Introduction and Roadmap

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Motivation

Understanding the dynamics of landscape evolution is a challenging problem, for two reasons. First, the processes involved are inherently destructive, and therefore the geologic record of landscape development is usually fragmentary. Second, the sculpture of terrain involves a fascinating but complex set of interacting nonlinear processes, and the complexity of the drainage basin "system" often defies intuitive understanding. While challenging, however, the problem is not intractable. Information on landscape history is still preserved in the form of topography itself, and often also in the form of associated sedimentary deposits such as alluvial valley fills. And despite the complexity of geomorphic processes and their interactions, the resultant landforms often exhibit an underlying similarity even under varying geologic and climatic settings.

One of the important challenges in modern geomorphic research is to investigate landscape dynamics by developing simulation models that incorporate the process interactions we observe in nature. This report describes the development of one such model. The Channel-Hillslope Integrated Landscape Development model (CHILD) is a descendant of earlier modeling efforts at the Pennsylvania State University and at MIT, and it incorporates many of the important processes not included in previous models. Its primary near-term purpose is to serve as a quantitative tool for investigating the impact of Quaternary-scale climate change on hillslope, channel, and floodplain evolution in non-glaciated drainage basins. Potential applications of the model range well beyond that immediate goal, however. This report focuses on the theory and implementation of the model itself, and on its application to several theoretical problems that are closely related to the problems of (1) geomorphic responses to environmental change, and (2) the related issue of the relationship between catchment geomorphology and the prehistoric archaeological record. Indeed, a large part of the motivation for developing CHILD has been to develop a better understanding of how the dynamics of hillslope, channel, and floodplain evolution influence the time-space distribution of late Quaternary sediments and their associated archaeological contents (e.g., Johnson, 1998).

The CHILD Model

The CHILD model is designed to simulate the evolution of fluvially-dominated landscapes formed chiefly by physical erosion (thus, it does not include glacial erosion or karst development, for example). It simulates the interaction of two general types of process: “fluvial” processes, a category which encompasses erosion or deposition by runoff cascading across the landscape (including slope wash and channel and rill erosion), and “hillslope” processes, which includes weathering, soil creep, and other slope transport processes. The computer code is written to maximize flexibility and modularity, so that the user is free to formulate the problem in a way that is suitable to the problem at hand, rather than being dictated by the software itself. To this end, the model provides a number of different options for activating or deactivating different processes and/or different formulations of the same process. An additional exciting development is that the modular computer code is designed to essentially decouple the routines that handle terrain representation from those that model processes occurring on the landscape. With the current version of CHILD, the decoupling is not complete, but our hope is that with further development the model will ultimately serve as the basis for a general “programmer’s toolkit” for many different types of environmental modeling applications.

The various components in the model are diagrammed in Figure 1. Some of the important capabilities include:

- Adaptive, irregular mesh: the model uses an irregular finite-difference gridding method based on the model of Braun and Sambridge (1997) to represent the landscape surface. Use of an irregular simulation mesh allows for the incorporation of lateral stream erosion and makes it possible to represent different parts of the landscape at different spatial resolutions. It also eliminates some of the gridding artifacts associated with fixed-grid methods, and opens up the possibility of coupling the model with three-dimensional tectonic deformation models (e.g., strike-slip or thrust faulting). Implementation of the irregular mesh is described in Section IC, "An Object-Oriented Framework for Distributed Hydrologic and Geomorphic Modeling Using Triangulated Irregular Networks."
- Stochastic rainfall forcing: Previous models of landscape evolution have always modeled sediment transport by using a single "effective" rainfall or runoff rate that represents a geomorphic average. CHILD relaxes that assumption by providing the option of stochastic rainfall input. The stochastic rainfall model is described further in Section ID, "A Stochastic Approach to Modeling Drainage Basin Evolution."
- Stream meandering and dynamic remeshing: this is the first landscape evolution model in which the processes of vertical stream erosion and lateral channel migration (meandering) are coupled. Meandering is simulated using a one-dimensional channel migration model embedded within the TIN mesh to allow dynamic point movement, addition, and deletion. The meander model and its incorporation into the TIN framework is described in Sections II-A, "Meandering: A Simple Nonlinear Model," and II-B, "A Nonlinear River Meander Model and its Incorporation in a Landscape Evolution Model" (the latter section constitutes a Ph.D. thesis by Stephen Lancaster). The algorithms for dynamic remeshing are also discussed in Sec-

tion II-B.

- Floodplain (overbank) deposition: the CHILD model includes an implementation of Howard's (1992) diffusion-based overbank sedimentation model, with modifications suitable for a stochastic, 3D framework. The floodplain sedimentation model is discussed in Section II-C, "Simulating Floodplain Dynamics: Implications for Alluvial Stratigraphy and Geoarchaeology."
- Eolian (loess) deposition: the model includes a simple module for wind-driven sedimentation, for application to loessal landscapes such as that of the U.S. Great Plains (Johnson, 1998) and the Loess Plateau of northern China. An example application of the loess deposition model, based on geomorphic data from Fort Riley, Kansas, is presented in Section I-G, "CHILD Eolian Deposition Model."
- Multiple sediment sizes: The CHILD model includes a model for mixed-size sediment transport of sand and gravel fractions. The transport model is reviewed in Section I-F; applications of the same approach within the framework of the GOLEM model are discussed in Sections III-B and III-C.
- Chronostratigraphy and artifact deposition: the CHILD model includes the ability to track the deposition of sediment layers at each point in the landscape. The model tracks the creation time, most recent modification time, and surface exposure age of each layer. Tracking surface exposure age provides a means of simulating geoarchaeological potential, since exposure age effectively represents the length of time during which a deposit is susceptible to input of artifacts at the surface. It also provides a rough proxy for paleosol formation. An example application of these techniques, based on geomorphic data from Wildcat Creek, Fort Riley, Kansas, is presented in Section II-C, "Modeling Floodplain Dynamics and Stratigraphy: Implications

for Geoarchaeology.”

Organization of this Report

This report is divided into four parts. Part I, “CHILD Model Overview and Applications,” describes the basic components of the CHILD model and presents theoretical results based on the model. Section I-B provides an overview of the model’s capabilities and its basic equations and algorithms. Section I-C discusses the data structures and algorithms used to implement the triangulated irregular mesh (this section is a copy of a manuscript in review by G. Tucker, S. Lancaster, N. Gasparini, R. Bras, and S. Rybarczyk). Section I-D discusses the model’s stochastic rainfall module and develops new theoretical results on the role of rainfall variability in controlling long-term rates of erosion. Section I-E develops a simple theory for the interplay between vegetation growth and erosion. (Note that the model described in Section I-E was implemented in an earlier version of CHILD (Version 1.0); because of its experimental nature, the vegetation module is not incorporated in the present version. We hope to develop and test this module further and include it in a subsequent release.) Section I-F briefly reviews the model’s approach to multiple grain-size transport and stratigraphy, and presents examples of both. Section I-G discusses the eolian transport model, with an example in which the model is applied to Forsyth Creek, Fort Riley, Kansas. Finally, Section I-H reviews potential future work, and Section I-J provides a list of references on the CHILD model and its “ancestors.”

Part II, “River Meandering, Floodplain Development, and Geoarchaeology,” focuses on results from the model’s river meandering and floodplain capabilities. Sections II-A and II-B describe the stream meander model and its incorporation into the larger landscape model (the latter section is a reprint of a Ph.D. thesis by Stephen Lancaster). Section II-C describes the model’s floodplain sedimentation, stratigraphy, and geoarchaeology capabilities. This section also includes an example application, based on Wildcat Creek, Fort Riley, in which the model is used to simulate the space-time distribution of alluvial deposits.

In Part III, “Other Applications,” the earlier GOLEM model is applied to two outstanding issues in theoretical geomorphology: (1) the role of hillslope processes and hillslope-channel interactions in controlling drainage density (Section III-A), and (2) the role of grain-size sorting in drainage basin evolution and the phenomenon of downstream fining (Sections III-B and III-C). Section III-A (a reprint of an article by G. Tucker and R. Bras published in Water Resources Research in October, 1998) presents new theoretical results related to drainage density. Sections III-B (a reprint of a masters’ thesis by Nicole Gasparini) and III-C (a preprint of a manuscript by N. Gasparini, G. Tucker, and R. Bras submitted for publication in Geology) present new theoretical results on the origins of downstream fining and the potential role of grain-size adjustment in governing large-scale drainage basin morphology.

Part IV consists of documentation on the CHILD model. Section IV-A is a user’s guide, Section IV-B contains a description of the program design, and Section IV-C is a listing of the C++ code. An electronic copy of the computer code also accompanies this report.

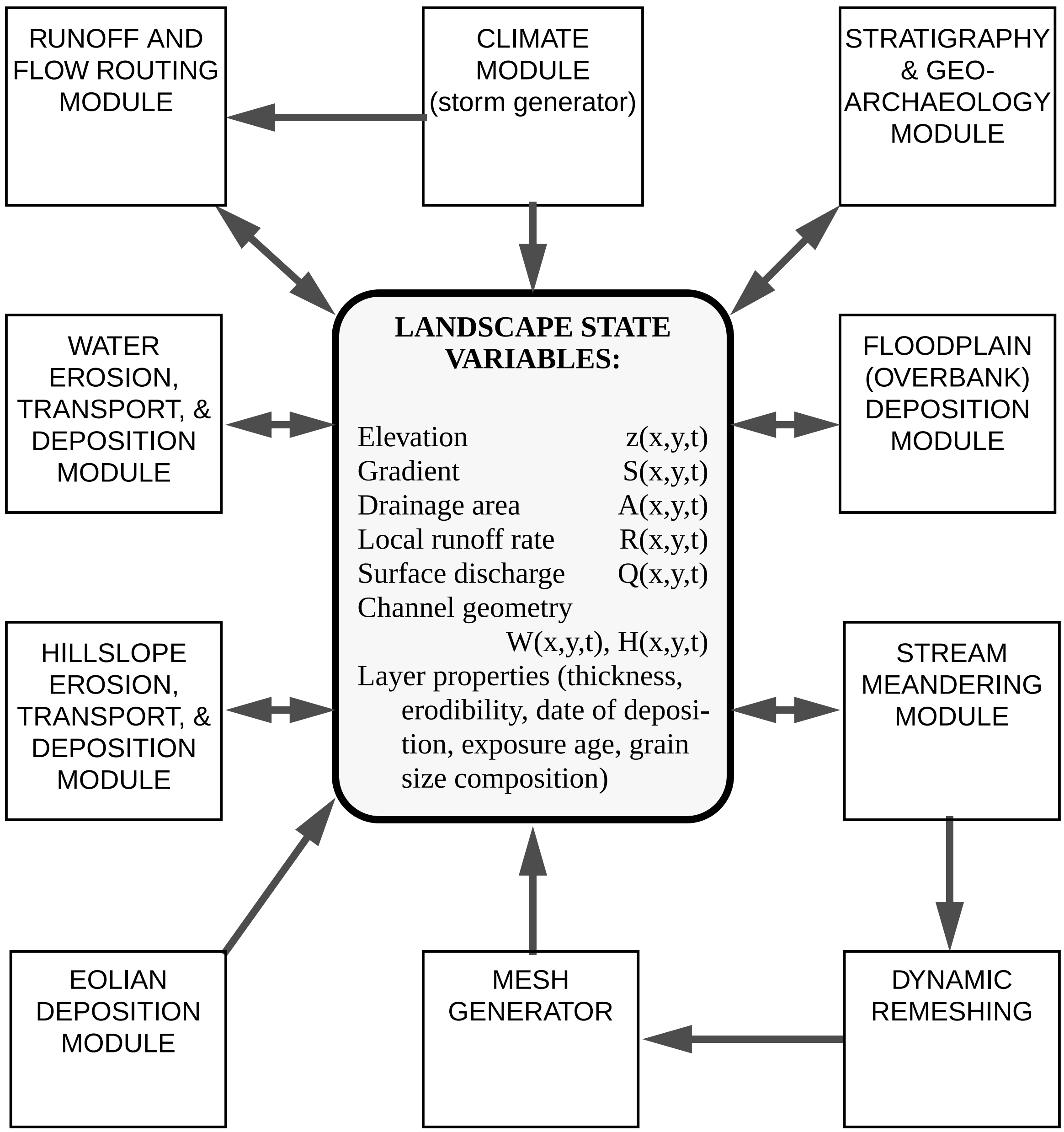

FIGURE 1. Schematic illustration of the state variables and process modules in the CHILD model.

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