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Abstract

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Morphogenetic modelling of coastal and estuarine evolution

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Abstract

Environmental pressures from climate change and anthropogenic activities have increased the need for quantitative morphogenetic models of coasts and estuaries. These quantitative models enable geoscientists to explain and forecast coastal and estuarine morphogenetic processes. Reducing model (predictive) uncertainties requires increasing awareness and reconsideration of common fundamental principles upon which existing models have built. Based on a review of most of the existing morphogenetic models applicable on open oceanic coasts and in estuaries, we use the Exner equations to clarify the potential of individual models. Fundamental coastal and estuarine behaviours, and cautions required when implementing the models, are also discussed on the basis of the Exner equations. Major differences between and difficulties with these models are in the derivation and computation of vertical and horizontal sediment fluxes; these can be even more complicated in estuaries than on open coasts because it is more important to consider estuarine systems in three dimensions and to account for a wider range of grain sizes. In addition, estuaries typically experience more complex interplay between physical and ecological processes as well as connections with both hinterland and the open coast. Tackling these difficulties requires more observational data to derive increasingly reliable parameterizations of sediment fluxes. Future model development and application across a range of spatial-temporal scales should be based on the Exner equations, modified to suit local coastal and estuarine settings, and incorporating natural complexities and hierarchical landform features.

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1. Introduction

Shoreline changes are an important issue for human communities living along the coast. These are compounded by climate change, particularly a continuously rising sea level and an increase in extreme storm events ([IPCC, 2013](#)). To predict coastal and estuarine morphological changes accurately is a difficult and challenging task to be solved by coastal scientists and engineers within the context of climate change. Future prediction also relies heavily on morphogenetic modelling, defined as modelling that focuses on morphological changes. Such models can be used to assess the vulnerability of coasts and estuaries to climate change (e.g. [Ranasinghe et al., 2013](#)). Furthermore, in case of insufficient historical information and limited observational data in time and space, morphogenetic models can serve as a tool to assist scientific research. For example, simulation models, incorporating a wide range of the processes known to effect a particular coastal system, can supplement interpretations of geological data by quantitative reconstructions of paleo-coastal morphological behaviours (e.g. [Cowell et al., 1995](#); [Stolper et al., 2005](#)). Exploratory models, by contrast, are usually based on as few processes as possible, in order to reproduce and better understand the essential processes that lead to poorly understood coastal behaviours ([Murray, 2003](#)).

Many approaches have been used to develop coastal and estuarine models that operate across a range of spatial and temporal scales ([Woodroffe and Murray-Wallace, 2012](#)). Behaviour-orientated models focus on large-scale processes (e.g. decades to centuries in time), whereas process-response models primarily simulate smaller scale processes (e.g. hours to years). Hybrid models include both large-scale and small-scale processes. Morphogenetic models can also be

nested to examine processes over a range of aggregated spatial and temporal scales (Cowell et al., 2003). Morphogenetic models have often been considered deterministic, forecasting a particular geomorphological outcome but providing little consideration of uncertainties that underlie the modelling process. Recently, probabilistic risk approaches that include distribution functions for these uncertainties have also been applied to generate stochastic simulations (Cowell et al., 2006; Ranasinghe et al., 2012; Wainwright et al., 2015).

However, quantitative models, including coastal and estuarine morphogenetic models, are generally an approximation or simplification of a reality that is incompletely known (Murray, 2013). By establishing physical or mathematical equations quantified from existing knowledge and geoscientific data, these quantitative models can deduce aspects of coastal behaviour that are yet to be studied. Increasing knowledge based on empirical data may improve the fundamental equations or enable the creation of new process parameters within models. Nevertheless, there remain model limitations that affect predictive accuracy (La Cozannet et al., 2014; Carassco et al., 2016). Intrinsic simplifications within these coastal models, and the diversity of geological, hydrological, meteorological and ecological settings, further increase these uncertainties and limit the accuracy of future predictions (La Cozannet et al., 2014; Deng et al., 2015; Carassco et al., 2016). Furthermore, existing models have generally been developed by different researchers, so connections between them are frequently unclear. Model users may not be familiar with how existing models were developed or the underlying principles, confounding efforts to select and modify appropriate models for solving particular problems. Therefore, in order to avoid misapplication of models, as has occurred with the well-known and overused Bruun Rule (e.g. SCOR, 1991; Cowell et al., 1995; Thieler et al., 2000; Cowell et al., 2003; Cooper and Pilkey, 2004; Pilkey and Cooper, 2004; Ranasinghe and Stive, 2009; La

Cozannet et al., 2014), there is increasing need to understand the scientific basis, the limitations, and the sources of uncertainties within the models.

Recently, several review papers have provided detail summaries of models that address the response of coasts to climate change (French and Burninngham, 2013; Cazenave and Cozannet, 2013; La Cozannet et al., 2014; Trenhaile, 2016). French et al. (2016) propose a new concept of “appropriate complexity” of modelling coastal and estuarine evolution at decadal to centennial scales, by conceptually recognizing the complexity level required by scientific or management problems. However, previous reviews of models have not provided quantitative synthesis of the models, and unified them by going back to their fundamental foundation. This requires an effective and quantitative way by which the models and their underlying principles can be properly understood. Therefore, in this review, a central hypothesis is that the Exner equations, describing coastal and estuarine morphological evolution (Wolinski, 2009), can be used as a fundamental and quantitative metric to evaluate and compare particular model capabilities and complexities, as well as conditions that render each model valid only in certain coastal settings.

The application of morphogenetic models in this paper is considered within a coastal compartment that contains cliffs, open sandy coasts and estuaries. Estuaries can act as sediment sinks from both the catchment and open coast. Different considerations become important when modelling embayments at successive stages of infill; when completely infilled, estuaries transition into deltas, but delta formation models are beyond the scope of this review.

Fig. 1. (a) Imagery of the Narrabeen Beach sedimentary compartment in Australia; (b) Map showing sedimentary connections between cliff, barrier and estuary (based on Quaternary Geological mapping from Troedson et al., 2015).

An example of a coastal compartment showing several coastal settings and their interrelationships is shown in Fig. 1. It comprises an embayed beach in northern Sydney, called Narrabeen Beach at its northern end and Collaroy Beach at its southern end, lying between two prominent headlands. The southern headland is called Long Reef, which has a prominent shore platform cut in the erodible Triassic Bald Hill claystone, whereas the northern Narrabeen Headland comprises a cliff formed in claystone overlain by the more resistant Hawkesbury sandstone. Narrabeen Lagoon is a barrier estuary formed in the past few thousand years through the accretion of a prograded sandy barrier of which the beach forms the current foreshore. In common with numerous other barrier estuaries along the NSW coast, Narrabeen Lagoon is gradually infilling through the delivery of fluvial sediment from the catchment and tidal

pumping of marine sand through the inlet entrance (Roy, 1984). The beach system within this coastal compartment is the best studied in the region (Short, 2012). It has been shown to alter its orientation, termed beach rotation, in response to variations in wind directions associated with the El Niño-Southern Oscillation phenomenon (Ranasinghe et al., 2004; Harley et al., 2015). The prograded barrier that has developed to occlude the estuary experiences erosion, particularly during the passage of east coast low-pressure systems (ECLs), with sand removed from the beach to the nearshore but recovering between such storm events (Harley et al., 2016). Sand is also sequestered into the flood tidal delta within the entrance to Narrabeen Lagoon, with the inlet being intermittently closed (Woodroffe et al., 2012). The natural functioning of this area has been altered as a result of the high degree of urbanisation; *ad hoc* seawalls have been reconstructed along part of the foreshore, and the beach is periodically replenished with sand extracted from the flood tide delta. Before providing the synthesis of the models, the Exner equations are introduced below.

2. The Exner equations

The Exner equation was originally developed to express morphological changes in the sense of sediment mass conservation in a river (Exner, 1920, 1925). It was further generalized to describe morphological changes incorporating physical and chemical processes (Paola and Voller, 2005). Wolinski (2009) has refocused the generalized Exner equations in relation to coastal areas. Based on his work, we consider two types of Exner equations: the generalized Exner equation based on the sediment column at a point or grid cell (Fig. 2), and the shoreline Exner equation based on a cross-shore profile of the shoreface which explicitly includes interconnections between external sediment fluxes, shoreline position, and relative sea-level

changes (Fig. 3). The generalized Exner equation describes the mutual dependencies between sediment fluxes and surface elevation changes (i.e. mass volume changes) of a single sediment cell (Wolinski, 2009), as can be seen in Fig. 2:

$$c_0 \partial_t \eta = -(\Delta q_{x,b} + \Delta q_{y,b}) + q_z - \sigma \quad (1)$$

Fig. 2. A three-dimensional cell indicating bed load and suspended sediment fluxes illustrating the generalized Exner equations in Eq. (1) and Eq. (2) where the subscript “f” denotes the flow, and “b” means the bed load. q describes sediment fluxes. Surface elevation η changes through time when there is unbalancing of sediment fluxes over three dimensions. σ denotes local land uplift or subsidence. c_0 and C are bed load and suspended sediment concentrations.

In Eq (1), $\partial_t \eta$ is bed surface elevation change; and σ denotes basement land subsidence or uplift. c_0 is bed surface sediment concentration (related to porosity: $\phi = 1 - c_0$) that may change

due to sediment compaction or other processes modifying sediment composition. Δq_x is cross-shore bed load sediment flux, Δq_y is alongshore bed load sediment flux. q_z is vertical sediment flux resulting from erosion and/or deposition of fine-grained sediments that are able to be suspended in the flow. q_z may also include any other *in-situ* produced sediment sources and sinks. Suspended sediment mass conservation can be described below (e.g. Paola and Voller, 2005):

$$q_z = \partial_t Ch + (\Delta q_{x,f} + \Delta q_{y,f}) \quad (2)$$

C is the suspended sediment concentration in the flow (Fig. 2) and h is water depth, $\Delta q_{x,f}$ and $\Delta q_{y,f}$ are the different horizontal suspended sediment fluxes. Sediment mass conservation over a cross-shore profile can be expressed by the shoreline Exner equation derived from Eq. (1) (Wolinski, 2009):

$$H_s \frac{ds}{dt} = c_0^{-1} (\Delta q_x + \Delta q_y + q_z) - LR - \frac{d(\bar{H}L)}{dt} + L \frac{dH_s}{dt} \quad (3)$$

Where s denotes the cross-shore (x dimension) shoreline position, H_s is net shoreface relief that is a sum of subaerial dune or cliff height and the subaqueous closure depth. Δq_x is net total cross-shore sediment flux consisting of both bed load and suspended sediment fluxes, Δq_y is net total alongshore sediment flux, R is relative sea-level rise consisting of land uplift or subsidence σ and eustatic sea-level rise, L is the shoreface length, and $\bar{H}$ is the average shoreface relief. It should be noted that vertical sediment flux q_z in Eq. (3) was neglected by Wolinski (2009), as Eq. (3) was originally derived only for open oceanic sandy coasts. However, in estuarine sedimentary environments vertical sediment flux may be significant; for example, fine sediments

can remain in suspension for a long time where turbidity maxima occur, as within the Changjiang (Yangtze) Estuary (e.g. Wu et al., 2012).

Fig. 3. Generalizations of (a) the Bruun Rule model (offshore sediment transport on steep coast) and (b) the RD-A model (landward sediment transport on gentle coast) (based on Bruun, 1962; 1983 and Davidson-Arnott, 2005), and (c) the Generalized Bruun Rule describing erosion behaviours at intermediate slopes of the hinterland (Cowell et al., 2006). s denotes the cross-shore (x dimension) shoreline position.

Characteristic morphological parameters of the cross-shore shoreface, such as shoreface length, have been used in many models; for example, the standard Bruun Rule model (Bruun, 1962, see Fig. 3). If the shoreface shape $\bar{H}L$ and relief H_s are independent with time (i.e. $\frac{d(\bar{H}L)}{dt} = 0$ and $\frac{dH_s}{dt} = 0$) and sediment fluxes are balanced, Eq. (3) can be converted, as shown by Wolinsky and Murray (2009) to the standard Bruun Rule: $H_s \frac{ds}{dt} = -LR$ (Fig. 3). Eq. (3) clearly indicates that the Bruun model is only a subset of complex coastal geomorphic behaviours from the perspective of sediment mass conservation.

In the sections that follow, we consider application of the Exner equations more broadly through a coastal compartment. We review the extent to which similar parameterization can be applied to cliffs, initially in a two-dimensional profile relaxing the conservation of mass as rock is eroded but not preserved as sediment, but also recognising recent modelling in which the development of perched beaches may occur, or the products of erosion from rocky coasts may be transported alongshore to contribute to other components of the coastal system. The case of estuaries is also examined, where it is shown that it becomes necessary to consider the system in three dimensions and to account for a range of sediment sizes and their appropriate behaviour.

This paper reviews, and compares, models for open oceanic cliff, sandy barrier, and estuary, which can be components of a sediment compartment (Fig. 1). We synthesize models on the basis of the Exner equations to identify how the models have been progressively developed, and to summarize methods that calculate sediment fluxes, clarifying their underlying assumptions. We also discuss relationships between observations and model predictions, as well as cautions to be considered in model application in relation to their use of the Exner equations.

3. Models in different coastal settings

3.1. Cliffs

Table 1 lists cliff erosion models including behaviour-orientated and process-response models. The development of the behaviour-orientated models can be identified based on the shoreline Exner equation, and the Bruun rule model that was originally developed for sandy beaches has served as a basic component for many of these. The process-response models in Table 1 are higher resolution models that can reflect processes at smaller spatial-temporal scales than the

behavioural models. Process-response models usually consider morphological changes at the scale of individual sedimentary cells (Fig. 2), while behavioural models consider morphological changes across each geomorphic unit, such as the coastal profile.

It has been found necessary to modify the standard Bruun Rule for open sandy coasts where there is evidence of overwash and aeolian processes on the backshore, or where longshore processes overwhelm the simple cross-shore approach adopted by Bruun. On cliff-backed coasts, the steep geometric shape and height prevent onshore sediment transport processes (Donnelly et al., 2006). An eroded cliff cannot recover between erosion events, as a beach can, and sediment transport is uni-directional (Trenhaile, 2009). Bray and Hooke (1997) demonstrated that the Bruun concept could also form a basis for modelling soft rock cliffs and their retreat. This extended application can be expressed in terms of the shoreline Exner equation; Bray and Hooke (1997) added subaerial cliff sediment volumes and sediment concentration as a cross-shore sediment influx $c_0^{-1}\Delta q_x$ to the standard Bruun Rule model. Using the shoreline Exner equation, Wolinski and Murray (2009) emphasised the importance of the slope of the underlying bedrock in relation to shoreline retreat over the long term, with hinterland gradient affecting the retreat trajectory (Fig. 4). On time scales of centuries, the shoreline retreat trajectory is linear (consistent with the Bruun Rule model), whereas it becomes non-linear on time scales of millennia due to increasing cliff height. Young et al. (2014) developed a sand budgeting approach to estimate cliff retreat in response to relative sea level rise, balancing eroded sandy mass volume from cliffs and alongshore sediment flux. Due to its simplistic nature, this approach provides an estimate of only an order of magnitude that is statistically appropriate for the high-volume beaches in front of the cliffs along the southern Californian coast. In the Dynamic Equilibrium Shore Model (DESM),

220 [Deng et al. \(2014\)](#) considered the shoreface shape $\frac{d(\bar{H}L)}{dt}$ in Eq. (1), in addition to subaerial cliff
221 volume and hinterland slope. This model applies sediment mass balancing between erosion and
222 accretion of coastal segments, using historical data on coastline change, the modern Digital
223 Elevation Model (DEM), and relative sea-level change, adopting an iterative inverse modelling
224 method to reconstruct dynamic changes of the shoreface shapes ([Deng et al., 2015](#)).

Models	Type	Dimensions	Main principles	Input data	Geomorphic environment types
Bray and Hooke, 1997	Behaviour model	Cross-shore two-dimensional profile	Sediment mass conservation including subaerial cliff erosion volume; fixed coastal geometry	Sea level; length of active shoreface profile; closure depth; cliff height; sand concentration as proportion	Soft rock cliff, beach
Soft Cliff and Platform Erosion, SCAPE model (Walkden and Hall, 2005, 2011; Walkden and Dickson, 2008)	Hybrid (process response + behaviour model)	Cross-shore profiles, quasi-three dimensions by linking these profiles	Erosion rate by Kamphuis (1987) that applies to the cross-shore profiles under the water level that changes with tides and mean sea level; a simple cliff erosion module; beach evolution described by one-line approach (Hanson, 1989); erosion shape function	Tidal amplitude; Baseline angle; Offshore contour depth and direction; Wave heights, periods and directions; CERC coefficient; Run-up limit; Beach slope; Cliff top elevation; Cliff content and material resistance	Soft and Hard rock cliff, platform and beach
Wolinski and Murray, 2009	Behaviour /analytical model	Cross-shore two-dimensional profile	Sediment mass conservation including subaerial cliff erosion volume and hinterland slope (Exner equation, Wolinski, 2009)	Hinterland surface elevation and slope; substrate sand concentration; hinterland and nearshore deposit sand concentration; initial and equilibrium cliff relief; rate of sea level rise; shoreface length; closure depth; beach length	Soft rock cliff and beach
Trenhaile, 2009, 2010	Process Response Model	Cross-shore two-dimensional profile	Shear stress erosion at inter- and sub-tidal zones; beach thickness controlled abrasion; bluff erosion by surf stress	Beach sediment volume, sediment grain size; time series of wave or a wave distribution: wave height, period, frequency; tides including tidal range and duration	Cliff, Soft Rocky platform, beach
Bayesian probabilistic model (Hapke and Plant, 2010; Gutierrez et al., 2011)	Bayesian probabilistic model	Shoreline models	Bayesian network of the prior causal relationship between relative sea-level rise rates, geomorphic setting, geological constraints, hydrodynamic forces and historical shoreline change rate	The height and slope of the cliff, a descriptor of material strength based on the dominant cliff-forming lithology, and the long-term cliff erosion rate that represents prior behaviour	Cliff, barrier, estuarine shores
Zhang et al., 2011, 2012, 2014: BS-LTMM model	Hybrid (process response + behaviour-orientated)	Coastal 2 Dimensional Horizontal (2DH) area model	Cliff recession model (Sunamura, 1992) integrated into the coastal area model simulating long-term coastline changes; Aeolian models	Paleo-DEM; representative wind climate and storm climate; Relative sea-level change rate	Pleistocene till cliff and sandy shores
Castedo et al., 2012	Process Response Model	Cross-shore two-dimensional profile	Modified Kamphuis (1987) erosion formula; geotechnical cliff failure model including ground water level, cliff stability and production of talus wedge	Beach sediment volume, sediment grain size; critical threshold values and other coefficients; bluff height, Ground water table; wave height, period and frequency	Cohesive clay, beach
Castedo et al., 2013	Process Response Model	Cross-shore two-dimensional profile	An improvement on previous work by Castedo et al. (2012) by using erosion model of Trenhaile (2009); wave induced run-up involved	Beach sediment volume, sediment grain size; critical threshold values and other coefficients; bluff height, Ground water table; wave height, period and frequency	Cohesive clay cliff, beach
Hackney et al., 2013	Hybrid (statistical , process response) model	One dimension	Peak wave energy governing the cliff erosion rate	Wave, sea level, historical cliff retreat rates	Soft rock cliff
Young et al., 2014	Behaviour model	Cross-shore two-dimensional profile	Active beach profile translating to balance sandy mass volume; Subaerial cliff hinterland slope; cliff sand concentration; external sand sources or sinks	Beach profile; Wave climate; Sea level rise; External sand budget; Precipitation; Cliff profile and composition	Soft rock cliff and beach
Dynamic Equilibrium Shore Model, DESM (Deng et al., 2014; Deng et al., 2015)	Behaviour model	Quasi-three-dimensional model by integrating cross-shore profiles	Dynamic equilibrium evolution of coastal profiles in adaptation to three-dimensional sediment mass conservation based on the Bruun Rule concept	Coastline change; Modern DEM; relative sea-level change	Pleistocene till cliff and sandy shore

Fig. 4. Contrasting cliff and barrier retreat behaviours on different time scales affected by hinterland landscape: (a-b) short-term (centuries) evolution, (c-d) long-term (millennia) evolution, and (c) final deposits. Initial hinterland topography shown as black dashed line and successive nearshore profiles as black curves. Successive sea levels shown as thin gray lines, shoreline positions as gray circles, and shoreline trajectory as a thick gray curve. Black dotted line shows average nearshore slope. (based on Wolinski and Murray, 2009).

The shoreface shape change and cross-shore flux Δq_x in the Exner equation of Eq. (3) can result from varying short-term processes at the beach and submarine platform as well as geotechnical processes at the subaerial cliff face (Fig. 5). These small-scale processes can be modelled by the process-response models of cliff erosion included in the Table. 1. These process-response models mainly obtain cliff erosion rate using one of two approaches (Sunamura, 1992): (1) by calculating a ratio between wave erosion forces and material resistant forces; or (2) by quantifying hydrodynamic forces and the critical threshold values that represent local sedimentological properties (i.e. material resistant forces).

The first of these approaches simply parameterizes the recognition that cliff erosion is proportional to hydrodynamic force and inversely proportional to the resistant strength of the material (primarily sediment).

$$\frac{ds}{dt} \propto \frac{F_w}{F_r} \quad (4)$$

The shoreline or cliff recession rate $\frac{ds}{dt}$ is proportional to hydrodynamic eroding forces (F_w), and inversely proportionally to material resistant forces (F_r). Eq. (4) expresses only the erosion case of the cliff. The equation does not fully express the physics of erosion processes; it usually consists of a constant coefficient value that needs to be calibrated against observational data. [Sunamura \(1992\)](#) used the logarithmic form of the right-hand side of the Eq. (4) explicitly to express non-recession when wave erosion force is in equilibrium with material resistant forces. The wave erosion force is represented by $A\rho gH$ where A is a non-dimensional coefficient, ρ is water density, g is gravitational acceleration and H is wave height. Eq. (4) does not include beach sediment protection and subtidal erosion, and presumes uniformity of other factors such as sediment grain size and material components. In the SCAPE model ([Walkden and Hall, 2005](#); [Walkden and Dickson, 2008](#)) listed in Table.1, the wave erosion force is described by the [Kamphius \(1987\)](#) formula, that is $H_b^{13/4}T^{3/2} \tan a$ where a is the average slope across the surf zone, H_b is the breaking wave height and T is the wave period. F_r is a coefficient representing the material resistant strength. The SCAPE model employs a site-specific erosive shape function derived from field data to model submarine and intertidal platform erosion (Fig. 5) that is primarily driven by storm waves ([Walkden and Hall, 2005](#); [Walkden and Dickson, 2008](#)). Erosion of cliffs supplies material that may be entrained by longshore drift or incorporated into beaches in front of the cliffs, in which case the Bruun profile is used to model beach morphology. Moreover, sediment volumes are determined by the locally available sediments and alongshore sediment fluxes induced by wave breaking processes. A regional pattern of the retreat of rocky

coasts and supply, and re-deposition, of sand-sized sediment derived from such soft cliff retreat has been generated by such modelling (Dickson et al., 2007; Hanson et al., 2010). Zhang et al. (2011) adopted the Sunamura (1992) equation, and used a 2DH area model to compute wave erosion forces (F_w) along the cliffed coastline, and F_r is expressed using a non-dimensional constant and compressive strength of the material. There are reasonable representations of wave erosion forces, but the coefficients used to represent material resistant strength F_r create uncertainties that have to be determined by calibration and validation procedures. The model adopted by Castedo et al. (2012) also split this into unconfined compressive strengths (UCS) and a constant coefficient, reducing the significance of uncertainties associated with the F_r term.

The second approach describes whether erosion or recession occurs when the wave-induced bed shear stress exceeds the critical threshold:

$$E = k(\tau - \tau_c) \quad (5)$$

Where E is the erosion rate (m/yr), k is a coefficient, τ can be the bed shear stress or other quantities of hydrodynamic forces, and τ_c is the critical threshold value. Eq. (5) has been primarily used in cliff erosion models by Trenhaile (2009). Cliff erosion consists of three components: submarine erosion, cliff toe erosion and beach erosion (Fig. 5). There is a critical bottom shear stress for submarine erosion, and critical surf stress for subaerial cliff (or bluff) erosion. As bottom shear stress decreases with water depth and only storm events can induce strong bottom shear stresses exceeding the erosion threshold, this model does not need to define an erosive shape function as the SCAPE model does for submarine platform erosion. Such models enable the progressive development of horizontal rock platforms, generally called shore platforms, at the base of cliffs, although considerable debate remains about the relative

significance of wave erosion as opposed to subaerial lowering of platform surfaces by wetting and drying processes (Trenhaile, 2000; Stephenson, 2000). Erosional trends are still more complicated where such rocky coasts are covered by ephemeral beach deposits. Beach erosion is controlled by sediment thickness that is a function of the beach slope and the *in-situ* available sediment volume. The basic principle of beach-thickness controlled abrasion is that long-term abrasion rates decrease with beach sediment thickness. Beach slope is a function of sediment grain size, wave breaking height and period. In addition to the surf stress, Castedo et al. (2013) added wave-induced run-up stress to a model of bluff erosion. Among the models in Table 1, only Castedo et al., (2012) and Castedo et al. (2013) incorporate a more complex geotechnical cliff-fail module that deals with the occurrence, type, size and frequency of cliff failures (Fig. 5).

The input data required for these models in Table 1 also differs; wave information, in particular, is critical input data for nearshore erosion. The SCAPE model uses linear wave theory to represent wave refraction, diffraction, shoaling, breaking and setup. Trenhaile (2009) also employed a linear wave module to model wave shoaling and breaking. Among these models, Zhang et al. (2011) simulate offshore and nearshore waves driven by winds using 2DH wave models. Castedo et al. (2012) directly use measured offshore data.

303

304 Fig. 5. Conceptual diagram depicting (a) cliff and (b) dune evolution of primary driving forces,
305 taking coastal retreat as an example (based on [Davidson-Arnott, 2005](#); [Walkden and Hall, 2005](#);
306 [Trenhaile, 2010](#); [Castedo et al., 2012](#); [Rosati et al., 2013](#); [Deng et al., 2014](#)). The dashed line
307 represents the past coastal profile and the former mean sea level, and the solid line denotes the
308 present ones. Note that sediment volumes in this diagram are dimensionless and their actual
309 dimensions depend on local processes and lithological settings (e.g. rocky platform, clay or
310 sandy shore).

311 To sum up, several models assume that extreme forces can cause significant erosion of the
312 subaerial cliff, or submarine platform, or even sandy seafloor abrasion (e.g. [Trenhaile, 2010](#);
313 [Zhang et al., 2011](#); [Hackney et al., 2013](#); [Deng et al., 2014](#)), but these are not clear about the role
314 of long-term cumulative forces during calm weather or the sinks of the eroded sediments.
315 [Castedo et al. \(2012\)](#) and [Castedo et al. \(2013\)](#) have also incorporated subaerial cliff failure

mechanisms involving geotechnical properties of cliff materials. At the lower shoreface, there may be deposition of fine-grained sediments, involving low-order processes usually not incorporated into models focused at such scales (Cowell et al., 2003). Cliff erosion as incorporated into 2DH coastal area models by Zhang et al. (2011) appears to be the most complex, as it has directly simulated nearshore hydrodynamic and sediment transport processes that receive sediment sources from cliff erosion. A subaerial cliff erosion mechanism is included in the model by Castedo et al. (2013). A model by Hackney et al. (2013), applying statistical regression to the process-response relationship, adopts Eq. (5), but uses wave energy instead of bottom shear stress as a hydraulic driving factor. The coefficients in their equations are not determined in the usual way involving calibration, but by an empirical linear regression using historical data. This model has to assume a time-stationary linear relationship between accumulated excess wave energy and cliff retreat. The latest models start to take alongshore and cross-shore sediment sources and sinks into account, and apply sand balancing in three-dimensional space (Limber et al., 2014; Limber and Murray, 2014; Deng et al., 2014; Young et al., 2014). They utilise a closed compartment for developing the model to predict beach response to sea-level rise on rocky platforms (Taborda and Ribeiro, 2015). Rocky platforms are highly resistant and limit beach sediment mobility. Erosion on hard rock coasts usually occurs at the water surface where there is strong energy dissipation, which means that modelling of hard rocky coastal retreat should be considered differently from that of soft sedimentary coasts (Trenhaile, 2016).

There are other models in Table 1 which have applied probabilistic approaches (e.g. Hapke and Plant, 2010; Gutierrez et al., 2011). In general, probabilistic models all need past

observational data to create a probability distribution of relationships between shoreline changes and other factors. These probabilistic distributions may be converted into a form that can be used to forecast future shoreline changes. The Bayesian Network model used by [Hapke and Plant \(2010\)](#) can take full advantage of historical observational data as prior knowledge, and account for the uncertainties of predictions. The Bayesian approach can also imply a causal relationship between known variables. This model assumes stationary probability distributions of input parameters such as waves that are dynamically changing. Furthermore, predictions are sensitive to historical erosion rates that may vary significantly over selected time spans. Probabilistic models usually cannot adequately incorporate sediment transport processes in the Exner equations leading to morphological changes, but can provide probabilistic estimates based on purely observational data. Because many numerical models are now generally considered to need substantial improvements, probabilistic approaches are likely to become a necessary component of future modelling in order to provide uncertainty estimates for predictions. Examples of hybridisation of morphogenetic models and probabilistic approaches are given in the next subsection.

3.2. Sandy barriers

Table 2 lists models for sandy barrier coasts. Many originate from the standard Bruun rule model, in some cases further modified by considering onshore and alongshore sediment fluxes using the shoreline Exner equation. The standard Bruun Rule has been widely applied to consider erosion and retreat of beaches as a result of sea-level rise. In its simplest form, it foreshadows the loss of sand from the beachface and its transfer into the nearshore out to a predefined ‘closure’ depth. There have been various attempts to use observational data to provide

validation for the Bruun process; for example [Zhang et al. \(2004\)](#) compared averaged coastline erosion alongshore for coastal compartments of the U.S. east coast with relative sea-level rise rates, and found relatively good agreement when excluding the influence of tidal inlets. Defining closure depth has proven difficult and it is increasingly apparent that such a seaward limit will be time-variant ([Nicholls et al., 1998](#)). Although erosion of a beach and transfer of the eroded sand seaward can be observed during storms, longer-term geomorphological processes have been shown to be effective at moving sand landwards, augmented by wind processes on dune coasts and overwash on barrier islands. Accordingly, a broader range of responses needs to be modelled wherein some sand can also be transported landwards; a formulation that has been termed the generalized Bruun Rule by [Cowell et al. \(2006\)](#), see also Fig. 3). Substrate slope is a key determinant of the degree to which there is onshore or offshore sediment flux in this generalized Bruun model ([Cowell et al., 2006](#)).

372 Table 2. Barrier/dune coastal erosion models

Models	Type	Dimensions	Main principles	Input data	Geomorphic environments
Bruun Rule (Bruun, 1962; 1983)	Behaviour model	Cross-shore two-dimensional profile (alongshore averaged)	Sand mass conservation; fixed shoreface shape; dominant onshore or offshore sediment transport	sea-level change; modern shoreface morphology;	Beach and foredune
RD-A model (Davidson Arnott, 2005)	Behaviour model	Cross-shore two-dimensional profile (alongshore averaged)	Sand mass conservation; fixed shoreface shape; dominant onshore sediment transport	sea-level change; modern shoreface morphology;	Beach and dune
Shoreface Translation Model, STM (Cowell et al., 1995)	Behaviour model	Cross-shore two-dimensional profile (alongshore averaged)	Sand mass conservation; Substrate slope governing the profile translation modes; Geological data driving model behaviours or calibrating geometrical and sediment budget parameters in the model; Idealized geometric forms;	Modern representative cross-shore morphology; stratigraphic data; sea-level change;	Barrier, shoreface
Geomorphic model of Barrier, Estuarine and Shoreface translations, GEOMBEST model (Stolper et al., 2005; Moore et al., 2010; Walters et al., 2014)	Behaviour model	Cross-shore two-dimensional profile (alongshore averaged)	Sand mass conservation; graded substrate erodibility; Depth-dependent shoreface response; Estuarine infill reducing shoreface transgression rate; Geological data driving model behaviours or calibrating parameters in the model; Saltmarsh	Modern representative cross-shore morphology; stratigraphic data; sea-level curve; estuarine infilling rate; erodibility index; sand/mud ratio; depth dependent shoreface response rate;	Barrier, shoreface, estuarine basin
Wolinski and Murray, 2009	Behaviour and analytical model	Cross-shore two-dimensional profile	Sediment mass conservation including subaerial overwash zone, back barrier and shoreface by applying shoreline Exner equation (Wolinski, 2009); Idealized geometric forms;	Hinterland surface elevation and slope; substrate sand concentration; hinterland and nearshore sand concentration; rate of sea-level rise; shoreface length; closure depth; beach length; Barrier island of length and height; Back-barrier slope; equilibrium back-barrier relief	Barrier, shoreface, estuary
Lorenzo-Trueba and Ashton, 2014	Process response model and exploratory model	Cross-shore two-dimensional profile	Barrier behaviours determined by dynamic shoreface, rate of sea-level rise and overwash flux; Idealized geometric forms;	Overwash flux, depth of the shoreface toe, relative sea-level rise rate, back-barrier lagoon slope, critical barrier width, critical barrier height the top-barrier, shoreface slope at static equilibrium, shoreface response rate, maximum overwash sediment flux, maximum deficit volume	Barrier, shoreface, estuary
Storms et al., 2002, 2003 (BARSIM)	Process response model	Cross-shore two-dimensional profile	Sea level, storm wave base and topography governed erosion; deposition controlled by the sediment travel distance and sediment flux	Rate of sediment supply and relative sea-level rise; sediment grain size class; maximum coastal erosion rate; local wave efficiency; storm wave base; substrate slope; initial coastal profile; back-barrier lagoon water level;	Barrier, shoreface, estuary
Bayesian probabilistic model (Gutierrez et al., 2011)	Bayesian probabilistic model	Shoreline models	Bayesian network of the prior causal relationship between relative sea-level rise rate, geomorphic setting, geological constraints, hydrodynamic forces and historical shoreline change rate.	Tidal range; wave height; relative sea-level rise; coastal slope; shoreline change rate; geomorphic setting;	Cliff, barrier, estuarine shores
Ranasinghe et al., 2012	Process-based, probability	Zero dimension	Simplified wave impact dune erosion model by Larson et al. (2004) implemented by the Joint Probability Method (JPM)	Dune recovery rate and dune height; beach slope and sediment grain size;	Dune

	models		model developed by Callaghan et al. (2008) plus prescribed dune recovery rate. Dune erosion is only caused by storm events	storm climate; Rate of relative sea-level rise;	
Ranasinghe et al., 2013	Physically based, scale aggregated model	Foredune shoreline model	Four main physical processes contribute to coastline change adjacent to barrier estuaries/lagoons: SLR-driven landward movement of the coastline (the Bruun effect), basin infilling due to the SLR-induced increase in basin accommodation space, basin volume change due to Climate Change-driven increases/decreases in river flow, and increases/decreases in fluvial sediment supply	Basin area and volume; active profile slope; catchment area; length of affected coastline; mean ebb tidal prism; change in annual average river flow and rainfall by 2100.	Barrier, shoreface, estuary, tidal inlet

A number of more complex models have been developed to further simulate the morphological evolution of sandy barrier coasts during sea-level rise. The Shoreface Translation Model (STM) is a sediment budget model that simulates morphodynamic attributes in a coastal compartment on a sandy barrier coast (Cowell et al., 1995). It includes a stratigraphic representation of alongshore-averaged surface morphology and stratigraphic geometry of both coarse and fine sediments, and lithified material. The STM simulates redistribution of sediments (sand and mud) within a coastal cell kinematically (*i.e.*, through movements in the bed level) based on geometric rules of shoreface, barrier, and estuarine accommodation potential, in order to quantify, amongst other things, horizontal and vertical translation of the shoreface under sea-level change.

The GEOMBEST model (GEOMorphic Model of Barrier, Estuarine and Shoreface Translations) is a similar model that takes substrate erosive potential into account, and explicitly adds the estuarine infilling rates to determine back-barrier accommodation space (Stolper et al., 2005; Moore et al., 2010; Walters et al., 2014). The STM and GEOMBEST models both adopt the “Coastal Tract” concept developed by Cowell et al. (2003) to abstract a three-dimensional system to a two-dimensional cross-shore profile. Both the STM and GEOMBEST models can be used to understand coastal evolution quantitatively at geological time scales, supplemented by geological data collected in the field and qualitative explanations. Also, these two models can be applied for long-term coastal management on time scales of decades to centuries (Woodroffe et al., 2012).

Wolinski and Murray (2009) developed an analytical model based on the shoreline Exner equation (Eq. (3)), and further refined the STM hypotheses about different modes of coastal

erosion. They suggest that the relative steepness and composition of the nearshore system and hinterland landscape exert a first-order control on whether it is a standard Bruun retreat or a generalized case involving landward transport as well, as with retreat in the RD-A model. [Wolinski and Murray \(2009\)](#) produced representative simulation results, shown in Fig. 4, which show that on a gentle coast, hinterland topography plays a first-order control on the back-barrier accommodation space of barrier retreat, and over time scales of millennia shoreline retreat trajectory becomes non-linear.

One variant of the Bruun model appropriate for coasts on which aeolian processes deliver sand to dunes was developed by [Davidson-Arnott \(2005\)](#). When sea level rises, shoreline recession occurs on a dune coast together with landward migration of the upper shoreface driven by onshore sediment transport processes, and this model, termed the RD-A model, includes aeolian sand transport and storm overwash deposition (Fig. 3 and 5). This onshore sediment transport is usually the dominant mode of coastal erosion on gently sloping beaches ([Aagaard and Sørensen, 2012](#)). Other researchers, such as [Rosati et al. \(2013\)](#), also support this concept and quantitatively add landward deposition (due to overwash and aeolian processes) to the standard Bruun Rule.

[Lorenzo-Trueba and Ashton \(2014\)](#) developed a morphodynamic model coupled with geometrical behaviour rules applicable to barriers. In this model, barrier behaviours are determined explicitly by dynamic shoreface flux, the rate of sea-level rise and overwash flux. This model appears to be able to reflect extended barrier modes of landward retreat such as periodic retreat and including more processes within the system, compared to previous behaviour models such as the STM and GEOMBEST models, but it is not as complex as the model

developed by Storms et al. (2002).

The two-dimensional barrier model described by Storms et al. (2002) and Storms et al. (2003) incorporates small-scale processes of storm impact, classes of sediment grain sizes, rates of relative sea-level rise, and sediment supply. The model is based on the assumption that shoreface morphology represents a dynamic equilibrium between erosion and deposition. The model appears applicable to most types of large-scale barriers and their geomorphological behaviour. It has been used to simulate retrogradation, aggradation, and progradation of coastal barriers, and discontinuous retreat determined by high rates of sea-level rise. This model can simulate variable coastal morphology including an equilibrium profile. The latest application of this model investigates primary processes driving Holocene prograded barrier formation in eastern Australia, in which disequilibrium (i.e. convex) shoreface morphology can facilitate shoreface sand supply to the beach (Kinsela et al., 2016). However, the modelling does not well represent coastal processes, such as longshore drift, operating during fair-weather conditions when beaches recover from erosion. The subaerial aeolian flux is also not included, and this flux may be significant in building foredunes. Based on Eq. (1) and Eq. (2) as well as leaving out suspended sediment volume Ch , the total sediment flux results from the net sediment volume between erosion and deposition:

$$\vec{\nabla}q = E - D. \quad (6)$$

In this equation, E denotes the rate of erosion and D represents the rate of deposition. E is governed by topography, sea level, and storm wave base, while D is controlled by depth-dependent travel distance that is a function of sediment grain size, and sediment supply.

In an effort to overcome the deterministic nature of many of these models, probabilistic simulations have been advocated in which multiple model runs simulate the range of possible input parameters (Cowell et al., 2006). Ranasinghe et al. (2012) presented a probabilistic model that consists of a process-based storm-driven dune erosion model (Larson et al., 2004) and a Probabilistic Coastline Recession (PCR) model. In this model, the Joint Probability Model (JPM) by Callaghan et al. (2008) generates the time series of storm characteristics. The increasing amount of wave and tidal gauge data globally facilitates broad application of this PCR model. However, developing an effective process-based model of dune recovery remains a challenge. The probability distribution of storm time series is derived from historical data, as with other probabilistic models, and is assumed stationary in future projections of relative sea-level rise scenarios (Woodroffe et al., 2012; Hanslow et al., 2016). Unlike the Bruun Rule which provides a single predicted value for retreat, these models can generate probabilistic estimates of coastline retreat, inferring future shoreline positions with apparent likelihoods that are increasingly required for risk-based management activities.

Whereas there has been some effort to incorporate transport of sand from the beach into the dune, and in some cases overwash, into a sediment budget perspective on shoreline response, there are relatively few models that incorporate open coast exchanges with adjacent estuaries. As emphasized in the case of the Narrabeen compartment in Figure 1, sand is lost from the beach system into the estuary mouth with implications for both the behaviour of the beach and that of the estuary. A couple of preliminary attempts have been made to address these issues, for example by coupling of the SCAPE model of soft cliff profile retreat with a simple estuarine model (ASMITA) (Whitehouse et al., 2009) and the inlet-interrupted retreat model proposed by

460 [Ranasinghe et al. \(2013\)](#). The role of estuaries and how they may be modelled is considered
461 below, and these approaches are examined there.

462 Table 3. Estuarine models

Models	Type	Main principles	Input data	Geomorphic types
Estuarine transgression model: inverse Bruun rule (Allen, 1990)	Conceptual and regime model	Estuary “rollover” is that sediment is transferred from outer estuary to inner estuary when sea level rises	Estuarine stratigraphy and geometry	Tide dominated estuaries;
Estuarine Sedimentation Mode - ESM (Stopler, 1995; Sampath et al., 2011; Sampath et al., 2015)	Two-dimensional area model; Behaviour orientated model	Prescribed functions of depth-dependent sedimentation rates or tidal inundation frequency controlled sedimentation rates; subtidal erosion and deposition are modelled by assuming constant tidal quantities in the estuary	The long-term net accretion rate coefficients for the depth range, representative sedimentation rates, and cumulative sea- level rise for the total time period	Tidal creeks, or sheltered tidal environments
Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast - ASIMITA: Stive et al., 1998; Van Goor et al., 2003; Rossington et al., 2011)	Semi-empirical box models	The tidal inlet system is schematized to a set of elements characterized by one variable – volume defined using prescribed empirical tidal prism equations; conservation of sediment in the sense that the total exchange of sediment between one element and its neighbours balances local sedimentation or erosion; differences between global and local equilibrium concentrations governing sediment exchange between elements	Tidal range; area, volume of geomorphic elements; vertical and horizontal exchange coefficients; global equilibrium concentration of the tidal inlet system	Tidal inlet with a small tidal basin
Karunaratna et al., 2008; Reeve and Karunaratna, 2011	Behaviour-orientated inverse model	Two dimensional diffusive equation with a source function; source function is determined by the inverse method based on historical data	Series of high-resolution historical bathymetric data; sediment diffusion coefficient derived from field measurements	Tide dominated estuaries
Di Silvo et al., 2010; Bonaldo and Silvo, 2013	Two-dimensional area model; process-based model	The long-term equilibrium transport concentration determined by stirring factors of wave, tide and sea forces; Hydrodynamic sub-model based on the assumption of short tidal lagoon and constant rate of tidal elevations all over the basin	Tidal range and period; river discharge; river average concentration; river tidal prism; equilibrium concentrations by sea, wave, tide and river; Chezy coefficient; relative sea level change: eustasy and subsidence	Tidal network; small tidal basin;
Townend, 2010;2012	Three dimensions; Behaviour orientated model	Equilibrium relationships between hydraulics (i.e. tide and wave) and an idealized funnel 3D form including intertidal flat; channel hydraulics is modelled by one-dimensional tidal propagation assuming constant depth and tidal amplitude	Tidal amplitude; river flow; basin area; wind speed; average sediment concentration; average sediment grain size; bed shear stress; maximum depth of marsh species; mean depth over marsh	Tidal inlets; drowned river valley and coastal plain estuaries dominated by single channel; finite sized tidal basins
Delft 3D: van der Wegen et al., 2011; van Maanen et al. 2015: eco-morphodynamic model	Coastal area models	Based on mechanics of flow and sediment dynamics	Forcing data of tides, initial bathymetry, sediment grain sizes	Tide dominated estuaries

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3.3. Estuaries

Table 3 includes estuarine models, summarizing the main principles and input data. These can also be linked to the Exner equations as a major framework for understanding their modelling methodologies. In contrast to most open coast systems, estuaries represent a sediment sink. There is considerable variability in estuary geomorphology (Roy, 1984; Dalrymple et al, 1992; Roy et al., 2001; Townend, 2012), largely encapsulated in the definition by Pritchard (1967) that estuaries are semi-enclosed waterbodies in which freshwater input dilutes seawater through mixing by a combination of river, wave, and tidal processes. Narrabeen Lagoon, shown in Fig. 1, is an example of a barrier estuary formed by accumulation of the sandy barrier that has prograded over the past 6-7 millennia, on which the contemporary beach marks the modern shoreline. Barrier estuaries of this type are common along the southeastern coast of Australia. A conceptual model of their infill has been developed by Roy (1984), recognising gradual impingement on a central vertically-accreting mud basin by terrestrially derived sands forming a fluvial delta and marine sands that intrude through the entrance forming a flood tide delta (Roy, 1984; Roy et al., 2001). Adjacent estuaries at various stages of infill provide further evidence for the succession of stages, although a recent hypothesis by Adlam (2014) suggests that complete infill through mud basin accretion may not occur because wind wave forces will prevent further sedimentation after basin depth reduces to a certain threshold.

The stratigraphy of estuaries records the accumulation of sediments. Intertidal or estuarine margin sediments overlie the pre-Holocene topography and Allen (1990) has demonstrated how the depositional chronology of sediments in the macrotidal Severn Estuary in the U.K. indicates estuarine “rollover” in response to relative sea-level rise. As the sea has risen, muddy sediments

have been deposited over the previously subaerial substrate in the newly available accommodation space around the estuary margin. This has been compared to the Bruun principle by [Pethick \(2001\)](#) who points out that the processes of sediment transfer are the inverse of those attributed to the Bruun effect on open sandy coasts. Whereas on beaches sand is eroded from the beachface and deposited on the shoreface, in the case of estuaries sea-level rise is inferred to result in entrainment of muddy sediments from the estuarine basin and their advection into peripheral intertidal or estuarine margin environments. Further details of this rollover process are examined by [Townend and Pethick \(2002\)](#) for the Humber estuary in the U.K.

The shoreline Exner equation might be appropriate for some sandy shorelines around estuaries, but vertical fluxes involving suspended cohesive sediments need to be incorporated. There is also a greater variation in sediment grain size within estuarine sedimentary environments, requiring more complex models than appropriate on the open oceanic coast when treating the estuary as a whole. The estuarine models use the generalized Exner equation (Eq. (1)), where bed load sediment fluxes are neglected. The suspended sediment fluxes ($\Delta q_{x,f} + \Delta q_{y,f}$) are parameterized either by a depth-dependent function, by adopting the geomorphic diffusive transport law of Eq. (8), or by incorporating hydrodynamics. The vertical flux q_z is calculated by the difference between erosion and deposition, or through deviations from the equilibrium concentration of suspended sediments. Another important feature of estuarine models is also using mathematics to describe the aggregated characteristics of each geomorphic unit such as the volume of the tidal flat and channel or the shape of tidal flat, which is a function of hydrodynamic parameters. In estuaries, complex models, such as the Delft3D coastal area

morphodynamic model (e.g. Lesser et al., 2004), are needed in order to simulate sediment erosion, transport, and deposition for the diverse sedimentary environments that may have complex hydrodynamics and topographic boundaries as well as a wide range of sediment grain sizes. There are two major applications of this kind of model: 1) direct application at a real estuary with validation against measured data (e.g. Wu et al., 2010; van der Wegen et al., 2011); or 2) adoption of the exploratory modelling concept (Murray, 2003) to improve understanding of the primary processes by reducing complexity of boundary conditions and physical processes (e.g. Zhou et al., 2014; van Maanen et al., 2015). Biophysical interaction that modifies the physical processes has increased the complexity of modelling estuarine morphological evolution, as the biological and ecological processes and their interactions with hydrodynamic and sediment transport processes have to be taken into account as well (Fagherazzi et al., 2012; van Maanen et al., 2015).

The conceptual model of estuary infill developed by Roy (1984) stimulated development of the Estuarine Sedimentation Model (ESM) by Stopler (1995, see also Bruce et al., 2003). Sampath et al. (2011, 2015) adopted the ESM to hindcast morphological evolution of Guadiana Estuary in Portugal and made future projections on the basis of sea-level rise scenarios. In this model, morphological changes are only induced by the gradient of vertical sediment flux Δq_z in Eq. (6).

$$q_z = E - D \quad (7)$$

The sedimentation rate is calculated using $D = \frac{C_b W_s}{\rho_{sed}}$ where C_b is the near-bed sediment concentration, ρ_{sed} is sediment grain size, and the erosion rate is a function of tidal flow

(Prandle, 2004): $E = \frac{\gamma f \rho_{water} U^2}{\rho_{sed}}$ where U is tidal current speed; γ and f are coefficients respectively for sediment erosion and bed friction. Spatial variation of Δq_z is parameterized by pre-defined large-scale depth-dependent accretion rates in the subtidal zone derived both from geological data and from contemporary observations. Furthermore, calculations of accretion rates in this model do not account for spatial differences of tidal amplitude and wave impact that may cause bed load sediment fluxes. Therefore, this model is only suitable to be applied in sheltered estuarine environments where aggradation is dominant in driving morphological change (Sampath et al., 2015), for example, the central mud basin in the estuary in Fig. 1.

Large-scale behaviour models adopt a known connection between hydraulic and geomorphic aggregated characteristics. On the basis of field data from a wide range of tidal inlets, a linear equilibrium relationship between tidal prism P and inlet cross-section area A was established by O'Brien (1969). A basic empirical power-law relationship is given below:

$$A = kP^a \quad (10)$$

Where the scaling parameter a lies in the range 0.85-1.10 (e.g. O'Brien, 1931, 1969; Friedrichs, 1995; D'Alpaos et al., 2010), and k is a coefficient derived from field data. Such P - A relationships exist at tidal inlets that do not have external sediment sources and sinks (Friedrichs, 1995; Lanzoni and Seminara, 2002). D'Alpaos et al. (2010) also used both field evidence and numerical models to verify the applicability of the P - A relationship for sheltered tidal channels. By extending this P - A relationship to the intertidal flat, ebb delta and tidal channel, a model named the Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast (ASMITA) was developed by Stive et al. (1998). ASMITA can model

interactions between lagoons, the adjacent open oceanic coast, and the submerged delta. The ASMITA model schematises each estuarine geomorphic element to one variable – volume that is a function of tidal prism P , basin area A_b and tidal range H . In the ASMITA model, diffusive sediment transport processes dominate the transport of suspended sediment fluxes (Eq. (8)). The diffusive sediment flux is a function of the differences between total sediment concentration Ch of adjacent geomorphic elements in ASMITA. Here, h represents the water volume in each element. This (dynamic) equilibrium concentration of sediments indicates the extent of the actual volume deviating from the equilibrium volume. This local dynamic equilibrium concentration will not be stable until the entire system is in equilibrium when no erosion and deposition occurs. The dynamic equilibrium concentration appears to be a step forward from the model by [Di Silvo et al. \(2010\)](#). A sediment source of the tidal inlet system is required as an input called global equilibrium concentration to govern sediment diffusive exchanges between geomorphic elements. By adding sea-level rise to increase water volume, [Van Goor et al. \(2003\)](#) have used ASMITA to investigate the impact of different rates of sea-level rise on the morphological equilibrium configurations of tidal inlets, with case studies at ‘Ameland’ and the ‘Eierlandse Gat’ in the Dutch Wadden Sea. [Rossington et al. \(2011\)](#) refined and improved the schematisation of estuarine elements. This new schematisation method is supported by two case studies in U.K. estuaries.

ASMITA has also been applied to study human interventions on tidal inlet morphological evolution and the associated system time scales ([Kragtwijk et al., 2004](#)). Based on the premises of equilibrium between tidal prism and (dry or wet) volume, the ASMITA model is a useful tool for investigating equilibrium adaptation of tidal inlet systems responding to external forces of

sea-level rise and human intervention. It can be applied to the geomorphic environments of subtidal flat, intertidal flat and the channel in Fig. 1. The time scale of inlet morphological response to changing tidal prism is still not clearly defined. Due to intermittent opening and closing of tidal inlets, such as the entrance to Narrabeen Lagoon in Fig. 1, the P - A relationship may not be applicable to barrier estuaries and coastal lagoons in southeastern Australia (Woodroffe, 2003). Recent studies indicate that large fluvial discharge can influence the P - A relationship (Stive et al., 2012; Hinwood et al., 2012; Zhou et al., 2014), and that significant river input has an effect on the tapering of macrotidal estuaries (Davies and Woodroffe, 2010).

The response of estuaries may also be a function of the behaviour of sediment transport on adjacent open coasts. An attempt to integrate the two types of coast was made on the soft rock cliffs of East Anglia. SCAPE was used to characterize erosion on the open coast, and this was linked to ASMITA in adjacent estuaries (Whitehouse et al., 2009). In a similar approach, Ranasinghe et al. (2013) used the Bruun Rule model to estimate retreat of the foredune on an inlet-interrupted shoreline. Their model only takes the Bruun effect LR and the additional net alongshore sediment flux $c_0^{-1}\Delta q_y$ into consideration in Eq. (3). The sediment exchange via the inlet between the open oceanic coastline and the estuarine basin is incorporated by using a physically-based scale-aggregated approach. Sediment import volume from erosion of the open coast is estimated to maintain the equilibrium basin volume and cross-section area of the inlet when sea-level rise and climate change affect fluvial discharge and sediment supply. On inlet-interrupted coastlines, the Bruun effect could be significantly overwhelmed by other factors such as sea-level rise-driven basin infilling and variations of fluvial discharge and sediment supply.

Another contribution to estuarine evolution modelling is the inverse model that assumes that estuarine evolution is governed by diffusive and non-diffusive processes (Karunarathna et al., 2008). The diffusive equation is a simplification of the Exner equation of Eq. (1) where the sediment fluxes are a function of the gradient of the topography itself (Wolinski, 2009):

$$\vec{\nabla}q = \vec{\nabla} \cdot (K\vec{\nabla}\eta) \quad (8)$$

where K is a diffusive coefficient, that may not be constant. Non-diffusive processes, including any processes other than diffusive processes, are aggregated as an additional source term. The source term is derived by solving an inverse problem using high-resolution consecutive historical bathymetric datasets of the Humber estuary (UK) covering a period of 150 years. This model has been used to study relative impact of diffusive and non-diffusive processes on evolution of the Humber estuary, building on earlier work by Townend and Pethick (2002). After extrapolating source functions with a premise about the stable trend of morphodynamic evolution, Reeve and Karunarathna (2011) can make a projection of decadal morphological evolution in the Humber Estuary. However, the necessary time sequence of high-resolution historical bathymetric data is rarely available for other estuaries.

The two-dimensional area model used by Di Silvo et al. (2010) computed Δq_z by deviations between the transport sediment concentration C and the equilibrium concentrations C_{eq} of suspended sediments at both shoal and tidal channel:

$$q_z = w(C - C_{eq}) \quad (9)$$

Where w is vertical exchange coefficient. The equilibrium concentration represents the tidally average state that does not induce erosion or deposition. Therefore, erosion or deposition occurs

to maintain dynamic equilibrium with local hydrodynamics. Changing hydrodynamics may ensure the system is always in a dynamic equilibrium state that means this equilibrium concentration should be dynamically changing too. However, this model by [Di Silvo et al. \(2010\)](#) presumed the static equilibrium condition to drive the sediment erosion and deposition. [Di Silvo et al. \(2010\)](#) develop the hydrodynamic poisson sub-model simplified from classical two-dimensional shallow-water equations. In further work by [Bonaldo and Di Silvo \(2013\)](#), multi-classes of sediment grain size are introduced, and net erosion and deposition are calculated for each class. With the static equilibrium assumption, this model is useful to study the relative impact of different anthropogenic interventions on estuarine evolution, and [Bonaldo and Di Silvo \(2013\)](#) report a case study in Venice lagoon, Italy.

Taking Venice Lagoon as an example, extensive wave-formed tidal flats in three tidal inlets inspired [Townend \(2010\)](#) to develop a three-dimensional form model whose hydraulic forces include both waves and tides. The model consists of a planform whose channel width decreases upstream exponentially, intertidal flats whose shapes are influenced by tides and waves ([Friedrichs, 1995](#)), and a parabolic subtidal channel profile shape. The model by [Townend \(2010\)](#) is a hybrid model where Eq. (1) was used to determine changes of the shape term involved in the shoreline Exner equation of Eq. (3). A one-dimensional tidal propagation model was applied based on water depth, the rate of estuarine convergence, and assuming little river inflow relative to tidal flow ([Townend, 2010](#)). Fetch was used to determine significant wave height and wave period, and to obtain a wave-influenced intertidal profile. A zero-dimensional sediment mass balance of q_z is calculated by Eq. (7). Erosion is calculated by using bed shear stress of Eq. (5), and the rate of deposition is a function of suspended sediment concentration C

and the representative sediment fall velocity W_s . Applications of this model at the tidal inlets of Venice Lagoon and UK estuaries have improved the accuracy with which gross estuarine properties are predicted when including waves (Townend, 2010, 2012). A numerical process response model by Lanzoni and D'Alpaos (2015) is able to produce this characteristic three-dimensional form driven by tidal dynamics, and provide a processes-based modelling tool to study tidal channel funnelling. A dynamic equilibrium tidal flat morphology represents time-related force-response equilibrium between tidal flat morphology and the local climate of waves, tides, and sediment sources and sinks (Fig. 6b, Friedrichs, 2011). Townend (2010) only considered two end members of this dynamic equilibrium – wave flat profile and tidal flat profile using a kinematic approach plus Eq. (7). By implementing the dynamic equilibrium concept of Friedrichs (2011) in Fig. 6b, Hu et al. (2015) have developed a morphodynamic model that accounts for the spatial-temporal varying forces on dynamic equilibrium evolution of tidal flats.

To sum up, an estuary consists of various sedimentary environments, so the models are usually focused on only specific parts, such as the tidal network, tidal flat and tidal channel. Effects of waves on morphological changes have become increasingly important in the modelling. Estuarine models have also often been linked to the open oceanic coasts, while effects from the hinterland are rarely considered. In the next section, we discuss the comparison of fundamental behaviours between cliffs, sandy barriers and estuaries, which affect modelling approaches related to the Exner equations.

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658 Fig. 6. (a) Conceptual diagram of equilibrium beach profile of [Dean \(1991\)](#) and its dis-equilibria
 659 due to positive or negative net sediment supply (fluxes); (b) Simplified conceptual diagram of
 660 tidal flat shape (convex-up or concave-up) responding to sediment supply and erosion
 661 ([Friedrichs, 2011](#)). Note that these two diagrams can be explained via the shoreline Exner
 662 equation between the shape term $\frac{d(HL)}{dt}$ and sediment fluxes $\vec{\nabla}q$.

4. Discussion

4.1. Fundamental behaviour and the shoreline Exner equation

There are fundamental differences between cliffs, sandy coasts and estuaries. However, there are also important interactions between these systems, which can become significant when estimating sediment budgets. Although the imperceptible erosion of cliffs and shore platforms forming headlands at either end of the compartment in Fig. 1 is unlikely to supply sediment to the adjacent beach, the exchange between rapidly eroding soft cliffs and adjacent estuaries is an issue requiring management consideration (Dickson et al., 2007; Hanson et al., 2010). By contrast, the sequestration of sand from Narrabeen Beach into the entrance of Narrabeen Lagoon does have a measurable effect on the sediment budget (Fig. 1). The entrance is intermittently closed following persistent swell, and morphodynamic adjustment of the system is further disrupted by anthropogenic activities that include regular replenishment of the beach with sand from the flood tidal delta, and the *ad hoc* construction of seawalls to protect several of the properties along the foredune (Woodroffe et al., 2012). Whereas cliffs are generally modelled two-dimensionally in cross-shore, and often without accounting for volumes of material produced by erosion, beaches require consideration of cross-shore and longshore movement of sand, generally observing conservation of mass. Estuaries encompass a wider range of sediment sizes and require modelling in three-dimensions. These differences necessitate consideration of more dimensions as models extend beyond cross-shore sediment fluxes Δq_x of the shoreline Exner equation within the two-dimensional system.

The major differences between the models, based on this summary of the reviewed studies, lie in the methods of computing sediment fluxes within the Exner equations. These methods vary

685 between models for cliffs, sandy coasts and estuaries. For cliff erosion models, erosion rates
686 usually adopt Eq. (4) and Eq. (5). These two formulae rely on the input of hydrodynamics and
687 sedimentological properties, whereas model behaviours are usually constrained by calibration of
688 free parameters using available information. Mass balancing between erosion and accretion is
689 commonly adopted in the models that can be described by the shoreline Exner equation, and as a
690 consequence model behaviours are relatively tractable. Models for barrier coasts appear to
691 require higher model complexity than cliff models, as cross-shore sediment fluxes can be either
692 onshore-directed or offshore-directed. These open coast models are also influenced by the
693 subaerial hinterland slope and back-barrier accommodation space. The configuration of the
694 underlying substrate and consequent accommodation space becomes even more important when
695 modelling estuaries, as does the hydrodynamics which affect sediment fluxes (Fig. 3). The
696 simpler estuarine models adopt generalized approaches such as depth-dependent sedimentation
697 (ESM) or semi-empirical box models (ASMITA), but as processes and fluxes are usually three-
698 dimensional, more complex simulations are often necessary, involving coastal area
699 morphodynamic models (e.g. Delft3D). Sediment fluxes for estuarine models are computed with
700 a range of methods from Eqs. (7) – (10) and need to consider sediment fluxes from open oceans.
701 The successful application of these models suggests that sediment mass conservation should be
702 used to constraint model behaviours and reduce possible volume estimation errors. Estuaries
703 involve suspended sediments that contribute vertical sediment fluxes and bed-level changes.
704 Moreover, the geological environments within which estuaries form, for example the wave-
705 dominated barrier estuary in Fig. 1, may consist of rock, alluvial plain, estuarine deposits, and
706 unconsolidated or poorly lithified barrier sands. The fundamental principles used in estuarine
707 models vary for different geomorphic units. For example, in the central basin, vertical

aggradation processes are mostly dominant until wind waves start to limit sedimentation (Adlam, 2014).

In the case of intertidal flat evolution, there is a dynamic equilibrium between forces and responses on tidal flats (Friedrichs, 2011), driven by sediment erosion and deposition as shown in Fig. 6. Here, this dynamic equilibrium change of tidal flat shape is explained simply by terms in Eq. (3). Only the shape term $\frac{d(\bar{H}L)}{dt}$ and sediment fluxes $\vec{\nabla}q$ remain. The increasing net sediment fluxes reduce available water volume, and the shape becomes more convex-up (Fig. 6). On the contrary, negative sediment fluxes, induced primarily by wave erosion, create a more concave-up shape by removing sediments. A simplified geomorphic diffusive sediment transport law (Eq. (8)) has been used to obtain the sediment fluxes, as in the ASMITA model. The *P-A* relationship creates a simple mathematical linkage between characteristic morphological and hydrodynamic parameters, which provides a condition for the ASMITA model to obtain a dynamic adjustment between the tide and geomorphology. However, waves become non-negligible in some estuarine settings (e.g. Townend, 2010; Friedrichs, 2011; Hunt et al., 2015), which require models of increased complexities to better calculate sediment fluxes. Ecological processes that compound computation of sediment fluxes are another challenging task (Fagherazzi et al., 2012; Coco et al., 2013; van Maanen et al. 2015). While there are already examples that link sediment fluxes and exchange between cliff and sandy coasts (e.g. Deng et al., 2014) or sandy coasts and estuaries (e.g. Walters et al., 2014), three-dimensional morphological modelling considering open coasts and estuaries is likely to also be a future challenge, requiring efforts to link sediment sources and sinks with fluxes between cliffs, sandy barriers and estuaries.

Equilibrium morphology is also widely adopted in the models reviewed for calculating

sediment fluxes and constraining model behaviours. [Zhou et al. \(2017\)](#) discuss the difference between natural variability and the idealized equilibrium in modelling. They address different ways to achieve this (mass-flux stable) morphodynamic equilibrium, based on the generalized Exner equation. According to Dean's equilibrium concept (Fig. 6a), equilibrium shape is affected by net sediment fluxes. This concept can also be explained by the shoreline Exner equation, when only the time-dependent shape term $\frac{d(\bar{H}L)}{dt}$ and sediment fluxes $(\Delta q_x + \Delta q_y)$ are kept in Eq. (3). The DESM model has extended the equilibrium concept developed by [Dean \(1991\)](#) quantitatively to quasi-three dimensions ([Deng et al., 2014; Deng et al., 2015; Deng et al., 2016](#)). Equilibrium morphology will be attained when sediment fluxes are not unbalanced for a certain period. In a form of shoreline Exner equation, integrating smaller scale processes can help better understand the fundamental processes driving shape change. Steady driving forces may result in a dynamic equilibrium retreat of the coastal profile that retains its shape, whereas rising sea level or seasonal and inter-annual water levels may change nearshore hydrodynamic forces ([Walken and Dickson, 2008; Trenhaile, 2010; Castedo et al., 2013](#)). This dynamic equilibrium retreat means leaving out the time-dependent shape term $\frac{d(\bar{H}L)}{dt}$ in the shoreline Exner equation. The cumulative effect of storms depends on their frequency and intensity through time (e.g. [Trenhaile, 2010; Deng et al., 2014](#)), and appears to be important in modifying equilibrium profiles by influencing sediment fluxes.

On the basis of the shoreline Exner equation, this review shows that the simple Bruun Rule model has served as a foundation for progressive model developments. Hence, the Bruun Rule model is one type of response reflecting fundamental coastal behaviour that can be extended to a wider range of coastal behaviours. Within a closed two-dimensional cross-shore system (Fig. 3),

provided there is sufficient hydrodynamic energy causing erosion of the upper shoreface and a steep coast preventing onshore sediment transport (Cowell et al., 1995; Wolinski and Murray, 2009), the eroded sediments will all be deposited on the shoreface. On a coast with a gentler gradient, onshore sediment transport including aeolian sand transport and storm overwash, become dominant in coastal recession (Fig. 3b, Davidson-Arnott, 2005). On coastlines of intermediate slope (Fig. 3c), both onshore and offshore sediment transport induce coastal recession (Cowell et al., 1995, 2006). There remains a challenging task to predict when and where onshore sediment transport will be dominant. Wolinski and Murray (2009) also indicate that the initial morphology, lithology and hinterland landscape have a first-order control on coastal retreat behaviour through their influence on sediment sources (cliff) and back-barrier accommodation space. Shoreline retreat can differ between centennial and millennial time scales (Fig. 4). The standard Bruun Rule and the RD-A model appear valid only at centennial scales. During such time scales, hinterland sediment sources and sinks are not sufficient to impact the mass balancing that the Bruun Rule and RD-A model considers.

The standard Bruun Rule and RD-A models represent those cases when there is a threshold amount of (hydrodynamic and aeolian) force that induces coastline recession calculated by $H_s \frac{ds}{dt} = LR$. This threshold concept can also refer to Eq. (5). When the hydrodynamic forces are too weak to erode the coast, relative sea-level rise will only cause inundation. Exceeding the threshold value, or being less than it, would cause changes of profile shape and/or closure depth in the shoreline Exner equation of Eq. (3). The sediment redistribution processes also require sufficient hydrodynamic energy to initiate sediment motion. Furthermore, an idealized threshold of hydrodynamic energy may exist to create an equilibrium response to relative sea-level rise

(i.e. sedimentation rate equals the rate of relative sea-level rise). This still requires a process response model to test the concept to reveal processes of sediment erosion, transport and deposition.

4.2. Cautions to be considered in relation to model predictions

As discussed above, the methods of computing sediment fluxes vary between models and involve many underlying assumptions. This difference is one of the reasons why particular models cannot be applied everywhere ([Le Cozannet et al., 2014](#)). But the reason for the limited application may also be that modellers have insufficient prior information to modify the models to suit local coastal settings. The modifications may involve more sediment fluxes or revision of the methods by which sediment fluxes are calculated in the Exner equations. The increasing amount of observational data enables further testing of model behaviours, facilitating appropriate modifications. The Exner equations can be a foundation to identify the proper methods of computing sediment fluxes from observed data, which could fundamentally improve prediction. Following progressive model developments, increasing amounts of data are usually required to constrain model behaviours when model complexities increase. For example, when cliff sediment sources and composition, and landward dune deposition volume, are added, the Bruun model capability can be extended. DEMs, maps of relative sea-level change, and historical coastline changes are required for a quasi-three-dimensional model - DESM. Further model developments will enable future predictions that should continue to make use of the increasing amounts of data.

Instrumental observation data, historical data, and geomorphological facies data revealing the past can help us understand coastal behaviour at different time scales. Knowledge from the past

serves as a guide to develop and validate models to predict future coastal responses to many natural and anthropogenic driving factors (Woodroffe and Murray-Wallace, 2012). However, historical information is not always available for all terms in the shoreline Exner equations. Therefore, a strategy based on Eq. (3) is proposed here to provide a quantitative foundation to project historical data for future projections, without the need to have a significant amount of observed data to constrain model behaviours. On the basis of the shoreline Exner sediment mass balancing equation, a physical extrapolation of past information to the future can be converted from Eq. (3):

$$H_{s,2} \frac{ds_2}{dt} - H_{s,1} \frac{ds_1}{dt} = c_{0,2}^{-1}(\Delta q_{x,2} + \Delta q_{y,2}) - c_{0,1}^{-1}(\Delta q_{x,1} + \Delta q_{y,1}) - (L_2 R_2 - L_1 R_1) - \left(\frac{d(\bar{H}_2 L_2)}{dt} - \frac{d(\bar{H}_1 L_1)}{dt} \right) + (L_2 \frac{dH_{s,2}}{dt} - L_1 \frac{dH_{s,1}}{dt}) \quad (11)$$

In this equation, the subscript “1” means past values of variables, and the subscript “2” indicates future values of variables. The behaviour models reviewed in this article can be readily converted into this physical extrapolation form of Eq. (11), such as the model by Bray and Hooke (1997) and Deng et al. (2015). The shoreface relief, shape, sediment flux gradients and sand concentration may change, or some of them may remain stable in the future. With past information, such as historical data on shoreline and sea-level changes, Eq. (11) is appropriate to assess the effect of stationary or non-stationary aggregated factors on future shoreline changes. Some time-dependent variables (for example, closure depth which is time dependent. Nicholls et al., 1998) need to be stationary to evaluate adjustments of other variables to future shoreline change. For example, under conditions of stationary hydrodynamic force and sufficient available sediment, sediment flux in 100 years must be significantly larger than ten years. Increasing

amounts of observational data in the future may make application of Eq. (11) easier. When considering alongshore variability, Eq. (11) which adopts cross-shore profiles is only suitable for shorelines with small curvatures.

Another approach based on use of historical observed data for future prediction is the probabilistic approach which indicates the likelihood of an outcome (Hapke and Plant, 2010; Gutierrez et al., 2011). However, a stationarity from the past to the future has to be assumed when using probabilistic distributions to predict the future. A shortcoming of this kind of probabilistic approach is that it cannot reflect the sediment transport processes in the Exner equations, and requires abundant historical data to obtain the probability distributions.

From the reviewed material, hydrodynamic information is required for most formulae to compute sediment fluxes when high resolution is required, or in complex sedimentary environments such as estuaries. But observational power is limited in time and space. For example, for geological reconstructions, it is impossible to measure historical hydrodynamic information which limits the capability to fully reconstruct morphological evolution processes. The “appropriate complexity” concept, recommended by French et al. (2016), implies the need to incorporate necessary hydrodynamic information to improve both model capability and accuracy. Numerical modelling of hydrodynamics to obtain missing information is needed to infer the sediment fluxes in the Exner equations for such morphological modelling.

A coastal system can be viewed as a hierarchy of landforms across increasing spatial-temporal scales (Cowell et al., 2003; French et al., 2016). Therefore, methods of calculating sediment fluxes could differ at different spatial and temporal scales. For example, coastline changes and the associated morphological changes on time scales of decades to centuries are an outcome of a

838 series of processes acting cumulatively on the coast, which is illustrated at a cross-shore coastal
839 profile in Fig. 5. At the active surfzone that is dominated by wave-breaking processes,
840 morphological changes at smaller scales, such as nearshore bar migration, might be detectable on
841 time scales of seasons and years. At larger time scales of decades to centuries, a trend of
842 landward retreat of the whole coastal profile would be expected, and nearshore bar migration
843 represents a fluctuation operating on smaller spatial-temporal scales around this trend. At still
844 larger scale modelling, on millennial scales, only that trend of landward retreat of the profile and
845 its morphological parameters, such as shape defined by the shoreline Exner equation, is
846 considered. Incorporating smaller processes operating within this larger behaviour helps better
847 model that large-scale behaviour and its natural variability ([Werner, 1999](#); [Werner, 2003](#)).

848 Simplistic forms of these models that have fewer required boundary conditions need less
849 information to constrain model behaviour than complex coastal area morphodynamic models do.
850 Accordingly, coastal area morphodynamic models are usually not easily applied for
851 reconstructing paleo-morphological changes; they usually require multidisciplinary team efforts
852 that consider climate, geology, geography and oceanography (e.g. [Wu et al., 2010](#); [Harff and](#)
853 [Lüth, 2007](#)). Moreover, implementation of coastal area morphodynamic models also requires
854 caveats on sediment fluxes calculations that involve free parameters. Coastal area
855 morphodynamic modelling is a reductionist approach based on the mechanics of flow and
856 sediment dynamics. This approach models large-scale geomorphic behaviour by extending the
857 simulation of processes at small spatial-temporal scales (e.g. hours in time and tens of meters in
858 space) via interactions of grid cells (Fig. 2) in space and accumulations of morphological
859 processes in time. Hence, applications of coastal area morphodynamic models are able to provide

sedimentary connections between subaerial and submarine sediment erosion, transport and deposition (e.g. Lesser et al., 2004; Wu et al., 2010; van der Wegen et al., 2011; Harff et al., 2011; Zhang et al., 2012; Zhang et al., 2014; Deng et al., 2014; Zhou et al., 2014; van Maanen et al., 2015). These sedimentary processes are reduced into cells represented by the mesh grids. However, it should be noted that there are limitations to the formulae used in computing sediment fluxes; for example, different sediment transport formulae in the models produce distinct patterns of morphological changes (Coco et al., 2013). Given the principle that morphological change operates much more slowly than hydrodynamics, long-term coastal area morphodynamic models adopt a morphological acceleration technique (Roelvink, 2006), and use “reduction” techniques (e.g. de Vriend et al., 1993; Latteux, 1995) to generate representative input driving forces to simulate long-term morphological changes. The key challenge of this kind of model is its upscaling approach involving non-stationary factors (e.g. representative climatic forces) that may require clarification (French and Burninngham, 2013). Furthermore, as stated by Roelvink and Reniers (2012), calibration and validation procedures cannot guarantee the accuracy of future predictions. The initial condition of paleo-geomorphology and setting of driving forces may have long-term impact on morphological changes (Harff et al., 2011; Kinsela et al., 2016). Therefore, applications of these coastal area morphodynamic models to large-scale simulations have limitations and the model results are complex as well. Nevertheless, these complex models can serve as comparative methods for simpler approaches targeting specific problems.

There is also a dilemma between model prediction accuracy and computational efficiency limited by the mesh grid size and numerical schemes in the coastal area morphodynamic models,

where a finer mesh resolution generally achieves better accuracy but requires much more computational power. The model resolutions reflect the spatial and temporal scales to be considered in the problem to be solved by applying the model, but lower resolution means a larger numerical error. When a simpler modelling approach might derive similar outcomes to the more complex models, it should be used, because it may be able to reconcile model efficiency and accuracy, as well as improve the clarity of governing physical processes and associated intrinsic errors resulting from simplification and abstraction of reality.

There are usually many parameters in the models, and determining proper values for these parameters requires observed data to conduct a rigorous calibration for each parameter, which is not an easy task. Models that incorporate many parameters, whatever category they belong to, may be more useful for investigating key factors or model settings and the coastal morphological evolution within these, as suggested by [Trenhaile \(2009\)](#), than generating numerical predictions, because of the uncertainties as to how individual parameters might vary in time and space. There are several examples that explored fundamental questions related to tidal basin evolution by applying complex coastal area morphodynamic models on idealized environments to make modelling more tractable (e.g. [Zhou et al., 2014](#); [Hunt et al., 2015](#); [van Maanen et al. 2015](#)).

When models are developed by applying the Exner equations and calculating sediment fluxes, it requires significant cautions about intrinsic error propagation in the numerical methods utilized resulting from approximations of sediment fluxes and errors from boundary conditions. These errors may produce numerical phenomena other than physical ones, especially for more complex models. Solutions to reduce numerical errors might adopt the strategy used in climate change modelling that compares model results between the control period and a future period. The time

span, all parameters, and coefficients in these models between two periods have to be identical. As model errors will be quite similar between two periods presuming that the model is not sensitive to the initial conditions, changes in modelling outcomes, other than numerical errors, will represent the ones produced mainly based on the principles underlying the models.

Model uncertainties can be estimated by applying stochastic simulations to existing morphological models (Cowell et al., 2006; Ranasinghe et al., 2012). Indicating the likelihood of future erosion risks and accounting for uncertainties in the models are needed for coastal engineering and planning activities (Wainwright et al., 2015). However, stochastic simulations are not easy to apply for complex models requiring significant computational effort such as the coastal area morphodynamic models. Hence, a less complex model developed for a specific problem is more straightforward, in which model uncertainties and limitations can be clearly indicated.

5. Conclusions

This paper has reviewed morphogenetic models that can be applied on open coasts and within estuaries. The following conclusions can be drawn from this overview:

(1) The models reviewed can be unified into a form of the Exner equations (Eqs. 1-3). The major differences between models are in the methods of calculating terms that describe the sediment fluxes in these Exner equations.

(2) In general, modelling approaches applicable to barrier coasts are more complex than cliff models in terms of sediment fluxes. Estuarine modelling approaches appear to be the most complex, reflecting these complex sedimentary environments (Fig. 1). Integrated modelling

of sediment sources and sinks, and estimations of sediment budgets and exchanges, across these three geomorphic environments remain challenging tasks.

(3) Increasing modelling complexity coincides with the fundamental differences in substrate characteristics and operative processes between cliffs, sandy coasts and estuaries. The Bruun Rule, and minor reformulations of this such as the RD-A model, represent the most fundamental components of the shoreline Exner equation. Other models have progressively developed, based on this concept, by incorporating more terms in the equations and more complex ways to estimate sediment fluxes. Complex model formulation is required to develop estuarine models in comparison to the relatively simplified cross-shore morphodynamic models applied to open coasts.

(4) Additional hydrodynamic information is needed when targeting complex sedimentary environments as occur in estuaries or high resolution modelling such as process-response modelling for cliffs. A mathematical connection with characteristic hydrodynamic parameters such as the P - A relationship may also need to involve hydrodynamic information. Incorporating hydrodynamics is necessary to understand subaqueous geomorphic behavior, such as the causes of morphological changes, which have generally been ignored in existing simple models such as the Bruun Rule.

(5) Observational data on patterns of morphological change constrain the degree of model complexity, and hence the credibility of applications that involve future predictions. Where historical information is lacking, a strategy based on the shoreline Exner equation may be possible for future predictions, whereas a probabilistic approach is advocated for those instances where there is sufficiently abundant data. Models are expected to continue to

increase in their complexities, with increasing demand for observational data, particularly in estuaries. The improvement of models relies on fundamental research into computing sediment fluxes, based on the increasing amount of empirical data, which may facilitate development and refinement of estuarine models and improve their predictive capabilities.

(6) Models solving part of the Exner equations address specific scientific or management problems and are suited to particular local coastal and estuarine settings. Selecting or developing the proper methods to compute sediment fluxes and other terms in the Exner equations depends on the scale at which a hierarchy of landforms is considered, and the resolution of their various geomorphic units.

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