THREE-DIMENSIONAL NUMERICAL MODELING OF DELTAS

IRINA OVEREEM, JAMES P.M. SYVITSKI, AND ERIC W.H. HUTTON
Environmental Computation and Imaging Facility, INSTAAR, University of Colorado,
Campusbox 450, Boulder, Colorado 80309, U.S.A.
e-mail: irina.overeem@colorado.edu; james.syvitski@colorado.edu; eric.hutton@colorado.edu

ABSTRACT: Deltaic systems are controlled by a complex interaction of sediment supply, accommodation, and coastal energy, each varying in time and space, making three-dimensional study necessary. Numerical simulation models of such complex systems are thus required to be 3D. This paper evaluates the state of 3D delta modeling and demonstrates that existing forward simulation models are still too limited to be applied to the full range of deltaic environments. Floodplain dynamics, as well as longshore transport, are generally lacking in present models. Many models lack the capacity to deal with multiple grain-size classes.

Two advanced 3D models, AquaTellUs and 3D-SedFlux, illustrate how quantitative theoretical experiments provide insight into the dominances of processes acting and the evolution of a fluviodeltaic system. Depositional architecture and coastal progradation patterns depend strongly on the frequency of channel switching. Results from the AquaTellUs model suggest that channel switching may be an even more important control than the rate of change of sea-level fall.

To further develop predictive 3D sedimentary models there is a need for field-test cases with quality input data, and with estimates of their associated uncertainties. Furthermore, process descriptions require efficient quantification and appropriate scaling. Only then will numerical models be able to address the responses of complex delta systems to specific forcing variables.

INTRODUCTION

The purpose of this paper is to review three-dimensional numerical forward models of siliciclastic systems capable of simulating deltaic systems. Below we outline the basic process modules that a delta model needs to incorporate and compare this model architecture to existing 3D models. We show two examples of model experiments using AquaTellUs and 3D-SedFlux. Finally, the paper discusses the future of three-dimensional modeling of deltas.

A delta is “a discrete shoreline protuberance formed where a river enters an ocean or lake, it has a broadly lobate shape in plan view narrowing in the direction of the feeding river, and a significant proportion of the deposit is derived from the river” (definition is adapted based on Elliott, 1986; Bhattacharya and Walker, 1992; and Bhattacharya and Giosan, 2003). This implies that deltas are influenced by a variety of fluvial and marine processes and thus several sedimentary sub-environments are normally present (Bhattacharya and Walker, 1992).

The internal depositional architecture of deltaic systems is controlled by a complex interaction of three important factors: (1) sediment supply: reflecting drainage characteristics, water discharge, and sediment load (i.e., grain size and suspended-sediment concentration), (2) accommodation: reflecting sea-level fluctuations, offshore slope, tectonics, subsidence, compaction, and isostasy; and (3) coastal energy: waves and tides, longshore and cross-shelf transport (Coleman and Wright, 1975; Orton and Reading 1993; Postma, 1995).

Deltas are an obvious candidate for numerical modeling for several reasons. Firstly, direct experimentation on deltas is impossible because of their large spatial and temporal dimensions, yet we need to know how large engineering projects like dam construction will change the morphology of the associated delta. Delta models should aid in long-term floodplain and coastal-zone management, especially in view of a changing global climate. Secondly, the sedimentary record of deltas is intrinsically complex, making it difficult to infer the development of stratigraphy. The complexity is due to the variety of interacting processes, and the fact that deltaic systems are bypass zones, where only a portion of the sediment that travels down a river is retained. The record of the coastal zone is subsequently strongly modified by erosion and redeposition by storms, waves, and fluvial incision. River channels and delta lobes switch their location over time, leaving deposits in different locations. The incentive for understanding the resulting deltaic sedimentary architecture is that it facilitates the modeling of oil-, gas-, or groundwater-bearing reservoirs. Thirdly, numerical simulation models allow at least indirect experimentation on the influence of forcing functions and boundary conditions. Numerical models can create a quantitative stratigraphic framework that can be tested and used as a predictive tool (Watney et al., 1999). Numerical models are a quantitative expression of our ideas about the way things work. They induce sharp questioning in order to rule out apparently plausible scenarios or to uncover unanticipated scenarios (Howes and Anderson, 1988; Cross, 1989; Watney et al., 1999; Paola, 2000).

The classic concept of fluviodeltaic systems is largely twodimensional. The 2D nature is inherent in the name “delta Δ”. Herodotus projected the Greek character delta, Δ, to describe the plan-view geometry of the fluvial and coastal plain of the Nile. Classification of deltas has been based on 2D plan-view geometry (Galloway, 1975; Coleman, 1976) without taking into account long-term dynamics and the evolution of deltaic systems.

Present cross-sectional 2D numerical fluvial–deltaic models capture the basic longitudinal patterns of deposition, but they cannot describe lateral heterogeneity of the deposits, such as the lateral bypassing of sediment that would result from delta-channel switching. They often simulate a monotonous coarsening-upward sequence in a 2D deltaic setting and neglect the distinction between lobe and interlobe deposits.

Different regions of the same depositional system can be differently affected, so three-dimensional study is necessary. Even within a single delta system, the relative influence of the forcing factors can vary both spatially and temporally. For example, the San Juan River delta is differentially influenced by river discharge, wave action, and tides at its outlets (Restrepo et
al., 2002). Similarly, the northern part of the Danube delta is wave-dominated system, whereas the southern part is discharge-dominated (Bhattacharya and Giosan, 2003). The depositional architecture resulting from these varying processes can be fully recorded only in three dimensions.

**TYPES OF NUMERICAL MODELS**

In this paper we will focus on “process-imitating forward modeling”. We do not talk about interpretive 3D models, such as based on 3D seismic data, GPR surveys, or well logs. Those models are more or less geometrical and describe “how things are”, and not “how things work”. Koltermann and Gorelick (1996) introduced the very useful terms “structure-imitating” models versus “process-imitating” models. It is the latter which simulate the sedimentary evolution of a delta system through time that we discuss.

Another distinction in types of models is directionality: forward or inverse. Forward models start at some point in time and simulate the subsequent development, whereas inverse models reconstruct the sedimentary evolution backwards on the basis of a given state. Inverse models can be extremely useful if we want to constrain the sedimentary evolution by data, e.g., the simulation model generates a host of possible scenarios based on certain core information. The inverse modeling technique is not yet used for three-dimensional models, so that the following discussion is restricted to forward simulation models.

Every model is by definition a simplification. However, models operate on a sliding scale of complexity from using simple rule-based process descriptions to empirical equations to physics-based descriptions. Oversimplification is an imminent danger; applied rules can be intuitive guesses. The use of empirical equations can be problematic if the physical basis is unknown. Those equations are based on the behavior of modern-day systems, but their applicability to ancient systems may not be justified. On the other hand, comprehensive physics-based description of many sediment transport processes is not established; the flow dynamics over a floodplain during floods is a well-known example. Another aspect that defines the complexity of a model is the degree of coupling. To model a range of environments requires coupling, as in a delta coupling of the complexity of a model is the degree of coupling. To model a range of environments requires coupling, as in a delta coupling of the flow dynamics over a floodplain during floods is a well-known example. Another aspect that defines the complexity of a model is the degree of coupling. To model a range of environments requires coupling, as in a delta coupling of the

**THE IDEAL DELTA MODEL ARCHITECTURE: WHAT NEEDS TO BE MODELED?**

Forward numerical models commonly consist of three components: input, engine, and output (Watney et al., 1999). Elaborate delta-classification schemes identify the important controls for delta development. A large number of processes are of secondary importance, like biological feedbacks or eolian transport, and are considered important for specific deltas but less so for a global framework. These two organizing principles provide us with an idealized model architecture (Fig. 1).

**Input and Boundary Conditions**

**Sediment Supply.—**

A delta does not exist without the discharge and the sediment supply from a river, but these are not constant over time. Field studies show that discharge and sediment supply are not constant, and this variability is a major control on depositional architecture in deltas (e.g., Hori et al., 2001; Overeem et al., 2001). It is emphasized that modest shifts in average climate conditions (i.e., 1 to 2°C; <20% precipitation; Knox, 1993) have large impacts on the behavior of the flood response and consequent sediment yield of a river (Faul, 2001). Across longer geological periods, an increased monsoonal regime, for example, may cause the flux of sediment to vary by a factor of 2.5, as occurred in the Ganges–Brahmaputra River during Early Holocene (Goodbred and Kuehl, 2000a, 2000b).

It is critical to capture the rare high-energy but commonly short-lived events that carry and disperse most of the sediment (Vogel et al., 2003). The timing and magnitude of river floods may determine the importance of sediment supply. For example, the Brazos delta would not even be a delta if decadal floods did not supply large amounts of sediment to the delta and cause significant progradation (Rodriguez et al., 2000). In 1977 the Eel River, California, had an extreme flood in 1965, which carried more sediment to the ocean than it had in the preceding or following eight years of discharge (Syvitski and Morehead, 1999).

In 1977 the Eel River had an average sediment discharge of 0.6 kg/s, and in 1965 the mean sediment discharge increased to 4838 kg/s, providing a five-orders-of-magnitude increase. The time step of a numerical model should therefore match the frequency of important delivery events.

A complete delta model must also incorporate several grain sizes (Orton and Reading, 1993). Sediment grain size has impor-
tant consequences for both the delta-plain gradient and channel morphology. Sediment originating from longshore transport can also be important. The sediment can be derived from great distances; for example, Amazon-sourced sediment influences the Orinoco delta located ~1600 km farther north (Aslan et al., 2003).

**Accommodation.**—

The most obvious boundary condition relating to accommodation is the initial model space. Each forward simulation needs some sort of conditioned volume to start with. When erosion processes are dominant, the initial volume needs a realistic distribution of subsurface architecture and grain sizes. This implies that even when a case study is focused on a specific time interval, data on the previous time intervals are essential. Ideally, the initial state is provided by a known surface, such as a seismic reflector penetrated by cores to provide information on architecture and grain size. In practice, numerical models are often initialized with idealized surfaces and equal grain-size distributions. Another common strategy is to “self-initialize” the model; the model is run for some time to reach equilibrium conditions and to build its own volume of sediments. Only after this self-initialization does the actual run start.

Any framework of delta modeling needs to handle a time-continuous base-level curve and calculate variable coastline positions. Distinctly different patterns of delta development have been related to base-level changes (Bhattacharya and Walker, 1992; Postma, 1995; Kroonenberg et al., 1997; Overeem et al., 2003a; Overeem et al., 2003b).

Sediment loading can strongly affect the development of a delta like the Mississippi (Roberts, 1997; Coleman et al., 1998). Rapid sedimentation causes thick sedimentary deposits that take time to consolidate because of their excess pore pressures. After a lobe switch, compaction processes become more important and allow the ocean to migrate landward, as in Louisiana today.

There is extensive evidence for tectonic control on delta development over long geological periods. Many large deltas occur in long-term subsiding basins. Lobes also switch as a result of tilting or earthquakes. On a more detailed level, faults influence the basin topography or bathymetry; relative sea level differs for different parts of the basin, or sediment is captured in subsiding sub-basins in the source area. These tectonic feedbacks appear to be more often described in outcrops or reservoirs (e.g., Chough and Hwang, 1997; Muto and Steel, 2000; Clason et al., 1999) than for active systems (e.g., Soter, 1998; Goodbred and Kuehl, 2000b). Such tectonic effects are modeled by appropriately modifying the computational model grid.

**The Engine Needs Several Key Processes**

**Delta-Plain Dynamics.**—

River channels erode, and deposit levees and bars, leaving unique traces in the sedimentary record. Flood events deposit crevasses and overbank clays, which differ temporally and spatially (Middelkoop and Asselmann, 1998; Asselmann and Middelkoop, 1998). The trapping efficiency of delta plains can be enormous. Estimates for the Amazon, the Ganges, and the Yellow rivers are respectively 20, 55, and 82% of the total load (Meade, 1996). While no algorithm yet predicts this trapping efficiency, it appears to scale to the number of active distributary channels: the greater the number of channels, the greater the amount of sediment trapped on the delta plain (Meade, 1996).

**Hypopycnal and Hyperpycnal Plumes.**—

Satellite images of any delta emphasize the importance of delta plumes. The behavior of a plume is dependent on the density contrast between the river water and the standing water (Alberson et al., 1950; Bates, 1953). Ocean water has a high density, and the plumes often flow buoyantly on the surface (hypopycnal). The sediment concentration of the river adds density to the freshwater, but usually the effluent remains below the density of seawater. The shape of a hypopycnal plume depends on a variety of factors:

- The angle between the river course at the entry point and the coastline;
- The strength and direction of the coastal current;
- The wind direction and its influence on local upwelling or downwelling conditions;
- The mixing (tidal or storm) of energy near the river mouth; and
- The latitude of the river mouth and thus the strength of the Coriolis effect.

Often there are strong interactions among these factors. For example, if the angle of entry is in the direction of the Coriolis effect (i.e., deflection to the right in the Northern Hemisphere), then the plume will likely form a coast-hugging (Kelvin) plume. Otherwise the plume will detach from the coast. Even in coarse-grained delta systems, like the Homathko River delta in the Bute Inlet fjord, Canada (Syvitski et al., 1985), the fine suspended load forms a significant component in the pattern of deposited sediment (Nemec, 1995). Sediment particles settle out relatively quickly from river plumes that enter the ocean, because of flocculation (Syvitski et al., 1995).

Less common is the occurrence of hyperpycnal plumes (Imran and Syvitski, 2000). These develop when the incoming flow has a larger density than the receiving basin, as during a river flood. A hyperpycnal plume is capable of entraining sediment from the bed and as such has important influence on the sedimentation patterns (Mulder and Syvitski, 1995; Wright et al., 1986).

**Waves, Currents, and Tides.**—

Waves, currents, and tides each have their own unique influence on the rate of reworking of the sediments injected into the basin by the river. The power of large waves produces well-sorted sand bodies oriented parallel to the coast (Coleman and Wright, 1975). Currents work to move sediment both alongshore and off/onshore and can thus act both as a sediment-supply term (as previously discussed) or as an erosive agent.

The recurrence time of significant storm events, and the resulting current direction, appears to be as important as the dynamics of the river input. The effect of high-energy events versus prevailing mean conditions has been measured in several modern coastal environments—e.g., the Ebro Delta (Jimenez et al., 1999) and along the Californian coast (Hicks and Inman, 1987)—but it is unknown over longer time scales and is a unique boundary condition for every delta system.

Tides force reversal of river flow over the tidal cycle, which results in large linear subaqueous ridges with complex patterns of grain-size distribution. Tides also work to keep channels relatively straight and wide (Coleman and Wright, 1975).
FitzGerald and Nummedal (1983) report a 670% difference in channel width over an average tidal cycle of the Price Inlet in South Carolina. Consequently, these channel-geometry dynamics control the delta-plume sedimentation temporally and as such are an important coupled parameter.

Submarine Slope Failures.—

Oversteepening and overloading are the two prime causes of sediment failure in deltaic environments. Deltas that have prograded to the shelf–slope break or enter steep margins (fjords) deposit their bedload rapidly, creating foresets that slope between 5° and 30° to depths between 10 m and 50 m. These foreset beds prograde seaward onto prodelta bottomset beds that dip much more gently between 0.1° and 5°. Seasonal or semicontinuous failures of these typically sandy, possibly gravelly, foresets occur as numerous small-scale (10° to 10° m) displacements and continually adjust to maintain maximum slope stability (Prior et al., 1987; Syvitski et al., 1988).

Deltaic sediments can be highly underconsolidated, and may fail under their own weight. Failures may be triggered by outside stimuli, such as earthquakes or human activities. In undrained deposits, a critical pore pressure may develop because of earthquake shocks, high sedimentation rates, loss of buoyancy during an extreme low tide, the sudden change of hydrostatic pressure by wave action, and/or development of free gas within the sediment. On deltas, the overpressurizing of the pore fluid permits the formation of very gently dipping slip planes (Mandl and Crans, 1981). Sudden pore-pressure disequilibria in a sediment mass can also result in liquefaction. During the 1964 Alaska earthquake, liquefaction-type slides incorporated sand layers exceeding 50 m in thickness (Andresen and Bjerrum, 1967). Most models that take into account sediment failure use a factor-of-safety approach that numerically analyzes the ratio of driving forces to resistance forces (Syvitski and Hutton, 2001).

Model Output

To make model predictions useful, many outputs—i.e., grain size, bulk density, porosity, permeability, et cetera—are needed for comparison with field observations. Different case studies require output of different properties. We advocate a three-dimensional framework (x, y form the horizontal dimension, z is the vertical or depth dimension) in which properties of the sediment column can be stored (Fig. 2). For example, a model sequence ~ 20 m thick in a 10 km x 10 km delta may require 100 m x 100 m x 10 cm gridcells. Each cell would store three relevant sedimentological attributes in the form of floating-point numbers (4 bytes), for example, the mean grain size, and the volume fractions of fine and coarse sediment. Even at this rather coarse resolution, already the stored data volume adds up to ~ 23 Mb. The data volume should allow other derivative properties, like thickness and layering characteristics, to be retrieved. Timelines or age of the sediments can also be preserved for comparison with dating based on fieldwork.

STATE OF THE ART IN DELTA MODELING

Two tables give an overview of the capabilities of several 3D models developed over the last 15 years. Table 1 gives the input and boundary conditions, and Table 2 shows the processes included in each model.

All models surveyed can ingest an initial topography (idealized to some extent) as well as a changing sea level. Here, the devil is in the details, and specific cases are usually not described. How do the models cope with local minima or topographic highs in the offshore (like mouth bars, for example)? Meijer (2002) noted the sensitivity of the system to its initial state in a series of runs. The character of the statistical noise superimposed on the general grid topography influences the simulated river development more strongly than expected. Also, digital-elevation-model (DEM) resolution affects erosion and sedimentation rates, because the constants used in the transport algorithms are not scale-invariant (Schoorl et al., 2000).

Most models can deal with basin subsidence, which is imposed on the grid, although this has not always been tested (Table 1). Another distinguishing criterion is the capacity of the models to deal with variations in river discharge, \(Q_s\), sediment supply, \(Q_{so}\), or wave climate. Although the majority of the models appear to be set up to deal with time-varying \(Q\) and \(Q_{so}\), most of them do not use that capacity. Wave climate is varied for only a few models (Komar, 1971, 1998), and tidal ranges are held constant in all models, except Delft3D (Table 2).

At one end of the spectrum of models there is FUZZIM (Nordlund, 1999), which employs fuzzy logic instead of conventional physics. For example, the rule for deposition may be formulated as follows: "IF shallow AND near river THEN much
AND coarse”. Geological understanding is often formulated qualitatively, so the framework of FUZZSIM forms a good base for thought experiments or as a teaching tool.

A 3D bulk sediment transport model has been developed to simulate coarse-grained delta sedimentation (Ritchie et al., 1999). The model is rule-based and uses simple slope-and-discharge-dependent sediment transport and includes lobe switches over the delta plain. It has been designed to test hypotheses about large-scale sedimentation patterns (e.g., 12 km x 10 km with 40 m x 40 m gridcells and 20 year time steps). Ritchie et al. (1999) and Gawthorpe et al. (2003) model fan deltas under the influence of varying subsidence rates and eustatic change. The model results raise important questions about the chronostratigraphic significance of key stratal surfaces, because the model shows different system tracts developing contemporaneously within a basin over distances of just a few kilometers. Clevis (2004) presents a stratigraphic model slightly larger in scale (75 km x 75 km with 500 m x 500 m gridcells and 10 year time steps), which models dual lithology and includes mass-movement processes as well as marine carbonate deposition. Figure 3 illustrates a 2-million-year

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**Table 1.** Overview of the incorporated boundary conditions in various 3D numerical sedimentary models. X = input variable, - = not possible to ingest this variable, ± = potential variable but not shown in case study.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Initial topography</th>
<th>Sea level (t)</th>
<th>River (t)</th>
<th>Basin</th>
<th>Tectonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEDSIM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DEPO3D</td>
<td>X</td>
<td>-</td>
<td>±</td>
<td>±</td>
<td>-</td>
</tr>
<tr>
<td>DIONYSIS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>constant</td>
<td>constant</td>
</tr>
<tr>
<td>Ritchie et al.</td>
<td>X</td>
<td>X</td>
<td>constant</td>
<td>constant</td>
<td>-</td>
</tr>
<tr>
<td>Clevis et al.</td>
<td>X</td>
<td>X</td>
<td>constant</td>
<td>constant</td>
<td>-</td>
</tr>
<tr>
<td>Meier et al.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
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<tr>
<td>SedFlux3D</td>
<td>X</td>
<td>X</td>
<td>±</td>
<td>±</td>
<td>X</td>
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<tr>
<td>AquaTellUS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Sun et al.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FUZZSIM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>±</td>
</tr>
<tr>
<td>Komar et al.</td>
<td>X</td>
<td>X</td>
<td>constant</td>
<td>constant</td>
<td>X</td>
</tr>
<tr>
<td>Delft3D-MOR</td>
<td>X</td>
<td>±</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 2.** Overview of the incorporated process modules in various 3D numerical sedimentary models. X = process modeled, - = process not included, ± = process potentially included but not shown in case study.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Delta plain dynamics</th>
<th>Delta plumes</th>
<th>Reworking processes</th>
<th>Slope failure</th>
<th>Compaction Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>channel switching</td>
<td>channel erosion</td>
<td>hypopycnal</td>
<td>hyperpycnal</td>
<td>waves</td>
</tr>
<tr>
<td>SEDSIM</td>
<td>±</td>
<td>X</td>
<td>±</td>
<td>X</td>
<td>X</td>
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<tr>
<td>DEPO3D</td>
<td>-</td>
<td>±</td>
<td>±</td>
<td>-</td>
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<tr>
<td>DIONYSIS</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>processes lumped as diffusive transport</td>
<td>±</td>
</tr>
<tr>
<td>DIBAFILL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>processes lumped as diffusive transport</td>
<td>±</td>
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<tr>
<td>Ritchie et al.</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>'bedload dumping'</td>
<td>-</td>
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<tr>
<td>Clevis et al.</td>
<td>X</td>
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<td>-</td>
<td>processes lumped as diffusive transport</td>
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</tr>
<tr>
<td>Meier et al.</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>processes lumped as diffusive transport</td>
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</tr>
<tr>
<td>SedFlux3D</td>
<td>X</td>
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<tr>
<td>AquaTellUS</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Sun et al.</td>
<td>±</td>
<td>X</td>
<td>-</td>
<td>lumped as diffusion</td>
<td>-</td>
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<tr>
<td>FUZZSIM</td>
<td>±</td>
<td>-</td>
<td>-</td>
<td>lumped in fuzzy rules</td>
<td>±</td>
</tr>
<tr>
<td>Komar et al.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>constant</td>
<td>X</td>
</tr>
<tr>
<td>Delft3D</td>
<td>-</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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</table>
experiment characterized by pulsed flexural subsidence and cyclic eustatic sea-level fluctuation. The two snapshots show the landscape at eustatic lowstand and simultaneous tectonic quiescence. An axial trunk fluvial system flows along a fault front, adjacent to alluvial fans. Both models show results in accordance with field observations of fan deltas of similar scale in the Gulf of Corinth, Greece (Gawthorpe et al., 2003) and the Pyrenees (Clevis, 2004).

Meijer's (2002) model mimics the evolution of a river system on exposed shelves under a fluctuating sea-level regime. It aims to represent hundreds of kilometers and millions of years scale. It uses a perfect sorting algorithm to break sediment down into a coarse and fine fraction. Resulting modeled stratigraphy shows large coarse sediment bodies on the upper continental shelf, i.e., lowstand deltas, and across-shelf incised river valleys, which are embedded in fine sediment. Significant added value to traditional 2D stratigraphic basin-scale models comes from the ability to quantify the probability of occurrence of coarse-grained sediment bodies (Meijer, 2002). AquaTellUs (Overeem et al., 1999) is

Fig. 3.—Development of fan delta and a trunk fluvial system under the influence of subsidence and eustatic sea-level changes. At 0.9 Myr the axial fluvial system is deflected towards a fault front and adjacent to alluvial-fan fringes. The axial system (1) develops to a confined braidplain (2) into a delta plain (3). Falling sea level caused some incision (4). At 1.9 Myr the marine embayment is almost entirely filled and the local fan deltas have deflected the trunk fluvial system (1) away from the fault and a new delta lobe has formed (2). (Figure courtesy of Quintijn Clevis.)
similar to the Meijer model but incorporates multiple grain-size classes as well as rules for floodplain sedimentation. It is discussed in detail below.

Diffusive three-dimensional models include DIBAFILL (Quiquerez et al., 2000) and DIONYSOS (Diffusive Oriented Normal and Inverse-Simulation Of Sedimentation (Granjeon and Joseph, 1999)). Both models can deal with multiple grain sizes. The simplified approach has been justified, because it is used mainly for long-time-scale development and assumes that all transport is gravity-driven. DIBAFILL appears to be useful mainly for theoretical experiments, whereas DIONYSOS has been evaluated for more detailed cases (e.g., fluviodeltaic sedimentation and in the shallow marine of the Gulf of Lions; Rabineau, 2001). DIONYSOS uses the same set of diffusion equations in the fluvial and marine domain. Because the model does not include explicit solution for wave and tidal processes, it is assumed to be applicable only in fluvial and gravity-driven environments.

SEDSIM and its “derivative” DEPO3D were the first ambitious attempts to model geological sedimentary systems in 3D (Tetzlaff and Harbaugh, 1989; Bitzer and Pflug, 1989). It is a physics-based model, describing flow with an integrated continuity and momentum equation. As such, it is computationally expensive. SEDSIM includes simplified fluvial processes as well as nearshore processes (Martinez and Harbaugh, 1993). It has been applied successfully for modeling an ice-contact delta (Tuttle and Wendorbourg, 1999) as well as for an ancient delta system in offshore Australia (Griffiths et al., 2001). Although no longer in the public domain, SEDSIM is still under development and is now used in the oil industry (Tetzlaff and Priddy, 2001; Griffiths et al., 2001).

SedFlux, which originated as a 2D delta model (Syvitski and Daughney, 1992), takes a more 3D approach (Syvitski et al., 1998a). It incorporates a number of coupled physics-based routines to simulate plume deposition, turbidity currents, debris flows, ocean storm reworking, and longshore transport for multiple grain-size classes (Syvitski and Hutton, 2001; Stewart and Overeem, 2002). SedFlux is capable of ingestion of daily climate data series (either real-world data or generated by the climate-driven hydrological model HYDROTREND; Syvitski et al., 1998b; Syvitski et al., 2004).

Recently, a physics-based fluvial–fan delta model (Parker et al., 1998) has been coupled with a cellular model of channel evolution (Sun et al., 2002). These models use a single grain size and do not take overbank sedimentation into account, which appears reasonable assumption for the fan-delta case but limits further application to more mud-rich deltas. A few theoretical tests confirm expected evolution patterns.

Delt3D originated as an engineering model. The model is physics-based and input-intensive, because it is developed for comparably short-term simulations (hours–days). It consists of dynamically coupled routines for river-, wave-, and tide-driven flow and coupled sediment transport. It has been tested extensively against short-term field measurements, and it performs well for tidal basins and coastal areas (e.g., Guillon et al., 1999; Elías et al., 2000). Recently, the morphology module MOR has been used to do medium-time-scale simulations (up to 500 years), which opens up possibilities for geological questions (van Leeuwen et al., 2003).

EXAMPLES

Floodplain Sedimentation—AquaTellUs

AquaTellUs uses a nested model approach: a 2D longitudinal profile, embedded as a dynamical flowpath in a 3D grid-based space. Overeem et al. (1999) and Overeem et al. (2003b) discuss the 2D model equations used in AquaTellUs. A main channel belt is modeled as a 2D longitudinal profile that responds dynamically to changes in discharge, sediment load, and sea level. Sediment flux is described by separate erosion and sedimentation components. Multiple grain-size classes are tracked independently.

Erosion flux depends on discharge and slope, similarly to process descriptions used in hill-slope models (e.g., Kirkby, 1992; Tucker and Slingerland, 1994) and independently of grain size. Offshore, where we assume unconfined flow, the erosion capacity decreases with increasing water depth. The erosion flux is a proxy for gravity flows in submarine channels close to the coast and for downslope diffusion over the entire slope due to waves, tides, and creep (Kaufman et al., 1992). Erosion is restricted to the main flowpath. This appears to be valid for the river-channel belt, but it underestimates the spatial extent and variability of marine erosion processes.

Deposition flux depends on the stream velocity and on a travel-distance factor, which depends on grain size (i.e., settling velocity). The travel-distance factor is different in the fluvial and marine domains, which results in a sharp increase of the settling rate at the river mouth, mimicking bedload dumping.

Dynamic boundary conditions such as climatic changes over time are incorporated by increasing or decreasing discharge and sediment load for each time step. The feedbacks for climate and discharge are complex and may be quite different for each case study.

Lateral Sediment Distribution in the Fluvial Domain.—

The main channel belt is the most dynamic zone of sedimentation and erosion. An alluvial ridge is created because net sedimentation rates are higher in the channel belt than on the adjacent floodplain (Allen, 1965; Bridge and Leeder, 1979; Pizzuto, 1987; Bryant et al., 1995). This differential sedimentation must be reflected in the algorithm. Lateral sediment distribution has been described empirically by an exponential function with deposition decreasing with distance from the channel (Pizzuto, 1987). On the scale of a single event, this trend may still apply (Asselman and Midelkoop, 1998), but spatial variability is significant (Middelkoop and Asselman, 1998). We follow Paola (2000), who suggests a Gaussian distribution and thus an error function as the characteristic solution for this spatial pattern:

$$F(y) = \frac{1}{\sqrt{2\pi \sigma}} e^{-\frac{(y-m)^2}{2\sigma^2}} \quad (1)$$

Here, y is the horizontal distance normal to the flowpath, s is the standard deviation across the sedimentation zone, and m is the position of the flowpath axis in the y direction. The integral of the Gaussian distribution is the error function, erf(y):

$$erf(y) = \frac{2}{\sqrt{\pi}} \int e^{-t^2} dt \quad (erf (0) = 0, \ erf (\infty) = 1) \quad (2)$$

The error function is the sedimentation function. The relative surface areas under the Gaussian curve are calculated to determine the proportion of the total sediment load to be deposited in the specific lateral reach. The total sediment load consists of proportions of grain-size classes. We simplify selective deposition by assuming that the coarsest sediments are deposited closest to the flowpath and progressive fining occurs laterally (analogous to the use of travel distances in the longitudinal direction).

The lateral width of the sedimentation function, L_{river}, depends on the geometry of the local cross profile and the cross-sectional discharge. Confined channels have a narrow sedimen-
tation distribution curve, whereas unconfined channels have a wide sedimentation curve. This rule has been implemented as follows. The cross-sectional discharge \( \frac{dA}{dt} = \frac{Q}{dx} \) is compared stepwise with the storage capacity of the channel belt. The lateral width is set when the storage capacity is reached (Fig. 4). The more confined a channel is, the higher its storage capacity, which limits the lateral extent of the sedimentation curve. High local cross slopes thus result in more localized deposition, which increases the probability of avulsion in the subsequent time step. This agrees with concepts in which high local cross-channel slopes are mentioned as a dominant influence on crevasse sedimentation and avulsion (Slingerland and Smith, 1998; Bryant et al., 1995). It also incorporates the notion that avulsions will occur more frequently if the sedimentation rate is high, as is observed in analog models of fluvial systems (Bryant et al., 1995) and in field studies (Törnqvist, 1993; Stouthamer and Berendsen, 2000).

**Model Settings.**

The following experiment shows short model runs (100 time steps) with time steps in the order of 10^2 years. The grid consists of 100 x 140 cells, each 500 m in size, which gives a length scale of 50 km x 75 km. The initial gradient of the floodplain and offshore slope have been set at 0.1 m/km, and random uniform noise has been added to the topography. The input parameters are listed in Table 3. The following numerical experiments touch strongly upon three-dimensional aspects. The analysis serves to inspire the discussion on cause-and-effect relations in three dimensions.

**Experiment 1: Frequency of Channel Switching.**

The main justification for three-dimensional modeling of deltas is that they switch location over time. Here, an experiment examines the effect of the frequency of switching on stratigraphy. The scenarios are geologically simple: allocyclic controls are considered constant. Sea level is stable, and no tectonics or climatic changes are imposed. Two cases have been compared (Figs. 5, 6):

- **A** The location of the channel is kept stable over the total simulation time.
- **B** A high frequency of avulsion results in recalculation of the flowpath in almost every time step (see Table 3 for switch parameters).

A belt approximately 10 km wide with surrounding levees builds up rapidly on the floodplain if a channel remains stable. The vertical grain-size trends in the levees vary, reflecting the temporal variation in sediment load and discharge. Lateral fining of the levees occurs as well. Deposition of coarse mouth-bar sediments can be seen in the deltaic domain (A-75, Figs. 5, 6). These coarse deposits are recognized in the later phases when the mouth bars have prograded towards the position of cross section A-75. Lateral fining is obvious in the deltaic cross section, where the coarsest sediments have been deposited in the axis of the delta plume.

Frequent channel switching leads to more widespread deposition. The zone in which active sedimentation occurs has widened to approximately 25 km. Naturally, the local deposition rate decreases because of this widening (compare the thickness of the deposits of A and B in Fig. 6). The channel location is recalculated at almost every time step, but it does not switch its position each time, because it is bounded by its levees.

Several channel–levee complexes can be recognized in section B-45. The delta-plume axis switches its location according as the channel switches on the floodplain. Consequently, sedimentation is much more widely dispersed in section B-75 (Fig. 6).

**Experiment 2: Autocyclic Versus Allocyclic Controls on Progradation Patterns.**

The influence of autocyclic factors (e.g., avulsions and bifurcations) versus allocyclic factors (e.g., sea-level change and sediment supply) on fluvial architecture is a hotly debated issue. We compare two simulations in which the channel is rather stable (A1 and A2 in Fig. 7) and two simulations in which the flowpath is recalculated frequently (B1 and B2 in Fig. 7). In the base case, A1, the external controls are stable, whereas in A2, B1, and B2 a 4 m sea-level fall occurs. The lower half of the falling limb of a sine curve represents the rate of sea-level fall: initially high and diminishing in the course of the simulation.

The commonly used model in sequence stratigraphy is that sea-level falls are associated with strong progradation and mini-
mal channel switching, because the gradient of the fluvial system increases, forcing the channel to incise its bed (i.e., a Type 2 sequence). A decrease of the avulsion frequency during sea-level falls due to limited buildup of superelevation has also been proposed. However, systems with high rates of sediment supply and low-gradient delta systems, where the offshore gradient of the delta front is very similar to that of the delta plain, may behave quite differently. The factors that govern the responses of the modeled systems A1 and A2 are the high rate of sediment supply and the low shelf gradient. Considerable progradation takes place in both cases, with minor differences related to the magnitude of sea-level fall (0 and 4 m, respectively). Progradation of the levee deposits over the deltaic wedge (A2-85, Fig. 6) and a coarsening-upward trend in the deltaic deposits (A2-115, Fig. 6) are clearly visible. The frequency of channel switching is proportional to the rate of sediment supply. The main reason for this coupling is that changes in a flowpath depend on topographic variations, which build up more rapidly if the net sedimentation rate in the channel belt increases. This effect justifies the assumption made in simulations B1 and B2 that the channel location can switch frequently, even during falling sea level. One can imagine a fluvial braided plain experiencing a transition from cold to glacial conditions, accompanied by a glacioeustatic sea-level fall. The difference in delta geometry between the stable channel (A2) and the frequently switching channel (B1) under conditions of falling sea level is evident. Because of the channel switching, sediment is distributed over a wider zone along the delta front (B1-85 Fig. 6) and only very limited progradation occurs. How-

### Table 3.—Simulation parameters for the AquaTellUs experiments.

<table>
<thead>
<tr>
<th>SIMULATION PARAMETERS</th>
<th></th>
</tr>
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<tbody>
<tr>
<td><strong>Time scenario</strong></td>
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</tr>
<tr>
<td>total simulation time (undef.)</td>
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</tr>
<tr>
<td>time step (undef.)</td>
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<tr>
<td><strong>Grid dimensions</strong></td>
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<tr>
<td>gridlength (gridcells)</td>
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<tr>
<td>grid width (gridcells)</td>
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<tr>
<td>gridcell length and width (km)</td>
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<td><strong>Sea level scenario</strong></td>
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<td>sea level at $t = 0$ (m)</td>
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<tr>
<td>sea-level amplitude (m)</td>
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<td><strong>Initial topography</strong></td>
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<tr>
<td>elevation at grid cell 0 (m)</td>
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<tr>
<td>slope gradient in fluvial domain (m/km)</td>
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<tr>
<td>noise-random uniform deviate (m)</td>
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<tr>
<td><strong>Discharge and sediment load</strong></td>
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<td>$Q$ at $t = 0$ (m$^3$)</td>
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</tr>
<tr>
<td>$q$ at $t = 0$ (m$^3$)</td>
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</tr>
<tr>
<td>$Q$ variation range in time (→)</td>
<td>0.8–1.2</td>
</tr>
<tr>
<td>$q$ variation range in time (→)</td>
<td>0.8–1.2</td>
</tr>
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<td><strong>Grain-size characteristics</strong></td>
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<td>number of grain-size classes</td>
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<tr>
<td>proportion distribution</td>
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</tr>
<tr>
<td>Grain sizes (µm)</td>
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<td><strong>Sediment transport coefficients</strong></td>
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<td>travel distances, fluvial domain (km)</td>
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</tr>
<tr>
<td>travel distances, marine domain (km)</td>
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<tr>
<td>erosion capacity, fluvial domain</td>
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</tr>
<tr>
<td>erosion capacity, marine domain</td>
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</tr>
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<td><strong>Channel switch parameters</strong></td>
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<td>initial channel column position (gridcell)</td>
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<tr>
<td>initial channel position range (gridcells)</td>
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<td>switch threshold</td>
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<tr>
<td>time-step dependence</td>
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</table>
Fig. 6.—Stratigraphic cross sections for experiment 1 shows the grain-size distributions in the fluvial (A-45 and B-45) and deltaic (A-75 and B-75) domain under different switching regimes. Positions are indicated in Fig. 5. Stratigraphic cross sections for experiment 2 (positions are indicated in Fig. 7) show the effect of changing controls (sea-level fall in A2-85 and A2-115) and channel switching regime (B1-85) and increased sediment supply (B2-85).
ever, differences between B1 and B2 are far from spectacular: the rate of progradation is hardly affected by an increase of the rate of sediment supply. The width of the zone of influence of the channel belt does increase. The deposits are coarser, because the river mouth, where bedload is dumped, is closer to section B2-85 than to B1-85. Larger differences between B1 and B2 could have been expected in case of a full coupling between avulsion frequency and rate of sediment supply.

The model results relate the factors that control delta morphology in a low-gradient setting. It appears that the autocyclic mechanism of channel switching, which determines the progradation pattern, is in turn governed by the allocyclic mechanism of sediment supply.

**3D-SedFlux**

3D-SedFlux is a process–response numerical model designed to simulate the filling of sedimentary marine basins over time scales of decades to tens of thousands of years. It is based on the premise that the modular 2D SedFlux can be adapted to the third dimension (Syvitski and Hutton, 2001; Stewart and Overeem, 2002). The model keeps track of sediment deposition and subsequent reworking. The basic architecture is a regular two-dimensional grid on which are situated columns of cells with variable thickness. Each vertical cell preserves the sediment state at a resolution much greater (tens of centimeters) than the horizontal length scale (tens of meters). This spatial architecture permits...
processes to operate independently or together to supply, remove, or rework sediment. Separate modules implement the physics of the various physical processes affecting the sediment distribution. The full 3D structure of the sediment distribution and information about the state of the marine basin is available to all modules. In this way, the model is designed to easily incorporate new algorithms that model new processes or existing processes in different ways.

Stochastic Delta Switching.—

To mimic avulsion of the river over a delta plain, the river-mouth position at a specific time is determined by a distance and angle from the apex (Fig. 8). At specific time steps, \( t + \Delta t \), the river-mouth angle, \( A \), changes by an amount drawn from a Gaussian distribution:

\[
A_{t+\Delta t} = A_t + \Delta \theta
\]

\[
\Delta \theta = \mu X
\]

This approach is a fast way to compute changes in river-mouth position. The rate of switching is controlled by changing the scaling factor, \( \mu \) of the Gaussian deviate, \( X \). The choice of a Gaussian deviate implies that large switches of location do occur but are uncommon compared to smaller changes. In this way, switching lobes and spreading of sediment is mimicked without a specific delta-floodplain model.

Hypopycnal Plumes.—

Bedload is first dumped across the tidal range fixed for the environment. Next sediment is deposited from hypopycnal plumes. The plume equations follow those of Albertson et al. (1950), developed for a jet flowing into a steady ocean. This general solution is then geometrically distorted to simulate the effects of complicating conditions. We have found that the conditions at the river mouth (depth, width, velocity), oceanic currents, the Coriolis force, and the angle at which the river enters the ocean all strongly affect the resulting plume. Plumes of similar shape but differing concentrations result for each grain size in the model.

Plume dynamics are governed by the following steady 2D advection–diffusion equation:

\[
\frac{\partial I}{\partial x} + \frac{\partial v I}{\partial y} + \lambda I = \frac{\partial}{\partial y}\left(K \frac{\partial I}{\partial y}\right) + \frac{\partial}{\partial x}\left(K \frac{\partial I}{\partial x}\right)
\]

where \( x, y \) are coordinate directions, \( u, v \) are velocities, \( K \) is turbulent sediment diffusivity, \( I \) is sediment inventory, and \( \lambda \) is the first-order removal rate constant. The position of the centerline of the plume is defined as

\[
\frac{x}{b_0} = 1.53 + 0.90\left(\frac{u_0}{u_c}\right)^{0.37}
\]

where \( b_0 \) is the river-mouth width. Sediment concentration, \( C \), around the centerline is given by

\[
C(x, y) = C_0 e^{-\lambda t} \frac{b_0}{\sqrt{\pi C_1 x}} e^{-\left(\frac{y}{2C_2 x}\right)^2}
\]

where \( C_0 \) is the initial concentration and

\[
u(x, y) = u_0 \sqrt{\frac{b_0}{\sqrt{\pi C_1 x}}} e^{-\left(\frac{y}{2C_2 x}\right)^2}
\]

\[
u_c(x) = u_0 \sqrt{\frac{b_0}{\sqrt{\pi C_1 x}}}
\]

\[
t(x, y) = u_0 t_c(x) + 7u(x, y)
\]

and \( C_1 \) is an empirical constant 0.109.

Subaerial Erosion and Deposition by Rivers.—

We have adopted the approach of Paola et al. (1992), based on first principles of mass and momentum conservation, to predict erosion and deposition along the subaerial long profile:

\[
\frac{\partial h}{\partial t} = v \frac{\delta h}{\delta x}
\]

where is the height of the bed, \( t \) is time, \( x \) is the position along the long profile, and is the diffusion coefficient. The diffusion coefficient is expressed as

\[
v = -8(q)A\sqrt{c_f}
\]

where \( q \) is the discharge, \( c_f \) is the drag coefficient, \( c_v \) is the sediment concentration of the bed, \( s \) is sediment specific gravity, and \( A \) is a river-type-dependent constant. \( A \) differs for meandering rivers (\( A \equiv 1 \)) and braided rivers (\( A = (1 + s) \)). The value of \( s \) relates the shear stress, \( \tau \), in the center of the channel to the critical shear stress, \( \tau_c \), needed for bank erosion (\( = (1 + s) \)). Parker (1978) presents measured values of \( s \) to be typically about 0.4. It is possible to account for spatially varying discharge, by substituting the discharge \( q \) into the derivative (Equation 11). In 3D-SedFlux the channel width is assumed to be grid-cell width. Sediment moves as either bedload or suspended load based on grain size. Significant channel incision and subsequent backfill can result of a rapid sea-level fall and rise.

Subsidence and Compaction.—

Steady or non-uniform subsidence due to tectonic movements is simply user-defined, allowing for vertical displacements over space and time. Subsidence due to loading is modeled using an elastic flexure model (Lambeck, 1986), as described in Syvitski and Hutton (2001). The lithospheric subsidence is modeled with a delay function, because the viscous asthenosphere has to flow out before the lithosphere can deflect.

Predictions of sediment compaction are essential to estimate relative sea level. Sediment porosities typically decrease with depth as the weight of the overlying sediment compresses the underlying material (Athy, 1930). Models of this compaction process have shifted from simple empiricisms to complex numerical models (Bahr et al., 2001). A simple exponential function is frequently all that is necessary to describe the basic compaction process.
In the following simple theoretical experiments SedFlux is run for 1000 years. We simulate a fine-grained system, in which there are five grain-size classes with their means at 200, 100, 40, 10, and 1 mm. For these short-time-span experiments, subsidence and compaction have been neglected. The experiments simulate meandering river conditions ($A = 1$), because the delta floodplain slope is low.

Figure 9A and B show the effect of changing avulsion frequency. The scaling factor is respectively 0.3 in scenario A and 0.03 in scenario B. Sediment supply and discharge (200 m$^3$/s) are constant, as is sea level. Scenario A shows high switching frequency, resulting in uniform delta progradation and relatively limited lobe formation. Scenario B shows two more distinct protuberations, where a channel has been stable over longer time and increased progradation has taken place along a distinct delta arm.

The effect of controlling factors on hypopycnal plumes using similar constant sediment supply and discharge (200 m$^3$/s) is illustrated in Figure 9C and D. The plume flows straight into a calm ocean, but there is a strong Coriolis effect (Fig. 9C). The Coriolis force drives the plume into a constant shore-parallel direction. The resulting progradation is asymmetric (~2.7 km versus 4 km), even over a 1000 year simulation. In scenario D the plume enters an ocean with a strong directional coastal current (0.5 m/s), causing the flow to move up along the coast. In addition, the river mouth switches only a couple of times over the simulation. The resulting deposition forms curved elongated delta arms.

Figure 9E and F show two time slices of the same experiment focused on channel incision. Figure 9E is at lowstand (~25 m) and shows two incised valleys in the delta topsets and several smaller channelized features in the delta slope. Figure 9F shows the situation at the end of the run when sea level has risen again (~12 m). The flooded delta top is evident and the features in the delta slope can still be recognized whereas the incised valleys on the delta top have been partly filled in. Figure 10 shows the internal stratigraphic architecture of the deposits generated during the

**Simple 1000 Year SedFlux Experiments.**

In the following simple theoretical experiments SedFlux is run for 1000 years. We simulate a fine-grained system, in which there are five grain-size classes with their means at 200, 100, 40, 10, and 1 mm. For these short-time-span experiments, subsidence and compaction have been neglected. The experiments simulate meandering river conditions ($A = 1$), because the delta floodplain slope is low.

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**OUTSTANDING PROBLEMS**

There are still many issues that need to be addressed to advance the present-day numerical models. Firstly, there is a need for quality input data. More and more datasets are becoming globally available through the Internet. Obvious parameters, like temperature and precipitation, discharge data, and buoy data of waves and currents, are accessible from a dense global network of stations on a daily basis. Initial topographies and drainage-basin characteristics can be retrieved from digital elevation models and bathymetric grids. Remotely sensed data combined with GPS measurements even provide information on present-day tectonic movements. Sedimentary modelers can use those data to feed and to calibrate their models for short-term experiments (i.e., on a decadal scale), provided that the data are quantitatively related to rates of sediment transport processes or to morphological changes.

However, the further the hindcasting the sparser the input. One has to use proxies creatively but remain well aware of their limitations. For example, $^{18}O$ records from ice cores have been used as a time-continuous temperature signal, but their extrapolation to locations other than the Inner Arctic is uncertain. To advance delta modeling, local sea-level curves and paleo–storm records (or wave-climate records) are important. It is a possibility to integrate output of community climate models, glaciological models, and ocean models in the sedimentary models. These output data carry their own assumptions and uncertainties. It is vital to develop a format in which uncertainties are attached to model inputs.
FIG. 9.—1000 year SedFlux experiment. A and B show the effect of changing avulsion frequency, C and D illustrate the effect of controlling factors on hypopycnal plumes using the same constant sediment supply and discharge, and E and F show two time slices of the same experiment focused on channel incision under a changing sea-level regime.
Secondly, we simply lack quantitative understanding of different processes in three dimensions. Avulsions and channel switches, mouth-bar deposition and its influence on the delta plume, and longshore transport in geometrically complex coasts are examples of processes for which we do have rule-based insights but no comprehensive physical models. Simplification has to be drastic, considering the computational requirements. Longer-term geological models (> $10^3$ years) simply cannot reproduce millimeter-scale bedding or detailed meter-scale lateral variations for a whole delta system. Facies models that are conditioned to controlling processes similar to those used in simulation models may provide us with the possibility of generating valid downscaled data volumes. Another issue that needs resolving is which processes can be time averaged and which need high (and costly) time resolution. A triggered turbidity current is a relatively short event which leaves a distinct body in the sedimentary record. To capture such event beds the models actually need to simulate relatively short-term processes. Upscaling techniques are being developed which use an event-based approach, wherein major sediment-transporting events are modeled in detail as separate events and the fair-weather conditions are averaged (Storms, 2003; Overeem and Storms, 2003). Real-world data on major flood and storm events and their effect on the delta morphology and stratigraphy is needed to evaluate these upscaling techniques.

Thirdly, most 3D models so far are not well tested. Philosophers argue that models in earth sciences can never be tested in the genuine sense, because the modeled system is never closed and models require input parameters that are incompletely known (Oreskes et al., 1994). Despite this difficulty it is very worthwhile to compare different algorithms against each other and to compare model output against observed data. The field community can help to generate well-constrained quantitative field studies of specific environments that represent the primary processes to be modeled. It will be a challenge for the modeling community to further advance the application of goodness-of-fit criteria and to design testing protocols.

Many steps may still need to be taken. Nevertheless, even highly simplified 2D models have been shown to provide insight and be able to predict general stratigraphic patterns. Computational power and community understanding of the important processes are converging to make models which are complex enough to capture the essential features of real geological settings. Ideally, the best aspects of each model will be incorporated into future versions of all models. In the end, modelers would like to create models that represent the important real-world processes in an efficient way and link them in the model architecture so that they operate in concert with each other. Models then provide a framework for investigating processes–responses in a way that every unique realization of the geological record does

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**Fig. 10.**—SedFlux internal stratigraphy as shown by “depth slices” at -15, -125, and -195 m through the deposited volume of sediment of the channel-incision experiment (Fig. 9E and F).
not permit. Testing the interaction of processes is certainly a realm where simulation models can be of great help.

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IRINA OVEREEM, JAMES P.M. SYVITSKI, AND ERIC W.H. HUTTON

30


