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Sustainable Coastal Zone Management: A Concept for Forecasting Long-Term and Large-Scale Coastal Evolution

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ABSTRACT

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Climate change exerts pressure on the coastal zone by altering sediment supply from the hinterland and rising sea levels. Human activity affects the dynamics of the coastal zone as well. Both natural and human-induced changes in variables that govern coastal dynamics have a profound effect on the long-term and large-scale evolution of the coastal zone. In this paper, we introduce a concept that addresses the components relevant in sustainable integrated coastal zone management. We illustrate that quantifying sediment budgets in the coastal zone might improve our understanding of long-term (>100 y) coastal evolution. The increasing attention within sustainable coastal management on sensitivity analyses of climate change impacts and socioeconomic activities in the coastal zone implies an increasing demand of probabilistic scenarios of coastal evolution spanning a time interval of ~100 years. Within probabilistic scenarios of coastal evolution, the quantification of the coastal sediment budget cannot be discarded.

ADDITIONAL INDEX WORDS: *Coastal zone management, sediment budgets, coastal dynamics, coastal modeling.*

INTRODUCTION

Coastal areas are amongst the most heavily populated areas around the world and are the places of intensive economic development. At present, approximately 44% of the global human population lives within 150 km of the coastal zone (COHEN *et al.,* 1997). Population growth and economic pressure in the coastal zone will continue to increase not only in the near future, but also centuries from now. Especially in the light of projected global climate change (IPCC, 2007), it is of paramount importance to comprehend the long-term (decades to centuries) and large-scale (10–10^2 km^2) evolution of the coastal zone for sustainable coastal management and related coastal impact assessments. For instance, coastal authorities in the United Kingdom are faced with the need to forecast coastal evolution on a timescale of 100 years, and are required to present a sustainable "vision" of the coast (DEFRA, 2004). Within these sustainable visions, shoreline management plans are developed that are targeted at determining future coastal defense policies and strategic long-term planning of shoreline evolution. Forecasts of coastal changes and quantitative risk assessments spanning this time interval are the key requirements (BURGESS *et al.,* 2001). However, present coastal research still mainly focuses on forecasting coastal system evolution in response to changes in hydrodynamic processes and sea level on rather small temporal scales, *e.g.,* the tidal cycle. The overall trend or direction the coastal system evolves to on longer temporal scales can greatly affect and alter the impact of smaller-scale processes, but still little is known on how to account for changes in long-term system evolution. We aim to illustrate how geologic information from the (sub)surface combined with the quantification of sediment budgets helps in assessing the long-term trend of the coastal system. The long-term trend provides the boundary conditions for processes and system evolution on smaller temporal and spatial scales.

Furthermore, we will describe how the prediction of coastal changes can be enhanced when a holistic "source-to-sink" view is adopted. We define the coastal zone as the transitional region between land and sea within a sediment dispersal system (Figure 1). A sediment dispersal system is the natural unit in the source-to-sink view of earth–surface dynamics. It comprises an erosional basin in which sediments are generated (the source) and a sedimentary basin in which they are deposited (the sink). The recent trend in the earth-science community to consider earth–surface processes within a source-to-sink framework has been fuelled by the prospect of providing new insights into the responses of our planet to (anthropogenic) environmental perturbations (BROMMER, WELTJE, and KETTNER, unpublished data). This development is exemplified by the community surface dynamics modeling system (CSDMS, 2008), which is aimed at developing, supporting, and disseminating integrated software modules that predict the erosion, transport, and deposition of sediment and solutes in landscapes and sedimentary basins.

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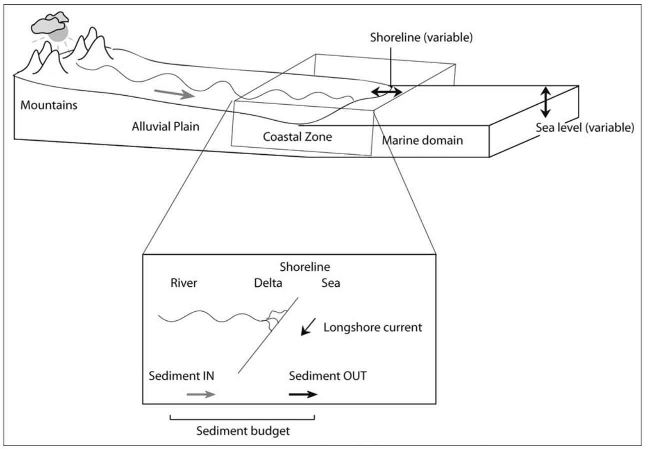

Figure 1. Illustration of the coastal zone as a component of a sediment dispersal system.

This paper is organized as follows. First, we will discuss how different scientific disciplines regard and study the natural system and which temporal and spatial domains form the focus of their research activities. Most disciplines involve the study of system evolution at specific predefined temporal and spatial scales. As a consequence, different research approaches as well as modeling techniques arise, which only can be applied to these often narrow bandwidths of temporal and spatial scales. Second, the role of sediment dynamics in understanding long-term coastal evolution is discussed. Several case studies are mentioned that illustrate the usefulness of sediment budgets in understanding and forecasting long-term system behavior. We introduce a conceptual framework in which the research topics of the different scientific disciplines are placed. Within this framework, we discuss the gaps in present coastal zone management activities. We will end with the conclusions and recommendations.

SCIENTIFIC DISCIPLINES AND THEIR VIEW ON THE COASTAL SYSTEM

Stratigraphic Community

Stratigraphers study the result of past sedimentary processes and conditions by analyzing the stratigraphic record. Data usually at hand to the stratigrapher include detailed analysis of the subsurface on the basis of sediment cores and seismic or electromagnetic interpretation (*e.g.,* high-resolution seismics and ground-penetrating radar), and numerical models to test hypotheses on sedimentary system evolution. Paleoclimate records are used to formulate the boundary conditions and associated uncertainties. The main objectives are to infer sedimentary system evolution from the stratigraphic record and relate the inferences to processes such as changes in climate, sea level, and sediment supply. However, several complications arise. First of all, the stratigraphic record is seldom complete (TIPPER, 2000). Second, the inability to scale inferred processes and mechanisms from a specific site up to larger spatial and temporal scales; third, sedimentary system evolution involves nonlinear and sometimes chaotic behavior (LORENZ, 1993: MEIJER, 2002; SMITH, 1998; WERNER, 1999), and finally, the problem of nonuniqueness, the notion that more than one model construction can produce the same output (ORESKES, SHRADER-FRECHETTE, and BELITZ, 1994), although this problem is well known in other disciplines as well.

A potential step to include is to predict the evolution of sedimentary (coastal) systems for the coming 100 years on the basis of a combination of knowledge of present-day processes and stratigraphic data with other types of (geological) information. To achieve such a goal, dynamic stratigraphic modelling could play a central role in linking the present processes to the stratigraphic record (BROMMER, WELTJE, and KETTNER, unpublished data; SYVITSKI and HUTTON, 2001).

Geomorphological Community

Geomorphologists study land forms, and more specifically, they are interested in how sediment is distributed within a system. From studying landforms, geomorphologists deduce process information.

Since the 1970s, emphasis in geomorphologic research shifted toward examining the mutual interactions and changes between landforms and the processes acting on these landforms. These processes are hydrodynamic or aerodynamic (or both) forces involving the motion of sediment, as they occur at different temporal and spatial scales. These processes are called morphodynamic processes (WRIGHT and THOM, 1977), or morphodynamics. Coastal systems are the result of the continuous adaptation between coastal morphology and water motion. This is called the morphodynamic loop (BEVEN, 1996).

It is, however, difficult to deduce process knowledge from merely studying forms, although this is often done. Also, geomorphologists reconstruct past environmental conditions by studying landforms. Whereas stratigraphers are primarily concerned with the subsurface, the geomorphologists are mainly focused on the earth surface. However, forecasting system evolution by studying landforms is difficult, especially on longer time- and spatial scales. Some attempts are made in this regard. Statistical techniques, based on data/measurements, are used to forecast system evolution (*e.g.,* bulk statistical methods such as the mean and standard deviation and also more advanced techniques such as empirical orthogonal function analysis). For a full discussion on statistical techniques and their use in forecasting system evolution, see, *e.g.,* LARSON *et al.,* 2003 and SOUTHGATE *et al.,* 2003.

Coastal Engineering Community

The coastal engineering community—as opposed to the stratigraphic and morphological community—focuses on the measurement and simulation of coastal processes on smaller spatial and temporal scales, *i.e.,* seconds to decades. Coastal engineers use the following methods to study the problem of interest: (1) small-scale measurements, usually laboratory experiments; (2) process-based numerical models, often calibrated on results of the laboratory measurements; and (3) behavior-oriented models. Given the impossibility to design one model that covers the wide range of processes operating at different spatial and temporal scales in the coastal zone, coastal engineers use different model approaches. Process-based models are useful for simulating the smaller-scale hydrodynamic processes, whereas behavior-oriented models are designed to cope with difficulties regarding the prediction of large-scale phenomena. These latter models do not take into account complete process knowledge, but rather use empirical relationships between system variables and, as a result, assumptions are made with regard to the governing processes. Another disadvantage of behavior-oriented models is the often crude spatial coastal schematization, which makes it difficult to evaluate the effects of, *e.g.,* smaller-scale coastal policy measures, such as beach nourishments on a local scale. Process-based models have, in general, a more sound scientific basis. This is mainly because small-scale processes are easier to measure and can often be simulated by means of laboratory experiments. A disadvantage is the restricted range of temporal and spatial scales over which they can be implemented (Bras, Tucker, and Teles, 2003). Furthermore, since the process of interest is isolated in laboratory experiments, interactions between processes and dynamic feedback mechanisms that do occur in nature are not accounted for (Haff, 1996). In addition, the geological framework and system boundary conditions are absent in the laboratory. Process-form interactions and transformations, however, all become more pronounced on larger scales (Wright and Thom, 1977). Also, processes that may be ignored at the small scale can have significant effects on the large scale and vice versa (de Vriend *et al.,*, 1993).

Present coastal engineering research still mainly focuses on forecasting system evolution in response to changes in hydrodynamic processes and sea level on small spatial and temporal scales. In consideration of long-term coastal morphodynamic predictions, the general objective of the coastal engineering community is to evaluate how coastal systems evolve over time in response to local changes in sediment transport due to human interventions such as the construction of groynes (small-scale) or breakwaters (large-scale) (for further references see Battjes, 2006). However, time in this perspective is limited to months and sometimes years because of the duration of modelling efforts (computer time) but also to the nonlinear and chaotic behavior of natural phenomena.

SCIENTIFIC DISCIPLINES AND THE PRIMARY SCALE RELATIONSHIP

In natural scientific research it is assumed that temporal and spatial scales are closely linked, so we can describe a process or phenomenon in terms of its characteristic scale (de Vriend, 1991). This direct coupling between the scales of processes and the scales of forms is called the primary scale relationship (de Vriend, 1991). The primary scale relationship assumes that processes operating on a certain scale level are in dynamic interaction with morphological behavior on a similar scale. This means that morphological behavior at a certain scale is mainly the result of processes operating at the same scale (de Boer, 1992; de Vriend *et al.,* 1993). The pri-

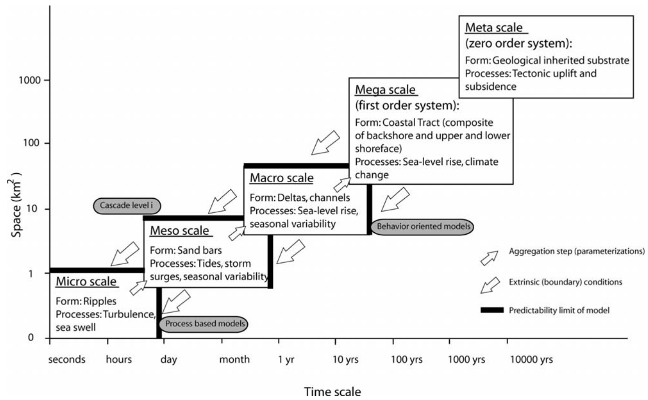

Figure 2. Coastal tract cascade (after Cowell *et al.,* 2003).

mary scale relationship assumes that processes operating at a smaller scale than the scale of interest can be considered as noise, whereas the larger scale processes impose the boundary conditions to the scale under consideration. Hence, it is assumed that there is no dynamic interaction between processes and behavior at different scale levels. The primary scale relationship reflects a hierarchy structure in morphological systems: every morphological system consists of and physically contains a hierarchy of ever-smaller, higher-level systems (intrinsic conditions). The system, however, is at the same time part of a hierarchy of ever-larger, lower-level systems (extrinsic conditions, Cowell *et al.,* 2003; de Boer, 1992; Malanson, 1999). In a hierarchy, a higher- and a lower-level system are linked by an exchange of matter or energy.

Recent developments in the field of coastal research, on the basis of the assumption of a hierarchy structure in coastal morphological systems, were made by Cowell *et al.* (2003), who introduced the "Coastal Tract" as a framework for the aggregation of processes in the modeling of low-order, *i.e.,* large-scale, coastal change. This framework is based on Wright and Thom (1977) and altered by Terwindt and Battjes (1990). The Coastal Tract Cascade (Figure 2) provides a framework for separating lower-order coastal change from morphodynamics on smaller scales. The Coastal Tract, the largest compounded morphological feature, forms the first-order level in this hierarchy structure, which is constrained by the zero-order system, *i.e.,* tectonic movements and the geologically inherited substrate. Each level in the hierarchy sees the lower levels as boundary conditions and the higher levels as intrinsic processes. At successively higher levels in the hierarchy, these intrinsic processes lose their relevance to the level of interest and may be treated as 'unimportant' (noise) or must be generalized (parameterized) for representation at the scale of interest. The coupling between the different scales—and, hence, the coupling of different morphological models—in this approach is still not thoroughly understood.

Authors such as Church (1996), Phillips (1992), van Vuren (2005), and Werner (1999) doubt the tenability of the primary scale relationship, since most natural systems exhibit features of dynamic and stochastic behavior. Dynamic systems can be extremely sensitive to perturbations (slight changes in initial conditions), which results in a completely unpredictable solution, known as deterministic chaotic behavior (PHILLIPS, 1992). This implies that the aggregation or upscaling of small-scale processes is not suitable for predicting large(r)-scale morphologic evolution, which is commonly used in modeling practices. A promising morphodynamic updating technique to bridge the gap between short-term hydrodynamic changes (daily timescale) and long-term morphodynamic (yearly timescale) behavior is discussed in ROELVINK (2006), who presents a highly dynamic case of the evolution of a tidal inlet to a complex geometry with an intricate pattern of channels and shoals. Further work remains to go from a yearly timescale to a decadal scale.

The discussion on different (coastal) scientific disciplines illustrates that each discipline focuses on certain aspects of system evolution and hence on a certain temporal and spatial scale domain of coastal evolution. Each discipline is confined by its theoretic consideration, in which a holistic approach is lacking. In the scope of sustainable coastal zone management, merely upscaling of small-scale process knowledge will yield unrealistic results, as well as omitting the geologic trend, which covers spatiotemporal scales even larger than that required for coastal management planning horizons.

SEDIMENT DYNAMICS AND LONG-TERM COASTAL EVOLUTION

River sediments are the source of 80% to 90% of beach sand (SUMMERFIELD, 1991). Supply-dominated coastal areas are able to prograde during times of rising sea level, provided that the input of sediment in the coastal zone is sufficient to keep pace with sea-level rise (MCMANUS, 2002). This is, for instance, illustrated by the evolution of the Italian shoreline surrounding the Po Delta area in the Adriatic Sea (NELSON, 1970; STEFANI and VINCENZI, 2005) and the Kura Delta in the Caspian Sea (HOOGENDOORN *et al.,* 2005).

Changes in sediment fluxes and patterns to the coastal zone may alter the stability of the shoreline (COLEMAN and WRIGHT, 1971). Previous observations reveal that shoreline erosion and reduction in (suspended) fluvial sediment supply are closely related (FRIHY, DEWIDAR, and EL BANNA, 1998; LIQUETE *et al.,* 2004). Human activities affect sediment production, transport, and storage in the river basins and influence thereby the fluvial sediment flux from source to basin (SYVITSKI *et al.,* 2005), which might not be noticeable in the short term, but has profound effects in the long term (NELSON, 1970). Still, little is known *to what extent* humans interfere with the natural system (LARCOMBE, 2007).

According to SYVITSKI *et al.* (2005) the net global reduction in sediment flux to the coastal zone is ~1.4 BT/y over prehuman loads due to sediment retention behind dams. YANG, ZHAO, and BELKIN (2002) demonstrated that decadal river sediment discharge and suspended sediment concentrations of the Yellow River (China) had reduced by 34% and 38%, respectively, between the 1960s and 1990s. The decreases of these numbers have been assigned to a combination of dam and reservoir constructions. GIOSAN *et al.* (1999) reported a 45% decrease in sediment discharge of the Danube River due to river engineering improvements and dam construction. As a consequence, the shoreline of the Danube Delta in the Black Sea is presently eroding at rates of 20 m/y. In the Ebro Delta, Spain, retention of sediment behind dams has led to sediment starvation along the seaward margin (MCMANUS, 2002). In addition, coastal erosion occurs because of the wave-driven longshore current that carries the available sand-sized sediments dispersed by the river Ebro alongshore at a high rate (SANCHEZ-ARCILLA, JIMENEZ, and VALDEMORO, 1998). In the Netherlands, it is estimated that the off-shore Dutch coast requires roughly 6 million m^3/y of sand nourishments to maintain the upper shoreface between −6 m and +3 m NAP (Dutch mean sea level) with the present rate of relative sea-level rise (ELIAS, 2006; MULDER, 2000). The largest sand losses are observed along the coast adjacent to the Texel Inlet where the effects of the closure of the Zuiderzee are far from damped out (ELIAS, 2006).

Another example from the Netherlands shows that the current sediment deficit in the diked lowlands of the Netherlands is estimated at 136 ± 67 million m^3/y (VAN DER MEULEN *et al.,* 2007). About 85% of this volume is the hypothetical amount of sediment required to keep up with sea-level rise, and 15% is the effect of land drainage (peat decomposition and compaction). These examples suggest that many coastal areas around the world receive too little sediments to keep pace with sea-level rise. As a result these coastal areas erode at an alarming pace. To prepare a long-term vision that incorporates the natural dynamics of the sediment dispersal system we propose to strive to (1) better understand sources and sinks in the sediment dispersal system on different spatial and temporal scales; (2) quantify within the coastal zone the actual need for sediments to determine the sediment budget of the sediment dispersal system; and (3) link the sediment budget to (decadal) shoreline behavior.

Sediment Budgets

The sediment budget concept provides a valuable framework for the quantification of sediment mobilization, delivery, storage, and output at the catchment scale (DIETRICH and DUNNE, 1978), and at a (sedimentary) basin scale (Figure 1). The sedimentation capacity of a site is defined as either the amount of space available for sedimentation or the amount of space from which sediment can be released into transport by erosion. Sediment budgets can be used along with measurements of sediment delivery pathways to determine systematic variations in sediment sources that occur with changes in basin area (PRESTEGAARD, 1988). Establishing a sediment budget provides a means of clarifying the link between upstream erosion and downstream sediment yield and the role of sediment storage effecting nondelivery of sediment at basin outlets (WALLING, 1983, 1999).

The quantification of the coastal sediment budget helps determining sediment sources and sinks (or supply and dispersal) to and from the coast, and offers a quantitative understanding on coastal dynamics in response to changes in sea level and sediment supply. The sediment balance, which is the difference between sediment input to and sediment output from a unit area over unit time, must ultimately be zero. However, in most real-world examples the balance is not zero and this introduces a powerful property of the approach (SLAYMAKER, 2003). A nonzero sediment budget implies that the area defined by the budget must be either eroding or depositing. Consequently, SLAYMAKER (2003) argues that those timescales at which the sediment budget is either negative or positive can indicate the timescales associated with landform change within that system.

MISELIS and MCNINCH (2006) used this approach and were able to link changes in near-shore sediment volume to shoreline change and found that the geologically defined near-shore sediment volume is a useful predictor of decadal shoreline behavior for the northeastern Outer Banks (North Carolina). Other studies have shown a variety of methods on the quantification of the Holocene coastal sediment budget (KELLEY *et al.,* 2005; LOCKER, HINE, and BROOKS, 2003; SCHWAB *et al.,* 2000). These studies, however, did not yet link sediment budgets to shoreline changes.

Modeling of Sediment Supply

Knowledge on rates of mass transfer from source to basin on geological timescales is essential for stratigraphic as well as geomorphologic modelling (LEEDER, 1997; PAOLA and SWENSON, 1998; WELTJE, MEIJER, and DE BOER, 1998). However, long-term records of mass transfer from source to basin are scarce (KETTNER and SYVITSKI, 2008). Therefore, a lot of effort has been put in developing hydrological transport models that enable the prediction of sediment flux and discharges of global rivers (MOREHEAD *et al.,* 2003; SYVITSKI and ALCOTT, 1995; SYVITSKI *et al.,* 2005). The climate-driven hydrological model BQART in conjunction with the model HydroTrend, for instance, provides a powerful tool for generating synthetic water discharges and sediment load records at the river outlet (KETTNER and SYVITSKI, 2008; SYVITSKI and MILLIMAN, 2007). The predictive capabilities of the model BQART/HydroTrend have been demonstrated in a series of tests on modern rivers (KETTNER and SYVITSKI, 2008; SYVITSKI *et al.,* 2005). In addition, BQART/HydroTrend has been used to simulate the liquid and solid discharge where observational data are limited (KETTNER and SYVITSKI, 2007), or to evaluate human impacts on suspended sediment loads of rivers (SYVITSKI *et al.,* 2005). Recently, BQART/HydroTrend has also been used in reconstructions of basin-fill histories (KUBO *et al.,* 2006; OVEREEM *et al.,* 2005). However, the performance of BQART/HydroTrend over long timescales (20,000 y) has been formally evaluated by BROMMER, WELTJE, and KETTNER (unpublished data) by means of a data-model comparison in the closed Adriatic Basin, Italy, using the principle of mass balance. The authors demonstrated that simulations of the BQART/HydroTrend model are in agreement with the quantity of sediment derived from the stratigraphic record, yet only for the time interval covering the past 5500 years. Beyond this time interval, the data-model comparison does not satisfy the principle of mass conservation, mainly because of the erosive nature of critical bounding surfaces of the stratigraphic units.

In the scope of an integrated coastal management approach, the use of hydrological models that generate sediment loads and discharges for past and future time intervals can be important. Simulated sediment loads of the past can be matched to the stratigraphic record of the coastal zone to obtain sediment budgets with an estimate of the bandwidth in which these simulations fall (BROMMER, WELTJE, and KETTNER, unpublished data). Interpretation of the stratigraphic record therefore provides useful information to past coastal settings, and can also help us to understand present and future changes in the environment. Calculating sediment budgets for a given coastal area and integrating these budgets in forecasting long-term evolution provides a quantitative framework to estimate the future amount of space, and determine future areas of sediment loss (erosion) and sediment storage (deposition) in the coastal zone. Since the stratigraphic record contains the results of sediment transport processes over time periods long enough to distinguish mean depositional trends from fluctuations associated with storms and other unpredictable occurrences, stratigraphic knowledge should be incorporated into (numerical) models to predict future coastal evolution records (STOLPER, LIST, and THIELER, 2005).

Summarized, in integrated coastal zone management, the incorporation of geological knowledge and large spatial and temporal scales in morphodynamic predictions is still underexposed. Yet, geological and morphological knowledge offers great potential to enhance the predictive capability of numerical models, a key tool in river, estuarine, and coastal management (DE VRIEND, 2004). Bringing together information from both domains requires a multidisciplinary approach, and hence the development of a common language.

DISCUSSION

The role of the different communities, their research objectives, and their temporal and spatial research domain are indicated in Figure 3, on the basis of VAN DER BURGH and BROMMER, 2006. The "integrated coastal model" illustrates the gaps in coastal research activities and planning activities in the framework of sustainable coastal management. Fluvial processes (hinterland characteristics), changes in sediment budget (sediment transport processes), and human activities are at present omitted in forecasting long-term, large-scale coastal changes and are therefore indicated with a cross. The mega scale (tectonic movements and the geologically inherited substrate) provides the boundary conditions for the processes that govern changes in the coastal zone. Process-based and behavior-oriented models in conjunction with global climate change models and sea-level rise scenarios are used to simulate future coastal development (present approach in coastal research [Figure 3]). Focus should not only be on sea-level rise scenarios but also on changing sediment supply scenarios, hinterland characteristics, and socioeconomic activities in and around the coastal zone.

Natural *vs.* Social Systems

Assessing human impacts on the natural system is hindered because of a different notion of scale in the socioeconomic sciences. In the natural sciences, choosing a scale level at which phenomena are examined refers to time and space.

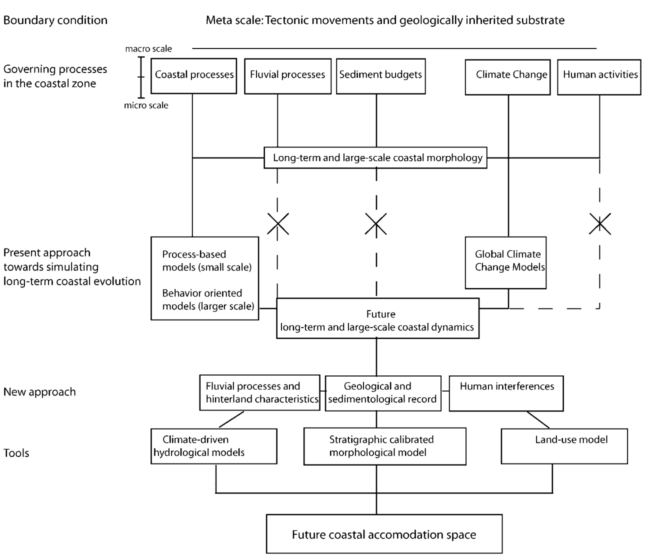

Figure 3. The integrated coastal model. A multidisciplinary integrated approach to enhance future coastal development scenario-building (modified from: van der Burgh and Brommer, 2006).

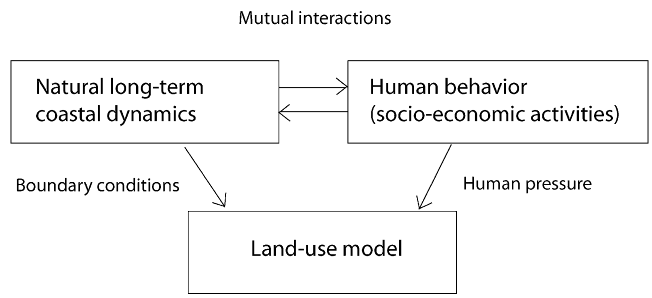

Figure 4. Coupling the natural long-term coastal evolution to a land-use model (from van der Burgh and Brommer, 2006).

Scale in socioeconomic research, however, has a more abstract meaning and can often not be expressed in terms of temporal and spatial units. Therefore, assessing the impacts of socioeconomic processes remains a difficult and ambiguous task, since this requires a thorough understanding of human behavior. In addition, motives of people change rapidly, so forecasting human behavior and associated socioeconomic changes on long timescales are surrounded by great uncertainty. At present, models to simulate the effects of human interferences are poorly developed. Different techniques have been developed to express socioeconomic processes in spatial entities. One of such techniques is agent-based modeling (ABM). Another technique to express socioeconomic changes are land-use models, which simulate the effects of people on nature and landscape. For instance, spatially detailed land-use maps of the Netherlands for the year 2030 have been constructed by DE NIJS, DE NIET, and CROMMENTUIJN (2004), in which the effects of different national economic and demographic scenarios were taken into account. However, present land-use models do not take into account the mutual interactions between the natural and socioeconomic systems (Figure 4).

Linking Human Impact to Natural Coastal Dynamics

Both ABMs and land-use models are promising tools for assessing socioeconomic impacts in time and space and they may produce output that can be linked as probabilistic model input to *natural* morphodynamic predictions. How to link the socioeconomic/human system to the natural (long-term) system remains a challenging question. The problem of linking natural and social systems is widely acknowledged (NICHOLLS and KLEIN, 2005). So far, most social research in densely populated deltas and coastal zones has focused on socioeconomic changes in isolation from the natural system. Ideally, we should have a means to quantify the human impacts in the coastal zone. The quantification of changes in the coastal sediment budget is a potential approach to enhance forecasting of coastal evolution, which is illustrated by ELIAS (2006). The author demonstrated that for the western Wadden Sea (the Netherlands), the sediment deficit after closure of the Zuiderzee is still at least 5 to 6 million m^3/y to obtain an equilibrium. Sediment budget studies such as these underscore not only the importance of understanding how human impacts alter the natural dynamics of the coastal system, they also quantify the actual sediment need in the coastal system.

Morphodynamic Forecasts

Studying past coastal behavior provides data sets upon which numerical models can be calibrated. It is often possible to reconstruct coastal development by means of historical maps and documents (MCMANUS, 2002; NELSON, 1970). When compared with present-day digital elevation or terrain models, volumetric changes of the coastal area over a certain time interval can be calculated. This 'historic' result can then be compared with volumetric changes determined by means of numerical modeling. SHA (1989) quantified the evolution of an ebb-delta complex (Texel Inlet, the Netherlands), which enabled comparison with reconstructions from historical maps (SCHOORL, 1973). CORREGGIARI, CATTANEO, and TRINCARDI (2005) estimated the volume of several off-shore delta lobes of the Po River, and compared their evolution with historical data. These are promising results, and suggest that if both estimates are in reasonable agreement, we may use the outcome to estimate a future budget as a result of changes in hinterland, sea level, or human interferences.

Uncertainties

Forecasts of natural and social dynamics (and their mutual influence) are surrounded with great uncertainties. We propose the construction of long-term probabilistic scenarios as one of the means to deal with these uncertainties and variability. Probabilistic scenarios provide a range of morphodynamic states. These scenarios can lead to answers on how future social and natural changes affect the development of the coastal zone that accommodates a variety of activities that are valuable in environmental and economic perspectives. Quantitative modeling of this interaction at all relevant scales is therefore needed.

CONCLUSION

In this paper, we have illustrated the importance of integrating different types of scientific information in forecasting long-term coastal evolution. The combined use of numerical models simulating sediment supply (BQART/HydroTrend) and stratigraphic information to estimate sediment budgets may provide a useful calibration technique for forecasting system evolution. The impact of human activities on long-term coastal evolution should as well be accounted for. Different disciplines adopt different theories, which are restricted to a certain temporal and spatial domain. We should aim to integrate these different types of information in the scope of sustainable coastal zone management. Rather than striving for a single-valued prediction, we should aim for providing probabilistic scenarios on coastal evolution in which relevant components contributing to uncertainties have been properly analyzed.

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