3.2 Wave propagation, cliff and shore platform erosion and active layer

The next step within the main loop is to propagate the user input wave conditions from deep water to breaking for each raster grid cell and to store a representative set of wave properties at every point along the coast line. Wave energy is the main driver of cliff and shore platform erosion and alongshore sediment transport which, can be characterized by the wave height, period and angle at breaking. Wave propagation can be calculated either using the current DEM (i.e. as in many coastal area models),

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or assuming a simplified bathymetry (e.g. bottom contours parallel to the shoreline). Whatever method is used, the propagated wave height and angle results are stored in each cell of the raster grid. The wave propagation method currently implemented in CoastalME is based on linear wave theory and the assumption of parallel bottom contours equivalent to the method used by Hurst et al. (2015) in COVE. At every time step, only a few raster cells are within the area where waves are breaking and therefore morphologically active (surf zone) in Fig. 10. Once the wave properties are estimated for all raster grid cells, the model automatically calculates a set of representative wave property values (by default the wave height and angle at breaking) for each node along the coastline. This representative wave property will be later used to calculate cliff and shore platform erosion, as well as the alongshore sediment transport gradient.

Once the offshore waves conditions have been propagated, the next step in the main model loop is to calculate cliff and shore platform erosion. Within CoastalME, the horizontal cliff erosion and collapse of the aerial cliff, and the downwearing or lowering of the submerged shore platform are calculated by two different but interdependent methods. The potential (i.e. unconstrained by sediment availability) downwearing erosion ε is calculated first at every coastline-normal profile; then these values are used to estimate potential downwearing erosion for all raster cells between coastline-normal profiles; finally, the actual (i.e. constrained by sediment availability) downwearing erosion for all raster cells is calculated. Potential downwearing erosion is defined as the maximum erosion estimated to occur during the time step for a given breaking wave height and angle. Eroded consolidated fine sediment is assumed to become part of the suspended sediment mass fraction. Eroded consolidated coarse and sand fractions are transferred to the unconsolidated coarse and sand fractions (i.e. as a local source of sediment), adding to the total beach unconsolidated material. An important reduction factor to shore platform erosion is included based on the concept of an active layer. An active layer concept is required as soon as erosion rates are managed separately for the different sediment fractions –to include the interaction between the different sediment fractions- (Le Hir et al., 2011). The erosion of any fraction is therefore limited to the mass of that fraction available in the "active" layer (not to be confused with the active zone). If this restriction is not applied, the erosion of easily suspended fine fraction would be likely to occur at substantially greater depths than for coarse layers, which is physically inplausible. In CoastalME a default concept of active layer is included through the definition of the availability factor α (0 for none to 1 for all sediment available) for each one of the three sediment fractions (coarse, sand and fine, denoted by subscript i). The actual total erosion for each time step is calculated by:

$$\frac{dz}{dt} = \sum_i \epsilon_i \alpha_i \quad (2)$$

Where ϵ_i is the potential erosion for sediment fraction i and z is the thickness of each sediment fraction.

3.3 Polygon-based calculation of alongshore unconsolidated sediment flux

The conservation equation for beach sediment expressed in terms of local coordinates states that the change in position of the shoreline ($d\eta$), perpendicular to the local shoreline orientation (s) through time (t) is a function of the divergence of alongshore sediment flux (Q).

$$\frac{d\eta}{dt} = f\left(\frac{dQ}{ds}\right) \tag{3}$$

Typically, in bulk alongshore transport laws, flux depends on the height (H_b) and angle (α_b) of breaking waves, e.g. CERC equation (Eq. 4) and Kamphius (1987) equation (Eq. 5) (see comparison by van Rijn (2002)):

$$Q_{ls} = K_{ls} H_b^{5/2} sin2\alpha_b \tag{4}$$

$$Q_{ls} = 2.33\left(T_p\right)^{1.5}(tan\beta)^{0.75}(D_{50})^{-0.25}(H_b)^2[sin(2\alpha_b)]^{0.6} \tag{5}$$

Where T_p is peak wave period; $tan\beta$ is beach slope, defined as the ratio of the water depth at the breaker line and the distance from the still water beach line to the breaker line; and D_{50} is the median particle size in surf zone (m). Both the CERC and Kamphius equations estimate the potential immersed weight rate (Q_{ls} *in kg/s*) for all active zone. This is converted to bulk sediment transport rate (Q_v *in* m^3/s) by:

$$Q_v(m^3/s) = Q_{ls}(kg/s)/\big((1-p)(\rho_s - \rho)g\big) \tag{6}$$

with p is the sediment porosity (~0.4), ρ is the sediment density (~2650 kg/m^3 assuming quartz sand), ρ_s is the water density (~1025 kg/m^3 for sea water) and g is the acceleration of gravity (~9.81 m^2/s).

In order to resolve Eq. (3), CoastalME calculates the alongshore sediment fluxes in and out of each sediment sharing polygon. The net fluxes of unconsolidated sediment volume for all polygons are calculated in two steps, explicitly acknowledging that the potential alongshore sediment transport may be limited by availability of unconsolidated sediment. The potential alongshore sediment bulk (sediments and voids) transport flux magnitude (m^3/s) and direction (up-drift or down-drift) for each polygon is quantified using a user selected equation (such as Eq 4 or 5), and a potential sediment budget constructed for all polygons. Then in the second stage, we first focus on those polygons with net potential erosion, and calculate actual totals of erosion of unconsolidated sediment (in three sediment size classes) by considering the availability of unconsolidated sediment. Finally, we distribute these actual volumes of unconsolidated sediment on those polygons with net deposition.

To calculate potential sediment transport on each polygon, average wave height and wave incidence angle along each polygon's coastline segment- and the average beach slope are determined. For each node along the coastline, coastline orientation is the

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angle (measured from the azimuth) of the straight line linking the two adjacent coastline nodes (i.e. the nodes up-coast and down-coast from the node of interest). Wave angle at breaking (α_b) is calculated as the angle between the shoreline orientation and the wave front. The coastline algorithm automatically detects if the sea is at the right or left hand side of the coastline orientation and identifies if the alongshore sediment transport is towards the direction along which the coastline indexes increase (positive flux) or decrease (negative flux). The average beach slope is calculated as the ratio between the average depth of breaking and the average distance of breaking for all raster cells within each polygon (averaged beach slope is used in Eq. 5).

Unlike COVE, where transport-limited conditions are assumed, so that there is always sufficient beach material available for transport, in CoastalME the actual alongshore sediment transport can be smaller than the potential bulk alongshore sediment transport. The amount of unconsolidated sediment available on each polygon is defined by the sediment volume between an assumed beach equilibrium profile and the top elevation of the consolidated shore platform and the active layer. As a result, CoastalME can resolve a larger number of combinations of beach and shore platform geometries. In CoastalME the beach profile is assumed to have a user-defined equilibrium profile. The beach equilibrium profile currently assumed in CoastalME is the Dean profile (Dean, 1991) calculated by:

$$h(y) = A(D_{50}) \times y^{2/3} \tag{7}$$

with $h(y)$ equal to the vertical distance below the highest point in the profile at a distance y from the landward start of the profile; and $A(D_{50})$ is a scale factor that varies with the sediment (D_{50}) size of the unconsolidated sediment. By allowing shore platform to adopt any slope, we do not need to use the analytical expressions used in COVE to calculate the shoreline changes as a function of volume changes, but instead use a numerical iterative algorithm.

For each polygon with net potential erosion of unconsolidated sediment, we determine actual sediment flux by traversing the polygon's existing coastline, at each coast node fitting an equilibrium beach profile that is parallel to one polygon boundary (which is, of course, itself a coastline-normal profile). We then consider the elevation difference between the fitted equilibrium beach profile and the existing elevation of the unconsolidated profile. At each point along the profile, if the elevation of existing unconsolidated sediment is greater than the elevation of the assumed equilibrium profile, then some unconsolidated sediment is removed so that the elevation at that point becomes that of the assumed equilibrium profile. Sediment which is removed then becomes available for deposition elsewhere. But if, at that point, the elevation of the existing unconsolidated sediment is below that of the assumed equilibrium profile, then sediment is taken from the available sediment and deposited so that the elevation at that point becomes that of the assumed equilibrium profile. This is repeated for every point on the profile. If the available sediment is then smaller than the target for potential erosion per profile for this polygon, the equilibrium profile is moved one cell landward iteratively until the available sediment equals the target potential erosion or the cell is out of the grid or the consolidated profile is hit. The target potential erosion per profile is obtained as the ratio between the polygon's previously calculated potential erosion sediment flux and the length of the coastline segment (units are m^3 sediment per *m* of coastline per unit of time). This is repeated for every coastline point, and repeated traversing the coastline in the opposite direction to ensure that no cells are missed. At the end of these iterative loops, the available unconsolidated sediment for this polygon is either equal to the potential sediment flux (if enough sediment is available) or smaller (if constrained by sediment availability).

If a polygon has more than one adjacent polygon in the direction of sediment movement, then the fraction of total sediment volume exported to each of these adjacent polygons is assumed proportional to the shared length of boundary between these polygons, as in COVE. A potential sediment movement budget for each polygon may now be drawn up. For those polygons with net loss of unconsolidated sediment, the active layer availability equation (Eq. 2) is applied for each sediment fraction. This gives us the actual (supply-constrained) volumes of sand- and coarse-sized sediment to be deposited on those polygons with net gain of unconsolidated sediment. At present, CoastalME just tracks the actual volume of eroded fine sediment: this is assumed to go into suspension, but in future developments we can incorporate transport rules for suspended material to make it available in estuarine settings. Actual elevation change (erosion or deposition) for unconsolidated sediment on each raster cell within each polygon is iteratively calculated as described above, by fitting Dean profiles: We search along the coast of each polygon and fit Dean profiles, iterating inland (for erosion) or seaward (for deposition) until each profile's target is met; then traverse the coast in the opposite direction if necessary.

The new DEM at the end of each time step is calculated as the differences between the initial DEM and the changes in elevation at each raster cell. To avoid unrealistic step changes between cells a volume preserving smoothing algorithm is included. Only those cells within the active zone are smoothed to minimize numerical artefacts affecting the cells. Until the end of the simulation period is reached, the new DEM becomes the initial DEM for the next time step and the main loop is repeated.

3.4 Polygons at the boundaries of the DEM domain

Boundary conditions are invariably a problem for simulation models (Favis-Mortlock, 2013b). CoastalME is no exception. Profiles at the start and end of the coastline vector are assumed to project along the main intersecting global axis rather than being normal to the coastline location. This is needed to avoid profiles at the edges moving out of the raster grid domain when projected seaward. To specify the sediment fluxes coming in and out of the polygons with boundaries intersecting or at the edge of the raster grid domain the user can select among three types of boundary conditions: (1) an open boundary condition, which permits export of sediment at all grid edges, (2) a closed boundary condition, which assumes that no sediment enters or leaves the raster grid, and (3) a "Mobius" boundary condition is which sediment exported from one end of a coastline is re-imported at the other end of the coastline. For simulations where wave direction produces a net updrift or downdrift alongshore movement of unconsolidated sediment, the open boundary option gradually leads to impoverishment of, even total removal of, unconsolidated sediment at the updrift end of the coast, while the closed boundary option eventually leads to a pile-up of sediment at the downdrift end of the coast. The "Mobius" option in effect a "virtual conveyor belt" of sediment with none of the disadvantages of the other two boundary conceptualisations.

3.5 Cliff collapse and platform erosion

In SCAPE, an initially uniform slope under the attack of breaking waves starts developing a cliff notch somewhere in between the high and low tidal levels. After a user defined number of erosive events SCAPE assumes that any overhanging material is removed (i.e. the cliff collapses) which produces a vertical cliff starting from the most landward location of the notch. In CoastalME our DEM is represented by cells that can only change elevation. Consequently, we represent cliffs by means of a Coastal Landform sub-class named Cliff. As in SCAPE, we assume that the cliff and shore platform can only be eroded (i.e. no creation of new consolidated platform is allowed).

A new parameterization is required to make use of the equations used in SCAPE to reproduce cliff and shore platform evolution. The horizontal recession at a given shore platform elevation (z_s) is calculated in SCAPE by:

$$\frac{dy_s(z_s)}{dt} = \frac{F}{R} f_1(h(t) - z_s) tan\left(\frac{dz_s}{dy_s}\right) f_2(z_{beach} - z_s) \quad (8)$$

Where shore platform horizontal and vertical dimensions are y_s and z_s, respectively; t is time and $F = H_b^{13/4} T_p^{3/2}$ is the erosive forces under random waves of a given wave height at breaking (H_b) in meters and peak period (T_p) in seconds; R is a calibration

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parameter that varies with the material strength and some hydrodynamic constant in $m^{(9/4)}s^{(2/3)}$; f_1 is a shape function that describes how the erosive forces (F) varies with water depth ($h(t) - z$), with $h(t)$ equal to the changes in the SWL due to tides at a given time t; $\frac{dz}{dy_s}$ is the local slope at the platform elevation z; f_2 is a discontinuous function that is equal to 0 if the beach thickness (the difference between the elevation of the beach and the elevation of the consolidated platform $z_{beach} - z_s$) is larger than $0.23H_b$ and increases linearly up to 1 if there is no beach on top of the shore platform. For submerged blocks (i.e. blocks for which the top elevation is below SWL), the original horizontal SCAPE erosion (Eq. 8) is converted into its vertical component, $\frac{dz}{dt}$, by applying the following simple trigonometrical conversion;

$$\frac{dz_s}{dt} = \frac{dy_s(z_s)}{dt} tan\left(\frac{dz_s}{dy_s}\right) \quad (9)$$

All parameters in Eq. (9) are either readily available or can be derived from existing CoastalME parameters. Local slope, $\frac{dz_s}{dy_s}$, can be derived from the coastline profiles. For each profile, the erosive force is calculated as a function of the wave height at breaking stored in the coastline geometry object and the user defined wave peak period. The same shape erosion function as used by SCAPE is used to estimate the shore platform erosion as a function of the ratio of water depth to wave height at breaking. The known length of the profile is used to ensure that the numerical integral of the shape function equals 1 (i.e. no energy is created or destroyed from wave breaking until the shoreline, but only distributed). The beach thickness is calculated for each cell along the profile as the elevation difference between the beach surface elevation and the consolidated bedrock surface elevation at each cell. For each sediment-sharing polygon the coastline is traversed from one polygon boundary to the other, drawing at each node along the coastline segment parallel profiles. These profiles are needed to calculate the local slope used on Eq. (9). The unconstrained vertical erosion is then calculated for each cell along the profile. The active layer Eq. (2) is then applied to each cell to estimate the actual vertical erosion. The coastline node is moved up one location and the actual vertical erosion for cells along the new profile are calculated as before. The loop is continued until the other polygon boundary is encountered. Checks are performed during this loop to ensure that cells are not eroded several times and that there are no cells within the active zone of this polygon at which the actual erosion potential has not been calculated. The user is equipped with an additional smoothing algorithm of the slopes and grid elevation that can be switched on or off and tuned if needed.

Cliff collapse is implemented in CoastalME as shown in Fig. 11 using the cliff landform class. Wave energy is accumulated at every cliffed point on the coastline: this results in the development of a cliff notch in the raster cell at this point. The cliff notch is considered to have its base a user-specified depth d_1 below the SWL, and to be eroded a length L_1 inland (Fig. 11a).

As the simulation progresses, the cliff raster cell is subjected to more wave energy and the length of L_1 increases. When L_1 reaches a user-specified value L_{max}, cliff collapse occurs (Fig. 11b). A volume of sand- and/or coarse-sized sediment with depth d_2 (i.e. from the base of the cliff notch to the elevation of the top layer of sediment on the cell) is removed from the cell, and deposited on the seaward cells as unconsolidated talus (the fine-sized sediment is, at present, just added to the accumulated total suspended sediment). The coastline-normal elevation profile of this talus is a Dean profile. The seaward length of the talus is a user-specified value; in plan-view, the width of the talus is also user-specified, and the elevation of the talus at its coastward end is set at a user-specified fraction of the cliff height, measured from the notch base. The Dean profile is fitted iteratively (as in SCAPE): if a Dean profile of talus starting immediately seaward of the cliff cannot accommodate the required volume of sediment, then the whole Dean profile is shifted one raster cell seaward, with the cell landward of the new start position (i.e. immediately seaward of the cliff cell) set to the same elevation as that of the cell on which the Dean profile starts. This procedure is iterated until the Dean profile can accommodate the required volume of talus. The simulation continues with a new notch being incised into the cliff cell (Fig. 11c). Further collapses may occur as L_3 is extended. When the notch is eventually incised to the point that no further cliff collapse is possible on this cell (i.e. the total of all notch incision on this cliff cell equals the length of the cell side) then the cell is no longer flagged as a cliff cell. At the next iteration, the coastline-tracing procedure will treat this cell as a sea cell (Fig. 11d). As the platform becomes wider, the energy reaching the cliff toe decreases and therefore so does the likelihood that a notch eroding event occurs. As the beach also becomes thicker the actual erosion of the shore platform is reduced.

4. Examples of model output and discussion

Verification of the integrated SCAPE-COVE version of CoastalME will be treated in a separate paper focussed only on this aspect. In this section we verify that the model is behaving as expected for different setup conditions. In particular, we show how the integrated model, starting with the same DEM and forced by the same external boundary conditions but with different stratigraphy data, results in a different DEM evolution. With this exercise we aim to illustrate the emergent behaviours that the integrated framework can produce and how this is different from the capability of the component models alone.

The initial DEM is made of 1m regular square cells that extent an area of 1000m x 500m being and has an average slope seaward of 10.25 degrees that varies (±0.25deg) alongshore to represent a cuspate coastline. Wave forcing is assumed to be constant with offshore significant wave height of 2m, 10 seconds wave period and 270deg wave direction. For this initial

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DEM, three different sediment sizes compositions have been assumed: (1) all 100% DEM sediment is consolidated fine material, (2) 80% is consolidated fine and remaining 20% is consolidated sand and (3) 100% sediment is unconsolidated sand. The Dean profile scale factor A is assumed to be 0.062 $m^{1/3}$ that correspond to a mean grain size of 0.15mm (Dean, 1991). The SCAPE rock strength calibration variable R is assumed equal to the value used by Walkden and Hall (2011) for the soft cliffed coast of North Norfolk (East UK) and equal to $6x10^6$ $m^{9/4}s^{3/2}$. The scaling factor for the alongshore sediment transport for the CERC equation is assumed K_{ls}= 0.4 and, sediment porosity of 0.4, and sand sediment density of 2650 kg/m^3. The DEM boundaries are assumed to be open boundaries where sediment is allowed to exit the domain but input sediment is assumed. The input files for each case can be downloaded from the dedicated website (see code availability).

The different emergent behaviours are best revealed by focussing on a section of the initial and final DEMs. Figure 12 illustrate a before and after detail (20m x 100m) of the full DEM (1000m x 500m). In all three cases the initial DEM is eroded but to different degrees. As the percentage of sand increases across the three cases the average net erosion decreases, being a maximum of -40m for the case of 100% fine material, with an intermediate of -35m where the DEM is composed of 80% fine and 20% sand, and a minimum of -30m recession for the case of 100% unconsolidated sand. Eroded fine material is assumed to be stored as suspended sediment. For the case where only fine material is available, and SWL is constant, no beach is created and the platform erosion rates drops asymptotically as the platform is widening and dissipating more wave energy by breaking. For the case of the DEM with a small sand fraction, a layer of unconsolidated sand material reduces the erosive potential of the waves by protecting the consolidated platform beneath it. The amount of sediment released during the simulated period is not enough to create a wide beach, but it is sufficient to reduce cliff top retreat relative to the 100% fine sediment case. The last simulation is fully made of unconsolidated sand sediment with no consolidated platform (e.g. transport limited beach). After a few time steps a wide beach forms from the eroded sand and sediment is then only lost at the boundaries of the domain, driven by the alongshore sediment transport gradient. In the case of 100% fine sediments, the only process able to reduce coastal erosion is platform widening, while in the case of the mixed fine and sand cliff a new process (i.e. beach platform protection) emerges as soon as the beach thickness is sufficient to provide protection against the breaking waves. Beach width further controls the amount of sediment lost from the domain by controlling the gradient of the alongshore sediment transport. In the case of a DEM made only of unconsolidated sand sediment, the main coastal change is fully controlled by the gradient of the alongshore sediment transport.

The CoastalME-integrated SCAPE and COVE has a number of capabilities than make the integrated model more appealing than the individual models components (Table 2). The most obvious additional capabilities relative to COVE alone is the ability to represent cliff and shore platform erosion and beach interaction (i.e. COVE2015 is limited to unconsolidated sediment alone) and the new additional capability relative to SCAPE alone is the ability to reproduce highly irregular coastlines. Less obvious, but equally important is the added capability, to both SCAPE and COVE, of capturing effect of the regional bathymetry on the local alongshore sediment transport. Similarly, to other one-line models (e.g. Hanson and Kraus, 2011), the offshore contour orientation in SCAPE and COVE upon which the incoming waves are refracted is assumed to be parallel to the shoreline orientation. This assumption is to ensure that the incident waves are realistic while preserving feedback between shoreline change and the wave transformation. However, this assumption has a limitation: an open coast without structures or sources or sinks of sediment will evolve to a straight line if a standard shoreline response model is run a sufficiently long time. In the integrated CoastalME model, waves are propagated upon the full DEM and therefore the local gradient of the alongshore sediment transport is a combination of the local orientation of the shoreline and the regional orientation of the bathymetry (i.e. regional bathymetry controls wave propagation). Figure 13 illustrates the effect of this regional bathymetry influence on the three simulated cases. For the case of DEM being made of all fine consolidated sediment, the shoreline retreats following the regional bay-shaped bathymetry. The sediment sharing polygons at the end of the simulation are similar to the ones at the beginning, but translated landward. For the case of mixed consolidated fine and sand DEM, the shoreline also follows closely the regional bay shaped bathymetry since most of the beach sediment volume is not at the shoreline, but as submerged bar parallel to the shoreline. For the case of DEM being made of unconsolidated sand, the bay shaped of the shoreline is less evident (i.e. shoreline is roughly parallel to the incoming wave fronts). In this last case, the sediment sharing polygons at the end of the simulation has not only being translated landward but also have a more intricate sediment sharing shapes to the ones at the end of the two other cases (i.e. fully fine DEM and mixed-sediments DEM).

5. Future work and implications

The current version of CoastalME (v1.0) has a number of limitations when compared with the stand-alone constituent models; these deficiencies will be remedied in future work. For example:

- Simple rules for wave shadowing and diffraction are included in COVE which are not yet implemented in CoastalME.
- While software place-holders for human interventions are included in CoastalME, this need to be fully implemented to be able to reproduce the interventions included in COVE and SCAPE. For example, a common intervention of

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fixing the shoreline can be simulated by changing the block resistance along the fixed shoreline but how this resistance might change over time needs further analysis.

- The integrated model has implemented a simple active layer model, which is an addition to COVE and SCAPE but has not been yet validated (i.e. for the simulations shown here we have assumed that all tree sediment fractions have equal erodibility in Eq. 2).

Finally, the generic approach used to represent processes and spatial features in CoastalME's spatial domain may be useful for other landscape modelling applications. Whilst it may appear counter-intuitive to expect a performance gain by transforming spatial features between their raster and vector representations at every timestep, the approach does permit a computational emphasis on spatial linearity which is not straightforward to implement in a purely-grid-based model. Thus the dynamically hybrid raster and vector approach of CoastalME may also be useful as an alternative to CA modelling of flow in linear channels, such as rivers and erosional rills (cf Favis-Mortlock, 2013).

6. Conclusions

Complex coastlines involving multiple land forms require consideration of interactions between multiple coastal landforms. Despite effort to couple separate models (e.g. software wrappers), there is a need to deal more directly with the semantics of the various entities being modelled. We have presented here a description of, and proof-of-concept results from, a flexible and innovative modelling framework (CoastalME) for integrated coastal morphodynamic modelling at decadal to centennial timescales and spatial scales of 10s to 100s km. CoastalME integrate the concept behind each model as a set dynamically-linked vector and raster objects.

The rationale underpinning CoastalME results from the observation that most the existing simulation models of coastal morphodynamics at these temporal and spatial scales of interest conceptualize the real complex 3D topography of the coastal zone using simple geometries. Accordingly, we have devised a spatial framework which is consistent with these simple geometries, and which permits the representation of these existing models in terms of behavioural rules which operate within this spatial framework. Thus the DEM and stratigraphy is represented as a raster grid of regular cells, each of which holds some thickness of consolidated and unconsolidated sediment which is itself comprised from three size fractions (coarse, fine, sand). Vector-based objects are created at each timestep which represent features such as the coastline, profiles which are normal to that coastline, and polygons which are partially bounded by these normal profiles. Driven by external boundary conditions (waves, currents and sea level), coastal processes which manipulate sediment are simulated using these vector-based objects, and the resulting changes to the spatial distribution of sediment are then stored in the in raster grid. Modelled topography therefore changes as each cell's store of sediment changes its thickness during a simulation sediment being eroded in some cells and deposited in others, maintained in suspension or lost at the boundaries) due to external boundary conditions (waves, currents and sea level changes). In addition to the set of blocks or raster objects, the authors suggested a minimum set of classes needed to reproduce a generic morphodynamic model. We suggest that a variety of existing coastal models, each of which represents a single element or a limited range of elements, of coastal morphodynamics (e.g. estuary, salt marsh, dunes etc.) may be integrated within CoastalME's modelling framework. As a proof-of-concept example, we have integrated a one-line model for very irregular sediment-rich coastlines with a soft cliff and beach erosion model. We then verify that the integrated models behave as expected, for example by demonstrating that, given the same initial topography and forced by the same external drivers, differing stratigraphic inputs produce different coastal morphologies.

The next steps in CoastalME development is to include simple rules for wave diffraction and wave shadowing, a suite of human interventions (including hold the line, removal of defences, nourishment) and to fully implement the estuary landform class.

Code availability

The CoastalME is developed and maintained within the GitHub web-based repository hosting service. This repository allows users to download frozen versions of the model (version 1.0 at the time of writing) of to keep their local copy up to date. The version 1 can be found in https://github.com/coastalme/coastalme. A dedicated wiki-site to CoastalME which includes the model documentation, user manual, test cases, software requirements, installation guide, related publications and reports and a note about the framework developers can be found in http://www.coastalme.org.uk/. This Wiki site includes a section on frequently asked question. Any question regarding CoastalME can be emailed to admin@coastalme.org.uk.

This code is also available from the iCOASST project modes dedicated web site at the Coastal Channel Observatory web site (http://www.channelcoast.org/iCOASST/introduction/). The user accessing the code through this route will be able to see how CoastalME framework related with other existing modelling approaches of decadal and longer coastal morphodynamic.

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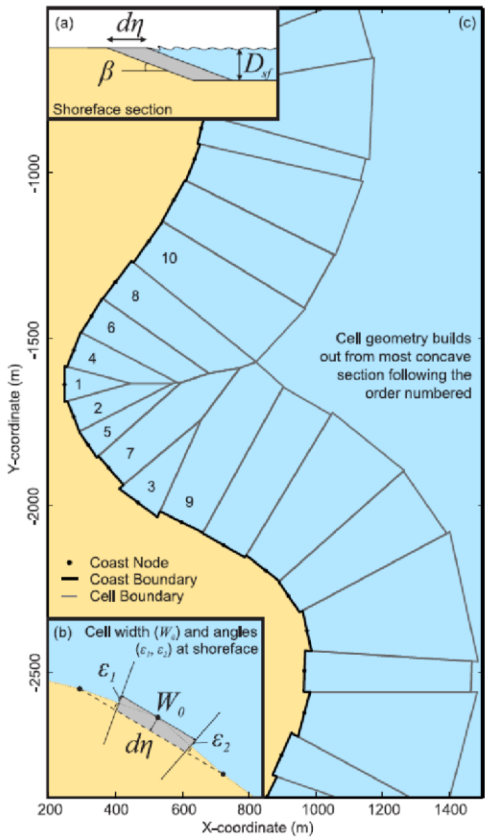

Figure 1. The shoreface can be conceptualised as a set of sediment sharing cells interconnected by the alongshore sediment transport: (a) COVE model assumes a sediment-rich (i.e. no shore platform) shoreface profile, (c) The scheme shows how the COVE model by Hurst et al. (2015) assumes triangular or trapezoidal cell geometries that best fit to the shoreline geometry.

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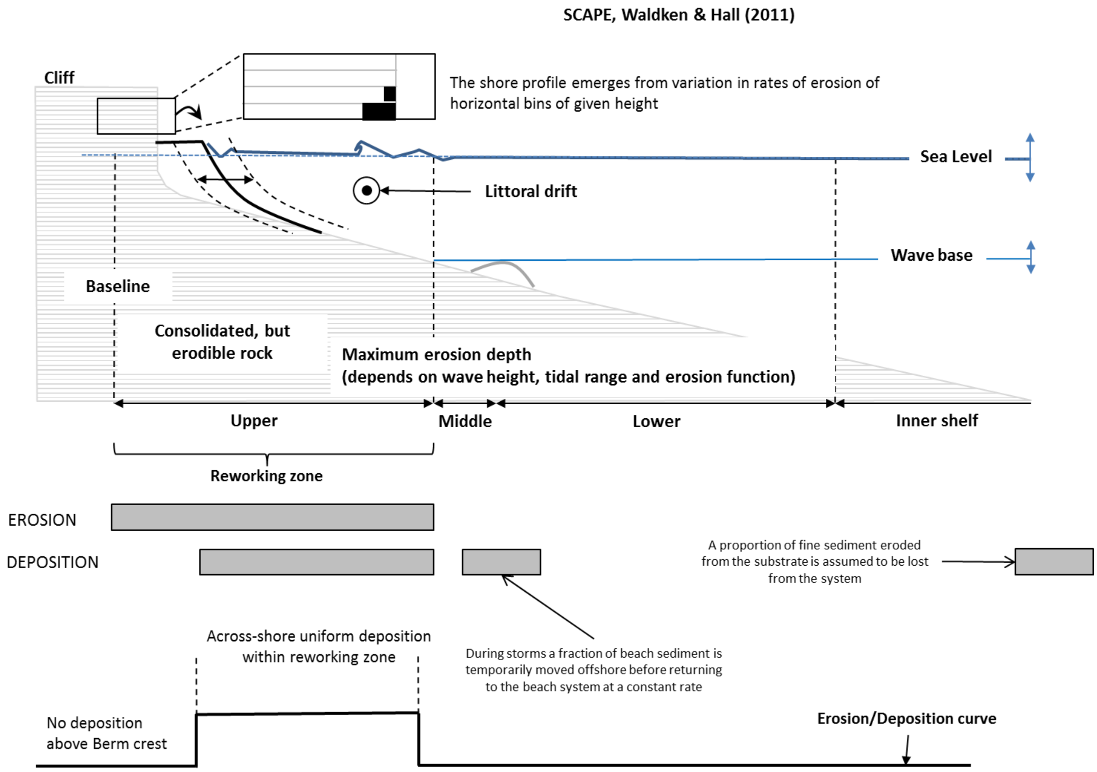

Figure 2. For non-sediment rich shorefaces the interaction between the beach and shore platform cannot be neglected. A schematic cross section of a shoreface, as used in SCAPE. The beach in SCAPE is treated as an equilibrium profile following a one-line approach. Approximate areas of sediment deposition and erosion are indicated (after Walkden and Hall, 2011).

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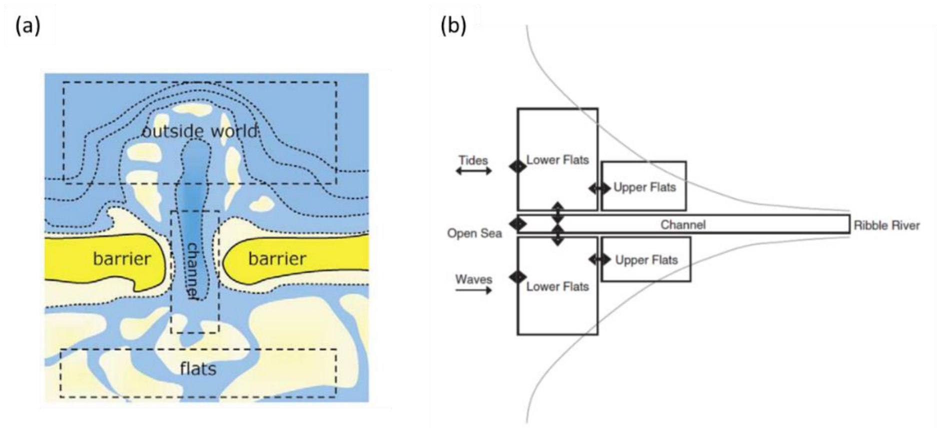

Figure 3. An illustration of two types of estuaries schematisations in behaviour oriented modelling. Different elements are represented as volumetric sediment sharing units; (a) typical three types and elements scheme, (b) three types and five elements scheme (Rossingnton *et al.*, 2011).

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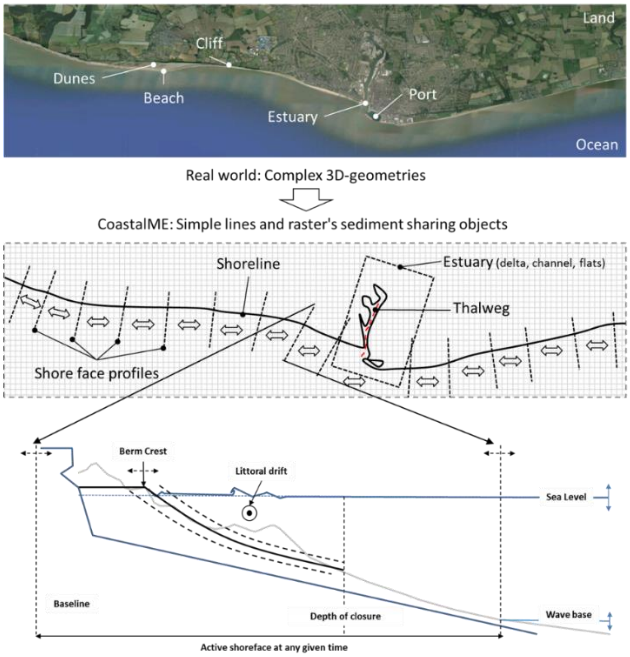

Figure 4. The CoastalME modelling approach. Coastal morphology changes are simulated as dynamically linked line and raster objects. The hierarchy of panels illustrate how a real coastal morphology (upper panel) is conceptualized as shoreline, shoreface profiles and estuary elements (middle panel). The shoreface comprises both consolidated and non-consolidated material that forms the cliff, shore platform and beach respectively (bottom panel).

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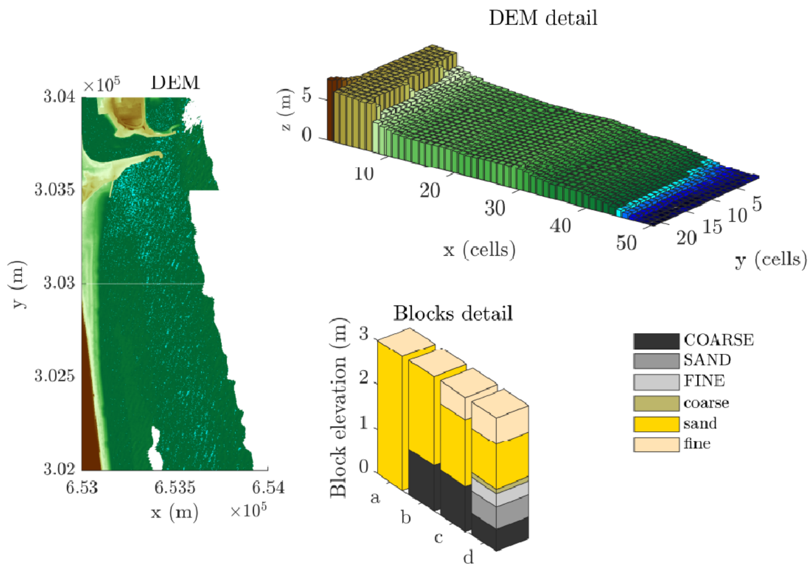

Figure 5. Ground elevation is characterized as a set of regular square blocks. Each block has a global coordinate x, y, z. Left panel illustrates the DEM of Gorsleston-on-Sea (east coast of UK) provided by © Environment Agency copyright and/or database right 2015 with a raster resolution of 2m (DEM detail). Each block might be composed of six different sediment fractions (Blocks detail) made of coarse, sand and fine sediment sizes. Each sediment size fraction can be in a consolidated (capitalised) or unconsolidated state (lower case). Block types a, b, c and d illustrate blocks of same total elevation but with different sediment composition.

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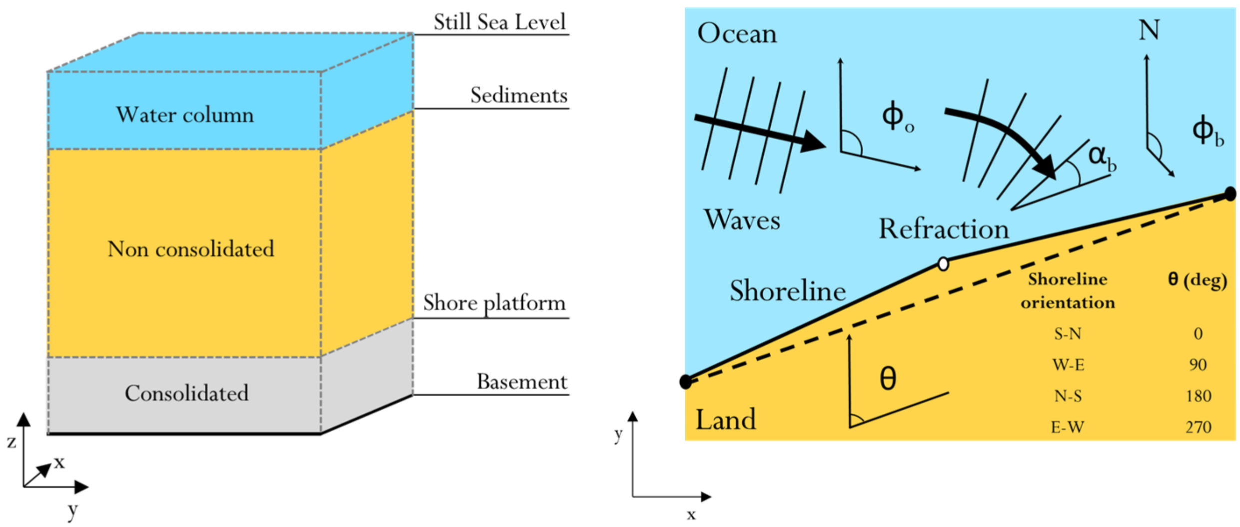

Figure 6. Convention used in CoastalME for global coordinate system and external drivers attributes. All layers (consolidated and unconsolidated) and sea elevations are referenced to a basement level (left panel). Shoreline orientation at each coastline node is defined as the angle relative to the azimuth clockwise which forms the straight line that connects the coastline points before and after (black dots) "this" (white dot) coastline node. Wave angle at breaking is obtained from the difference between the shoreline orientation and the wave front.

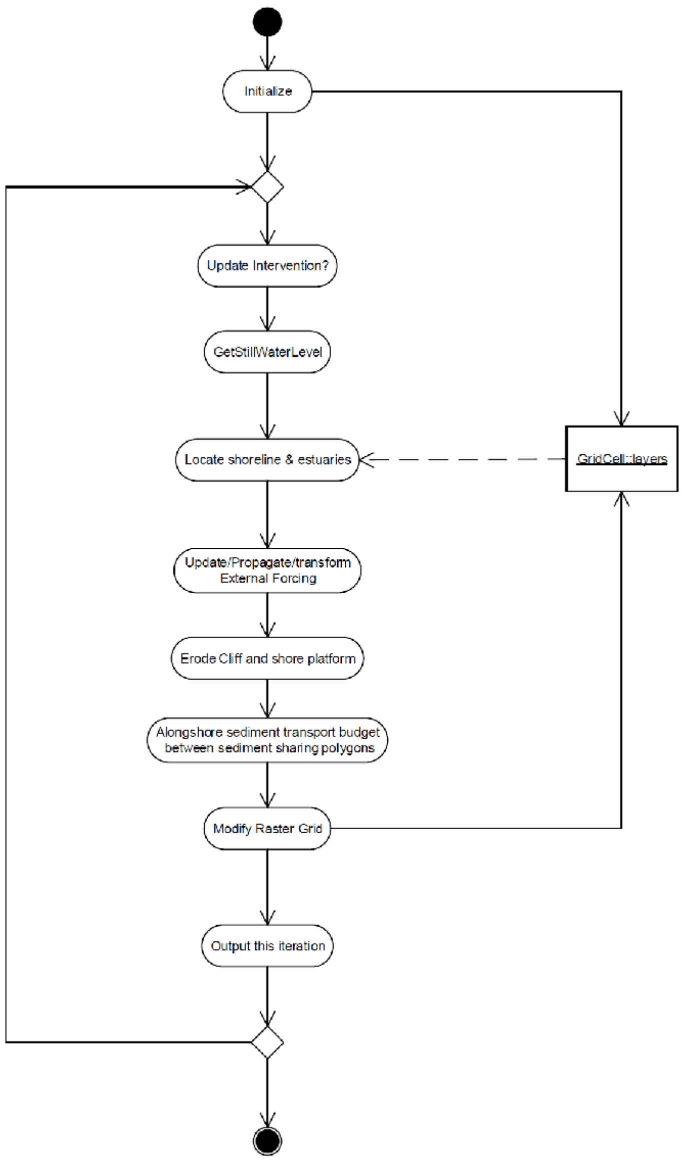

Figure 7. Activity diagram of a CoastalME timestep.

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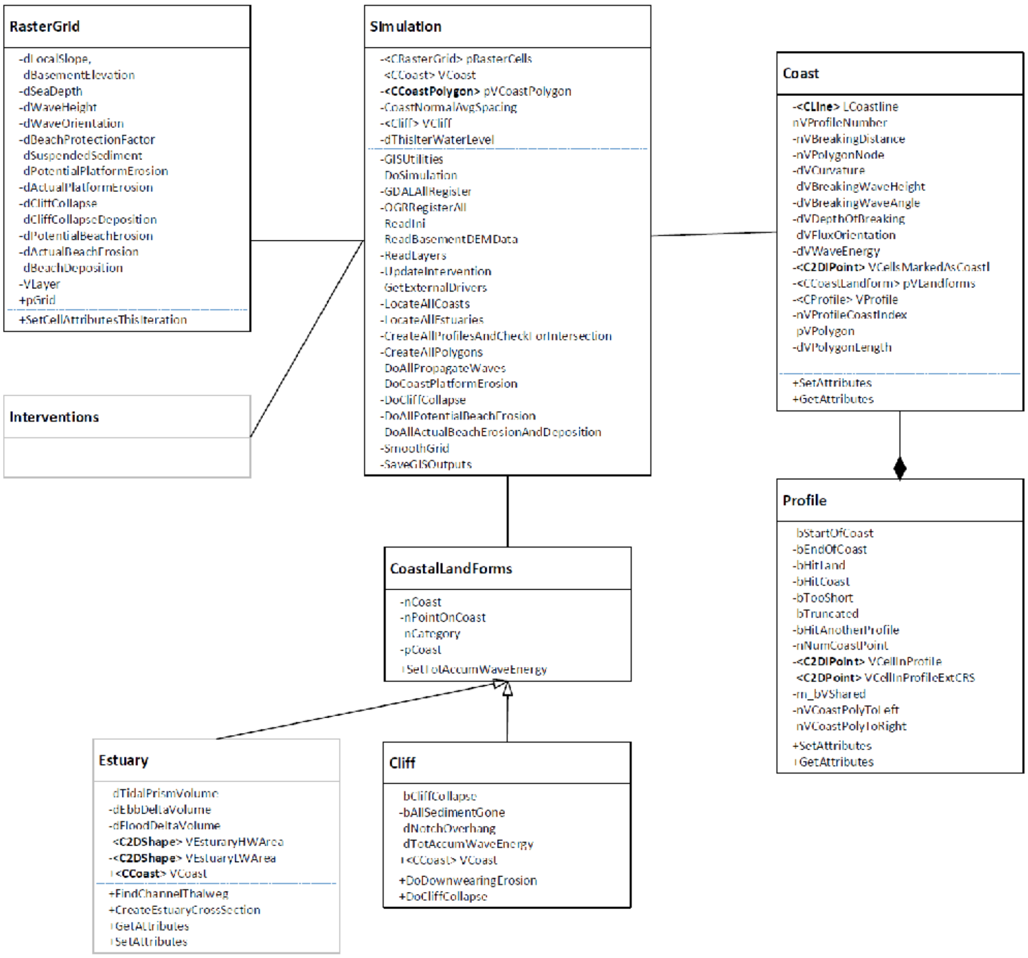

Figure 8. Class diagram for CoastalME classes. For clarity only the key classes, attributes and methods are shown. To avoid cluttering the diagram the more abstract geometrical classes are shown as **<ClassName>**. The classes Estuary and Interventions are just place holders for future CoastalME version.

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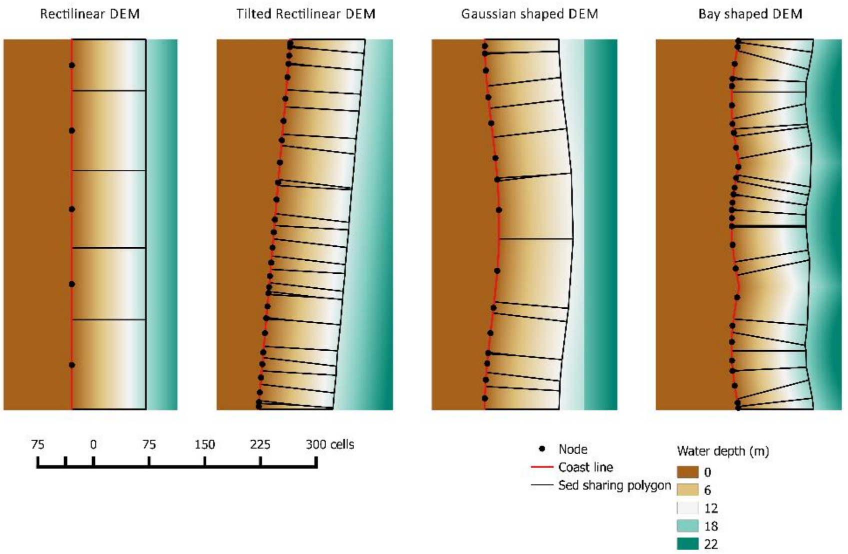

Figure 9. An illustration of the type of sediment sharing polygons that are automatically generated by the model for three different DEMs. The polygon node centroid location is shown as a black circle and the shoreline as a solid red line.

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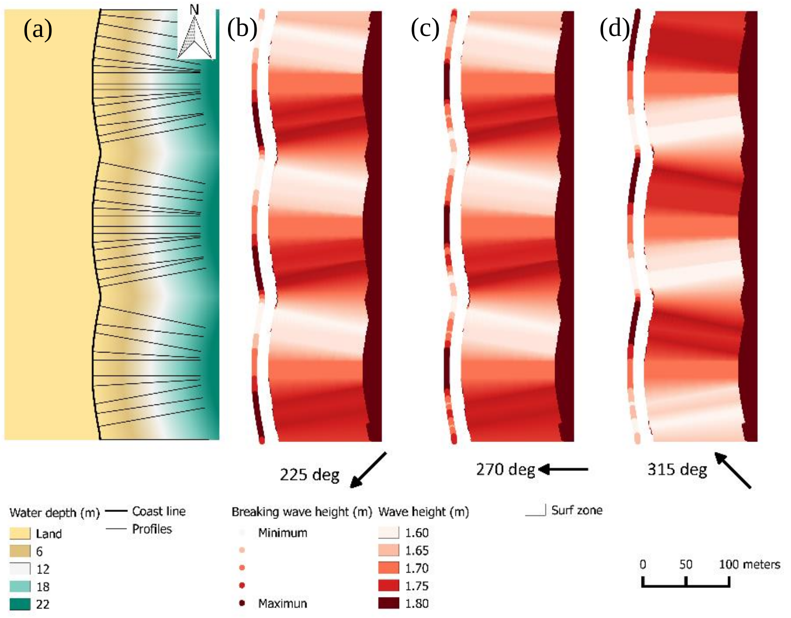

Figure 10. Calculated wave height for three different offshore incident wave angles; (a) a bay-shaped DEM and the location of the shoreline and profiles used to propagate the waves, (b,c and d) wave height at breaking for each shoreline point (coloured dots) and outside the surfzone (coloured area) for offshore waves incident propagation angle of 225deg, 270deg and 315deg. The white region between the coloured dots and coloured area represents the extension of the surf zone.

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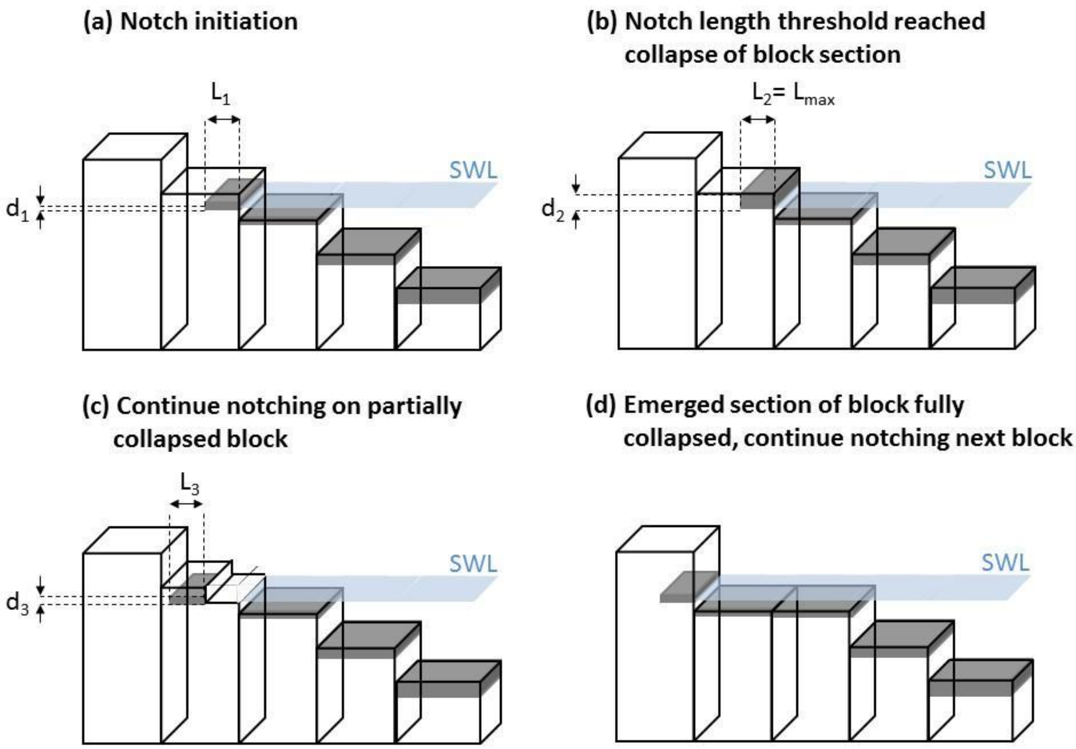

Figure 11. Illustration how notch evolution (from SCAPE) is simulated in CoastalME.

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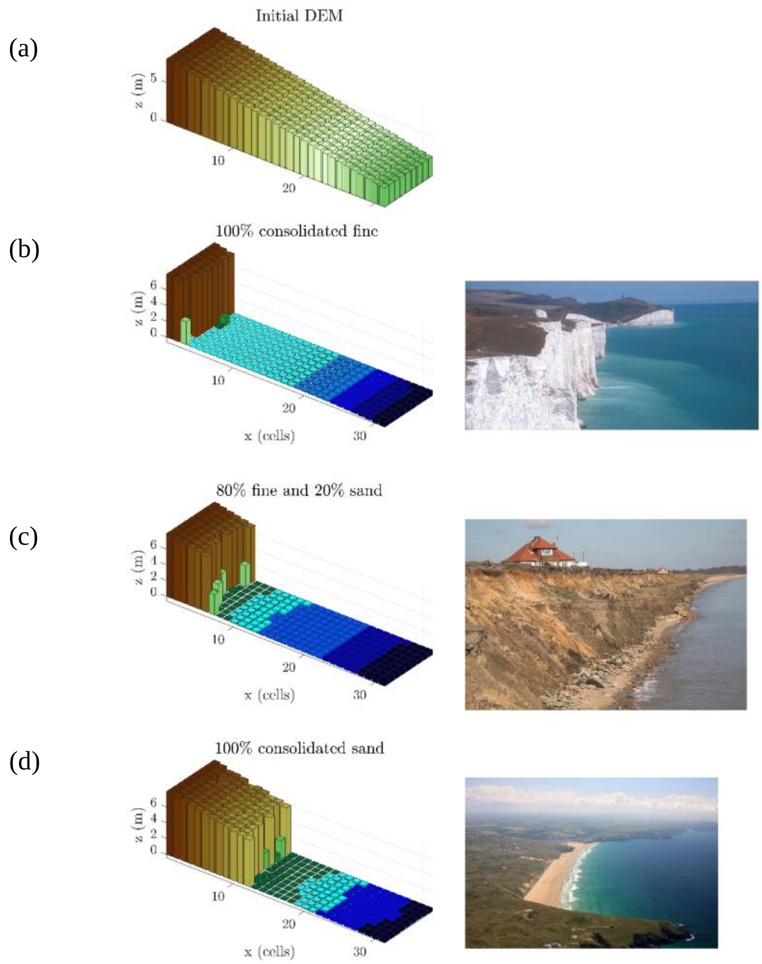

Figure 12. Illustration of how the same initial DEM, forced with the same external boundary conditions for one year can evolve very differently depending on the assumed stratigraphy. (a) Shows the elevation of the DEM relative to the mean sea level of the initial DEM. (b) Soft cliffs, such as the white chalk (limestone) cliffs of Sussex in South East England, erodes without forming a protecting beach. (c) Mixed fine and sand cliff and shore platforms might create small beaches from the material eroded from the cliff protecting the cliff from the breaking waves. (d) If all DEM is made up of sand, such as the Perranporth beach in South-West England, a wide beach is created minimizing the net shoreline retreat.

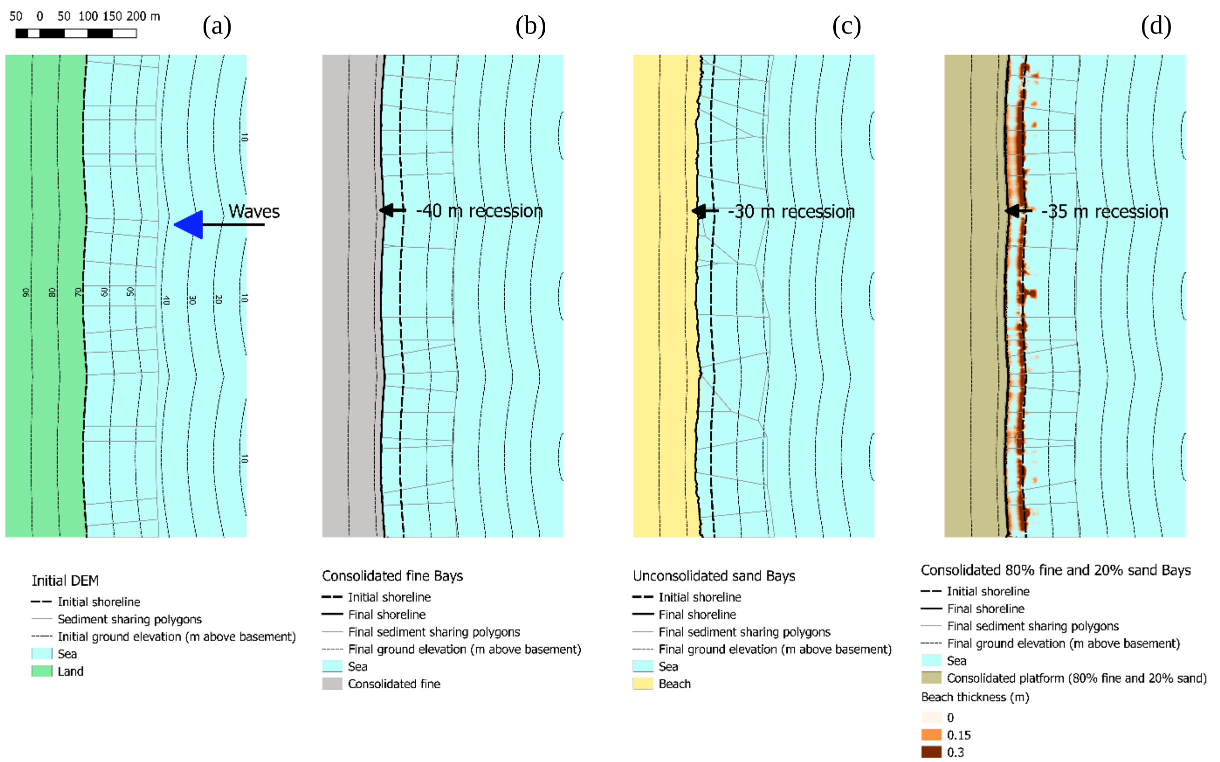

Figure 13. A novel capability of the integrated model is the capability of representing the effect of the regional bathymetry on the local alongshore sediment transport gradient. (a) Initial DEM contours relative to the basement, shoreline position (mean sea level is assumed to be 70m above basement) and the initial sediment sharing polygons. (b) A soft cliff will retreat following the regional contours. (c) A sand rich DEM will form a beach roughly parallel to the incoming wave fronts. (d) A mixed 80% fine and 20% will also retreat following the regional bathymetry but less thanks to the protection of the bar-alike emerging beach.

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Table 1. CoastalME adopted ontology of coastal landforms and human interventions (after French et al., 2016a)

Coastal landforms, hinterland and sediment stores			
Landform		**Hinterland**	**Sediment store**
Cliff	Inlet channel	High ground	Seabed grave
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	Brakish marsh		
Lagoon	River		
Human interventions			
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,
Embankment	Flood protection	Sediment bypassing	Continuity of sediment pathway;
Barrage	Flood protection	Sediment recycling	Resilience (beach profiling)
Breakwater	Wave energy		
Detached breakwater(s)	Wave energy		
Groyne(s)	Sediment retention		
Training wall	Channel		
Jetty	Varied		
Outfall	Drainage/dispersal		

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Quay	Navigation/trade
Dock	Navigation/trade
Weir	Regulation of river

Table 2. Capabilities of model components SCAPE and COVE and integrated CoastalME composition.

Capability	COVE	SCAPE	CoastalME
Soft cliff erosion and beach interaction	N	Y	Y
Highly irregular coastlines	Y	N	Y
Sediment supply limited environments	N	Y	Y
Transport supply limited environments	Y	Y	Y
Handle three different sediment fractions	N	N	Y
High Angle Wave shoreline instabilities	Y	N	Y[1]
Effects of regional bathymetry on local alongshore sediment transport gradients	N[2]	N[2]	Y

Y & N yes and no capability included

[1]Implemented but yet to be tested (i.e. need to include wave shadowing and diffraction)

[2]Regional bathymetry can be achieved in an offline manner, driving the model with more sophisticated wave transformation model