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The Coastal-Tract (Part 1): A Conceptual Approach to Aggregated Modeling of Low-Order Coastal Change

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ABSTRACT

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Evolution of coastal morphology over centuries to millennia (low-order coastal change) is relevant to chronic problems in coastal management (*e.g.,* systematic shoreline erosion). This type of coastal change involves parts of the coast normally ignored in predictions required for management of coastal morphology: *i.e.,* shoreline evolution linked to behavior of the continental shelf and coastal plain. We therefore introduce a meta-morphology, the *coastal tract,* defined as the morphological composite comprising the lower shoreface, upper shoreface and backbarrier (where present). It is the first order-system within a cascade hierarchy that provides a framework for aggregation of processes in modeling low-order coastal change. We use this framework in defining boundary conditions and internal dynamics to separate low-order from higher-order coastal behavior for site-specific cases. This procedure involves preparation of a *data-model* by *templating* site data into a structure that complies with scale-specific properties of any given predictive model.

Each level of the *coastal-tract cascade* is distinguished as a system that shares sediments internally. This sediment sharing constrains morphological responses of the system on a given scale. The internal dynamics of these responses involve morphological coupling of the upper shoreface to the backbarrier and to the lower shoreface. The coupling mechanisms govern systematic lateral displacements of the shoreface, and therefore determine trends in shoreline advance and retreat. These changes manifest as the most fundamental modes of coastal evolution upon which higher-order (shorter-term) changes are superimposed. We illustrate the principles in a companion paper (The Coastal Tract: Part 2).

ADDITIONAL INDEX WORDS: *Shoreface, backbarrier, scale, coastal tract, coastal cell, coastal-tract cascade, templating, data-model, behavior-oriented models, sediment-sharing systems, morphological coupling, sea level, sediment supply, coastal management, sea-level rise, transgression, barrier, continental-shelf, sediments, accommodation space, numerical-model.*

INTRODUCTION

Coastal management and engineering requires predictions of low-order (large-scale) coastal change to determine whether shoreline and seabed movements involve systematic trends. Such trends may cause chronic problems that require long-term planning and major engineering interventions. Morphological change entailing temporary fluctuations may cause acute problems, but these can usually be remedied with local measures. Coastal management strategies are very different for the two types of problem, and usually involve very different levels of expense. If estimates of the long-term change cannot be quantified, then it seems unlikely that predictions will discriminate adequately between chronic and acute coastal change.

Aggregated-scale approaches have been developed to sidestep upscaling problems (*e.g.,* DE VRIEND, 1998) from which emerge inadequacies in conventional perceptions and definitions of the coast and coastal processes. In particular, the boundary conditions and internal dynamics are poorly de-

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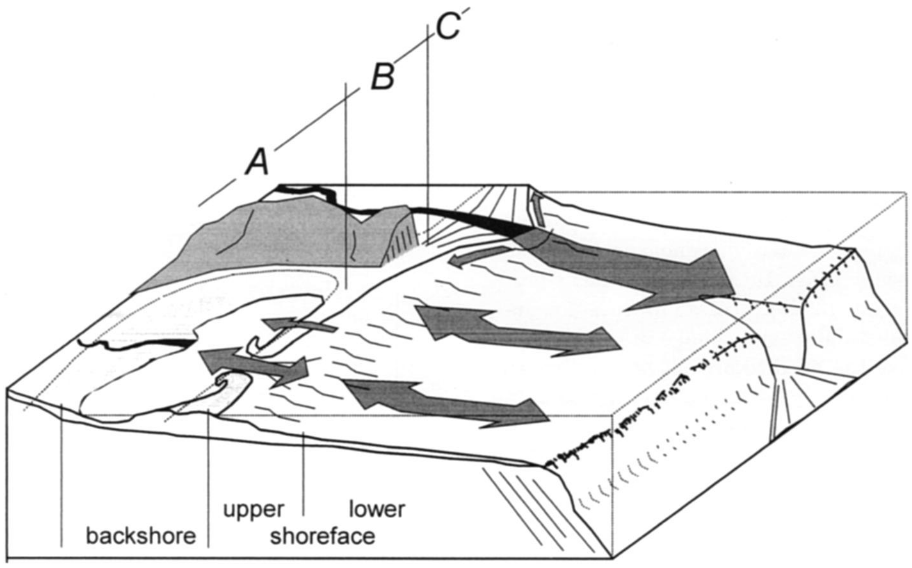

Figure 1. Physical morphology encompassed by the coastal tract (see text for explanation).

fined in site-specific analyses for long-term coastal management. The traditional focus on text-book morphologies (such as the beach, shoreface, dunes, estuaries, and deltas) has tended to promote a reductionist approach involving separate analysis of the classical morphologies. This approach has proved incapable of solving, or even properly addressing, large-scale coastal problems. We therefore need more appropriate concepts applicable to how the coast operates on large scales.

Consequently, we take a broader view of coastal processes by recasting traditional reductionist concepts about coastal morphology into a more unified framework. To establish this framework, we introduce a new, over-arching morphological entity that we term the *coastal tract* (Figure 1), borrowed from geological concepts on *depositional systems tracts* and related sedimentation processes (FISHER and MCGOWAN, 1967; BROWN and FISHER, 1977). The coastal tract is, for our purposes, a generalized term for the continuum of mutually dependent morphological units (surfaces and surficial deposits) on continental margins (Figure 1). Our new geomorphic feature therefore revises traditional ideas about the shoreface and, by emphasizing contiguity between the coastal morphologies, how these interact. More specifically, the revised concepts encompass sedimentary processes that occur not just on the beach and shoreface, but also well landward and seaward of the littoral zone (*i.e.,* to include the estuarine basin and continental shelf respectively).

The purpose of this paper therefore is to (a) introduce the coastal tract as a composite morphology that we can use in structuring problems of scale and aggregation in predicting coastal-change, and (b) propose a methodological framework for describing coastal behavior in nature with models that necessarily have a much lower dimensionality. That is, we introduce the coastal-tract concept to define the most fundamental (lowest-order) modes of morphological change on coasts. Then, based on the coastal-tract concept, a hierarchy of higher-order processes can be discriminated to organize and simplify methods of prediction and analysis. Our objectives therefore are to:

- establish physical principles of the coastal tract, especially regarding fundamental modes of coastal evolution that have been missing from previous approaches to quantitative prediction;
- provide a method to define the hierarchy of morphological processes that take place in the coastal tract (*i.e.,* the *coastal-tract cascade*); and
- provide a protocol, that we term *coastal-tract templating,* for mapping site-specific problems onto *data-models* (*i.e.,* to decompose real-world, measured complexity into constituents on the basis of scale and systematic distinction between external controls and internal responses).

In the companion paper, *Part 2* (COWELL *et al.*, 2003, this volume), we will illustrate the concepts through model applications that elucidate how the coastal tract operates.

METHODS

The new concepts presented here derive from a deeper understanding of our aggregate-scale behavior models (Part 2), forged through tensions over two aspects of work within the project PACE (Predicting Aggregate-scale Coastal Evolution). First, comparative modeling undertaken to determine where and how each of the models are best applied enabled us to formalize representation of process regimes for different elements within the coastal tract. Second, in comparing the models in terms of their alternative representations of aggregated processes (an exercise partly driven by our attempts to develop a hybrid 'super' model), we were forced to reconcile linkages between components of the different models. This led to a more complete picture of coastal-tract sub-systems and how these interact. Thus, paradoxically perhaps, the principles encapsulated formally within our models have been crucial in developing our concepts of the coastal tract and cascade templating.

COASTAL TRACT AND CASCADE HIERARCHY

The Practical Imperative

Low-order coastal change involves morphological evolution on a geological time scale (order 10^3 years) that has significance on coastal management time scales (10^0 to 10^2 years). Issues of morphological stability and change in coastal management largely involve the need to predict and control the position of the shoreline. At any location along the coast, the shoreline position is governed by gains and losses of sediments in the alongshore and across-shore directions (*i.e.,* the local sediment budget), and by tendencies toward flooding or emergence of the backshore due to changes in sea level. Sea-level change also mediates across-shore sediment displacements, and can influence alongshore sediment budgets through effects on the hydrodynamic conditions caused by changes in the effective bathymetry experienced by nearshore wave and current fields.

Prediction of shoreline change adopts different approaches, depending on the space and time scale over which predictions are required. For short-term (sub-decadal) coastal change (event and synoptic-scale changes occurring over hours through seasons to years), the focus is generally on the local sediment dynamics. These affect the shoreline planform and the across-shore profile (*e.g.,* shoreline and profile models described by HANSON *et al.*, 2003, this volume) in response to fluctuations in environmental conditions (*i.e.,* the wave climate, littoral sediment budgets, sea level and the effects of anthropogenic activities). Theoretical and empirical approaches to these sub-decadal time scales generally focus on changes to the upper shoreface (defined loosely as the *active zone*; *cf.* STIVE and DE VRIEND, 1995), which correlate with shoreline movements. These changes are moderated by littoral sediment budgets and by sediment 'production' via shoreline erosion cutting into onshore sand reserves (*e.g.* eroding dunes or cliffs), or through artificial nourishment of beaches.

The practical imperative for long-term prediction (decades or longer), requires an expanded scope that also includes the lower shoreface and the interaction between the shoreface and backshore environments (Figure 1). The upper shoreface has cross-shore length scales that are typically two to three orders of magnitude less than for the lower shoreface (depicted in Figure 1). This scale difference means that changes on the lower shoreface are associated with disproportionately larger changes on the upper shoreface, due to mass continuity for sediment exchanges between the two zones (ROY *et al.*, 1994; COWELL *et al.*, 1999a). The upper shoreface is subject to a similar interaction with the backshore which comprises a morphologically active zone located between the upper shoreface (ocean beach) and the mainland. This zone may variously include dunes, washover surfaces, flood-tide deltas, lagoonal basin, tidal flats (Figure 1A), mainland beaches

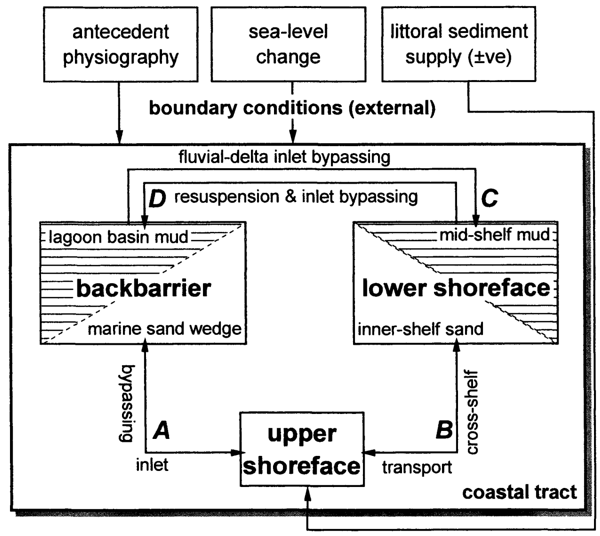

Figure 2. Schematic representation of mechanisms steering the location of the upper shoreface.

(Figure 1B) and fluvial deltas (Figure 1C). Each of these may be present or absent, depending on local conditions, especially the regional substrate slope (ROY *et al.*, 1994; COWELL *et al.*, 1995).

The sediment exchanges depicted by the arrows in Figure 1 occur in principle during any average year and on all time scales longer than this. These exchanges are summarised schematically in Figure 2 which differentiates sediment fluxes into sand and mud fractions. For coastal change on any scale, antecedent morphology, sea-level change and littoral sediment budgets can be regarded as boundary conditions for the coastal area of interest.

For sub-decadal prediction of horizontal movements in the upper shoreface, sand exchanges with the lower shoreface (Figure 2B) are usually ignored (HANSON *et al.,* 2003, this volume) because these fluxes are so small that resulting morphological change is negligible: *i.e.* the annual closure-depth concept (HALLERMEIER, 1981; NICHOLLS *et al.*, 1998). The fluxes of fine sediments (Figure 2, C and D) are not directly relevant to the upper-shoreface sediment budget because mud deposition there is negligible.

For long-term predictions however, none of the internal sediment exchanges depicted in Figure 2 can be ignored. This is because systematic residual fluxes, that are small on the sub-decadal time scale, eventually cumulate through time enough to produce non-negligible (*i.e.,* measurable) morphological changes. Moreover, the changes in morphology of the backbarrier, lower shoreface and upper shoreface cause these three zones to interact dynamically: *i.e.,* the sediment exchanges themselves become influenced by the morphological changes (see Low-Order Coastal Change below).

Definition of the Coastal Tract

We introduce the coastal tract as a composite morphology that is a physically identifiable feature. The composite form however also underpins a more abstract framework for aggregation methods (*i.e.,* the *coastal-tract cascade,* outlined below). Identification of the coastal tract provides (a) the rationale for spatial extension of coastal-change models (*i.e.,* to include the lower shoreface and backbarrier as intrinsic components), and (b) an explanation for end users of why these broader considerations are essential ingredients to long-term coastal management.

We formally define the *coastal tract* in both physical and abstract terms. Under the physical definition,

the coastal tract is a spatially contiguous set of morphological units representative of a sediment-sharing coastal cell.

Although we propose the tract as a natural physiographic feature, its composite nature means that its actual form can vary geographically in terms of its constituents (*cf.* regions A, B, and C in Figure 1). Thus, an individual coastal tract has meaning only in the context of a specific engineering, management or research problem. That is, the tract also is an abstract entity (or meta-morphology) constructed (or *templated*) for analysis and prediction of a specific site or region in nature, on an associated time-scale.

The physical definition contains three key terms: a) the *morphological units,* which are constituents within our formal framework (that we term the *coastal-tract cascade*) for partitioning and aggregation of processes within the tract on the basis of scale; b) *sediment-sharing systems,* which form the scale-related defining entities of the coastal-tract cascade, and c) the *coastal cell,* which defines the coastal tract in relation to alongshore homogeneity of morphology and processes. We elaborate on each of these three concepts in the following.

Coastal-Tract Cascade

We introduce the coastal-tract cascade to manage process aggregation. The tract cascade is thereby the means of separating out low-order coastal change from morphodynamics on smaller space and time scales. The contiguous morphological units referred to in the coastal-tract definition are associated with an intermediate morphodynamic scale in the cascade hierarchy. The contiguity relates to the coupling of adjacent morphologies within the coastal tract. The coupling manifests as coastal change (*i.e.,* movements in the shoreline and changes in elevation of the bed).

Physical Tract Constituents

In terms of the simple physical definition of the tract as a composite morphology, its constituent morphological units are arranged perpendicular to the shoreline within a coastal cell. The across-shore sequence is: mainland beach (or fluvial delta), estuary-lagoon, barrier-beach-dune complex, upper shoreface, lower shoreface and continental slope (Figure 1A). The fluvial delta and estuary-lagoon may be absent: *e.g.* in the case of a steep continental margin where the mainland beach (with or without dunes) fronts directly onto the shoreface (Figure 1B).

Only the lower shoreface departs from the conventional form, in that it is generalized to extend seaward to the edge of the continental shelf (Figure 3). This extended concept encapsulates the regions traditionally (albeit inconsistently) termed the shoreface, as well as the inner, mid, and outer continental shelf (COWELL *et al.,* 1999a). A lumped definition of the lower shoreface is essential if coastal change is to be understood across a sufficiently large range of time scales to enable practical prediction of low-order coastal behavior, and hence higher-order behaviors within a process cascade. Time scales for morphological change (Figure 3) decrease by several orders of magnitude between the upper shoreface and the shelf edge (NIEDORODA *et al.,* 1995). The extended lower-shoreface concept also admits the inclusion of fine sediments (*i.e.,* mud) into the problem through maximum aggregation of sedimentation processes: *i.e.,* across the entire contental-shelf surface.

The physical representation of the coastal tract as a composite feature is simple because the constituents are traditional text-book morphodynamic systems. These systems however collectively contain a large amount of complexity and are also numerous. Paradoxically therefore, the simple physical representation of the coastal tract is too complex as a basis for robust and transparent models of low-order change. Greater aggregation of the constituents is required to achieve this, for which reason we turn to the more abstract concept of the tract as a meta-morphology.

Tract Cascade Hierarchy

The coastal tract is a metamorphology forming the lowest-order level in a hierarchy of processes and morphologies (Figure 4). The hierarchy involves a process cascade in which coastal behavior at any intermediate level results from the residual effects of higher-order processes, while constrained by the effects of lower-order systems in the cascade (CHORLEY *et al.,* 1984). These constraints constitute internal boundary conditions that operate in addition to the external boundary conditions. The coastal tract contains and integrates the effects of all higher order morphodynamic systems in the cascade.

These ideas follow *hierarchy theory,* according to which nature can be partitioned into 'naturally occurring' levels that share similar time and space scales, and that interact with higher and lower levels in systematic ways (HAIGH, 1987; CAPOBIANCO *et al.,* 1998). Each level in the hierarchy sees the lower levels as extrinsic constraints or boundary conditions, and the higher levels as intrinsic (sub-scale or 'subgrid') processes. At successively higher levels in the hierarchy, these intrinsic processes may lose their relevance for lower levels, turning them effectively into some combination of unimportant variations ('noise') and sub-scale processes that must be generalized for representation at the scale of interest (Figure 4). The criterion by which we partition the cascade is that each level forms an internally sediment-sharing system.

Based on observations of large-scale coastal behavior, for example throughout the Holocene (BEETS *et al.,* 1992; ROY *et al.,* 1994; COWELL *et al.,* 2001), we consider a coastal-tract system to form the first-order level in the hierarchy (Table 1). At this level, the coastal tract behaves as a single unit

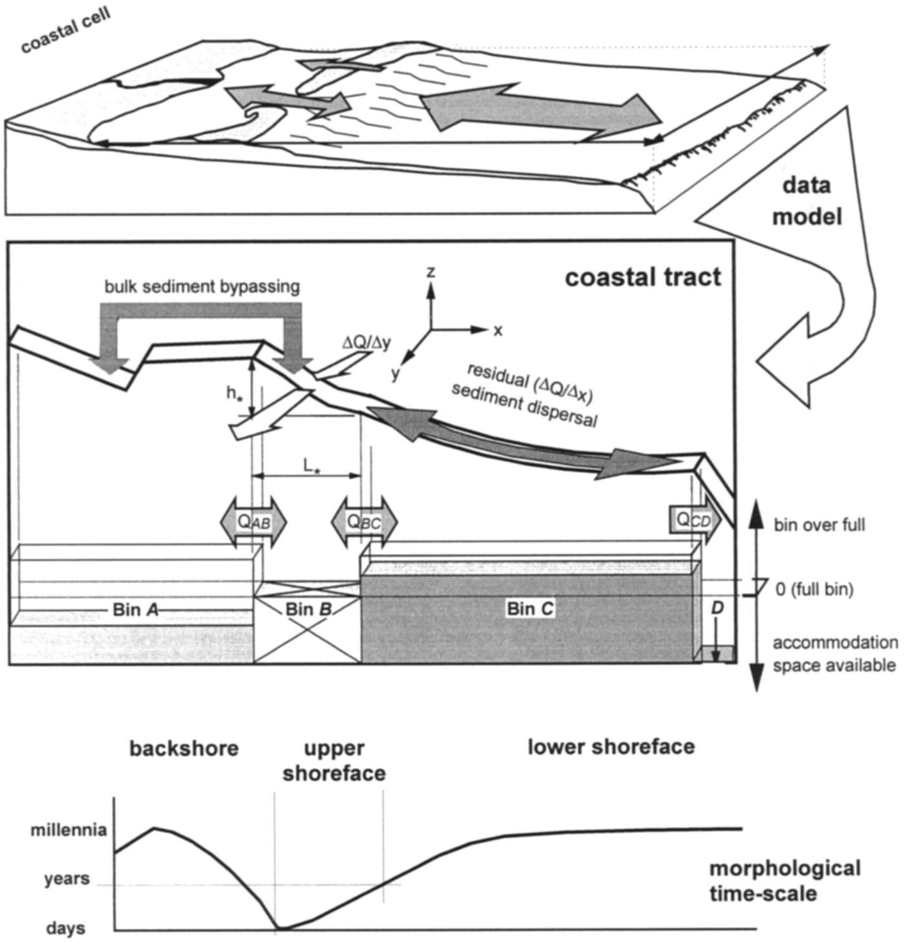

Figure 3. Definition sketch of the coastal tract and sediment-accommodation space as bins in a sediment-sharing system (see text for details).

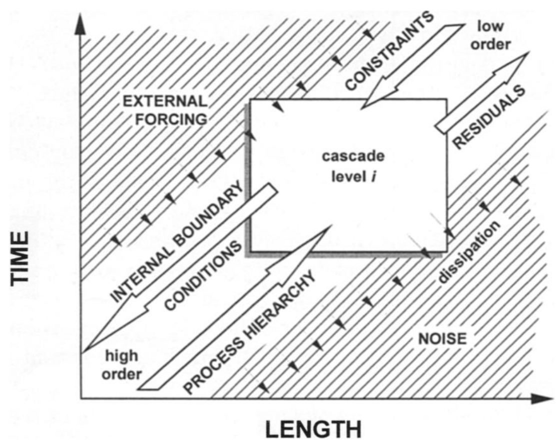

Figure 4. Coastal-tract cascade. Sub systems in the process hierarchy and internal and external constraints. Lower order systems have the largest length and time scales.

that adjusts internally in response to a) gross environmental factors, such as relative sea-level rise, coastal ocean climatology and external sediment sources (such as river input) or sediment sinks (such as submarine canyons), and b) lower level constraints, such as a geologically inherited substrate and tectonic movements (the zero-order system).

Table 1. *Coastal-tract systems and system scales.*

System	System-scale	Time Scale	Space Scale
zero order	meta-scale	Quaternary Period ($\geq 10^4$ yrs)	tract environment
first order	meta-scale	Holocene Epoch ($10^2 - 10^3$ yrs)	coastal tract
second order	macro-scale	late Holocene Age ($10^1 - 10^3$ yrs)	morphological complex
third order	meso-scale	years to decades	morphological unit
fourth order	meso-scale	seasons to years	morphological element
fifth order	micro-scale	days to seasons	sub-grid phenomena
≥fifth order	micro-scale	seconds to days	sub-grid phenomena

Second-order systems we term *morphological complexes* because they comprise aggregations of the various text-book morphologies that constitute the third-order systems (*morphological units* in Table 1). We introduce second-order systems to minimize aggregation errors and loss of model transparency (COWELL and THOM, 1994) that might result from integrating too much spatial and functional complexity across a single level in the *cascade.* The backbarrier is a morphological complex that may include dunes, estuaries (or tidal lagoons) together with the fluvial deltas entering them (Figure 1A), and the coastal lowlands formed as lagoons become sediment filled (Figure 1C). The upper shoreface is a morphological complex that may incorporate river and ebb-tide deltas as well as surf zone morphologies. We say "may", because the way we define morphological complexes depends on the site-specific problem and is part of the *templating* process involved in development of the *data-model.*

Similarly, we introduce a fourth-order level (*morphological elements* in Table 1), on even smaller temporal and spatial scales, with which we account for the spatial and functional complexity of the more traditional morphological units by distinguishing their main internal elements. Examples include,

- for beaches—the beach face and surfzone bars;
- for a tidal inlet—the gorge plus the bars and channels on the ebb- and flood-tide delta; and
- for the inner tidal basin—the channels, lower and higher tidal flats, plus fringing salt marshes or mangroves.
- Whereas here we consider first, second and third order systems with decades as the smallest time scale, the fourth-order system displays relevant behavior on the sub-decadal time scale. On smaller time scales (days to seasons), fifth-order systems may be distinguished, such as beach states on the upper shoreface. For the low-order processes (first to third), these fifth-order systems can be considered as noise (Table 1).

These distinctions provide a formal basis for aggregation methods used in development of models of coastal change in general, and for low-order change models in particular (as illustrated in Part 2).

Sediment-Sharing System

Heterogeneity of sediment-flux gradients implies mutual dependence of morphological units in coastal evolution: morphologically coupled behavior is mediated by sediment-volume exchanges. Thus, heterogeneity distinguishes the coastal tract as an internally *sediment-sharing system.* Sediment sharing constrains the internally coupled morphological behavior and is quantified by mass continuity in gross sediment exchanges between morphological units (Figure 2). In applying the coastal-tract concept to predict first-order shoreline displacement (upper-shoreface movements), the morphological coupling is represented through the volumetric effects of sediment transfers between sediment-accommodation bins (Figure 3).

Accommodation space is the volume between the actual bottom shape and the shape that would develop if the short-term physical processes continued to operate uniformly long enough for the morphology to cease changing. Zero accommodation within any of the bins occurs if the associated morphological sub system (second-order system) is in a state of equilibrium with respect to the sedimentation regime. Gross equilibrium does not exist if the coastal tract experiences external forcing (such as a change in relative sea level), or if there is a time lag between an earlier forcing and the attainment of equilibrium. For example, radiocarbon dates in SE Australia show that time lags for lower-shoreface and flood-tide deltas are of the order of 10^3 years (COWELL and THOM, 1994).

The significance of identifying a system that shares a common pool of sediments is that any morphological change in one sub system must cause corresponding changes in the other sub systems. That is, these morphological changes are coupled, with the overall system dynamics governed by flux rates of sediment exchanges between sub systems. This principle is simply the continuity constraint for sediment mass but, for the coastal tract, it takes a defining role in the partitioning and aggregation of processes within the cascade hierarchy. The sediment-sharing concept thus permits us to identify, simplify and thus analyse low-order coastal change.

Coastal-Tract Representation of a Coastal Cell

While the tract-cascade introduces concepts about the aggregation of processes, the cell part of the tract definition relates to aggregation of spatial dimensions. In many cases there is sufficient alongshore homogeneity to permit generalization of a littoral cell into a cross-sectional sediment-control volume of unit width (Figure 3). This is a special case of the more general concept outlined in the Discussion (where spatial and process dimensions are less readily aggregated). For present purposes, however, the special case provides a simpler illustration of coastal-tract principles. Aggregation procedures may involve transformation of process and morphological representations to meet the alongshore homogeneity assumption, if possible. This transformation is one function of templating procedures to construct the data-model.

The littoral cell defines the alongshore extent of the coastal tract. Natural boundaries of the cell may coincide with points of convergence, divergence or topographic barriers in the littoral transport system (CARTER, 1988). Alternatively, the littoral cell may be of arbitrary extent (*e.g.,* defined by administrative boundaries), depending on the site-specific problem. In general however, the littoral cell need not be closed to alongshore sediment transport, but net gains and losses of sediments across cell boundaries must be estimated. All of the boundaries of the coastal tract must be established where the sediment fluxes are extrinsic to all components within the coastal-tract cell.

Alongshore homogeneity is a fundamental assumption when defining a coastal tract. This does not mean however that alongshelf components of flows and sediment flux can be ignored. They are usually one or two orders of magnitude larger than their across-shelf counterparts (ROELVINK and STIVE, 1991; WRIGHT, 1995). Rather, the homogeneity assumption justifies treating alongshelf sediment fluxes as boundary conditions (*i.e.,* as a net input or output of the tract), provided that flux gradients can be assumed to be uniform. Thus, even when we can aggregate the coastal tract into a cross-shore profile of unit width, as in Figure 3, we implicitly include alongshore phenomena (such as littoral transport, and alternating shoreline features such as beaches, tidal inlets, promontories and their attendant processes). That is, although these phenomena are spatially aggregated into non-spatial forms, their effects are retained.

Overall therefore, reduction of the coastal cell from a planimetric- to a profile-representation depends upon assumptions of homogeneity in time-averaged morphology and processes parallel to the shore within the coastal cell (see below under *Cell Templating*). If the alongshelf homogeneity cannot be assumed, or if transformation of process and morphological representations to meet this assumption is not possible, then the *tract* must be treated as a surface with defined alongshore as well as cross-shore dimensions (see Discussion). Clearly, homogeneity does not exist perpendicular to the shore because of the systematic across-shore variation in water depths, morphological units, and associated differences in depth-dependent processes.

LOW-ORDER COASTAL CHANGE

The schematic representation of the coastal tract in Figure 3 generalizes the most fundamental modes of coastal behavior on the decadal to millennial time scales (*e.g.,* within the Holocene period). Behavior of the separate morphological complexes within the coastal tract (*i.e.,* the upper and lower shoreface, and the backbarrier sub systems) can also be treated separately in terms of smaller-scale components (such as surf-zone bars, shoreface-connected ridges, and tidal inlets and channel networks) through analysis at higher levels in the cascade hierarchy. For first-order coastal change however, the coastal tract not only constitutes the framework in which its sub-systems function, it also defines boundary conditions for the sub-systems.

The three morphological complexes of coastal tract (Figure 3) interact dynamically: a morphological change in one necessarily means a corresponding change in the others (*morphological coupling*). Morphological change of lower shoreface and backshore are thus mediated by sediment fluxes between bins in Figure 3: *i.e.,* these fluxes are internal variables within the first-order sediment-sharing system. Furthermore, if we were to focus separately on the lower shoreface and backshore, evolution of these second-order morphologies is not only governed by their internal sediment dispersal mechanisms. Their evolution also is constrained by the between-bin fluxes. Thus, whereas the between-bin fluxes are internal processes at first-order, they constitute boundary conditions to the second-order sub-systems.

Sediment Exchanges in the Coastal Tract

The backshore coupling (Figure 2*A*) involves either bypassing of sand from the shoreface to the lagoon behind the barrier (if a barrier exists), or the net supply of sediment to the overall coastal sediment budget. The latter can take place through deposition of muds in the lagoon, or through supply of terrestrial sands to the shoreface by estuaries that act as net-sediment sources rather than sinks (*i.e.,* fluvial deltas). Alternatively, the backshore may be closed to sediment bypassing to and from the shoreface if inlets and river mouths are absent. These conditions occur in coastal cells where the shoreface abuts the mainland, or where high dunes run uninterrupted along the coastline, isolating the coastal lowland from the sea. The mainland can act as a sand source during landward translation of the upper shoreface (Figure 1*C*) if the backshore is steeper than the shoreface (COWELL *et al.*, 1999b), and provided that the mainland is composed of soft sediments rather than bedrock. The mainland may act as a sand sink if landward-migrating transgressive dunes outrun the horizontally translating shoreface.

The lower-shoreface coupling (Figure 2*B*) involves long-term adjustments which tend to steer the upper shoreface in a landward or seaward direction, depending on whether evolution of the lower shoreface causes it to act as a net sink or source for sand-sized sediments. The actual direction of upper-shoreface translation depends upon combined effects of the upper-shoreface coupling with the lower-shoreface and with the backshore. For example, if the lower shoreface is a net sand source for the upper shoreface, but the volume of sand bypassing to the backbarrier exceeds that supplied from the lower shoreface, then upper-shoreface translation will be landward. This becomes manifest to coastal managers as chronic shoreline recession. In the case of the central Netherlands coast on the other hand, the sand supply from the lower shoreface appears to balance littoral losses to the Wadden lagoon (STIVE *et al.*, 1991).

A direct coupling between the lagoon and lower shoreface exists (Figure 2*C*) due to the possibility that fine sediments, discharged at the fluvial delta, bypass through the tidal inlet and upper shoreface to settle out of suspension on the lower shoreface as mid-shelf mud deposits. Conversely, upon resuspension on the lower shoreface (Figure 2*D*), these sediments may find their way back into the same or other lagoons where they contribute to reduction of backbarrier accommodation capacity (WOODROFFE *et al.*, 1989; BEETS *et al.*, 1992). The resulting decrease in the potential of lagoons to act as sediment sinks (*i.e.,* less accommodation space) also reduces the potential for sand loss from the upper shoreface to the lagoon. More generally, and of significance to coastal management, mud from any source, deposited in the central basin of the lagoon, reduces the rate of long-term recession of the upper shoreface.

Overall therefore, Figure 2 summarises the processes governing the fundamental modes of coastal behavior upon which all other coastal changes are superimposed. Further details of these processes and illustration of resulting low-order coastal evolution are presented in our companion paper (Part 2).

Morphological Coupling

The morphological coupling mediated by the various sediment exchanges outlined above is schematized in Figure 3. For long-term (hyperdecadal) predictions we can ignore the changes that occur within synoptic time scales, so that the upper shoreface assumes a time-averaged profile of invariant form, or a time-averaged form that evolves with secular changes in wave climate or sediment grain size (*e.g.*, due to changes in sediment provenance). The first-order, coastal-tract problem then reduces to prediction of time-averaged shoreline positions that move only with vertical and horizontal translation of the time-invariant (or slowly evolving) upper-shoreface profile. The vertical translations are governed totally by long-term movements in sea level. The horizontal translations are steered by two sets of gross processes. These processes involve a coupling of the upper shoreface to a) the backshore environment, and b) the lower shoreface.

Within the schema of Figure 3 therefore, the backbarrier (Bin A) may be absent (mainland-beach case) but, if present (barrier-beach case), sediment sharing between the backbarrier and the upper and lower shoreface is governed by sediment accommodation capacity, aggregated volumetrically as a set of storage bins for each complex in the tract. As illustrated here, the backbarrier (Bin *A*) has positive accommodation capacity and exerts a demand for more sediment to attain tidal-basin equilibrium, whereas the lower shoreface (Bin *C*) has a sediment surplus (*i.e.*, the continental shelf is shallower than its equilibrium elevation) and therefore acts as a sediment source for the continental slope (Bin *D*) and the upper shoreface (Bin *B*).

Changes in relative sea level alter the accommodation space of all bins. Under conditions of stable sea level, the upper shoreface (Bin *B* in Figure 3), where the morphological time scale is shortest, is permanently full (*i.e.*, in equilibrium). Since this bin can then undergo neither net gains, nor losses of sediments, transfers from adjacent bins (*A* and *C*) bypass the upper shoreface to adjacent bins. Depending on the balance between net sediment fluxes from both adjacent bins and external inputs from littoral sources (Q_{AB}, Q_{BC} and $\Delta Q/\Delta y$ respectively in Figure 3), the upper shoreface (Bin *B*) must advance or retreat (*progradation* and *retrogradation* respectively).

The accommodation of Bins *A* and *C* may be positive (unfilled), negative (over-full) or zero (full or equilibrium). Positive accommodation space means that the bin demands sediment, causing retreat of the upper shoreface and eating into the backbarrier (or mainland-beach) sediments to supply the demand and to return to equilibrium. Negative accommodation space exists if either Bin *A* or *C* are overfull: *i.e.*, they are sediment sources. Such a state implies that the lower shoreface (the continental shelf in general) is shallower than equilibrium under the prevailing shelf flow climatology (Roy *et al.*, 1994). The tendency then is for the shelf to degrade. Bin *D* is the continental slope and therefore is a deep hole in terms of accommodation space on time scales of millennia or less. Seaward sediment fluxes into *D* are one-way accordingly, provided that an ocean basin exists: ocean basins are absent from 'buttressed' continental margins (*e.g.*, the European North Sea coast).

The morphological coupling of the coastal tract complexes not only causes lateral (shore-normal) movements of the upper shoreface. Each of the bin boundaries in Figure 3 can undergo such lateral migration as a result of sediment transfers between the bins. Sediment transfers beyond the continental-shelf break (Q_{CD}) cause the coastal tract to extend itself seawards (ocean basin-margin fill). Feeding of the backbarrier from the upper shoreface involves a sediment recycling processes: barrier rollover (Leatherman, 1983). That is, the upper shoreface preserves its equilibrium bin-volume by retreating into the marine-sediment wedge at the seaward end of the backbarrier, thereby reworking this sediment-wedge further landward (a landward shift of *AB* in Figure 3). The backbarrier bin volume tends toward equilibrium through this process since a reduction occurs in the width of Bin *A* if there is no sea-level rise. With rising sea level, the processes are similar, except that the reduction of the backbarrier accommodation due to barrier rollover is offset by flooding of the backbarrier and retreat of the inland shoreline of the lagoon. This tends to maintain the width of Bin *A*. Conversely, falling sea levels cause a seaward migration of all bin boundaries (*regression*). Seaward translation of the upper shoreface and shoreline (a coastal *progradation*) also occurs if $Q_{BC} - \Delta Q/\Delta y > Q_{AB}$ in the absence of sea level rise, or if the positive difference of this inequality is sufficient to offset upper-shoreface accommodation demand created by a rising sea level.

This rationale broadly follows the qualitative concepts of Curray (1964) on coastline displacement due to the combined effects of relative sea-level changes and sediment supply, which in a narrower sense underlies the Bruun Rule (Dean and Maumeyer, 1993); although neither includes an interaction with the lower shoreface. Where net sources or net sinks for sediment are absent, regression occurs in the case of a falling sea-level or emergence, and transgression occurs in the case of a rising sea-level or subsidence. A net source of sediment shifts the balance toward regressive behavior for any given change in relative sea level, whereas net sediment losses to a sink shifts the balance toward transgression. Swift (1976) extended this qualitative tract model by specifying sources and sinks in terms of alongshore or cross-shore processes. He related alongshore processes to deltaic sediment sources and estuarine sinks, while the cross-shore processes depended on the relative importance of storm and fair weather conditions.

COASTAL TRACT TEMPLATING

We introduce the idea of *coastal-tract templating* as a protocol that not only guides design of computer experiments, but also helps clarify just what is and what is not being modelled in any given application. The term templating was introduced recently as a formal approach that guides the configuring of a geological concept-model to a given data set in explaining coastal evolution for a specific site or region (Zhang *et al.*, 1997; Parsons *et al.*, in press). We prefer to define templating in an opposite sense, as the procedures involved in preparation of a data-model (*cf.* Rhoads and Thorne, 1996, p.127).

Modeling and analysis have always required preparation of a data-model, but hitherto this generally has been a subjective and tacit exercise. Templating therefore is unavoidable since site-specific morphology must be generalized into the form required by the particular tools used in prediction: a requirement relevant to coastal analysis on all scales. However, formal treatment of this step in modeling procedures has been lacking until now, with the consequence that ambiguity and disagreement has often surrounded modeling objectives, limitations, and interpretation of predictive results (*e.g.,* PILKEY *et al.*, 1993). Thus, recognition of templating as a formal step in any modeling (or analysis) exercise is more likely to guarantee that a) documentation of analysis and modeling methods includes an explicit statement of templating procedures, and b) coastal managers take scale-dependence into account when defining site-specific problems.

Definitions

We define the *data-model* as the product of synthesizing raw data into a structure that complies with the scale-specific form and properties (*e.g.,* dimensions and parameters) of predictive models applied to a given problem. Any practical exercise in modeling or analysis of low-order coastal change must begin with procedures to define the tract. These procedures involve templating the observations about a specific case (or coastal region) in nature onto a data-model that is of dimensional relevance to the modeling or analysis method to be applied. The coastal-tract cascade is the template that guides these procedures. More specifically, templating involves any procedures that a) distinguish boundary conditions from internal dynamics on a specific level (cascade templating), b) delimit the spatial extent of the coastal cell (cell templating), and c) transform the data set so that the tract has the same spatial dimensions as the predictive model and contains comparable variables or parameters (data-set templating).

Templating procedures must be performed in the order listed above. Transformation of the data set is pointless until the scale of interest has been specified, the associated morphodynamic (sediment-sharing) systems isolated, and the coastal cell identified. Cell templating follows completion of cascade templating because alongshore extent of cells generally differs at each level in the scale hierarchy: *i.e.,* lower-order systems tend to encompass larger cells. This tendency exists because the homogeneity assumption, upon which cell definition depends, becomes less restrictive at lower order. That is, with a greater the degree of aggregation, the spatial detail (in flow fields and morphology) is progressively averaged out (lumped together).

Cascade Templating

Cascade templating is undertaken to determine a) the level of aggregation, and b) which of the nested morphodynamic systems in the cascade hierarchy must be included in the analysis. Both considerations relate to the practical problem and management objectives (*e.g.,* long-term planning or short-term remediation). Selection of the predictive model also depends upon the analysis objectives. Thus, both the analysis objectives and properties of the predictive model form the templates for the cell definition and the data-model.

In the context of the predictive modeling procedures specifically, the purpose of cascade templating is to discriminate components of the system that can be regarded as boundary conditions from those we are forced to retain as internal system components. In principle however, each of the internal components of a sediment-sharing system on a given scale has nested within it the dynamics of all higher-order systems (Figure 4). Formal discrimination between which internal components are primary and which are nested higher-order systems involve aggregation issues that are yet to be fully resolved (see Discussion).

In practice therefore, a pragmatic approach is simply to define cascade relationships on the basis of the morphological-scale classification in Table 1. The specifics on how this should be done will vary from case to case (both by site and management focus) and depend upon the predictive model for which the templating is undertaken. Generally however, the result will involve spatial averaging of morphology and lumping of process details within a sediment-sharing system (Table 1).

Cell Templating

For simpler cases, cell templating follows well established conventions for the littoral-cell concept: *i.e.,* that natural cell boundaries coincide with points of convergence, divergence or topographic barriers in the littoral transport system (CARTER, 1988). Alternatively, arbitrary boundaries are established for the purposes of sediment budget analysis (usually for engineering or planning projects), often coinciding with administrative boundaries or notable landmarks that otherwise do not interrupt littoral transport (*e.g.,* GELFENBAUM *et al.,* 1999). For this type of cell boundary, the non-zero estimates of alongshore sediment fluxes must be obtained. In the context of the coastal tract, cells that have natural boundaries with respect to alongshore surfzone-sand transport are unlikely to have corresponding boundaries with respect to alongshelf sediment transport far offshore. So cell templating generally involves contrived boundaries to some degree.

The Homogeneity Assumption

Cell templating requires the assumption of alongshore homogeneity in morphodynamics. The assumption is more readily satisfied at lower order because of aggregation of morphodynamics implicit in the tract-cascade concept. The homogeneity assumption relies upon the absence of strong systematic variations in morphology and transport processes parallel to the coast. In particular, variation in alongshore sediment-transport gradients must be weak enough for the flux difference across the coastal cell to be regarded simply as a net gain or loss at the cell boundaries. If this is the case, then we can treat deltas and estuaries outside the coastal tract as exogenous sources and sinks. The nature of these sources or sinks does not matter: they could equally be anthropogenic or due to up-drift coastal erosion or down-drift shoreline progradation, respectively. At first approximation therefore, the existence and magnitude of a source or sink adjacent to the coastal tract is considered as an independent variable, forcing the first-order system: one of the *Sloss variables* referred to by THORNE and SWIFT (1991) and outlined briefly in Part 2.

An example of an alongshore source is that of a hypothetical outbuilding river-delta (Figure 5a), while an example of

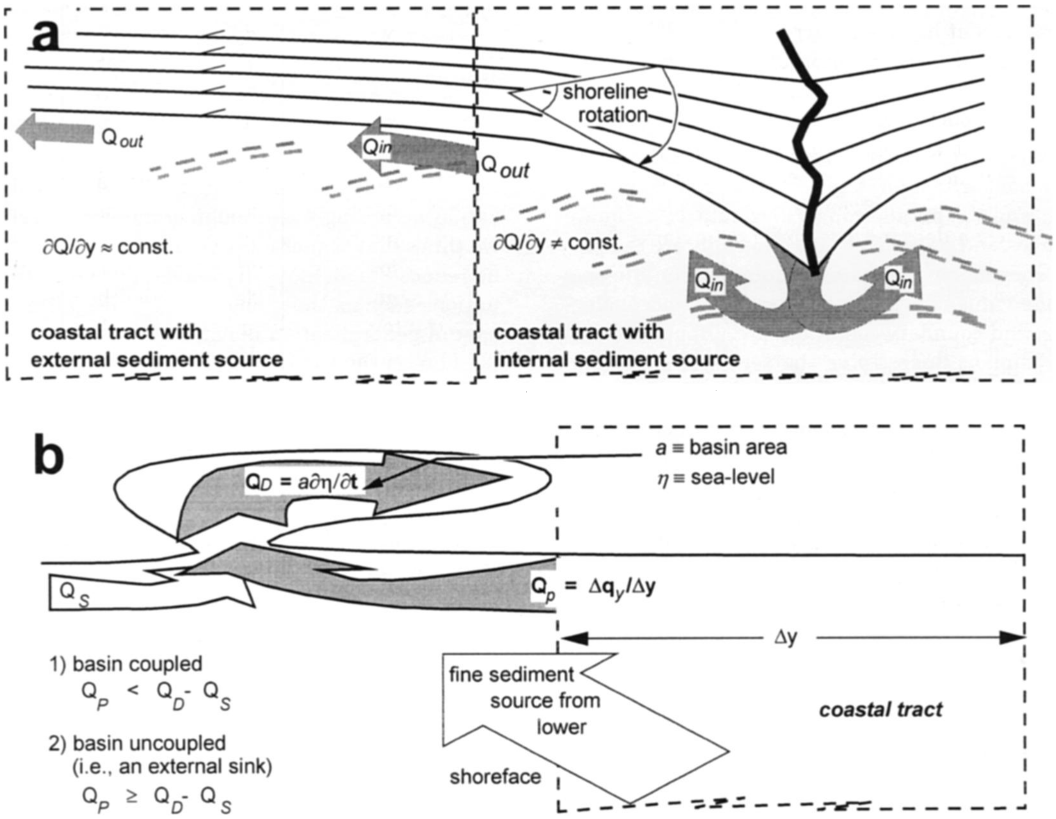

Figure 5. External and internal sources and sinks: a) Successive shorelines supplied by a river delta; and b) Estuarine basin as 1. dynamically-coupled sink, vs 2. external sink.

a sink is that of a hypothetical down-drift tidal basin providing accommodation space (or sediment volume demand, Q_D) due to relative sea-level rise (Figure 5b). The source is external for those parts of the coast where uniform gradients in littoral transport rates prevail ($\partial Q/\partial y \approx$ const.), causing parallel shoreline displacements (indicated by tick marks on successive shorelines in the left panel of Figure 5a). If the river sediment supply is greater than the littoral transport capacity, then shorelines will rotate (right panel, Figure 5a) and the wave-induced transport will be modified accordingly (*cf.* KOMAR, 1973). The source is then internal to the tract rather than an external forcing; so it no longer can be considered a Sloss variable. The tract and river delta co-evolve and are thus coupled.

The sink is external if the size of the sink does not effect the littoral transport rate within the tract: littoral transport represents a potential supply volume (Q_p) from the tract to the sink (Figure 5b). We adopt the model concept that the infill capacity per unit time (*i.e.,* Q_D) is proportional to the theoretical accommodation space of the basin. This proportionality is determined (empirically) by the deviation from an equilibrium between the tidal prism and basin volume relative to mean sea level (*e.g.,* WANG *et al.*, 1996). Homogeneity exists if $Q_p \geq Q_D$ since, under these circumstances, there is no tendency for the sediment demand of the sink to grow through time, and we may view the sink magnitude as a Sloss variable.

If the sink and source are coupled ($Q_p < Q_D$), the demand of the basin increases through time, which feeds back into Q_p through the effects of shoreline rotation: the sink-zone shoreline recedes more quickly than the source-zone shoreline, which in turn causes Q_p to grow due to increasing wave-incidence angles. The result is shoreline rotation and increasing alongshore transport gradients closer to the inlet (*i.e.,* $\partial Q/\partial y \neq$ const.). Under these circumstances, even if segments of coast containing the source shoreline and the estuary are geographically offset, they nevertheless constitute internal components of the same tract. That is, the two zones recede in unison so that the estuary effectively constitutes a backbarrier basin for the updrift shoreface. They are coupled intrinsically through their sediment sharing within a barrier rollover process (LEATHERMAN, 1983) on a tract width-averaged basis.

Two further complications exist. First, due to other littoral sources (Q_S), the effective demand imposed by the sink on the tract is reduced to $Q_D - Q_S$ (Figure 5b). Second, the sink demand also can be satisfied in part by supply of fine marine sediments resuspended on the lower shoreface (*e.g.,* WOODROFFE *et al.*, 1989) and transported toward the coast (Figure 2D). Since this direct exchange of fine sediments between the lower shoreface and the backbarrier can also operate in reverse, the linkage constitutes an internal coupling.

Data-Set Templating

Data-set templating involves (a) transformations of the tract and its dimensions into the same dimensional form as the predictive model or to allow the homogeneity assumption to be satisfied, and (b) distillation of the data to estimate values of variables and parameters used to calibrate the predictive model. Parameter estimates required from site-specific data include values for process parameters, morphological dimensions, and boundary conditions (*i.e.,* inputs and outputs such as sediment fluxes, plus the sea-level curve and energy inputs).

Transformations include spatial aggregation of processes and morphologies to suit the predictive model. Existing models for low-order coastal change (Part 2) are framed as a one-dimensional (1D) cross-shore profile (Figure 3). For the simplest cases in which alongshore homogeneity of processes and morphologies can be assumed in the coastal tract, spatial-aggregation generally involves a simple averaging alongshore of morphology, flow fields and sediment-transport rates. A cruder but common approximation is simply to take a representative, cross-shore transect through the tract. If the homogeneity assumption is strong, then such an approach is reasonable.

Transformation and aggregation of tract morphodynamics can be taken even further by representing the tract in a spatial (zero dimensional) form. For instance, the second-order system involving the tidal inlet, ebb and flood-tide deltas can be reduced to a representation involving only aggregate volumes for each of the morphological units and corresponding sediment-flux averages (STIVE *et al.*, 1998). These quantities can then be incorporated into the first-order system (*e.g.,* rates of sediment exchange between the shoreface and backbarrier complexes). This example illustrates that parameter-estimation aspects of data-set templating are closely related to the cascade templating.

DISCUSSION: UNRESOLVED ISSUES OF AGGREGATION

The concepts presented here on the coastal tract, cascade hierarchy and templating distil an epistemology implicit in our various approaches to modeling low-order coastal change (Part 2). Quantitative prediction for this type of coastal change (*i.e.,* on time scales of 10^2 to 10^3 years) has moved only recently beyond a simple Bruun-type analysis (DEAN and MAURMEYER, 1983). It is worth emphasizing that much of the controversy regarding that type of analysis, and coastal models in general (*cf.* PILKEY *et al.*, 1993; THIELER *et al.*, 2000), stems in part from the absence of a formal rationale on aggregation. Although we seek to address this problem, the issues run deeper than outlined in the previous sections. In particular, we are yet to resolve (a) adequate methods to deal with sites for which the alongshore homogeneity assumption cannot be justified (although work is in progress on this aspect), and (b) a comprehensive formalism for process aggregation down through the successive levels of the coastal-tract cascade.

Intractible Alongshore Heterogeneity

Cases for which alongshore heterogeneity cannot be ignored force us to increase tract dimensionality and require an unwelcome expansion in the level of model parameterization accordingly. Although from our collective experience we think that, under most circumstances, the data-model can be reduced to an alongshore-averaged cross-shore profile, situations such as those shown in Figure 5 illustrate that such spatial generalization is not always possible. Another example here is the Columbia Cell in NW USA (GELFENBAUM *et al.*, 1999), where a band of mud deposition running diagonally across the continental shelf northwest from the Columbia River mouth (STERNBERG, 1986) indicates a systematic along-shelf component of advection (idealized hypothetically in Figure 6). Major point-source rivers like the Columbia show an alongshelf logarithmic decrease in sediment accumulation rates, and also typically have alongshelf trends in both grain size (progressive fining with distance from source) and sediment structure (higher physical stratification close to source and greater bioturbation with distance) (NITTROUER and STERNBERG, 1981).

Such conditions require extension of the unit-width coastal-tract concept to provide a more general approach to mapping reality onto the data-model. Figure 6 schematically illustrates the problem: the river mouth corresponds to a divide in the net littoral transport of sand (indicated by the arrows). This transport varies in direction on shorter time scales (events to seasons), but there is a net direction to the flux over the long term (decades and longer). In this hypothetical case, estuaries exist with (Cell B) and without (Cell A) the complications of couplings referred to in the previous section.

Various possibilities for extending the unit-width coastal-tract concept are canvassed in Figure 6 for the different segments of coast. The equilibria and rates of change in segment labelled "A" can be analyzed along a simple cell-width-averaged offshore profile (Tract A). The effects of alongshore heterogeneity in the segment labelled "B" could be dealt with crudely by aggregating the river delta and Bay 1 into two separate sub tracts (Tracts B1 and B2) represented using two profile models: one to simulate progradation of the delta, and the other to simulate the recession caused by the sediment demand of Bay 1. We would need to couple the two profile models via their littoral sediment exchanges. These exchanges would depend on the relative displacement of the shorelines in the two sub tracts: the decreasing negative gradient in net fluxes away from the delta produces a shoreline rotation (*cf.* KOMAR, 1973). Thus, estimation of the sand exchanges would also require application of a shoreline model (*e.g.,* HANSON *et al.*, 2003, this volume) to simulate the effects of shoreline rotation on the wave field and littoral transport rates. As far as we know, a formalized hybrid model of this type is not yet available.

Both Tracts A and B assume that advective fluxes responsible for the fine-sediment band running diagonally across the shoreface can be ignored in modeling low-order behavior.

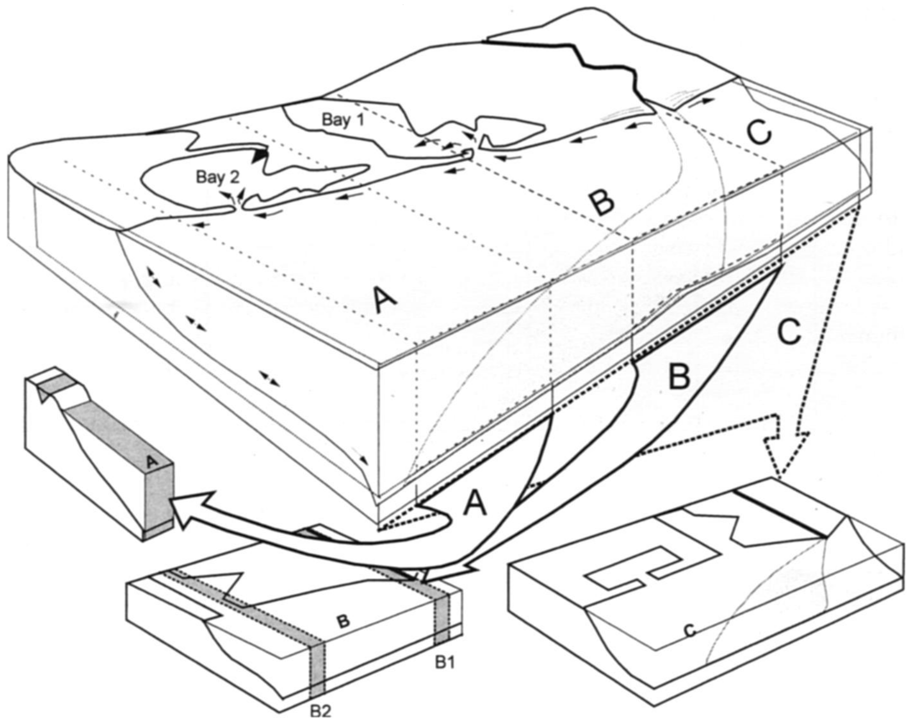

Figure 6. Extended coastal-tract generalizations for segments of coast a) without dynamic coupling between the shoreface and sediment sinks or sources, b) with time-dependent shoreline rotation due to alongshore variation in littoral transport, and c) with non-homogeneity in coast-parallel sediment transport due to advective processes on the shoreface.

If this assumption cannot be justified, then representation of the tract must include alongshore as well as across-shore components explicitly. Tract C in Figure 6 therefore would need to incorporate the entire length of coast. The processes responsible for the fine-sediment band involve deposition in water depths that vary systematically along the coast. Although the mud band looks discrete in Figure 6, in nature such deposits probably represent the modal track of otherwise stochastic plume dynamics. Unless we find some new trick for aggregating processes involved in this type of problem, we are stuck with the need to incorporate an undesirable amount of detail into modeling the low-order behavior. This is the case especially if we must include the shoreline-source/sink coupling as well. This type of problem is a subject of our ongoing research.

Aggregation Issues

Although we have mapped out the concepts and a pragmatic approach for defining the coastal tract to model low-order coastal change for any practical purposes (Table 1), the need to develop a formal aggregation theory for the tract remains. It is not enough to distinguish clearly between scales and orders of behavior within the cascade. We also must decide which higher-order effects constitute useful information. These effects need to be represented in some way at the next lower order: *i.e.,* the question is how to carry useful sub-scale information to the scale of interest. We have formal aggregation methods for some aspects of the coastal tract: *e.g.,* for the processes involving components of the tidal inlet and tidal basin (channels and flats) that have been aggregated and mapped onto the next low-order coupled shoreface-backbarrier behavior (STIVE *et al.*, 1998). We need however to formalise such methods for other aspects and levels of the tract cascade.

Adequate representation of sub-scale processes and effects requires application of a closure concept in aggregating processes into a simplified lower order model. This aggregation may be straightforward if we can assume that the dynamic interaction between higher and lower order processes is weak enough to be ignored, which may not always be possible. We have adopted the following viewpoints and definitions to schematize these aggregation concepts. By definition, the first-order system is a sediment-sharing coastal tract of such a spatial and temporal scale that its first-order evolution is determined by external boundary conditions and constraints alone. These external conditions are assumed to be known and to remain known on the time scale of the coastal change to be predicted. This implies that the integrated sediment mass balance of the first-order system is known. Note that the spatial and temporal scales of a first-order system depend upon site specific-conditions. To assess these scales requires a careful analysis of the system and in practice may require several iterations.

The internal dynamics of the first-order coastal tract are determined by the cascade of higher-order systems interacting within the first-order system (Figure 7). The concept

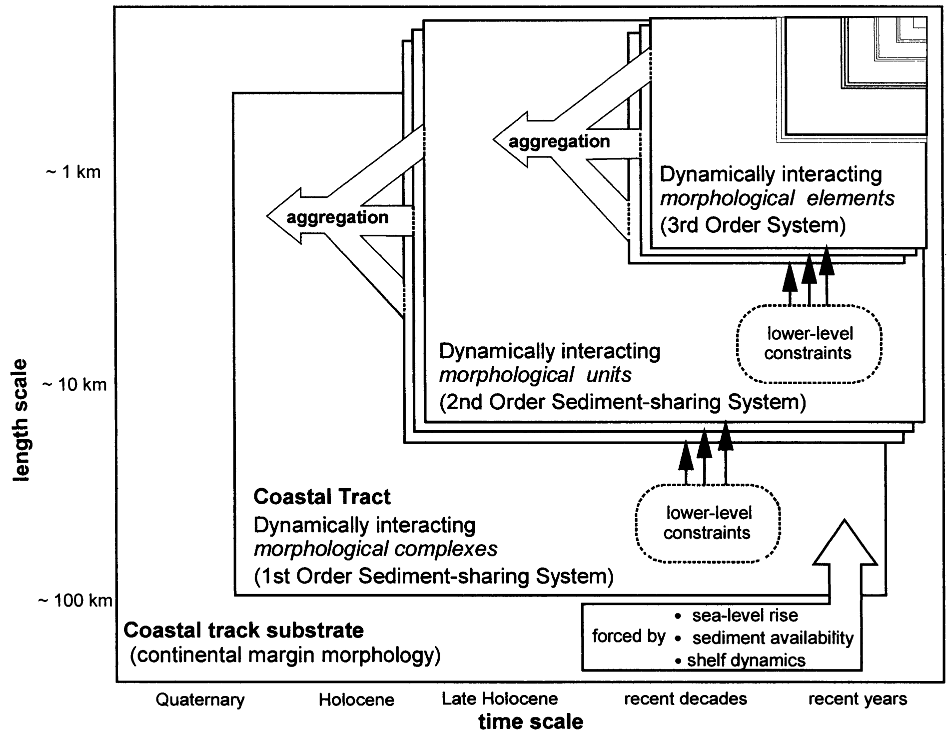

Figure 7. Nested systems of the coastal-tract cascade.

adopted here (*cf.* COWELL and THOM, 1994; DE VRIEND, 1998) is that the space and time scales of systems on each order are mutually coupled and confined, such that as the order increases the scales decrease (Figure 4). On larger space scales outside the dynamic interaction range, we find external conditions, while on smaller space scales we find 'noise'.

The first fundamental issue that we face is to define the order and scale of each higher-order system, including the boundary conditions and constraints that drive these systems. Commonly, a lower-order system will act as, provide or filter a boundary condition to the system on the next level up in the heirarchy (*i.e.,* one order higher). Ideally, multi-order systems have clearly different temporal and spatial scales at each level, so that we can discriminate between them. In spectral terms this implies that there exists a separation between their respective energy contents at the specific wave number and frequency ranges of their morphological features. In the less ideal cases, the different order systems have no clear spectral separation, which makes discrimination more difficult and sometimes arbitrary.

Morphological examples of ideal cases are wave- and current-induced bed ripples, which are known to be determined by local variables such as water depth, shear stress or mobility number and bed properties (NIELSEN, 1992). These higher-order dynamics can be separated through a local evaluation from a lower-order phenomenon such as shoreline and upper shoreface evolution due to alongshore-transport gradients. An example of a less ideal case are surfzone bars, which may interact with shoreline evolution, so that a separate evaluation is not obvious. In any specific case, higher-order effects that provide essential information to the lower-order scales must be identified.

The above reasoning implicitly suggests that we can describe the morphological state, behavior and identity of the system at each order over the full temporal scale of interest, given the external forcings and constraints. In practice, a complete description may not be possible due to a variety of limitations, such as lack of process knowledge, insufficient or uncertain information on the forcing, inherent unpredictable behavior, or practical limits such as insufficient computer power. Whatever of these limitations, either theoretical or practical, we still need to aggregate the knowledge of the dynamics of the higher-order systems into 'useful' information for the lower-order systems. That is, we need to find methods that allow us to sidestep theoretical and practical problems so that this useful information can be represented 'in some way' at the next lower order. Such pragmatism underlies the philosophy behind the behavior-oriented approach to modeling (STIVE *et al.*, 1995).

SUMMARY AND CONCLUSIONS

In an ideal world we would use knowledge of sediment dynamics based on first principles of physics to predict long-term change of shoreline position, in particular, and evolution of coastal morphology in general. Net sediment transport is, after all, the cause of all change in coastal morphology. Unfortunately we are unlikely ever to succeed with such an approach, for reasons that have been clear now for some time (DE VRIEND *et al.*, 1993; COWELL and THOM, 1994; DE VRIEND, this volume). We had at our disposal from the outset of this study, numerical tools (so-called behavior-oriented models) that provide an alternative approach to the prediction of long-term coastal change. These models encapsulate various elements of aggregated sediment dynamics and morphological behavior for coasts evolving over decades, centuries and millennia. What was lacking, however, was a systematic framework of where and how to apply these models, the relationships between the models themselves, and how each represents various aspects of low-order coastal behavior. Consequently, application of these models has required considerable expertise, but this expertise has been largely subjective.

We have addressed this methodological dilemma by devising three related concepts: (1) the coastal tract; (2) the coastal-tract cascade; and (3) coastal-tract templating. Implementing these concepts for any site-specific problem requires resolution of three issues:

(1) Distinguish which morphological features belong to which order, and discriminate their internal dynamics from external variables (cascade templating).
(2) Delimit the spatial extent of the coastal cell (cell templating).
(3) Transform the data set so that the tract has the same spatial dimensions as the predictive model and contains comparable variables or parameters (data-set templating), which involves
  (a) aggregation of higher-order dynamics into useful information for the lower-orders, which involves either a theoretical, or, if process knowledge is insufficient, a practical choice; and
  (b) mapping (representation of) the useful sub-scale information onto the scale of interest.

The practical benefits of these concepts for coastal management on time scales of decades to centuries are as follows.

- The *coastal-tract* concept provides a necessary framework for linking coasts in nature to predictive models. The concept does this by explicitly recognizing the fundamental modes of coastal change. This is a first and necessary step in prediction of low-order modes separately from higher frequency changes (*i.e.,* changes related to short-term disturbances such as storms or the evolution higher-order features such as surf-zone bars, dunes and tidal-channels). Characterization of low-order processes not only permits a physical explanation of long-term trends. It also places higher-order changes into an overall context. Apart from providing a more coherent basis for prediction of long-term change, recognition and understanding of coastal-tract behavior also should assist coastal managers to distinguish acute from chronic coastal-change problems, and to select more appropriate remedial or planning strategies in any specific case accordingly.
- The *coastal-tract cascade* formalizes concepts for separating coastal processes and behavior into a scale hierarchy, with the coastal tract as the most fundamental mode at the base of the hierarchy. The purpose of the cascade is to provide a systematic basis for distinguishing, on any level in the hierarchy, those processes that must be included as internal variables in modeling coastal change, from those that constitute boundary conditions (at lower-order), and yet others that may be regarded as unimportant 'noise' (at higher order). The criterion for internal variables is that they relate to features and processes that form a system sharing a common pool of sediment. Apart from its importance in guiding model application, the cascade concept discriminates between cause and effect on the basis of scale. This also should be a practical benefit for problem definition: *i.e.,* by explicitly separating components of the coastal-change problem, there should be less confusion and greater transparency concerning what is, and what is not being modelled (through adequate documentation of templating procedures and general recognition in coastal management that it is seldom possible to model or analyse all aspects of coastal change simultaneously).
- *Coastal-tract templating* provides a protocol for defining a site-specific problem (in coastal management, engineering or research). The protocol is a procedure by which data are interpreted or transformed into a *data-model.* The procedures give the data on the site (or region) the same structure and dimensions as the process model(s) to be used in predictive and explanatory simulations. The data-model thus defines the extent of coastline represented in any simulation-modeling exercise. It also defines the level in the cascade hierarchy that the modeling addresses. Templating procedures therefore generally involve spatial averaging (to reduce dimensions consistent with the process model), and identification of internal, external and unimportant variables (hence coastal-tract cascade templating). No universal recipe for templating can exist however, since each new problem requires its own templating. Because of this, scientific expertise remains an unavoidable requirement in coastal modeling, and the validity of modeling results remain contingent upon it. Although templating always occurs in a modeling exercise, albeit tacitly, formalizing these procedures as part of modeling protocols improves the rigor in coastal-change modeling overall: not least through recognition that templating procedures must always be documented in reporting modeling results.

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