From Mountaintops to Shorelines:
Report of the Community Surface Dynamics Modeling System (CSDMS) Terrestrial-Coastal Joint Working Group Meeting, October 2009

Compiled and edited by Greg Tucker and Brad Murray, with contributions from all of the attendees listed at the end of this document
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1. Introduction

In October 2009 the Terrestrial and Coastal Working Groups came together in Boulder, Colorado, for a joint workshop. The main purpose of the workshop was to develop ideas for proof-of-concept applications, as well as to bring the members of the two groups up to speed on the latest developments in the Integration Facility. This report summarizes the group's deliberations and recommendations. A copy of the agenda and a list of participants are included at the end of this report.

The bulk of the workshop was devoted to breakout group discussions. The topics were wide-ranging, but centered on two common elements: first, that each topic revolved around one or more important science questions, and second, each topic implied a potential proof-of-concept application for CSDMS – that is, a scientifically worthy and relevant problem whose solution would benefit greatly from a CSDMS-style coupled-modeling approach. The remainder of this report summarizes the main themes explored during these breakout discussions.

2. Links between Surface Hydrology and Landscape Dynamics

The generation and movement of sediments and solutes across the land are driven in large part by the hydrologic cycle. Quite a few interesting science questions revolve around the interaction between surface hydrology and landscape evolution. These include, for example:

- What is the role of "average" versus extreme events in modifying the landscape?
- In light of the importance of topography for precipitation dynamics, in what ways do topography, hydrology, and atmospheric flow interact? Orographic precipitation is one obvious case; Joe Galewsky has recently shown that it can be more complicated than is often assumed in long-term landscape evolution studies. Another interesting issue is enhancement and/or trapping of convective precipitation along ridges.
- In general, the influence of spatial variability in precipitation on landscape evolution is an open question.
- Identifying components of the landscape-hydrology-atmosphere system that are crucial, and those that are second-order details, is an important issue.
- One way to make progress is to use natural experiments to identify the role of individual components. For example, the Hawaiian Islands represent a natural experiment in the

geomorphic effects of a dramatic precipitation contrast across a relatively uniform lithologic and topographic template.

Questions dealing with atmosphere-precipitation-landscape interaction involve a large gap in time scales, between the time scale of a flood (on the order of hours to days) and the time scale of the evolving landscape. There is a need therefore for efficient methods to compute flow dynamics across a topographic surface. To date, the most common method assumes equilibrium with respect to a (usually but not always uniform) precipitation field, in the sense that flow out of a model cell equals the sum of inflows. Yet there are reasons to question this approximation, even for long time-scale problems. For example, the total volume of annual runoff in a large drainage basin may grow in proportion to the area of the basin, but the magnitude of flood peaks may grow much more slowly (O'Connor and Costa, 2004). Given the nonlinear relationship between discharge and sediment transport, this can make a difference to long-term landscape evolution (Sólyom and Tucker, 2004).

One approach is simply to couple event-based surface hydrology models with landscape evolution models. But this may suffer from unnecessary complexity. One alternative is to develop simplified rainfall-runoff models that do not include the full suite of processes, such as detailed evapotranspiration dynamics, but rely instead on a few simple ingredients, such as a Green-Ampt infiltration model to capture antecedent moisture effects. A related approach is to consider only a certain fraction of the largest storms and ignore intervening time periods (as for example the CHILD model does). There is a need for "numerical upscaling" in which detailed, high space-time resolution models are used to diagnose fundamental modes of behavior, which are then used as the basis for approximations in longer-term (upscaled) models. Another possibility is the meta-model concept, in which a representative group of model runs is used to develop a regression model that in turn is used to explore sensitivities and behavior.

The possibility of parallel computing solutions for surface runoff was also discussed. One possibility is a parallel implementation of the python language (called StarP) that could potentially improve performance by handling in parallel certain "one line" actions, such as calculations on all elements of a matrix. It was also noted that David Tarboton has developed a "tiling procedure" for computing flow routing on a DEM, and this could potentially be implemented in parallel.

3. Delta Evolution: Couplings Between Fluvial, Coastal, and Human Processes

Participants initiated plans for proof-of-concept projects involving couplings between terrestrial and coastal environments, including explorations of delta evolution under the combined influences of sea-level-rise, storm impacts, and increasing human manipulations of the fluvial, delta, and coastal systems:

3.1 Holistic Modeling of Natural and Human-Influenced Delta Dynamics

One break-out group (Andrew Ashton, Liviu Giosan, Dylan McNamara, Brad Murray, Ad Reniers, and James Syvitski) discussed the exciting opportunities for a multifaceted investigation of delta dynamics, including the crucial influences of human activities on delta behaviors, including terrestrial and coastal land use patterns and infrastructure, as well as (ultimately) feedbacks between human behavior and delta evolution. This project will build on one already planned for (see section 3.2), which will link an avulsion model (initially the Jerolmack-Paola model), a delta model (initially SedFlux3D), and a coastline model (initially CEM), to address questions about two-way coupling between fluvial- and wave-driven processes. After those couplings are accomplished, the broader investigation will proceed by progressively adding couplings with a fluvial sediment delivery model (initially Hydrotrend), a marsh/tidal channel model (initially the Kirwan-Murray model), a subsidence model, a storm-surge model (likely ADCIRC), and ultimately a model of human dynamics (initially the McNamara-Werner model), to address questions about how terrestrial land use and local human manipulations of delta processes shape deltas and their behaviors.

The human influences considered will include upstream changes to sediment delivery (land use and dams), artificial levees along river channels on the delta (which affect sediment distribution to marshes and channel networks on the delta, and to the coastline), and extraction of fluids which tend to increase subsidence rates. This project will allow an exploration of physical and biomorphodynamic processes relevant to humans vary in different climate change and human-manipulation scenarios, including: 1) river stability (avulsions verses static channels) and elevation relative to the delta surface; 2) increases or decreases in wetland elevation and extent (degradation, aggradation and progradation); and 3) storm surge elevations and extents.

3.2 Two-Way Couplings Between Fluvial and Coastal Processes

Another break-out group (Andrew Ashton, Doug Jerolmack, Liviu Giosan, Brad Murray, Eric Hutton, Andrew Wickert) refined plans for an investigation of two-way couplings between river avulsions and wave-driven alongshore sediment redistribution during delta evolution.

Preliminary applications of the Coastal Evolution Model (CEM) to deltaic environments yield a range of interesting delta behaviors observed in nature; these simulations, however, are limited by the current model usage of a fixed direction, unchanging river channel. Fluvial models of delta evolution do not have a wave-driven shoreline-change component. The objective of this proof-of-concept model is to couple fluvial models with CEM to allow dynamic interactions between development of river channels and the shoreline, in particular allowing channel avulsions to occur along the domain as model deltas grow. Natural examples of wave-dominated deltas demonstrate interesting similarity of form that we would like to investigate within a modeling framework, including the presence of multiple open channels that tend to keep fairly constant angles between one another. The delta fronts are smooth (from wave diffusion), with asymmetrical spit development on both proximal channel locations.

Currently, SedFlux implements avulsion using a statistical approach. The first goal is to improve handling of avulsions in SedFlux using existing models, which could include the Sun et al. model, but we chose the Jerolmack and Paola model. As this current model is a simple code in Matlab (not compatible with the CSDMS framework), we decided to have the avulsion criteria component of the code implemented directly into SedFlux. Sediment routing and the diffusive channel bed evolution can be computed by SedFlux as is. Once implemented, the model should be able to be run with the CEM, which has been implemented within the CSDMS. As the long-term objective of this research is a better understanding of delta evolution, the preliminary model experiments should suggest a number of testable hypotheses.

Action Items: Prioritized action item 1 is for the Jerolmack & Paola avulsion model to be incorporated as a component within SedFlux. Jerolmack will send code or pseudocode to Hutton for implementation. Once the implementation and coupling is complete, we should be ready to run some simulations and conduct initial experiments.

4. Stratigraphic Rhythms

A major question in surface processes and paleoclimate that could be addressed with CSDMS-generated tools is whether cyclic stratigraphic sequences record external forcing (i.e., climate, and ultimately changes in solar radiation due to quasi-periodic variations in Earth's orbit), or internal dynamics (Figure 1). This general question can be broken down into more specific ones:

1. Are external signals preserved as they propagate through a geomorphic system?
2. What cyclic or quasi-periodic signals are generated internally by a geomorphic system in the absence of external forcing?
3. If a sedimentary sequence that is generated entirely by internal dynamics is analyzed with tools commonly used to search for evidence of orbital forcing, what is the likelihood of incorrectly concluding that it was orbital forcing?

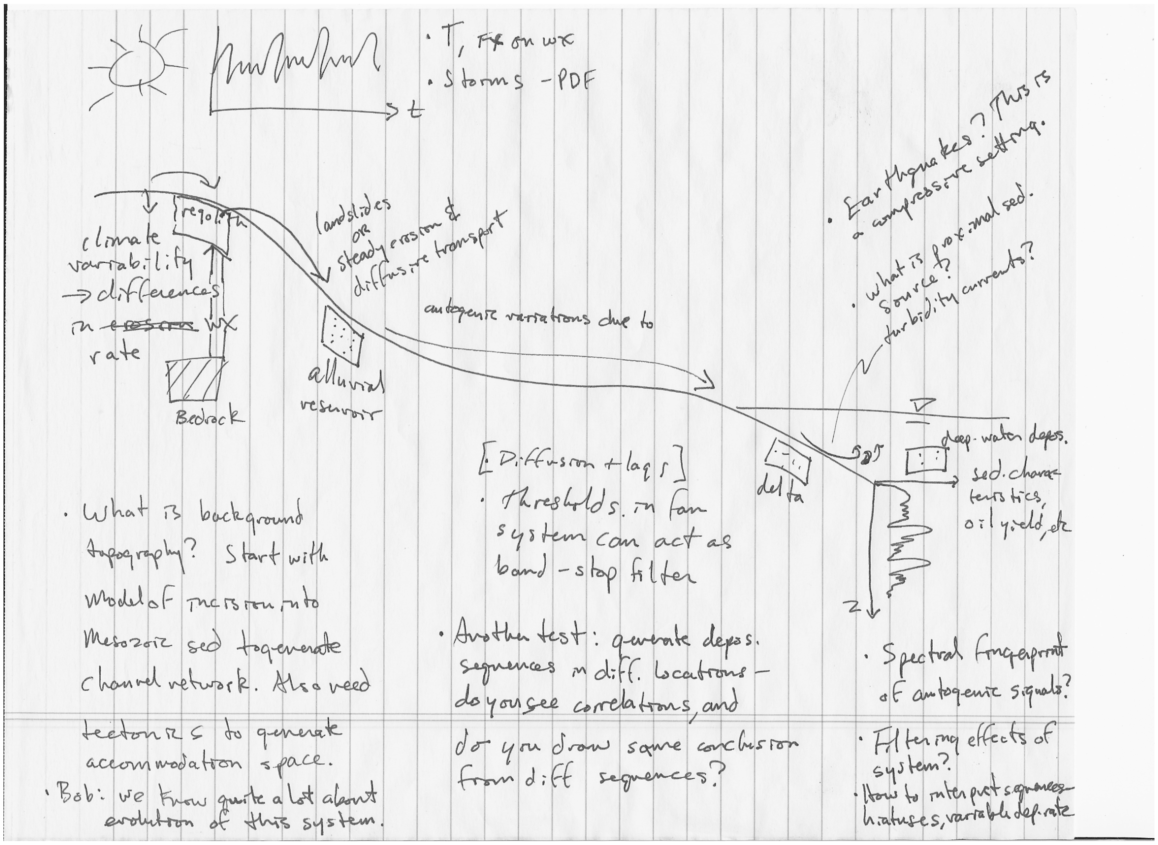


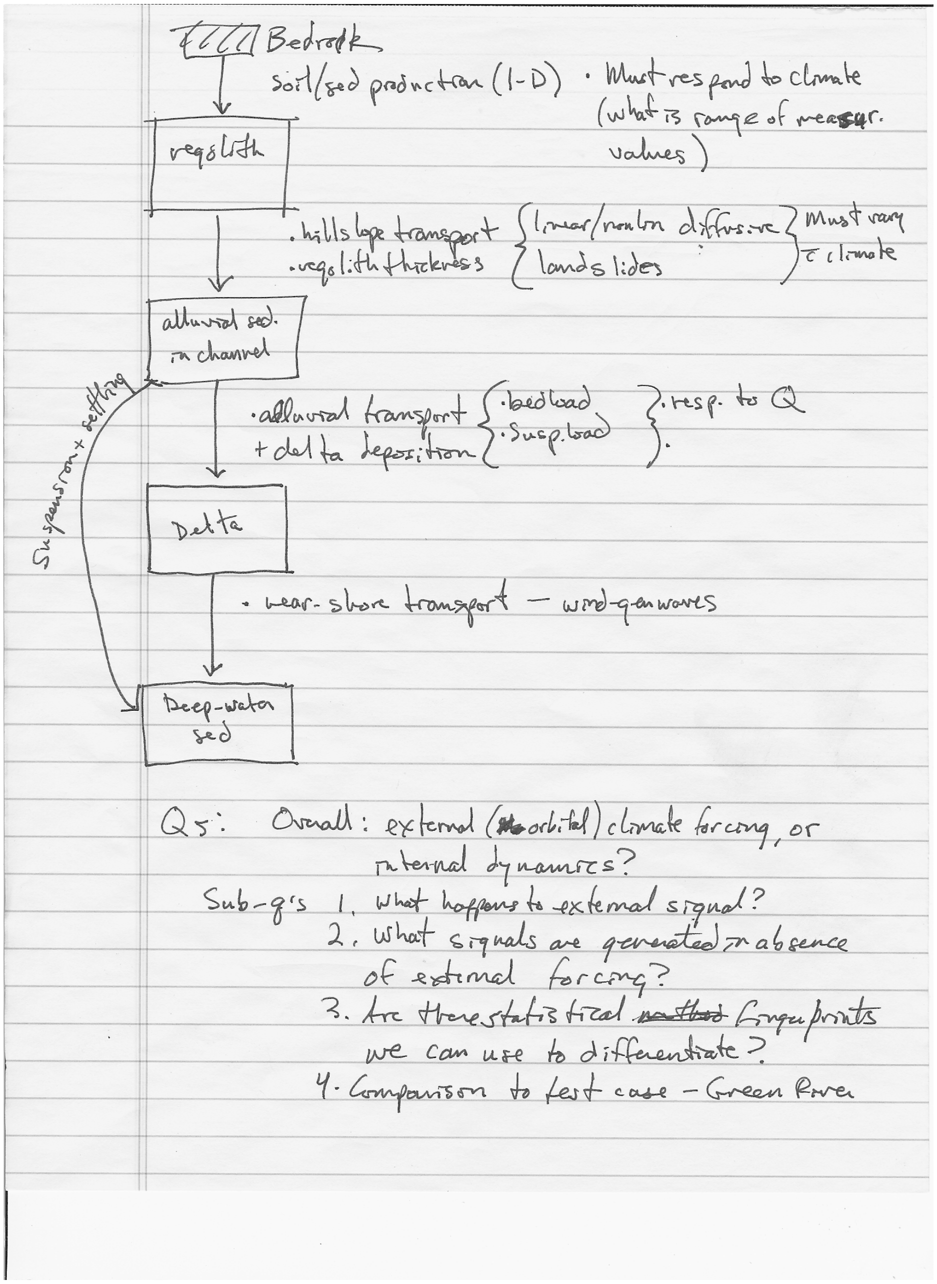
Figure 1: How do climate and surface processes generate rhythmic stratigraphy?

One suitable test case is the genesis of the ~40 Myr old Green River Formation in Wyoming, a mixed carbonate and siliciclastic sequence that formed in a large lake, and that has previously been suggested to record quasi-periodic, orbitally forced climate variability (e.g., Machlus et al., 2008). The Green River Formation is a scaled-down "source to sink" system with a well-studied depositional record. Geochronologic efforts currently underway promise to improve the control on the timing of sequence formation (S. Bowring, personal communication), so there will be a good observational dataset to compare with the output of a surface process model. CSDMS resources and products that could be brought to bear on this problem include:

1. A framework for coupling hydrologic and terrestrial models to predict how variable hydrologic forcing would influence the production and transport of sediment (this echoes research problem #2 above).
2. A framework for coupling models of different terrestrial processes to predict how an exernal signal such as climate-driven hydrologic forcing would propagate through hillslopes and channels, and how these terrestrial processes might generate internal signals (Figure 2).

3. Tools for coupling terrestrial, coastal, and carbonate models to predict how sediment inputs, hydrologic variables, and climate variables would combine to generate the stratigraphy of the Green River Formation.

The modeled stratigraphy could be analyzed with the same time series analysis methods that are applied to real sedimentary sequences to test for the presence of orbital signals.



Q5: Overall: external (orbital) climate forcing, or internal dynamics?
Sub-q's 1. What happens to external signal?
2. What signals are generated in absence of external forcing?
3. Are there statistical ~~method~~ fingerprints we can use to differentiate?
4. Comparison to test case – Green River

Figure 2: Modeling the origins of rhythmic stratigraphy, from source to sink.

5. Feedbacks between geomorphology and ecology in rivers

Aquatic ecosystems are widely considered to be under threat in many rivers worldwide, as those rivers respond to anthropogenic and natural changes in flow regime, sediment flux, and grain size. In general, there is a need to predict how changing flow regimes will impact geomorphic properties of a river – such as bed texture and bedforms, channel geometry, and water turbidity – and through these properties influence the habit for fish and other aquatic organisms. For example, changes in the amount and caliber of sediment flowing through a river can impact the spawning habit for salmonid fish. Likewise, as riparian and aquatic ecosystems change, they can potentially impact fluvial processes. A dramatic example is the removal of exotic riparian plant species along the Rio Puerco arroyo in New Mexico, leading to dramatic erosion and downstream sedimentation (Vincent et al., 2009). Moreover, in some cases there are feedback loops between biota, hydraulics, and morphodynamics. For example, herbaceous vegetation along ephemeral streams can dramatically increase roughness and sediment resistance to erosion; the growth of such vegetation is also a function of the local erosion or deposition rate.

Similarly, beaver dams can alter the flow regime of streams, potentially buffering flood waves and altering valley morphology, which in turn influences flood hydraulics and possibly riparian vegetation. This raises some interesting questions: can beavers "heal" channels that have been artificially straightened? Could the introduction of beavers essentially "capture" a significant fraction of spring runoff in valleys, releasing it slowly and thereby partly compensating for earlier snow melt? Is there a threshold crossed such that when a channel is straightened, beavers are no longer able to thrive – either because a straightened channel affords few potential dam sites, or because of loss of riparian forest due to water-table lowering, or both?

Clearly, a rich set of problems exists at the interface between rivers, plants, and animals. Addressing these problems requires robust models of hydraulics and sediment transport. For many problems, it will be necessary to couple these with models of vegetation growth and/or animal habitat.

As an example, one key problem concerns geomorphic controls on salmonid habitat. The widespread decline of salmonid fisheries has prompted substantial investment in research that tries to elucidate the causes and nature of this decline. One significant component is the degradation of their physical habitat in gravel-bed rivers, where geomorphic dynamics are a critical control. Although generally accepted ideas such as the shifting habitat mosaic and intermediate disturbance hypothesis promote the significance of geomorphic dynamics, neither the state-of-the-art nor the industry-standard ecohydraulic models of physical habitat quality for fish incorporate geomorphic dynamics. In these models, the geomorphology is represented as a static topographic boundary condition, and the net or direct effects of sediment transport processes are ignored. One might hypothesize that maintenance of habitat heterogeneity and associated biodiversity is inextricably linked to the nature of geomorphic dynamics. However, due to the timescales over which geomorphic dynamics shape rivers and their habitats, it is difficult to test this idea robustly from strictly a monitoring perspective.

A coupled morphodynamic and ecohydraulic simulation model could provide a viable alternative. However, existing morphodynamic models are not well suited for this problem in that they tend not to accurately or adequately resolve bar-scale morphology in gravel-bed rivers. Thus, there is a need to develop a flexible modeling framework to couple morphodynamic and ecohydraulic models to explore these biomorphodynamic interactions. Such a framework could be used to identify mechanisms and timescales over which geomorphic dynamics play a significant role in determining habitat quality and influencing biodiversity.

A proposal has been submitted to address some of these issues, in particular the development and testing of a 2D riverine morphodynamic model and its application to salmonid habitat quality.

6. Progress on Existing Projects or Ideas

Participants made further progress on proof-of-concept projects already planned or underway, including:

6.1 Two-Way Feedbacks Between Marsh and Barrier-Island Evolution

(Ad Reniers, Laura Moore remotely, Sergio Fagherazzi *in absentia*, Brad Murray facilitating remote input). Building on the results of the previous Working Group meeting, we further discussed the way that couplings between barrier island and marsh evolution can be addressed by coupling existing models. These two environments are likely to be strongly coupled in barrier settings, with marshes depending on barrier sediment to aggrade with sea-level rise and prograde with barrier migration, and islands depending on marsh platforms to trap sediment and mitigate the effects of storm surge or inundation. Promising avenues include coupling a model of cross-shore barrier island evolution (e.g. Geombest) with a model of marsh progradation and aggradation as a function of sea-level rise, sediment supply and basin depth (e.g. the Mariotti and Fagherazzi model), and with an event-scale model of addressing how overwash and sediment transport depend on the width and elevation of a barrier/marsh system (e.g. XBeach). A proposal for such an endeavor is planned.

6.2 Wave Transformations and Coastal Evolution

(Pete Adams and Dylan McNamara) This project involves linking alternate models of wave transformations over continental-shelf bathymetry (including Swan) to models of coastline evolution (initially CEM), to investigate how modeled behaviors, including responses to climate-change scenarios, vary with the degree of wave-propagation-model sophistication, and the degree of shelf-morphology complexity. This project represents a linkage between Marine and Coastal environments.

6.3 Land-Use/Coastal Process Coupling in the Evolution of the Ebro Delta

(Andrew Ashton, Albert Kettner) Depictions of the Ebro river mouth/delta (Spain) going back to Roman times suggest that historical land-use changes (deforestation, then later reforestation and development) have produced striking changes in the state of the coastline, from an indented estuary to a protruding delta that later developed flying spits on both flanks. Linking a terrestrial model (Hydrotrend) to a coastal model (CEM) will allow an exploration of this hypothesis and the associated human influences on coastal environments.

7. Recommendations

7.1 Surface Hydrology Components

A common theme to emerge in a number of the science questions discussed at the workshop is the need for reasonably simple and robust numerical components to solve various forms of the vertically integrated flow equations, so that these may be coupled with components that handle erosion and sediment transport. Requirements include:

- Flexibility (ability for the user to choose among various levels of hydrodynamic approximation, such as steady versus unsteady, kinematic versus dynamic, etc.)
- Computational efficiency
- Ability to handle spatially varying precipitation and/or runoff generation
- Ability to handle wetting/drying
- Ability to handle run-on infiltration
- Application either to whole-watershed models (with a precipitation boundary condition) or to a single river reach (with an upstream inflow boundary condition)

This list of requirements suggests a need for multiple, interchangeable components rather than a single large model. The current model repository lists a number of surface hydrology and hydrodynamic models, including TopoFlow, DHSVM, DR3M, Delft3D, GEOtop, GSSHA, MFDrouting, MFDrouting-Successive, ParFlow, RHESSys, TOPOG, WASH123D, and WEPP (note that this list does not include models in the “no IRF” category). These models vary widely in size, scope, and availability. All but three – TopoFlow, MFDrouting, MFDrouting-Successive – are currently in the “yellow” category, meaning that the source code is not available on the CSDMS repository. TopoFlow is especially promising because Scott Peckham has already re-written it in Python and divided it into a set of independent CSDMS-compliant components. An important test is whether it provides the computational performance required for long-term landscape-evolution simulations (given suitable simplifications in the governing physics), and whether it can be adapted to function with inflow boundary conditions. Also promising for 2D steady flow applications is an iterative algorithm developed by Jon Pelletier (e.g., Blainey and Pelletier, 2007), which converges toward a steady flow solution by sorting according to water-surface height rather than via a traditional (and computationally expensive) finite-difference solution to the 2D flow equations.

We recommend implementing a proof-of-concept project that couples a 2D landscape evolution model such as CHILD, ERODE, SIBERIA, or DELIM with one or more surface hydrology models. A first step is to inventory the hydrologic models, and potentially others not currently listed on the CSDMS web site, to determine whether (a) they meet any or all of the criteria above, and (b) could be developed into CSDMS components. Once components are identified, the following "sensitivity analysis" projects would serve to illustrate the versatility of using CSDMS components to investigate a range of hydrology-landscape interactions:

- Model experiments on the impact of spatially varying rainfall and runoff on erosion and landscape evolution (using, for example, an orographic precipitation distribution, or a random-cascade model of convective storm precipitation)
- Model experiments exploring the morphodynamic evolution of a sand-bed river valley under different flood-frequency scenarios
- Model experiments on the impact of run-on infiltration on the evolution of ephemeral channel networks and/or alluvial fans in an environment dominated by convective storms
- Model experiments on the time history of entrainment and sedimentation in a gravel-bed river channel during the rising and falling limbs of a flood hydrograph
- Model-data comparison in a sand- or gravel-bed river environment with a known discharge history and time-series measurements of bed topography (derived, for example, from ground-based laser scanning)

7.2 A Component-Based Landscape Evolution Model

Most landscape evolution models include code for multiple processes and algorithms, such as hydrology and flow routing, regolith generation, soil creep, landsliding, water erosion and transport, stratigraphy, and tectonic processes. Because different science questions require different sets of physics and different levels of simplifications, there are great advantages to be had in breaking up a landscape evolution code into multiple, interchangeable components. In fact, some LEM codes provide a certain level of flexibility via user-controlled "switches" that allow a user to choose, for example, among alternate hydrology schemes. Yet such flexibility is still limited – for example, one cannot at present easily combine one model's innovative treatment of process X with another model's treatment of process Y. Thus, we recommend that an existing landscape evolution model be divided into a set of interacting component models that can be mixed and matched to generate different configurations. This would go some way toward "a framework for coupling models of different terrestrial processes," as discussed above in the context of cyclic stratigraphy.

7.3 A Generic Terrain Modeling Library

One common ingredient among surface-dynamics models is the fact that all models must represent the earth's surface. A great many models do so by treating surface height as a single-valued function of geographic coordinates, z(x,y). This is true whether the underlying grid system is a regular grid, a triangular lattice, a Voronoi lattice, or some other form of unstructured mesh.

Today's models are typically hard-coded for a particular type of mesh, but in fact it is possible to represent any of a variety of mesh types using a graph-theory based data structure consisting of polygons (model nodes or cells; square in the case of a regular grid) connect by links. Such a data structure could serve as the basis for a generic, object-oriented class library for terrain. A typical component would then require one or more terrain objects as input ports (one might represent topography, while others might represent layers such as water depth and soil thickness). The advantages of such a code base to the model or component developer would be as follows:

- The same algorithms could be used for grids and TINs (for example, finite-volume methods integrate fluxes along links, and involve the same operations regardless of the number of links and polygon edges)
- A user or developer could invoke the power of unstructured meshes without the need to re-invent the necessary computational geometry
- Equipping standard terrain-modeling classes with automatic error checking (such as out-of-bounds indexing) would speed development time
- A common data format would be available for component ports related to spatially distributed data (water depth, wave energy intensity, sediment transport rate, etc., etc.)
- Generic data structures would automatically allow developers or users to assign variables to cell centers or cell boundaries as appropriate. For example, if my_domain is a data object that encodes the size and resolution of a model grid, a line of code like water_depth = new_cell_center_grid(my_domain) would create a grid to represent water depth at the center of each cell, while a line like velocity = new_cell_boundary_grid(my_domain) would create a grid for flow velocities at the interfaces between cells.

We recommend that a prototype of such a class library be developed and tested, in a common language such as Python or C++, and tested by building (1) a very simple and "generic" landscape evolution model, and (2) a finite-volume diffusion-wave shallow-water solver. Combining such a framework with a componentized landscape evolution model would make the resulting model components more general and versatile.

7.4 Priorities for Proof-of-Concept Projects

We recommend that the CSDMS Integration Facility (IF) resources be directed toward the model coupling needed for select, prioritized, proof-of-concept projects—projects that demonstrate the ability to couple models of different environments and/or processes, and which demonstrate the need for such coupling to address new, scientifically compelling and societal relevant questions that could not otherwise be considered. We recommend that the projects described in Section 3—involving couplings between terrestrial and coastal environments and processes, and addressing new questions about the dynamics of deltas which host large human populations and critical economic activities—be prioritized for implementation with the assistance of IF personnel. We also recommend that resources be devoted to implementing and testing an efficient 2D shallow water component for application to ongoing proof-of-concept applications in fluvial dynamics.

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COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

COASTAL AND TERRESTRIAL WORKING GROUPS (WG) JOINT WORKSHOP
THE MILLENNIUM HARVEST HOUSE HOTEL, BOULDER COLORADO
October 26-27, 2009
DAY 1: OCTOBER 26TH AGENDA

Hour	Topic	Presenter(s)	Duration
8:30 AM	Light Breakfast: Gathering	*	*30 min*
9:00 AM	Welcome, and updates On-Line participation (9:00-9:45 AM) Say welcome, and brief plan for morning Go around room with brief introductions James and Q/A GT/ABM: goals of CSDMS, goals of meeting Popup instructions Volunteers for morning Scribe, Timekeeper, PoC Popup Maestro, General Popup Maestro Foreshadow 3 questions	Greg and Brad	*45 min*
9:45 AM	Presentations of Proof of Concept projects underway On-Line participation (9:45-10:30 AM)	Eric, Albert and others	*45 min*
10:30 AM	*Morning Break*	*	*15 min*
10:45 AM	Very short presentations of P. of Concept ideas On-Line participation (10:45-11:45 AM)	Participants	*60 min*
11:45 AM	Discussion, brainstorming, and charge for Tuesday On-Line participation (11:45-12:30 PM) Open discussion Go around room with 3 questions: 1) What can CSDMS do for you? 2) What can you contribute? 3) How would you like to use time on Tuesday?	Greg/Brad	*45 min*
12:30 PM	*Lunch,* very short presentations on CSDMS-related topics	Participants	*90 min*
2:00 PM	Basic code-submission procedures+Q&A On-Line participation (2:00 – 2:45 PM)	Eric	*45min*
2:45PM	Working time; tutorial help with code-submission tasks	*	*165 min*
5:30 PM	End of Day 1		
***			
6:30 PM	*Dinner:* Laudisio Italian Restaurant (303-442-1300; www.laudisio.com)		

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DAY 2: OCTOBER 27TH AGENDA

Hour	Topic	Presenter(s)	Duration
8:30 AM	Light Breakfast: Gathering	*	*30 min*
9:00 AM	Organization of breakout groups	Greg/Brad	*30 min*
9:30 AM	Sub-group meetings	*	*105 min*
11:15 AM	*Morning Break*	*	*15 min*
11:30 AM	Presentations of ideas and progress, discussion On-Line participation (11:30-12:30 PM)	Greg/Brad	*60 min*
12:30 PM	*Lunch:*	*	*60 min*
1:30 PM	In Parallel: *Time for working on/writing about projects (for meeting reports, proposals, etc.)* *Time to work more on model submission for those who need/want it*	*	210 *min*
5:00 PM	Informal Session Ends		

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JOINT WORKSHOP
THE MILLENNIUM HARVEST HOUSE HOTEL, BOULDER COLORADO
October 26-27, 2009

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