You Want Me to Predict What?

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Application of geomorphic landscape models to issues relevant to land management offers geomorphologists opportunities to do interesting, relevant science. But, this type of modeling presents some special concerns. Working in conjunction with managers and policy makers presents the risk of the modelers' expectations coming into conflict with those of managers and policy makers. Geomorphologists must effectively communicate the capabilities and limitations of geomorphic landscape modeling. And, expanding the capabilities of landscape modeling to deal with issues relevant to land management calls for a level of model complexity that landscape modelers have not often embraced. Embracing a certain amount of complexity does not, however, mean constructing a management tool. The primary goal of geomorphologists should always be to advance scientific understanding. A secondary goal should be to adequately communicate relevant results to interested managers and policy makers.

1. INTRODUCTION

Geomorphic models have a wide range of capabilities in terms of prediction, and this range is part of the reason for this volume. *Haff* [1996] pointed out that landscape-scale geomorphic models are fundamentally ill-suited to precise prediction and that reductionism is ill-suited to landscape-scale problems. Geomorphic models run the gamut of spatial and temporal scales and modeling approaches, from linked sediment transport and computational fluid dynamics reductionist models applied to one or two meander bends [*Nelson and Smith*, 1989] to more rules-based landscape evolution models applied to entire orogens [*Tucker and Slingerland*, 1996]. Some problems involve a limited range of processes and scales and, thus, allow more straightforward simulation and precise prediction [*Iverson*, 2000; *Denlinger and Iverson*, 2001]. Landscape-scale geomorphic models, conversely, cannot in general give precise predictions.

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With faster computers, better models, and improved visualization techniques that include realistic, color, 3D, and/or animated graphics, modelers may become overenthusiastic about what they can predict. These enthusiasms may be picked up by or sold to managers, who have many reasons for wanting to know the future. In responding to pressures for answers, managers can imagine real-world uses for the realism they see depicted in such graphics, make connections that are not reasonable, and come to expect predictions of the unpredictable. If modelers are not careful they run the risk of making promises that cannot be fulfilled. Only later, as the enormity of certain promises made sinks in, does the modeler say in exasperation, "You want me to predict what?" Depending on the answer, the modeler may then be placed in the position of either dancing rapidly to meet expectations or backpedaling to dispel them.

As society becomes more interested in geomorphic problems, or as geomorphologists become more interested in societally relevant issues, the geomorphologist faces a risky opportunity. Beyond the opportunity to do research, societally relevant issues offer geomorphologists a certain satisfaction that is rarely found in, e.g., investigations of charm-anticharm asymmetries in high energy photoproduction

[*E687 Collab.*, 1996]. The risks are not always clear at the outset and revolve around the inapplicability of a strictly reductionist approach and the large uncertainties associated with modeling at the landscape scale. Is the science ready to be applied on such a scale? Will the funders be satisfied with the level of "prediction" possible with the model? In incorporating the necessary processes and making the necessary inferences, will the modeler be forced outside the bounds of their science and comfort?

This paper deals with the interaction between geomorphic landscape modeling and the world of policy and management. We attempt to offer a map for negotiating the risks associated with applying models to societally relevant issues in order to support the opportunity for interesting, rigorous science that is also socially relevant. The topics we will discuss fall into two broad categories: communication between geomorphic landscape modelers ("the modeler") and the managers and policy makers interested in and/or funding the research ("the manager"), and particular considerations for the modeler entering this dialogue. Here, we will focus on landscape models, i.e., geomorphic models that combine two or more processes and model them over spaces that are large relative to a single landscape unit. We define a landscape unit as the space needed to define a single process and where that process can be studied in relative isolation, e.g., a single hillslope in the case of diffusive transport or a single channel reach in the case of fluvial transport. Most real-world management problems involve consideration of large spatial scales and multiple processes.

2. SOME BACKGROUND ON OUR PERSPECTIVE

In the Pacific Northwest, forestry has historically been one of the cornerstones of the region's economy. Decades of forest harvest, on both public and private lands, coupled with a changing economic and sociological mix in the region and documented declines in both terrestrial and aquatic species has focused attention on the relationships between forest practices and habitat. The area is geomorphically and tectonically active, and certain geomorphic processes, notably landsliding and debris flows, are sensitive to locations, timing, and rate of timber harvest [*Montgomery et al.*, 2000; *Schmidt et al.*, in press] 2001. Moreover, these geomorphic processes have been shown to play key roles in structuring habitat in low- to middle-order sized channels [*Lisle*, 1986; *Bilby and Ward*, 1989; *Reeves et al.*, 1993; *Montgomery et al*., 1995; *Massong and Montgomery*, 2000]. Both public and private land managers must therefore consider the linkages among forest practices, including both harvest and road construction, geomorphic processes and aquatic habitat. The complex nature of these linkages results in a dialogue between managers and policy makers and scientists. From the managers' perspective, this dialogue is focused on identifying consequences of past, present, and forseeable future actions. Typical questions include: "We have implemented this policy to protect fish—will it actually help? Does it matter where or when I cut trees or build roads? How much of my landscape needs to be protected in some fashion in order to diminish risks to key populations of organisms?" Such questions can be associated with both support for research and expectations of useful results.

From the perspective of the scientists involved, however, the concerns of managers and policy makers are usually recast into a somewhat different and more fundamental set of questions, with the most fundamental being: "What are the linkages among the forest processes, debris flows, and sediment and wood dynamics in streams?" These relationships are complex and vary over spatial and temporal scales. Understanding them requires analytical and modeling tools that incorporate space, time, and landscape history in order to make first-order predictions about locations, rates, and fates of sediment and wood in response to changing hillslope conditions [*Benda and Dunne*, 1997a,b; *Lancaster et al.*, 2001]. For the scientist willing to construct models as part of their role in the dialogue, the specific questions faced become: "How can I best represent the complex dynamics of geomorphic processes over large spatial and long time scales? What type of modeling approach is likely to yield useful results while staying faithful to both scientific knowns and unknowns?

Because managers and modelers are asking different questions of themselves and each other, it is useful to consider the different world views that each group represents. The success or failure of the dialogue between managers and modelers often rests with how well each group understands the inherent motivations and limitations of the other's perspective.

3. CONTRASTS BETWEEN MODELER AND MANAGER

Modelers and managers may have contrasting views of models and their utility. This section outlines some of those contrasts.

3.1 Contrasting Views and Motivations

Managers are motivated to ask questions by laws, economics, and ecological considerations, and those questions can be constrained by their institutional culture. For forest managers this may reduce to, "What should I cut *vs.* protect? How much is too much? Do timing and spatial pattern matter?" Models designed for managers in this context essentially amount to operational accounting tools. Management models are fundamentally focused on scheduling things, such as harvests, in time and space to meet agreed-upon constraints, which may include legally mandated or institutionally acceptable thresholds or limits. Historically, such limits included constraints such as the Congressionally mandated "allowable cut" or market factors. Other limits involve interpretation of unacceptable geomorphic or ecosystem conditions. For decades, for example, to reduce risks of downstream hydrologic effects, the Forest Service in western Oregon has limited the amount of cutting on National Forests so that the percent of basin area in young "hydrologically immature" forest stands is less than an accepted threshold value [*Grant*, 1990].

While such operational models can easily incorporate such *a priori* thresholds, they are generally not good at evaluating or interpreting consequences, particularly where such consequences are dynamic and change over the timescales of implementation of management actions.The primary scheduling model used by the Forest Service through the 1980's to dictate rates and locations of cutting on Federal lands (FORPLAN), for example, was not spatially explicit (i.e., it treated forests of the same stand type and age similarly regardless of location), and did not evaluate the consequences of either the rate of harvest or resulting forest pattern on key organisms, such as endangered spotted owls, marbeled murrelets, or salmon runs [*Johnson*, 1987; *Milne*, 1987]. As a result, a series of court cases halted all logging on Federal lands, leading to development of the Northwest Forest Plan [*Johnson et al.*, 1999].

In contrast, scientists are motivated to ask questions by curiosity, novelty, and, increasingly, applicability and relevance to societal issues. For geomorphologists this essentially comes down to, "How does this work? Does the model agree with field observations? Is it a big number or a little number?" Geomorphic landscape models are primarily focused on the often complex consequences to landforms or process rates of interactions among multiple processes at multiple scales. While these geomorphic consequences may have management implications, this focus on dynamics, complexities, and nonlinearities, often limits precise predictions of how much, where, and when.

Many managers do not have extensive experience with either using or interpreting complex models. To the extent that managers have any experience with models, they will likely be (a) accounting tools or (b) engineering models. The first may involve geographic information systems (GIS) that depict landscape conditions in response to predictable actions or events, e.g., harvest patterns. The second may make a precise prediction, e.g., of failure or not, and include a factor of safety to incorporate uncertainty [*Haff*, 1996]. The manager will have very little experience with basic scientific models. As pointed out by *Haff* [1996], geomorphic landscape models have large uncertainties and may be poorly suited to the kind of precise or even factor-of-safety-type prediction given by engineering models, though some are making notable efforts to calibrate landscape models to real landscapes and apply those models to engineering solutions [*Willgoose and Riley*, 1998; *Evans et al.*, 2000; *Evans and Willgoose*, 2000; *Hancock et al.*, 2000].

3.2 Contrasting Modeling Approaches

Geomorphic landscape models are computational and, therefore, require specific, quantitatively defined assumptions that effectively isolate and enumerate the modeler's opinions and perspective. This quantitative basis is in contrast with the "expert opinion" models common to ecology. For the Northwest Forest Plan [*FEMAT*, 1993], for example, scientists were asked for advice with respect to management prescriptions such as required riparian buffers. The questions were quite broadly defined, e.g., how should forestry practices be altered to conserve aquatic habitat, time was short, and the answers were given in the form of hypothetical curves representing, e.g., the cumulative "effectiveness" of the riparian forest, *vis-à-vis* root strength, litter fall, shading, and coarse wood contribution, as functions of distance from the channel measured in tree heights [*FEMAT* 1993, p. V-27]. These curves were based on little data or, in some cases, only expert opinion. The implemented policy-based partly on these hypothetical curves, mandated extensive riparian reserves on federal lands, effectively halting logging on these lands in the Oregon Coast Range. Although such "expert models" have had substantial impact on policy, their underlying assumptions have never been rigorously examined [*CH2M-Hill and Western Watershed Analysts*, 1999].

Decision models based on knowledge bases and fuzzy logic, such as the Ecosystem Management Decision-Support (EMDS) system [*Reynolds*, 2001], are an improvement on the above scenario because assumptions and the weights assigned to different facts and measurements are stated explicitly and allow critical assessment of the factors leading to decisions, e.g., of assumed or inferred interactions between physical and biological watershed and stream characteristics [*Reynolds and Peets*, 2001]. But these models do not really provide any new information. Rather, they are frameworks for incorporation of assumptions, conceptual and quantitative models, restrictions, resources, and other information into the decision-making process. Although the EMDS system might potentially provide a means for incorporating predictive results of geomorphic landscape models into management decisionmaking, it is not in itself a predictive model.

In contrast, landscape-level geomorphic models (also known as landscape evolution models) generally have several properties that distinguish them from management models. Typically they are time-evolving, spatially distributed and interactive, and involve coupled processes. They are also potentially, though not easily, testable. Although some of the newest generation of landscape simulation models for managers are beginning to display some of these characteristics (e.g., *Spies et al.*, in press), such models are not widely available or used.

4. GEOMORPHIC LANDSCAPE MODELS

Here we consider some salient characteristics of geomorphic landscape models relevant to their application to management/policy issues. Scientists must communicate both the capabilities and limitations of any modeling study that is applied to policy issues. Geomorphic landscape models include a specific set of processes and their interactions and simulate their time evolution over a relatively large spatial domain. This capability is quite powerful, particularly for evaluating management scenarios over broad scales. At the same time, such models are subject to both quantitative and qualitative uncertainties, have limitations with respect to scale, and suffer from incomplete knowledge of history and initial conditions. Some aspects of the model may be testable while others are not.

4.1 Capabilities

Landscape evolution models are, by their nature, time-evolving. Simulations can represent a span of time rather than simply some typical or average time. This is a powerful capability when dealing with time-varying and stochastic phenomena. Landscape evolution and other geomorphic models have in the past often used the concept of a dominant discharge or climate regime [*Willgoose et al.*, 1991a,b] and have, therefore, been poorly equipped to deal with issues surrounding variations in precipitation, discharge, and other forcing functions. Newer models have shown that stochastic inputs can have a profound impact on, e.g., sediment storage [*Benda and Dunne*, 1997a,b; *Lancaster et al.*, 2001] and even stream gradient [*Tucker et al.*, 2001b]. This new generation of landscape models has the potential to quantify time variations of, e.g., sediment output, in response to stochastically variable inputs, e.g., precipitation and fire [*Benda and Dunne*, 1997a,b; *Lancaster et al.*, 2001]. Accounting for such variation is important because land managers need to assess landscapes and streams with respect to some fixed standard. Should we expect, say, the amount of sediment in a stream to vary much over time? If so, what fraction of time will that amount be above or below a standard amount that relates to its suitability for fish spawning habitat? Unlike static, GIS-based inventory-type models, geomorphic landscape models have the potential to address these questions.

Geomorphic landscape models are spatially distributed because they simulate a whole drainage basin or landscape rather than just a typical or average site. This capability is important because we expect that some landscape attributes vary spatially. For example, *Gasparini et al.* [1999] showed that surface sediment composition in a drainage basin varied systematically downstream when mixed-size sediment and transport were incorporated in a landscape evolution model with spatially and temporally homogeneous climatic, tectonic, and parent material inputs. *Lancaster et al.* [2001] showed that spatially variable debris flow inputs could lead to persistent local variations in valley sediment storage. Simulations that show spatial heterogeneity as the result of geomorphic processes can illustrate and quantify for managers whether a spatially uniform standard is appropriate.

Landscape evolution models are spatially interactive. That is, processes and phenomena in one part of the landscape can influence processes and phenomena in another part of the landscape. For example, a forest fire in one part of the landscape may lead to increased sediment volume in a downstream reach where the adjacent forest did not burn [*Benda and Dunne*, 1997a,b]. Or, an upstream sediment-trapping wood dam might lead to sediment starvation of a downstream reach [*Hogan et al.*, 1998; *Lancaster et al.*, 2001]. Spatially explicit, dynamic geomorphic models have the potential to show the effects of, say, forest practices in one part of the landscape on the rest of the landscape. For example, managers in the Pacific Northwest have attempted to increase sediment retention and improve fish habitat in some stream reaches with engineered log jams [*Abbe and Montgomery*, 1996; *Abbe et al.*, 1997]. Landscape models could indicate whether such changes in sediment retention in some parts of the stream network might affect sediment supply to and retention in other parts of the network [*Lancaster et al.*, 2001].

Landscape evolution models allow simulation of process interaction. Inclusion of what the modeler believes to be all important processes active in a landscape allows detection of unforeseen interactions and possible optimalities. Recent simulations with the model of *Lancaster et al.* [2001] showed that the presence or absence of forest wood could have a large effect on the distribution of debris flow runout lengths (S.T. Lancaster, unpublished results, 2002). This kind of modeling could be used to assess the effect of different riparian buffer prescriptions on debris flow runout lengths. For example, is an extensive but thin buffer prefer-able, in terms of minimizing effects on debris flows, to a wider but more limited buffer?

Because geomorphic landscape models are based on quantitative representations of processes, these models are, at least in part, quantitatively testable. A problem with all long-term landscape predictions is that such predictions cannot be truly verified. We can however, quantitatively test both our understanding of component process submodels, such as soil production [*Heimsath et al.*, 2001] and linear or non-linear diffusion [*Roering et al.*, 1999], and the realism of model outputs, such as debris flow runout lengths and sediment storage volumes [*Lancaster et al.*, 2001] and even drainage network morphology [*Moglen and Bras*, 1995; *Hancock and Willgoose*, 2001]. Although limited, such testing is only possible when models are based on quantifiable, measurable phenomena. A model based only on qualitative understanding or opinion, such as in the *FEMAT* [1993] example, cannot be tested in any real sense.

4.2 Limitations

The processes and parameterizations making up a geomorphic landscape model are, first of all, subject to simple quantitative uncertainty, i.e., the kind of uncertainty that is usually represented by error bars or, in engineering applications, a factor of safety [*Haff*, 1996]. These uncertainties can be due to measurement error, spatial heterogeneity, and approximation (e.g., linearization). The propagation of such errors in landscape models with many interacting processes may not be straightforward and must, therefore, be explicated by sensitivity analyses. Given that landscape models are often computationally demanding, exhaustive sensitivity analyses are often infeasible. To paraphrase G.E. Tucker (Oxford University, personal communication, 2001), as our models become more complex we run the risk of having two things we don't understand: nature and the model itself. We address this issue later.

Perhaps more important than the above quantitative uncertainties is that in geomorphic models the processes and their interactions may not be well understood. For example, the model might include one kind of mechanism (e.g., shallow landsliding) under conditions that could produce another kind of mechanism (e.g., deep-seated landsliding). Even when processes are well understood, their descriptions must often be simplified in order to operate within landscape models. Model predictions are likely sensitive to both the processes included and how they are simplified. As an example of this sensitivity, consider the case of two models that simulate forest fires, landslides, debris flows, and sediment transport at the landscape scale. The model of *Benda and Dunne* [1997a,b] assumes that sediment introduced to the stream network by debris flows travels at a constant speed downstream. This assumption results in sediment waves that evacuate sediment from headwater streams relatively quickly (years). Larger streams can have more persistent sediment accumulations or not depending largely on network structure and the timing of sediment waves arriving from upstream [*Jacobson*, 1995]. The model of *Lancaster et al.* [2001] assumes that sediment introduced to the stream network by debris flows is transported according to a power-law of discharge and stream gradient. This assumption results in relatively persistent but spatially heterogeneous sediment accumulations in headwater streams because deposits reduce upstream gradients and, thus, transport capacity. Larger streams receive a relatively constant supply of sediment from headwater streams because the persistent headwater deposits are released slowly. Although the two models might look very similar to a non-geomorphologist because they include similar suites of processes and differ only in the details of, e.g., sediment migration, the models' predictions might have very different management implications. The results of *Benda and Dunne* [1997a,b], on the one hand, could imply that some optimal pattern of disturbance, e.g., forest harvest, in headwater basins might be the best way for management to achieve a relatively constant sediment supply to fish-bearing streams. On the other hand, the results of *Lancaster et al.* [2001] could imply that retention of large wood in riparian zones is necessary to provide the kind of chronic sediment supply found in the natural system.

Landscape evolution models often have significant scale limitations. First, landscape models usually cannot resolve fine-scale stream and landscape characteristics. For example, a model that simulates sediment transport on the channel network scale will probably not resolve channel features such as distributions of pools and bars. Unfortunately, managers often care most about such features because they are most directly related to aquatic habitat. Conversely, models that are more detailed in their representation of landscapes and processes will be limited to smaller domains. Unfortunately, smaller domains limit the model's ability to reproduce process interactions over the full domain that is required for management decisions. The modeler must therefore negotiate a balance between detail and domain size. One option is to build nested models. For example, if detailed modeling at the reach scale is required, then sediment fluxes derived from large-domain models might be used to forecast mean changes in the details of smaller domains. Or, if knowledge at even larger domains is required, then those sediment fluxes could be included in models for examination of sediment dynamics in larger basins.

As *Haff* [1996] pointed out, geomorphic landscape models are often sensitive to initial conditions. These initial conditions are seldom well known even when modeling present conditions.

This sensitivity means that geomorphic landscape models are usually not well suited to reproducing actual events. For example, in 1996 the Oregon Coast Range experienced two major storms. These storms triggered many debris flows, which impacted much potential fish habitat and resulted in several human fatalities. It would be nice if geomorphic landscape models could provide alternative reconstructions of these storms' effects, e.g., given different harvest patterns. Unfortunately, the sensitivity of landscape models to initial conditions, such as soil depths, vegetation, and antecedent soil moisture, precludes such an application, even if we knew the spatial distribution of rainfall during the storms.

As noted above, though the quantitative basis of geomorphic landscape models allows some testability, these models are often, by their nature, not verifiable for several reasons. First, because the models are not well suited to historical reconstruction, simulation results are not directly comparable to, e.g., present conditions. Even if they were, though, the spatial extent of the comparison would be infeasible. Finally, because landscape simulations usually span times that are large relative to human lifetimes, true verification is often impossible.

In the end, the geomorphic modeler must simply decide what the essential, relevant processes are and the simplest feasible ways to represent those processes. Although this may not resolve to the same spatial scale at which management decisions are needed, one potential means of resolving this discrepancy is to use the complex geomorphic models to explore system behavior under different sets of assumptions, and then abstract these results into a set of "rules" or "principles" that could be used to guide decision-making at larger scales. For example, although it may be impossible due to computational or data limitations to predict or even simulate movement of wood or sediment through stream systems for large landscapes, it may be possible to use the models to distinguish "big" numbers from "little" numbers in terms of how much of a change in land use or climate is required to influence wood or sediment fluxes. The difference between "big" and "little" could then be codified in management practices or thinking. To extend the example, managers could use model runs to help establish "threshold" values for wood loading required to maintain or restore certain types of channel habitat. The models would not give these thresholds directly, but may well be able to distinguish at what level of riparian stand protection wood loadings actually increase significantly over time. To date there have been few examples of this sort of "hand off" between geomorphic and management models, but it represents a potentially lucrative arena for future work.

Better understanding of the limitations of geomorphic models would not necessarily lead to better decisions on the part of decision-makers but would help constrain the realm of the possible with respect to model applications. At a minimum it would dispel the illusion (often fed by enthusiastic modelers) of actual predictive capability. Better understanding would promote more of a sense of "tradeoff space" among alternatives, risks, and potential landscape conditions rather than rigid predictions (or prophesies, *sensu Beven*, 1993) of the future.

5. CONSIDERATIONS FOR MODEL CONSTRUCTION

Application of geomorphic landscape models to management-relevant scenarios requires some special considerations in terms of model construction. Some of these considerations may also be relevant to other types of applications.

The line between sufficient complexity and feasible simplicity is always difficult to walk, but it is especially so when applying models to management-related scenarios. The model must be complex enough to be relevant to the problem at hand. Especially when the management concern is related to process linkages, e.g., between geomorphology and the eco-system, the modeler is forced to construct a relatively complicated model even to address these linkages in a simple way. But, the model must also be "doable" on the most basic levels, i.e., constructible during the time allowed, communicable through the literature, and comprehensible to the modeler, the manager, and the geomorphological community at large.

Scientists generally prefer to thoroughly understand simpler systems before proceeding to more complex ones. In landscape evolution modeling this preference has led to models that lack much of the complexity of real landscapes. Modeled landscapes can be made to resemble real ones by using emergent rules rather than reductionist physics and calibrating the models to the landscapes [*Moglen and Bras*, 1995]. In this way, the model can use simple rules and neglect many of the complications introduced by geology, biology, climate, and geomorphic processes. But, the questions posed by managers usually involve the effects of changes in those complicating factors. Of particular interest to managers in the Pacific Northwest is vegetation and its interaction with geomorphic processes in the landscape. Some authors have begun to address vegetation in landscape models [*Howard*, 1999; *Evans and Willgoose*, 2000; *Collins et al.*, 2001; *Lancaster et al.*, 2001], and these studies show that the interaction between vegetation and geomorphic processes can indeed have profound consequences. Including the complicating effects of, for example, multiple processes

[*Gasparini et al.*, 1999; *Tucker et al.*, 2001a,b] or vegetation leads directly to the double-edged sword of, on one side, over-simplification of the component processes and, on the other side, over-complication of the integrated model. The component processes must usually be simplified in order to be feasibly incorporated, as in the familiar case of substituting a power law of discharge and slope for a more complicated and realistic sediment transport model. In the case of vegetation, it is probably infeasible to track and simulate the life cycle of each plant. Rather, it is sufficient to model only the features and characteristics of vegetation that interact with geomorphic processes, such as the resistance of grassy vegetation to erosion by overland flow [*Howard*, 1999; *Evans and Willgoose*, 2000; *Collins et al.*, 2001], the strength of roots with respect to slope failure [*Benda and Dunne*, 1997a; *Montgomery et al.*, 2000; *Lancaster et al.*, 2001], and the effect of biomass on mass movements and fluvial sediment transport [*Lancaster et al.*, 2001].

Ideally, the management or policy initiative provides the question and defines the necessary model. Worth considering is why a particular model might not exist. Possible reasons include: (1) All the processes are well understood and described by current models that could be conveniently combined, but nobody has thought of combining them into a landscape model. (2) At least some of the processes are not well enough understood or even fully identified, much less described by models that could be conveniently combined, The first possibility is a rare case: if it were easy, someone would have done it. The second possibility is common. Developing such a model almost always requires some innovation beyond the brute force of putting existing pieces together. In building the model, the modeler must reconcile the wishes of the manager with the demands of model feasibility and scientific pursuit to yield the spatio-temporal scales to be simulated and the output information. This reconciliation probably must occur at multiple stages in the model development through iterative adjustment to management and scientific objectives. It is also important to prioritize modeling goals and explicitly recognize which might be sacrificed. For example, which is more important, modeling a large area or including relevant processes, interactions, and sensitivities? Here again, nested models could be used. A landscape modeler might not consider making a fine-resolution model if working only in the science realm but would do so in a management context in order to provide the ability to locally interpret the coarse-resolution model output, wherein the local interpretation would likely be for an average or typical local setting. For example, empirical models might provide a relationship between management-relevant indices, such as pool density and other channel characteristics, and variables simulated by the model such as sediment and wood volumes or depths (e.g., *Montgomery et al.*, 1995).

6. COMMUNICATION BETWEEN MODELERS AND MANAGERS

6.1 Expectations

Prior to and during the modeling exercise, it is important to recognize and address expectations of both modeler and manager in order to assure that the modeler will be satisfied with and interested in the science and the manager will be satisfied with and interested in its implications.

It is important to keep expectations of both modeler and manager reasonable from the start. Here, the burden is on the modeler to develop a reasonable set of goals and expectations and to communicate those to the manager, i.e., what can a geomorphic landscape model do in the case at hand and what are its limitations, as addressed in the previous section.

Developing geomorphic models for application to management- and policy-related scenarios offers an excellent opportunity to further scientific understanding, but both modeler and manager need to understand at the outset that their perspectives or goals may differ. The science should be relevant to management/policy, but the model will probably not immediately be a management tool, i.e., a landscape model with a user-friendly graphical user interface and real-time animation of results that is designed specifically for, and limited to, some practical application. Building such a tool is usually beyond the scope of basic scientific research.

At the same time, and whether the manager or policy maker is actually funding the research or not, relevant science is only relevant when it is sufficiently communicated to those who should care. A great deal of the satisfaction that arises from doing relevant science is from actually making a difference in the way managers and policy makers treat the landscape (though it is important to remember that many decisions are necessarily made for social and political reasons rather than scientific ones).

So, the modeler should take every opportunity to communicate relevant results and highlight their importance. This communication is different from “hype” and marketing because the modeler must be clear, again, about what the modeling can and cannot do. This does not mean raising the hood and pointing out every frayed wire. Rather, it simply means being very clear about the legitimate and reasonable implications of the modeling results.

An important part of expectation and communication is explaining the modeling alternatives. Sometimes, no model may be appropriate and money should be spent on monitoring. Sometimes, a different model may be more appropriate—it might even be just a curve, based on intuition and expert knowledge, drawn on a graph with no numbers on the axes, as in the *FEMAT* [1993] example.

6.2 An Example From CLAMS

We draw on an example from the Coastal Landscape Analysis and Modeling Study (CLAMS) to examine how a reasonable set of management expectations might be developed by modelers and managers working together. Geomorphic modeling in CLAMS is described in *Wilcock et al.* [this volume]; here we focus on how results from the detailed geomorphic model of *Lancaster et al.* [2001] might actually be communicated to managers.

Briefly, the geomorphic model of *Lancaster et al.* [2001] predicts landslide initiation, debris flow runout, and channel evolution in response to forest growth and death, precipitation, wind, fire, and forest harvest. The model is physically-based in the sense that relevant geomorphic processes are driven by conservation of mass, momentum, and energy, but many simplifying assumptions are necessary in order to achieve parsimony in computational speed and spatial extent. Neither the spatial nor temporal scales of the model are congruent with typical management space or time scales. The model is currently parameterized for a small (200 ha) watershed in the Oregon Coast Range, smaller than the typical basin scale of “watershed analysis” or land management planning, and much smaller than the million ha CLAMS analysis area [*Ohmann and Gregory*, 2002], which includes most of the Oregon Coast Range.

So how can this model be relevant to land managers? Although the model is still in the prototype stage and is not predictive in the sense that it tells managers where or when something is likely to occur, it could offer managers a means of testing basic assumptions about landscape performance that are quite topical and relevant to current management decisions. For example, a critical question facing managers on both public and private lands is what extent of stream network merits protection through riparian reserves or “no-cut” areas bordering streams. This issue is critically important, because, in an area with as great a drainage density as the Oregon Coast Range (~ 4 km/km^2), even small changes in the length of streams protected, or the width of the protection zone have major consequences for the total area of landscape in reserve status. Model simulations could test alternative protection strategies focusing on which streams are protected (e.g., protect all headwater streams, protect only those streams below likely landslide initiation sites, or protect only streams larger than a critical drainage area) and the width of the protection zone (i.e., defined by channel widths or tree heights) on wood loading levels and debris flow runout lengths. In this example, the model would be used not to directly address how much of the network requires protection (a management question), but to assess the effects different strategies might have on key parameters of interest (a hybrid management/science question). Work on this application is continuing, and we are striving to communicate confidence not in the absolute magnitude of the results but in the ability of the model to distinguish big effects from smaller effects. We maintain that this is the appropriate role for complex models such as these in guiding management decisions.

7. CONCLUSION

Management/policy issues can offer geomorphologists interesting questions and the opportunity to answer them, but that opportunity is not without risks. Managers and policy makers, in general, have different motivations and views of model utility than do scientists and, in particular, geomorphologists. In addition, managers’ preconceptions of modeling capabilities, based largely on scheduling and engineering models, and unfamiliarity with geomorphic landscape models may lead to inappropriate expectations of the latter. Geomorphologic modelers involved in scientific investigations of management- and policy-relevant issues bear the responsibility of communicating their models’ capabilities and limitations to managers and policy makers and, thereby, maintaining realistic expectations.

For managers, the advantages of geomorphic landscape modeling are its capabilities for simulating time-evolving, spatially distributed and interactive, coupled processes and their interactions. These models also have the advantage of some, albeit limited, testability. The disadvantages of such models are, of course, their limitations, including both quantitative and qualitative uncertainties, limited spatial domain sizes, potential sensitivity to poorly known initial conditions, and limited testability.

In balance, we believe that, even for unwary modelers, the benefits of scientific opportunity and societal relevance outweigh the risks of managers’ persistent preconceptions and resulting inappropriate expectations, although these risks are best mediated by proper communication. Likewise, we believe that the capabilities of geomorphic landscape models could make them invaluable to managers faced with complex issues, even if these models cannot answer questions with the kind of specificity to which managers might be accustomed.

For successful interaction, both modeler and manager must typically adjust their methods and expectations. For the modeler, adequately representing real-world complexity will likely present the risk of developing an over-complicated model with over-simplified process components. The modeler may face the additional task of developing nested models in order to use landscape-scale model output to address managers' concerns at the scale of stream reaches. For the manager, utilizing the modeler's results will likely necessitate restatement of the former's questions, from specific questions of quantity and location to more general questions of degree, extent, and implications of impacts of management prescriptions. Finally, good communication and common understanding of the model's strengths, weaknesses, and appropriate applications provide the basis for judicious model use consistent with the model's capabilities.

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REFERENCES

Abbe, T.B., and D.R. Montgomery, Large woody debris jams, channel hydraulics and habitat formation in large rivers, *Reg. Rivers: Res. Mgmt.*, *12*, 201-221, 1996.

Abbe, T.B., D.R. Montgomery, and C. Petroff, Design of stable in-channel wood debris structures for bank protection and habitat restoration: An example from the Cowlitz River, WA, in *Management of Landscapes Disturbed by Channel Incision*, edited by S.Y. Wang, E. J. Langendoen, and F.D. Shields, Jr., pp. 809-815, University of Mississippi, 1997.

Benda, L.E., and T. Dunne, Stochastic forcing of sediment supply to channel networks from landsliding and debris flow, *Water Resour. Res.*, *33*(12), 2849-2863, 1997a.

Benda, L.E., and T. Dunne, Stochastic forcing of sediment routing and storage in channel networks, *Water Resour. Res.*, *33*(12), 2865-2880, 1997b.

Beven, K.J., Prophecy, reality and uncertainty in distributed hydrological modelling, *Adv. Water. Res.*, 16(1), 41-51, 1993.

Bilby, R.E., and J.W. Ward, Changes in characteristics and function of woody debris with increasing size of streams in western Washington, *Trans. Am. Fish. Soc.*, *118*(4), 368-378, 1989.

CH2MHill and Western Watershed Analysts, *FEMAT Riparian Process Effectiveness Curves: What is Science-Based and What is Subjective Judgment?* report prepared for the Oregon Forest Industries Council, Portland, Oregon, 61 pp., 1999.

Collins, D.B.G., R.L. Bras, and G.E. Tucker, Modeling the influence of vegetation dynamics on landscape erosion, *Eos Trans. AGU*, *82*(20), S194, 2001.

Denlinger, R.P., and R.M. Iverson, Flow of variably fluidized granular masses across three-dimensional terrain: 2, numerical predictions and experimental tests, *J. Geophys. Res.*, *106*(B1), 553-566, 2001.

Evans, K.G., M.J. Saynor, G.R. Willgoose, and S.J. Riley, Post-mining landform evolution modelling: 1, derivation of sediment transport model and rainfall-runoff model parameters, *Earth Surf. Proc. Landforms*, *25*(7), 743-763, 2000.

Evans, K.G., and G.R. Willgoose, Post-mining landform evolution modelling: 2, effects of vegetation and surface ripping, *Earth Surf. Proc. Landforms*, *25*(8), 803-823, 2000.

E687 Collab., P.L. Frabetti *et al.*, Charm-anticharm asymmetries in high energy photoproduction, *Phys. Lett. B*, *370*, 222, 1996.

Forest Ecosystem Management Assessment Team (FEMAT), *Forest Ecosystem Management: An Ecological, Economic, and Social Assessment*, U.S. Dept. Agriculture, U.S. Dept. Interior (and others), (irregular pagination), 1993.

Gasparini, N.M., G.E. Tucker, and R.L. Bras, Downstream fining through selective particle sorting in an equilibrium drainage network, *Geology*, *27*, 1079-1082, 1999.

Grant, G.E., Hydrologic, geomorphic and aquatic habitat implications of old and new forestry, in *Forests—Wild and Managed: Differences and Consequences*, edited by A. Pearson and D.A. Challenger, pp. 35-53, University of British Columbia, Vancouver, 1990.

Haff, P.K., Limitations on predictive modeling in geomorphology, in *The Scientific Nature of Geomorphology*, edited by B.L. Rhoads and C.E. Thorn, pp. 337-358, John Wiley and Sons, New York, 1996.

Hancock, G.R., K.G. Evans, G.R. Willgoose, D.R. Moliere, M.J. Saynor, and R.J. Loch, Medium term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model, *Austral. J. Soil Res.*, *38*, 249-263, 2000.

Hancock, G.R., and G.R. Willgoose, Use of a landscape simulator in the validation of the SIBERIA catchment evolution model: Declining equilibrium landforms, *Water Resour. Res.*, *37*(7), 1981-1992, 2001.

Heimsath, A.M., W.E. Dietrich, K. Nishiizumi, and R.C. Finkel, Stochastic processes of soil production and transport: Erosion rates, topographic variation, and cosmogenic nuclides in the Oregon Coast Range, *Earth Surf. Proc. Landforms*, *26*, 531-552, 2001.

Hogan, D.L., S.A. Bird, and M.A. Hassan, Spatial and temporal evolution of small coastal gravel-bed streams: Influence of forest management on channel morphology and fish habitats, in *Gravel-Bed Rivers in the Environment*, edited by P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, pp. 365-392, Water Resources Publications, Highlands Ranch, Colorado, 1998.

Howard, A.D., Simulation of gully erosion and bistable landforms, in *Incised River Channels: Processes, Forms, Engineering and Management*, edited by S.E. Darby and A. Simon, pp. 277-299, John Wiley & Sons, Chichester, 1999.

Iverson, R.M., Landslide triggering by rain infiltration, *Water Resour. Res.*, *36*(7), 1897-1910, 2000.

Jacobson, R.B., Spatial controls on patterns of land-use induced stream disturbance at the drainage-basin scale—an example from gravel-bed streams of the Ozark Plateaus, Missouri, in *Natural and Anthropogenic Influences in Fluvial Geomorphology: The Wolman Volume*, edited by J.E. Costa, A.J. Miller, K.W. Potter, and P.R. Wilcock, pp. 219-239, American Geophysical Union, Washington DC, 1995.

Johnson, K.N., Reflections on the development of FORPLAN, in *FORPLAN: An Evaluation of a Forest Planning Tool*, edited by T.W. Hoekstra, A.A. Dyer, and D.C. Le Master, pp. 45-51, *USDA For. Ser. Gen. Tech. Rep. RM-140*, 1987.

Johnson, K.N., R. Holthausen, M.A. Shannon, and J. Sedell, Forest Ecosystem Management Assessment Team assessments: Case study, in *Bioregional Assessments: Science at the Crossroads of Management and Policy*, edited by K.N. Johnson, F.J. Swanson, M. Herring, and S. Greene, pp. 87-116, Island Press, Washington, 1999.

Lancaster, S.T., S.K. Hayes, and G.E. Grant, Modeling sediment and wood storage and dynamics in small mountainous watersheds, in *Geomorphic Processes and Riverine Habitat*, edited by J.M. Dorava, D.R. Montgomery, B.B. Palcsak, and F.A. Fitzpatrick, pp. 85-102, American Geophysical Union, Washington, 2001.

Lisle, T.E., Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California, *Geol. Soc. Am. Bull.*, *97*(8), 999-1011, 1986.

Massong, T.M., and D.R. Montgomery, Influence of sediment supply, lithology, and wood debris on the distribution of bedrock and alluvial channels, *Geol. Soc. Amer. Bull.*, *112*(5), 591-599, 2000.

Milne, B.T., Hierarchical landscape structure and the forest planning model: Discussant's comments, in *FORPLAN: An Evaluation of a Forest Planning Tool*, edited by T.W. Hoekstra, A.A. Dyer, and D.C. Le Master, pp. 128-132, *USDA For. Ser. Gen. Tech. Rep. RM-140*, 1987.

Moglen, G.E., and R.L. Bras, The importance of spatially heterogeneous erosivity and the cumulative area distribution within a basin evolution model, *Geomorphology*, *12*(3), 173-185, 1995.

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess, Pool spacing in forest channels, *Water Resour. Res.*, *31*(4), 1097-1105, 1995.

Montgomery, D.R., K.M. Schmidt, H.M. Greenberg, and W.E. Dietrich, Forest clearing and regional landsliding, *Geology*, *28*(4), 311-314, 2000.

Nelson, J.M., and J.D. Smith, Evolution and stability of erodible channel beds, in *River Meandering*, edited by S. Ikeda and G. Parker, pp. 321-378, American Geophysical Union, Washington, 1989.

Ohmann, J.L., and M.J. Gregory, Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, U.S.A., *Can. J. For. Res.*, *32*, 725-741, 2002.

Reeves, G.H., F.H. Everest, and J.R. Sedell, Diversity of juvenile anadromous salmonid assemblages in coastal Oregon basins with different levels of timber harvest, *Trans. Am. Fish. Soc.*, *122*(3), 309-349, 1993.

Reynolds, K.M., Fuzzy logic knowledge bases in integrated landscape assessment: Examples and possibilities, *USDA For. Ser. Gen. Tech. Rep. PNW-GTR-521*, 24 pp., 2001.

Reynolds, K.M., and S. Peets, Integrated assessment and priorities for protection and restoration of watersheds, *Proceedings, IUFRO 4.11 Conference on Forest Biometry, Modeling and Information Science*, 26-29 June 2001, Greenwich, UK, 2001.

Roering, J.J., J.W. Kirchner, and W.E. Dietrich, Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology, *Water Resour. Res*., *35*(3), 853-870, 1999.

Schmidt, K.M., J.J. Roering, J.D. Stock, W.E. Dietrich, D.R. Montgomery, and T. Schaub, Root cohesion variability and shallow landslide susceptibility in Oregon Coast Range, *Can. Geotech. J.* 38, 995-1024, 2001.

Spies, T.A., G.H. Reeves, K.M. Burnett, W.C. McComb, K.N. Johnson, G.E. Grant, J.L. Ohmann, S.L. Garman, and P. Bettinger, Assessing the ecological consequences of forest policies in a multi-ownership province in Oregon, in *Integrating Landscape Ecology Into Natural Resource Management*, edited by J. Liu and W.W. Taylor, Cambridge University Press, in press.

Tucker, G.E., and R.L. Slingerland, Predicting sediment flux from fold and thrust belts, *Basin Res.*, *8*, 329-349, 1996.

Tucker, G.E., S.T. Lancaster, N.M. Gasparini, R.L. Bras, and S.M. Rybarczyk, An object-oriented framework for hydrologic and geomorphic modeling using triangulated irregular networks, *Comp. Geosci.*, *27*(8), 959-973, 2001a.

Tucker, G.E., S.T. Lancaster, N.M. Gasparini, and R.L. Bras, The channel-hillslope integrated landscape development (CHILD) model, in *Landscape Erosion and Evolution Modeling*, edited by R.S. Harmon and W.W. Doe, III, pp. 349-388, Kluwer Academic/Plenum Publishers, New York, 2001b.

Wilcock, P.R., J.C. Schmidt, M.G. Wolman, D. Dominick, M.W. Doyle, G.E. Grant, R.M. Iverson, T.C. Pierson, S.P. Schilling, and R.C. Wilson, When models meet managers, in *Prediction in Geomorphology* (this volume), edited by P.R. Wilcock and R.M. Iverson, Amercian Geophysical Union, Washington, 2002.

Willgoose, G., R.L. Bras, and I. Rodriguez-Iturbe, A coupled network growth and hillslope evolution model, 1, theory, *Water Resour. Res.*, *27*(7), 1671-1684, 1991a.

Willgoose G., R.L. Bras, and I. Rodriguez-Iturbe, A coupled network growth and hillslope evolution model, 2, nondimensionalization and applications, *Water Resour. Res.*, *27*(7), 1685- 1696, 1991b.

Willgoose, G.R., and S.J. Riley, An assessment of the long-term erosional stability of a proposed mine rehabilitation, *Earth Surf. Proc. Landforms*, *23*, 237-259, 1998.

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