GIS Modeling of Impacts of an Accelerated Rate of Sea-Level Rise on Coastal Inlets and Deeply Embayed Shorelines

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ABSTRACT

Scientific evidence suggests that an accelerated sea level rise will have a significant impact on shorelines over the next 50–100 years. Hence, coastal management and planning in the near future needs to evaluate the physical impacts on vulnerable coastlines. In Australia, the need to estimate potential coastal erosion and potential coastal property damage is acute, because >80% of the Australian population live in coastal areas. However, a limitation that has to be considered in Australia and in many other parts of the world is the lack of data for the coastal zone. Principles drawn from presently available coastal process models are used in this study to identify the potential physical impacts of sea level rise on barrier inlets and deeply embayed shorelines, including estuaries.

The models (Hybrid-Bruun, Aggradation, and Translation Models) are implemented into a geographic information system (GIS) environment as a set of equations, which are then applied to the terrain data. In principle, these are data that exist in the public domain, such as the 1:25,000 topographic map series and bathymetric maps at various scales. Changing parameter values in the models (such as the rate of sea level rise, depth of closure, dune height, the size of the flood-tide delta, sediment input from outside the embayment, or the rate of flood-tide delta translation) allows the user to run a number of impact scenarios for each model and locality. Output maps of these scenarios typically present the spatial distribution of hazards caused by rising sea level in a grading triage of risk classes: a definite risk, an uncertain risk, and a negligible risk according to each model. These modeling results can then be used by local government authorities for further detailed studies of individual sites potentially at risk.

Key Words: coastal erosion, GIS-based modeling, sea-level rise.

INTRODUCTION

Studies by the International Geographical Union's Commission on the Coastal Environment have shown that more than two thirds of the world's sandy coastlines have retreated during the past few decades, and only <10% have prograded (Bird, 1996). The erosion of sandy coasts is expected to deteriorate if predicted rates of sea level rise (SLR), induced by climate change, prove correct (Intergovernmental Panel on Climate Change (IPCC), 1998; McInnes et al., 1998). With half of the world's population living in the coastal zone (Leatherman and Nicholls, 1995), human assets are potentially at risk from SLR. Practical decision-making in coastal management requires cost-effective methods that allow fast determination of high-risk areas in the coastal zone at a regional scale. To model long-term changes, the nature and extent of physical changes in different coastal settings must be identified (Thom and Roy, 1988; Intergovernmental Panel on Climate Change (IPCC), 1996). Ideally, if we are able to identify those processes responsible for a hazard, we should be in a position to take appropriate action to avoid or mitigate the impacts associated with the hazard (Hennecke et al., 1997). By defining mathematical equations to represent the processes of these hazards, a computer can be used to simulate the impacts on areas of interest.

In practice this deterministic approach may not be readily applied, because:

1. the hazard may be created by a combination of coupled processes;
2. the process(es) may be understood too poorly to allow representation by a physical model (de Vriend, 1991; Wadge et al., 1993; Cowell and Thom, 1994);
3. simulation may be too computationally intensive for practical purposes; and
4. information on physical variables may not be available (Wadge et al., 1993).

The modeling of geomorphological processes, which are responsible for the erosion and deposition of coastal sediments, is difficult, as these processes are poorly understood especially at time scales relevant to engineering and planning (Cowell and Thom, 1994). Therefore, long-term morphological predictions need to be met with knowledge that is available today (Stive and de Vriend, 1993). This is often difficult due to the lack of high-resolution data, especially terrain data, in many coastal areas (Nicholls, 1993). Furthermore, whereas most studies so far have focused on responses of shorelines per se to SLR, little attention has been paid to the behavior of shorelines within inlets and bays, especially in respect to the coupling between shoreline and inlet processes that govern the overall adjustments to changes in sea level. This article adapts established ideas involving sediment-mass balance and coastal equilibrium for sea-level change on beaches to the equivalent problem for shorelines in bays and inlets. The purpose of the article is to describe the general principles of the underlying models and their incorporation into a geographic information system (GIS) and to consider some operational implications of the models.

Approach

The main emphasis of this article is the description of a method that allows a quick and cost-effective first estimate of physical impacts of an accelerated rise in sea level on tidal inlets over the next 50–100 years, before undertaking more intensive analysis. The study is concerned with general trends of shoreline change rather than small-scale changes, such as single property loss. Readily available data and knowledge obtained from previous studies are used and rule-based models are adopted to predict the range of broad-scale impacts on coastal inlets due to SLR.

Implementation of the models within a GIS allows site-specific data to be readily integrated into the models providing simple and pragmatic predictive tools. GIS models provide a useful method of dealing with uncertainty through computer simulation experiments (Thompson, 1992; Steyaert, 1993). They can be utilized to deal with the high uncertainty accompanied when predicting the impacts of climate change and the limited knowledge of near-future morphological changes as a set of scenarios, representing the potential outcome. The simplicity of the models is important to allow use of limited available data (usually bathymetric charts and 1:25,000 topographic maps).

The approach represents a departure from previous studies concerned with the prediction of coastal erosion. We implement process models within the GIS as a set of equations that are applied in remapping terrain data to predict continuous variation in shoreline recession alongshore due to a given SLR, which is in turn generalized and remapped more simply in terms of relative hazard levels. By using topographic maps and charts to define initial conditions, the automated GIS models estimate a range of coastal change for user-defined regional or local scenarios. The GIS models developed here are (1) Bruun-GIS Model; (2) Aggradation Model; and (3) Flood-Tide Delta Translation Model.

Scope and Limitations

Several restrictions limit this study. First, the models are applied only to coastal inlets and their flood-tide deltas. Coastal inlets are defined broadly here as shoreline reentrants constricted by barriers or rocky shores and also deeply embayed shorelines, including estuaries. Second, SLR and sediment inputs from rivers or the offshore region are considered as the only factors driving shoreline change. Other potential threats to the coast, such as an increase in storminess, are beyond the scope of this study. Furthermore, the models are applied to erodible shorelines only. Erosion-resistant, rocky shorelines are not considered, and passive inundation is regarded as the only agent of loss on rocky shores.

Littoral transport budgets are implemented in the models as a second-order effect, but engineering structures, such as dikes, seawalls, or groynes, are not taken into consideration, except so far as these changes are incorporated into definition of the terrain model (rock/sand and elevation). Also, the role of currents in the redistribution of sediments brought into the embayment is outside the scope of the study. The work is relevant to regional scales that extend over distances typically covered by individual local government areas and to an engineering and planning time scale of 50–100 years. Due to the typically medium to low resolution input data and uncertainties associated with climate change (Henderson-Sellers, 1993), results derived from all models must be understood as preliminary, first-order estimates that ignore details of internal redistribution of sediments and the effects of engineering structures.

The Aggradation and the Translation Models are based on theoretical concepts described in the literature (Van Straaten, 1954; Curray, 1964; Thom, 1984; Eysink, 1991; Louters and Gerritsen, 1994; Roy, 1994) and are developed for GIS application. Both models have not been tested and validated with field data. Each of the models is based on an aggregated approach and therefore suffers from the sort of limitations identified in relation to the Bruun Rule by Pilkey et al. (1993), although uncertainty in each of the models is amendable to sensitivity analysis. Further limitations stem from nongeneric properties of GIS software because different proprietary packages use different algorithms for data acquisition, conversion, interpolation, and calculations (van der Knaap, 1992). Therefore, the selection of a particular GIS software may have a significant influence on modeling results. However, the GIS applied here (Arc/Info, Environmental Systems Research Institute, Redlands, CA) was chosen due to its widespread availability and use. A comparison with modeling results from different GIS software was beyond the scope of the article.

MODEL IMPLEMENTATIONS

An aggregated model approach is adopted to side step the dynamic and stochastic complexity (Cowell and Thom, 1994) that characterises coastal inlets in nature. The rationale for this type of approach has a long tradition in geomorphology (Thorne and Swift, 1991) and at present appears to be the only viable option for quantitative prediction of long-term (decades to centuries) coastal change (Cowell et al., 1995; Niedoroda et al., 1995; Stive and de Vriend, 1995; Stive et al. 1998). Although full morphodynamic models are available for tidal inlets, their predictive capacity is limited to the subdecadal time scale due to strong state-dependent nonlinearity (Roelvink and van Banning, 1994).

GIS Modeling of Natural Hazards

The United Nations adopted the 1990s as the International Decade for Natural Disaster Reduction, focusing on the application of advances in science and information technology, including remote sensing and GIS (Coppock, 1995). GIS applications in environmental modeling are relatively new but not uncommon (Brinkley, 1997), and GIS models are believed to be well suited to integrating real-world data with deterministic and stochastic process models (Thompson, 1992).

GIS has been applied in climate-change modeling; however, such applications are rare in combination with coastal-process models, the only example found being that by Lee et al. (1992). Despite the general applicability of the models described in this article, each model can be expanded to more detailed applications, simply by developing add-in modules to the base model. Such modules, for example, could implement Hallermeier's (1981) or Bruun and Schwartz's (1985) approaches for the determination of the depth of closure. Also, more detailed information can be added to the existing database, e.g., detailed hydro-survey data, wave data, information on currents, detailed topography or cadastral data, and retrieved when necessary to calculate land loss.

Data Assimilation and Mapping

The main advantage of using GIS as a platform for the modeling is that it readily allows the assimilation of mapped data to constrain the models. Spatial data are not only used to define the initial conditions for the modeling. The rule-based models also draw information from the mapped data with respect to morphological conditions and dimensions that govern the modeled responses (e.g., initial area of the flood-tide delta, offshore distance of closure depths, proportion between erodible sandy shorelines and erosion-resistant rocky shorelines) (Hennecke et al., 1997). In this study, the models are constrained by limited data and the limited knowledge about physical processes involved. These constraints coupled with uncertainties in SLR estimates produce modeling outcomes. GIS procedures include the transformation of charts to a digital map and also the embedding of the process models as a set of equations and procedures within the map database.

Practical considerations in the preparation of the digital maps with the GIS are essential for computationally fast and efficient running of the models. All maps need to have the same pre-defined protocol when remapped and identical identifiers for different morphological features to allow the model to be applied correctly. This is guaranteed by a detailed coding system, as shown in Table 1.

Retaining pre-set digitizing rules for the direction of digitizing (e.g., generally North–South or South–North) is also important as some GIS commands (e.g., segmentation and buffer commands) are applied to the direction and therefore to the left or right of a digital line or vector. Not retaining digitizing rules will eventually cause an incorrect display of the results, as shown in Figure 1. For this study, landward shoreline changes are displayed to the left of a vector and seaward changes to the right. Vector a has been digitized according to the pre-defined digitizing rule and landward shoreline change is defined as a left buffer function in the GIS with respect to the direction of the vector. In contrast, applying the left buffer convention for landward shoreline changes to vector b, which is directed opposite to vector a, results in the display of a seaward but not landward shoreline change, i.e., an incorrect display of modeling results.

Taking the present state of the coast, the automated GIS models are used to provide continuous estimates for the alongshore variation in magnitude of coastal recession or progradation for a region. If input variables such as SLR, the depth of closure, sediment supply from outside the embayment, or the rate of translation are uncertain, GIS is used to simulate a range of potential impacts. By changing the values of the variables after each model run, the user has control of the model and the number of scenarios performed for every site. To improve the user-friendliness of the models and also to enhance their speed, menu-driven user interfaces have been developed.

MODEL CONCEPTS

The fundamental reason for modeling is a lack of full access, either in time or space, to the phenomena of interest (Oreskes et al., 1994), a situation pertaining to the prediction of coastal impacts of climate change. Although numerical models are used widely in earth sciences to represent

Table 1: Table of codes identifying morphological features in a digital bathymetric chart.

Feature	Identifier
Erodible shoreline	
Sandy shore	100
Muddy shore	101
Erosion-resistant shoreline	
Rocky shore	102
Seawall/training wall	103
Bathymetric contour	
−1-m contour line	−1
−2-m contour line	−2
−5-m contour line	−5
−10-m contour line	−10
−15-m contour line	−15
−20-m contour line	−20
Seaward boundary of the flood-tide delta	200
Landward boundary of the flood-tide delta	201

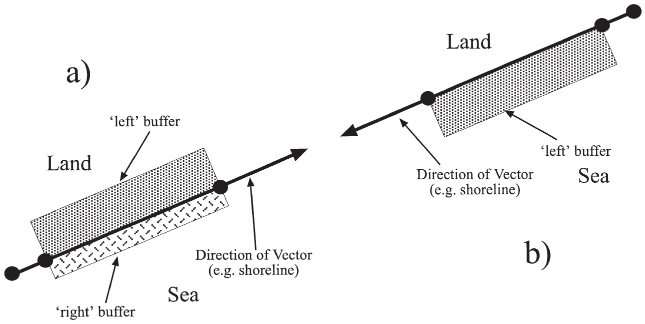


FIGURE 1: GIS buffer function with respect to the direction of a vector. (**A**) digitizing direction according to the pre-defined convention (south–north); (**B**) digitizing direction opposite the convention, resulting in the wrong display of modeling results.

complex, poorly understood systems (Oreskes et al., 1994), they also are being used in the public arena, often to justify or support controversial decisions. It is important to acknowledge therefore that the primary value of these models is heuristic. Coastal-impact models in this context are representations of natural processes, useful for guiding further study but not susceptible to proof, as explained clearly by Oreskes et al. (1994). This point is illustrated by the Bruun Model of shoreline responses to SLR (Bruun, 1988), the many derivative Bruun-type models, and the many attempts to validate these models. We therefore emphasize that our approach so far is heuristic in applying the Bruun-GIS Model, the Aggradation, and the Flood-Tide Delta Translation Model to describe and simulate responses of rising sea level in different coastal-inlet conditions. The models are designed for application in coastal environments dominated by waves or tides and areas with SLR lag effects, i.e., where a delayed response of the flood-tide delta to the rise of the water level occurs, such as the Dutch Wadden Sea (Peerbolte et al., 1991). Practical application must incorporate sensitivity analyses to assess uncertainty, and results must be evaluated in the light of the real-world complications outlined by Pilkey et al. (1993).

Bruun-GIS Model

The Bruun-GIS Model applies Bruun's concept (Bruun, 1962, 1988) for continuous alongshore variability in shoreline response to SLR in general and to inlet and embayment shorelines in particular. This GIS-based approach to applications of the Bruun Model has been applied previously at least once in developing coastal-management plans in New Zealand (J. Gibb, 1998, personal communication). According to Bruun,

$$R = \Delta s \frac{L}{h + D} \tag{1}$$

where R is the rate of shoreline recession (m); Δs the local/regional rate of SLR (m); L the length of the active profile (m); h the depth of closure (m); and D the dune height (m). The model is sensitive to the selection of the seaward limit of morphologic change (i.e., the definition of the depth of closure). In the absence of sufficient data, the theoretical and empirical relationships by Hallermeier (1981) or Bruun and Schwartz (1985) can be used as default values for shoreface parameters with respect to the limiting depth. In general, it is considered that the Bruun model is useful in providing an estimate of the minimum rate of recession associated with SLR, provided that it is applied over a sufficiently long-term period (Schwartz, 1967; Komar, 1991). In this study, the concept of the Bruun Model itself has not been modified as it has been in the past, for example, by Dubois (1977) or Dean and Maurmeyer (1983). The only "modification" described here is the implementation of the model in a GIS to allow for continuous alongshore variability of shoreline responses. The Bruun-GIS model is flexible enough to be applied to different sites. Each variable of the model is stored in the GIS as a separate column in the database of the digital map to account for differences in local Bruun parameters (Table 2).

User-defined variables (Δs, h, D) are entered after commencement of a model run. The profile length (L) is calculated automatically by the GIS as the offset distance between the shoreline and the depth of closure, and the rate of recession (R) is then determined from Equation 1. A loop function is implemented with the GIS model so that by changing the values of one or more variables, a number of scenarios can be run based on parameter variations. This also facilitates sensitivity analysis.

Aggradation Model

The Aggradation Model describes the vertical growth of a flood-tide delta in tide-dominated environments. The model is based on the work of Van Straaten (1954) which described the idea of tidal flat sedimentation for the Dutch Wadden Sea (Eysink, 1991). Van Straaten explained that one of the main processes of sedimentation in the Wadden Sea is the vertical deposition and upward growth of tidal flats at the same order as the relative SLR. Eysink (1991) supported Van Straaten's theory, stating that sedimentation in the Dutch Wadden Sea estuary and the local rate of SLR appear to be in equilibrium. Peerbolte et al. (1991) and

Table 2: Database of a chart with Bruun-GIS variables for sample transections along a beach in southeastern Australia.

Name	Δs[a]	L[b]	h[c]	D[d]	R[e]
Narrabeen (Sydney)	0.2	1350	24	5	9.3
Narrabeen	0.2	1450	24	7	9.4
Narrabeen	0.2	1280	24	8	8.0

[a]Δs, magnitude of sea level rise (m).
[b]L, length of profile (m).
[c]h, depth of closure (m).
[d]D, dune elevation (m).
[e]R, rate of recession (m).

Louters and Gerritsen (1994) described processes responsible for the rise of the Wadden Sea floor.

Niemeyer et al. (1995) stated that the large-scale morphodynamic balance in the Wadden Sea has not changed significantly during the last few hundred years, because sufficient sediment supply to the floor of the Wadden Sea allows it to follow the rising sea level. The tidal volume of the East Frisian Wadden Sea has not increased since 1650 despite a rise in sea level according to Niemeyer et al. (1995). However, the authors did not comment on the potential significance of land reclamation in that area since the Middle Ages, which could partly be responsible for a decrease of the tidal area. Jelgersma (1992) found that sedimentation in the Wadden Sea has kept up with a SLR of 1.5 mm/yr during the last 100 years.

Data for southeastern Australia have shown similar trends to the Wadden Sea. Based on research undertaken by Nielsen and Roy (1981) and Hennecke (1999), it can be suggested that flood-tide delta aggradation in estuaries in southeastern Australia started ~11,000 B.P. and was able to keep pace with rising sea level until ~6000–5000 B.P., i.e., between 500 and 1000 years into the stillstand period.

de Ronde (1993) assumed that the sedimentation in the Wadden Sea will also increase under future SLR conditions and that the Wadden Sea is able to keep pace with a 1-m SLR in 100 years. Louters and Gerritsen (1994) expect that most of the Wadden Sea is able to keep up if relative rise in sea level is only 20–60 cm per century in the coming century but not if SLR is as much as 1 m, as expected by de Ronde. Only in extreme situations, at a rise in sea level of 85 cm or more and a sharp increase in wind speeds, Louters and Gerritsen anticipate changes in the morphology of the Wadden Sea to such an extent that the tidal flats may disappear forever. The authors expect rather an effection of the morphological structure of the Wadden Sea at local level due to SLR, but the characteristic dynamic system of channels and tidal flats will continue to exist in the next hundred years in their opinion.

The sediment sources for the rise of the Wadden Sea tidal basin are the North Holland coast and barrier islands, according to Dieckmann (1985), Stive et al. (1990), and Louters and Gerritsen (1994). The concept described for the Wadden Sea is borrowed for the Aggradation Model; however, the model is not restricted to applications in the Wadden Sea. The sediment volume needed for the rise of the flood-tide delta is here defined as a function of the size of the area of the flood-tide delta (ΔA) and the rate of SLR (Δs). Such a simplified approach is believed to be an appropriate initial estimation for the calculation of the sediment demand of a tidal basin under SLR conditions (Niemeyer et al., 1995).

Model adaptations proposed here extend the concept by identifying three main sources of sediment (Figure 2) for raising the floor of the estuary (i.e., the flood-tide delta, ΔA):

1. a sediment volume ΔV_e, supplied from outside the embayment and being transported into the inlet (an assumed response to flood-tide currents and waves);
2. fluvial sediments, $\Delta V_{fl.}$, being deposited in the inlet; and
3. a sediment volume, ΔV_i, derived through the erosion of erodible shorelines inside the embayment.

For the present study, ΔV_e is defined as a composition of three sources of net sediment input:

1. littoral transport ($\Delta V_{lit.}$);
2. offshore sediment supply ($\Delta V_{of.}$); and
3. overwash processes ($\Delta V_{ov.}$).

Therefore, the total demand $\Delta V_{tot.}$ ($\Delta A * \Delta s$) = $\Delta V_{fl.} + \Delta V_e + \Delta V_i$. Generally speaking, the larger ($\Delta V_e + \Delta V_{fl.}$), the smaller is ΔV_i and therefore the risk of shoreline erosion in the embayment.

GIS procedures for the Aggradation Model are similar to the Bruun-GIS Model from a GIS perspective. Like the Bruun-GIS Model, the Aggradation Model (Equations 2–5) can be applied to different locations. All variables of the Aggradation Model (i.e., ΔA, Δs, $\Delta V_{fl.}$, $\Delta V_{lit.}$, $\Delta V_{of.}$, $\Delta V_{ov.}$, $\Delta V_{i.}$, D, and L_{es}, where L_{es} is the length of erodible shoreline in the embayment) are also defined as separate columns in the database of the digital map (Table 3).

The rate of recession R per meter of erodible shoreline can therefore be defined as follows:

$$R = (\Delta A * \Delta s)(L_{es})^{-1}(D)^{-1} \tag{2}$$

$$= (\Delta V_{tot.})(L_{es})^{-1}(D)^{-1} \tag{3}$$

$$= (\Delta V_e + \Delta V_{lit.} + \Delta V_{i.})(L_{es})^{-1}(D)^{-1} \tag{4}$$

$$= (\Delta V_{fl.} + \Delta V_{lit.} + \Delta V_{ov.} + \Delta V_{of.} + \Delta V_{i.})(L_{es})^{-1}(D)^{-1} \tag{5}$$

The user supplies the values of the variables (Δs, $\Delta V_{fl.}$, $\Delta V_{lit.}$, $\Delta V_{of.}$, and $\Delta V_{ov.}$) or an equation defining them when prompted by the GIS interface procedure. The net external sediment volume, $\Delta V_e + \Delta V_{fl.}$, supplied from outside the bay, is then subtracted from $\Delta V_{tot.}$ to determine the remaining sediment

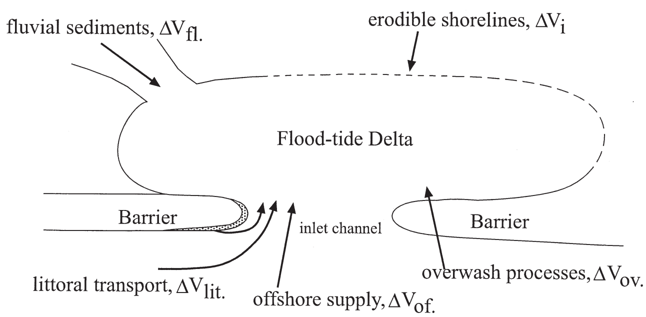


FIGURE 2: Sediment sources for the aggradation of a flood-tide delta in the Aggradation Model.

Table 3: Database of a chart with Aggradation Model variables for a coastal inlet in southeastern Australia.

Name	ΔA^a	Δs^b	$\Delta V_{tot.}{}^c$	$\Delta V_{fl.}{}^d$	$\Delta V_{lit.}{}^e$	$\Delta V_{of.}{}^f$	$\Delta V_{ov.}{}^g$	$\Delta V_{i.}{}^h$	$L_{es}{}^i$	D^j	R^k
Batemans Bay	19,630,000	0.2	3,926,000	0	0	0	0	3,926,000	12,000	3	109

[a] ΔA, area of the flood-tide delta (m^2).
[b] Δs, magnitude of sea level rise.
[c] $\Delta V_{tot.}$, total sediment demand (m^3).
[d] $\Delta V_{fl.}$, sediment supply from fluvial sources (m^3).
[e] $\Delta V_{lit.}$, sediment supply through littoral sediment transport into the inlet (m^3).
[f] $\Delta V_{of.}$, sediment supply from offshore (m^3).
[g] $\Delta V_{ov.}$, sediment supply through overwash processes (m^3).
[h] $\Delta V_{i.}$, sediment supply from erodible shorelines along the flood-tide delta (m^3).
[i] L_{es}, length of erodible shorelines (m).
[j] D, dune elevation (m).
[k] R, rate of recession (m).

demand to be supplied from inside the embayment (ΔV_i). The GIS is finally used to calculate an average rate of shoreline change for those erodible shorelines L_{es} inside the bay with an average dune height D and considered in the modeling.

Flood-Tide Delta Translation Model

The Flood-Tide Delta Translation Model (FTDTM) describes, in addition to behavior captured by the Aggradation Model, the horizontal translation of a sediment body in an embayment under SLR conditions. Shoreface translation has been described by Curray (1964) and further documented by Boyd and Penland (1984), Thom (1984), Wind and Peerbolte (1993), and Roy (1984, 1994). The model is essentially a combination of the Aggradation Model and a simplified Bruun Model (Dubois, 1977) and computationally resembles elements of the Shoreface Translation Model (Cowell et al., 1995). Waves and flood-tide currents are the agents of landward flood-tide delta translation. However, the redistribution of the sediment within the embayment or inlet is not considered as this is subject to local factors not captured in the model.

The translation distance is defined as a function of local SLR and the average slope of the embayment (Figure 3), i.e.,

$$T = \Delta s / \tan\alpha \tag{6}$$

where T is horizontal distance (translation) (m); Δs is magnitude of SLR (m); and α = average slope of the embayment floor (degree).

Shoreline changes associated with the flood-tide delta translation in the FTDTM are defined as volumetric changes of the flood-tide delta before (A-B) and after (A′-B′) translation (Figure 4). The delta front and the ramp of the flood-tide delta are dealt with separately to account for shoreline changes in the inner and outer part of the embayment. The sediment supply from offshore is initially assumed to be unrestricted for this model. Like the Bruun and the Aggradation Model, the FTDTM is implemented with GIS and designed for applications for three different embayment configurations. These are embayments with rectangular shapes, funnel-shaped embayments, and inlet-constricted embayments (Figure 5).

Rectangular Embayments

In bays with rectangular shapes (Figure 6), the landward (L_b) and seaward (S_b) boundaries are similar in length ($L_b \approx S_b$). The overall water volume above the flood-tide delta and thus the proportion between the water and sediment volume of the flood-tide delta remain constant during translation. As a result, the accommodation space for the translated flood-tide delta remains constant, and the flood-tide delta is assumed to rise at the same rate as sea level. The water depth at the seaward end of the flood-tide delta is expected to increase over time due to rising sea level and the landward translating flood-tide delta, eventually causing shoreline recession on the adjacent erodible shorelines. It is evident from Figures 5B and 5C that embayments with upstream shoreline convergence suffer less shoreline retreat

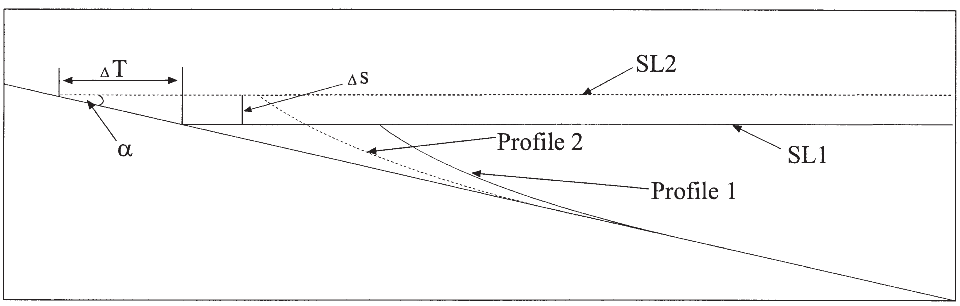


FIGURE 3: Translation distance of a flood-tide delta in an embayment under SLR conditions.

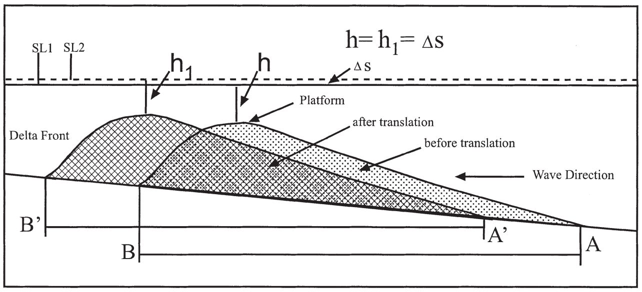


FIGURE 4: Profile of a flood-tide delta during translation from A to A′ and B to B′ under SLR conditions.

than do embayments with parallel sides, whereas divergent shorelines cause enhanced recession.

Funnel-Shaped Embayments

In funnel-shaped embayments (Figure 7), the seaward boundary of the flood-tide delta is longer than is the landward boundary ($S_b > L_b$) and the area of the flood-tide delta (FTD) before translation (FTD_0) is larger than at the end of the translation (FTD_1) (Figure 7B).

During flood-tide delta translation, the tidal delta is forced towards the inner, narrower part of the embayment. With the inner boundary of the flood-tide delta being shorter than the outer boundary, the accommodation space in the inner part of the embayment is reduced (Figure 7B). The water volume above the flood-tide delta is larger before translation than at the end, due to the funnel-shaped configuration of the embayment. Despite the usual assumption of a rise in the elevation of the flood-tide delta corresponding to SLR, the reduction of the horizontal accommodation space implies a reduced demand for sediment required for aggradation; a sediment surplus may even arise under these conditions. Beaches in the embayment will experience less erosion than under the Aggradation Model. If the reduced accommodation volume results in a sediment surplus, then the implication is that the beaches will prograde into the bay.

Constricted-Inlet Embayments

The third scenario (Figure 8) describes the translation of the flood-tide delta in inlet constricted embayments. Here, the seaward boundary (S_b) is shorter than is the landward boundary (L_b) of the flood-tide delta and the area of the flood-tide delta before translation (FTD_0) is smaller than at the end of the translation (FTD_1).

During flood-tide delta translation, the embayment widens toward the inner part of the bay, i.e., the horizontal accommodation space increases. Again, sediment is required to provide the vertical aggradation due to SLR, but an additional volume also is required due to the increase in horizontal accommodation space. To allow the flood-tide delta to rise at the same rate as sea level, as assumed in the Aggradation Model, the sediment deficit in this scenario has to be provided from the adjacent erodible shorelines.

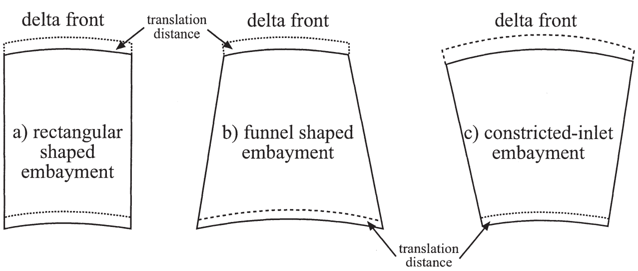


FIGURE 5: Embayment shapes considered in the Flood-Tide Delta Translation Model. (**A**) Rectangular embayments; (**B**) funnel-shaped embayments; and (**C**) inlet-constricted embayments.

MODEL APPLICATIONS

The generic behavior of the models can be illustrated by application to idealized, synthetic site data.

Bruun-GIS Model

The modeling results achieved with the Bruun-GIS Model in principle do not differ from "traditional" applications of the Bruun Rule. Recession along the shoreline varies inversely with dune and shoreface steepness, i.e., with $L/(h+D)$ (Equation 1). Thus, alongshore variations in dune height and distance of estimated closure depth from the shore, both given by the terrain model, produce continuous variation in recession along the coast; SLR impact is simply a function of terrain. Different scenarios for the expected magnitude of SLR (Figure 9), the resolution of the terrain model, and uncertainty regarding closure depth estimates can be examined through sensitivity analysis or as a set of scenarios. Figure 9 also illustrates how the GIS allows the terrain data to condition the Bruun Model to account for real-world variability. This conditioning is probably too exact because other processes, such as littoral transport, may smear the local effects of dune height and bathymetry between adjacent areas alongshore. Nevertheless, the results can be expected to provide a general indication of shoreline response to Bruun effects as well as assessment of the uncertainties pertaining to these effects. Figure 9 shows conceptual modeling results with the Bruun-GIS model for different sections of a beach. The figure is based on a single given SLR scenario and closure depth but with variation in L and D for different sections. In this example, dune height increases toward the upper part of the beach and the rate of shoreline recession decreases. Therefore, alongshore variation in shoreline recession is accounted for with the GIS model by providing the information for individual profiles to the GIS.

Aggradation Model

Modeling results of the Aggradation Model depend in principle on the relation between the net sediment supply

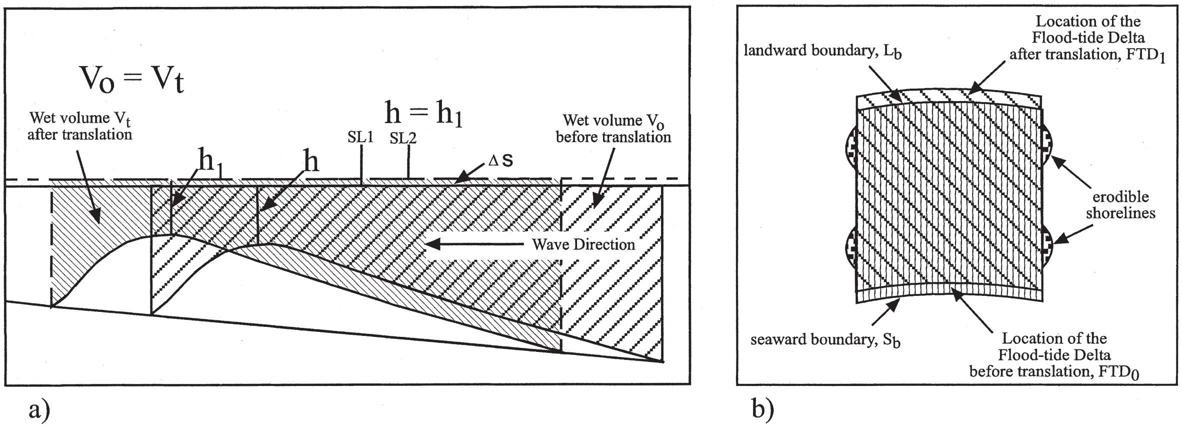


FIGURE 6: Translation of the flood-tide delta in a rectangular embayment; the wet volume remains constant and the flood-tide delta rises at the same rate as sea level. (**A**) Profile of the flood-tide delta during translation; (**B**) top view of the flood-tide delta during translation.

from outside ($\Delta V_e + \Delta V_{fl.}$) and inside ($\Delta V_i$) the embayment. In cases where the net external sediment volume ($\Delta V_e + \Delta V_{fl.}$) is smaller than the total sediment demand $\Delta V_{tot.}$ required to raise the flood-tide delta, shorelines will erode according to this model to supply the volumetric difference. The model works at first approximation so that the sediment demand extracted from shorelines within the coastal inlet is assumed to be apportioned equally for all erodable parts of the shoreline. Shoreline retreat, however, depends on the capacity of the local shoreline to supply sediments, and this is a function of dune height. Therefore, the predicted shoreline retreat varies alongshore in accordance with the onshore Digital Elevation Model (DEM).

In embayments where there is sufficient sediment supply, i.e., where $\Delta V_e + \Delta_{fl.} = \Delta V_{tot}$, no shoreline change occurs according to the model, despite SLR (e.g., the case of the Wadden Sea). In cases where $\Delta V_e + \Delta V_{fl.} > \Delta V_{tot}$, the shorelines in the embayment are predicted to build out into the embayment. With respect to ΔV_e, the magnitude of each component contributing to the marine sediment budget ($\Delta V_{lit.}$, $\Delta V_{of.}$, and $\Delta V_{ov.}$) varies between 0 and >100% of the flood-tide delta demand volume. Hence, an infinite number of scenarios is feasible in every case study, unless expert knowledge can provide more detailed information with regard to local sediment sources. This is not a trivial problem for profession specialists in coastal processes, so applications of these models by general staff, in for example local government, requires considerable caution. The application of a sensitivity analysis is thus mandatory. Figure 10 displays the concept of a range of modeling results achieved with the Aggradation Model. The figure includes one accretion and three recession scenarios, which are based on different values of the input variables. It is assumed for this example that parameter values in Recession Scenarios 1 and 2 are identical, except for the supply of marine sediments, i.e., the contribution of ΔV_e to $\Delta V_{tot.}$ is higher in Scenario 1 than in Scenario 2. To allow the flood-tide delta to aggradate at the rate of SLR, $\Delta V_i = \Delta V_{tot.} - (\Delta V_e + \Delta V_{fl.})$, implying a higher rate in shoreline recession for Scenario 2. Additional to the assumptions made for Scenarios 1 and 2, the dune height in Scenario 3 is assumed to be lower than in Scenario 2. With ΔV_i being a function of L_{es}, D, and the width of the dune, a

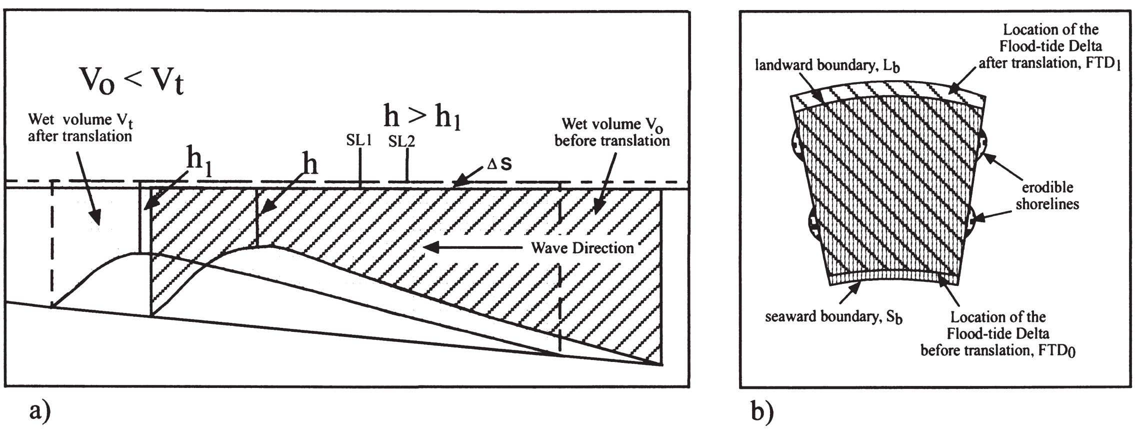
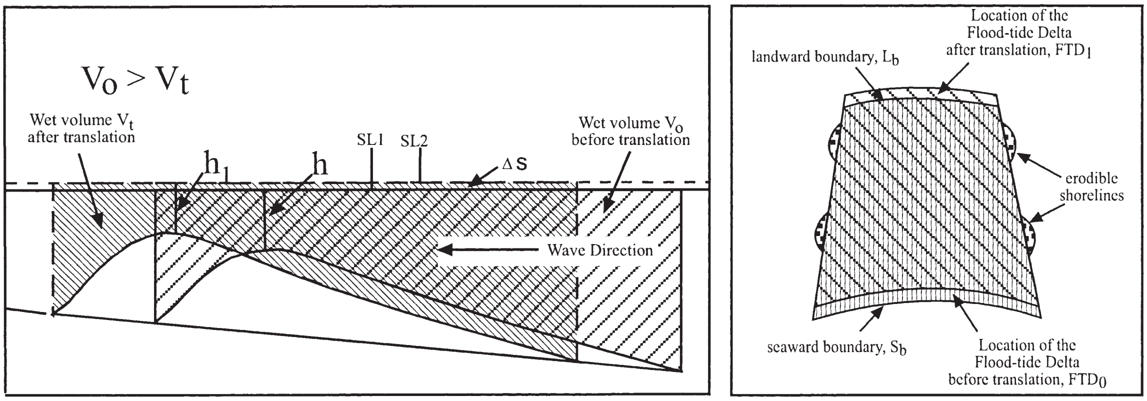


FIGURE 7: Translation of the flood-tide delta in a funnel-shaped embayment; the wet volume decreases and sediment demand for the rise of the flood-tide delta is reduced. (**A**) Profile of the flood-tide delta during translation; (**B**) top view of the flood-tide delta during translation.



a) b)

FIGURE 8: Translation of the flood-tide delta in a constricted-inlet embayment. The wet volume increases during translation and so does the sediment demand for the aggradation of the flood-tide delta. (**A**) Profile of the flood-tide delta during translation; (**B**) top view of the flood-tide delta during translation.

lower dune height ultimately results in higher shoreline recession. The Accretion Scenario is based on the assumption that $\Delta V_e + \Delta V_{fl.} > \Delta V_{tot}$, i.e., a surplus in sediment occurs in the inlet over time causing the shoreline to prograde into the inlet.

Flood-Tide Delta Translation Model

Generally speaking, modeling results for the FTDTM follow those for the Aggradation Model but with the addition that different embayment shapes and rates of flood-tide delta translation are included. Therefore, more variables need to be considered where flood-tide delta translation occurs. Figure 11 shows anticipated impacts of flood-tide delta translation based on embayment shapes shown in Figure 5. Shoreline accretion (reverse Bruun effect) is expected for funnel-shaped embayments (Figure 11B) as a result of a decrease in accommodation space and the reduced demand for sediment. Also, beaches landward of the delta front in rectangular-shaped embayment (Figure 11A) are expected to prograde into the inlet. For constricted-inlet embayments (Figure 11C), where the accommodation space and therefore the sediment demand increases, a widespread shoreline recession is the expected overall impact. Still, modeling results of the FTDTM are highly variable, but in principle depend on the rate of flood-tide delta translation, the embayment shape, and the sediment supply from offshore.

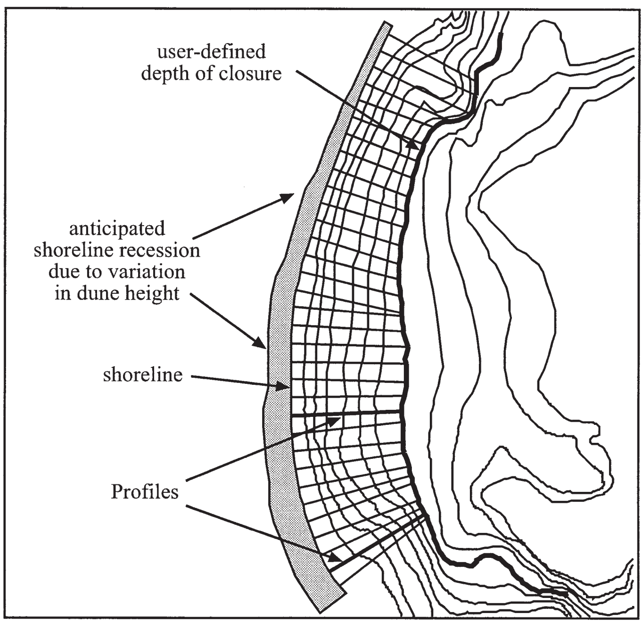


FIGURE 9: Modeling of continuous variation of beach recession due to changes in values for L and D between profiles, using the Bruun-GIS Model.

CONCLUSIONS ●

The potential threat of an enhanced rise in sea level demands methods that are useful for making practical predictions of a range of coastal impacts on a large spatial scale. Despite a number of uncertainties associated with climate change and inaccuracies associated with the mapping of low-resolution data and their further processing, a quick and low-cost method is believed to be a good start for hazard mapping at a large spatial scale.

The principles of three GIS-based models used to simulate and display a range of possible impacts of rising sea

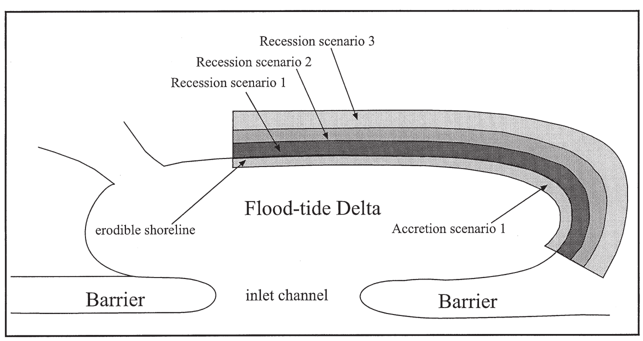


FIGURE 10: Conceptual recession and accretion scenarios derived with the Aggradation Model.

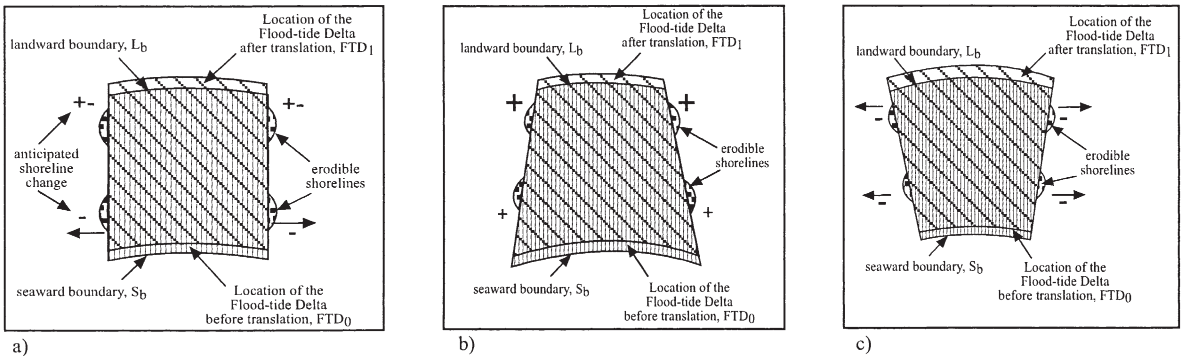


FIGURE 11: Conceptual modeling results for different embayment shapes with the Flood-Tide Delta Translation Model.

level on flood-tide deltas were introduced and discussed in this article. The advantage of GIS-based models compared to conventional methods clearly lies in their flexibility with respect to parameter value adjustments allowing the users of such systems to account quickly for morphological variability under SLR conditions in space and time.

With respect to the three GIS models described in this article, it can be summarized that:

- the Bruun-GIS Model allows for continuous alongshore variability of shoreline response, defining shoreline recession as a function of terrain (L/(h+D)) and the rate of SLR on both open ocean beaches and in inlets;
- the Aggradation Model also considers terrain as a factor of continuous shoreline change. Nevertheless, the proportion of the external sediment volume ($\Delta V_e + \Delta V_{fl.}$) required for the aggradation of the flood-tide delta compared to $\Delta V_{tot.}$ ($= \Delta A * \Delta s$) is the dominant factor in determining shoreline recession or advance;
- the Flood-Tide Delta Translation Model implements, in addition to the variables in the Aggradation Model, the translation of the flood-tide delta under SLR conditions for different inlet shapes, therefore accounting for a wider range of shoreline response than the other two models.

In summary, environmental modeling with GIS models and currently available and often limited information is possible if those limitations imposed by the models applied, the quality and resolution of the data used, and results achieved are taken into consideration. The increase in the number of variables in the models reflects the range in magnitude and type of shoreline response between the three models. Nevertheless, the range of results within each model and between the three models described in this article gives an appreciation of the uncertainty involved in geomorphic impact prediction, something missing from most existing approaches. It is believed that such methods are of particular value for end-users, such as local government, to screen out quickly areas of high risk to be able to undertake more detailed research in such areas. GIS models can be provided to local government as tools in future shoreline change estimation, but the decision about the selection of the most appropriate model still remains with the user of those tools.

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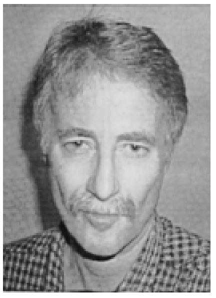

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