When Models Meet Managers: Examples from Geomorphology

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Geomorphic models are increasingly used to support public policy and natural resources management. We present five examples of the interaction between models and managers and consider factors that influence their success or failure. Essential elements include common objectives for management and models and clear communication of the assumptions, limitations, and uncertainty of models and their predictions. Where management and modeling objectives cannot be matched, it may be possible to define management actions that do not depend on exact predictions or to pursue alternatives to modeling such as monitoring or environmental history. In some cases, model predictions may be less important than the educational value of model construction and operation. An adaptive modeling process, in which the objectives, mechanisms, and tolerances of a model are adjusted interactively in an ongoing model-manager dialogue, may be useful, particularly when the policy context is contested or incompletely defined or when the social mandate is ahead of the science.

INTRODUCTION

As modeling becomes commonplace in geomorphology, models are increasingly used to support public policy and land management decisions. There is abundant anecdotal evidence that the encounter between models and managers does not always go well. From the modeler's perspective, it is not uncommon to hear that managers or policy makers do not understand the models and that model results have been taken out of context or misrepresented. Although we conducted no survey, it is not hard to envision a competing manager's perspective, focused on irrelevant models, debilitating estimates of uncertainty, and modeler's poor understanding of the issues managers face in their immediate need for a practical answer.

A successful model/manager interaction depends on a range of factors: characteristics of the models themselves, the policy context in which models are placed, and the personal interactions between modelers and environmental managers from a wide range of backgrounds. From the modeler's perspective, a well-informed interaction with management requires an understanding of not only environmental processes, but of the institutions, policies, and social forces that provide the context for the interaction and especially of the political process of decision making. The necessary understanding of economics, sociology, and political science is not typically part of a geomorphologist's experience. Nonetheless, some familiarity with science/society dynamics can only help geomorphological modelers to productively interact with managers. From the manager's perspective, a successful interaction with models requires an appreciation of what models can and cannot provide and a willingness to explore alternative approaches. Some environmental questions cannot be answered explicitly, others can only be addressed probabilistically, and all environmental predictions include (typically large) uncertainty. Management questions

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may need to be rephrased or a means found to make decisions despite incomplete or uncertain predictions. This uncertainty can clash with the need for prompt answers to specific “yes-or-no” and “how-much” questions. Managers may feel ill equipped to incorporate such uncertainty in their decision making and may be disinclined to make the effort in the face of political, economic or legal pressures, although more flexible approaches such as adaptive management are being considered with increasing frequency.

Many of the issues discussed in this paper are not particular to geomorphic models, or even to models in general (defined in the common sense of a numerical algorithm capable of prediction), but arise whenever scientific or technical methods are used to provide answers in a management context. Formal study of the role of environmental prediction in management decision-making is a young and evolving field. *Sarewitz et al*. [2000] provide a useful recent compilation of the interaction between prediction and policy in environmental issues. Although many of the better-studied environmental prediction/policy interactions operate on a larger socioeconomic scale than is common in geomorphology (e.g. global climate change, acid precipitation, flood and hurricane forecasting, nuclear waste disposal), they share many of the basic issues, such as the role of uncertainty, the necessity for clear modeler/manager communications, and the influence of policy context.

This paper explores the model/manager interaction and asks: what makes it succeed or fail? We present five vignettes that describe the interaction of geomorphic models with environmental management, including a brief outline of the setting, the model, and lessons learned. These examples are not intended to be comprehensive, but illustrative. They come from two broad applications—forecasting geomorphic hazards and informing land resource management—which comprise the bulk of geomorphic model/manager interactions. Following the vignettes, we ask whether these interactions were successful, examine some common themes, and look for those elements that help explain why a model/manager interaction might succeed or fail.

MODEL/MANAGER VIGNETTES

The Rise and Fall of a Debris Flow Warning System
(Raymond C. Wilson)

In early January, 1982, a disastrous rainstorm struck the San Francisco Bay region, triggering thousands of debris flows and other shallow landslides across the region, causing 25 deaths and many millions of dollars in property damage. Out of the many stories of grief and hardship from this storm, a particularly moving story involved the death of three children, crushed by a debris flow which struck the back of their home at the base of a steep hillslope in Pacifica. When the debris flow struck, shortly after 11:00 PM, the children were asleep in rear bedrooms, but the parents were still awake, watching the evening news on television in the front living room. The parents both survived. When interviewed later, one of the parents noted that the lead news story that night had been about flooding from the storm, but that nothing had been said about mudslides. Here was a modern family, connected to a real-time news source, yet there was no warning of a mortal danger in their own backyard.

Campbell [1975] studied the 1969 debris flows in Los Angeles and suggested a debris-flow warning system based on National Weather Service (NWS) forecasts and (pre-Doppler) radar imagery, but no system was developed. After the 1982 storm, a debris-flow advisory system began to seem like an urgent necessity. At the United States Geological Survey (USGS), we began with the “threshold” concept—that a critical amount of rainfall is required to trigger debris flows on susceptible slopes. By comparing eyewitness accounts of the timing of the 1982 debris flows with hourly records from a number of rain gauges across the region, *Cannon and Ellen* [1985] were able to establish a purely empirical, yet fairly precise, threshold relationship for the intensity and duration of rainfall required for abundant debris-flow activity in the San Francisco Bay region. *Cannon* [1988] further developed this threshold by establishing a correlation with the mean annual precipitation, allowing corrections for local orographic variations in the rainfall delivered by an individual storm. *Wieczorek* [1987] also developed a threshold relationship for individual debris flows in a small (12 sq. km), but highly susceptible area near La Honda, San Mateo County, using data from 1982 and several other storms.

At the same time, the NWS developed procedures for issuing quantitative precipitation forecasts throughout northern and central California and coordinated the development of the Automated Local Evaluation in Real Time (ALERT) system, a network of radio-telemetered rain gages across the San Francisco Bay region. The USGS installed an ALERT rain gage and a network of shallow (30 - 140 cm) piezometers on a hillslope in the La Honda study area. The ALERT network plus the Cannon/Ellen/Wieczorek thresholds formed the technical basis for the Landslide Warning System (LWS) [*Keefer et al*., 1987; *Wilson et al*., 1993]. Operation of the LWS was a joint effort between the landslide research group at the USGS in Menlo Park and forecasters and hydrologists at the nearby local NWS forecast office.

The first public warning was issued 14 February 1986 [*Keefer et al*., 1987] and the LWS operated until December 1995, when it was terminated due to a reduction in staff within USGS. During its decade of operation, the LWS issued more than a dozen public advisories, including several warnings. Significant debris-flow activity occurred in parts of the region during severe storms in January of 1993 and January and March of 1995. Debris-flow warnings were issued in each of these cases. In 1986 and again in 1995, some evacuations were ordered by local police or fire units. The number of people who actually evacuated, although not formally measured, was small.

When the LWS began operation, the lines of responsibility were fairly diffuse and informal. In the USGS landslide research group, we regarded the LWS as an experiment; the highest priority was to see if we could actually predict debris-flow activity. Public advisories were regarded as a by-product, potentially useful to some (unspecified) clientele, but not the central focus. The NWS forecasters, on the other hand, pressed us to consider seriously the criteria for issuing advisories and exactly how to word them. Over time, a detailed protocol was developed, with "boilerplate" texts for the various contingencies and expected levels of debris-flow activity [*Wilson et al*., 1993].

The warning system could not be completely automated. A person was needed to assimilate the data (NWS forecasts, ALERT data, news reports), then make an informed, yet subjective, decision about the potential hazard, and finally, choose the appropriate advisory to broadcast to the general public. These non-trivial judgments were made, not once, but many times over the course of a storm sequence that could last several days. False alarms create nuisances and erode credibility. On the other hand, the absence of an advisory when debris flows do cause death or destruction, becomes a dereliction of duty. Thus, the LWS had to be staffed on a 24-hour basis during periods of heavy rainfall. While the NWS was already staffed for such operations, the USGS side of the LWS was staffed on a “collateral duty” basis. In addition to our regular research duties, we had to provide at least four trained observers—one person per six-hour “watch”, 24 hours per day—who could not only monitor the data, but also make correct interpretations and take appropriate actions. This 4-person staffing requirement became a heavy burden as the permanent staff of the USGS landslide research group shrank from 10 in 1986 to 5 in 1994.

Beyond issuing warnings, one of the most important outcomes of the LWS was that it became a focal point for media attention and thereby served to raise public awareness of debris-flow hazards in the San Francisco Bay region. For example, we issued a press release when seasonal rainfall totals reached the “antecedent condition”: when early seasonal rainfall has replenished the soil-moisture deficit incurred during the long summer dry season [*Campbell*, 1975]. This annual press release, which always received wide coverage in the local news media, served not only to inform concerned local agencies, but also provided a “wake-up call” to the media and general public that a heavy winter rainstorm could bring a return of debris-flow activity. Following the disastrous Oakland Hills Fire in October 1991, the city planned mandatory evacuations of people living downhill from the burned area, if a debris-flow warning was issued. The following winter was fairly dry, however, so the need did not arise. It is likely that these measures would not have been taken, or pursued so vigorously, without the public awareness of debris-flow hazards already raised by the LWS.

Forecasting Lahar Inundation in Volcano Crisis Mode (Richard M. Iverson, Steven P. Schilling, and Thomas C. Pierson)

In June, 1998 Guagua Pichincha volcano (elevation 4794 m), located adjacent to Quito, Ecuador (population ~ 2 million), ended a long period of quiescence and commenced seismic activity that threatened to culminate in significant eruptions. Almost immediately, local scientists realized that if erupted ash were to accumulate on slopes of upland watersheds that drained into Quito, the potential for devastating, rainfall-triggered lahars would be great. Apprised of this situation, Ecuadorian officials requested assistance from the USGS to evaluate hazards from prospective lahars. Little time was available to conduct traditional field investigations or to construct detailed models, as the lahar threat appeared imminent.

The only tool available for rapidly forecasting the pattern and extent of probable lahar inundation was the statistically calibrated, GIS-based model, LAHARZ [*Iverson et al*., 1998; *Schilling*, 1998]. The model was developed specifically for use where time or resources are inadequate for more detailed, site-specific investigations. However, the model was calibrated using data from lahars that originated mostly from landslides or pyroclastic flows, rather than from rainfall on ash. We therefore cautioned that use of the LAHARZ model to assess hazards in Quito involved a questionable extrapolation. Nonetheless, Ecuadorean officials wanted to proceed with use of LAHARZ, because they needed any and all possible guidance for decision-making, and they needed it fast.

Application of the model faced two technical challenges. The first was to acquire digital elevation data (in the form of a DEM) for the eastern flank of Guagua Pichincha and adjacent areas of Quito. The accuracy of model results depends on the resolution and accuracy of the base DEM.

DEMs were produced by colleagues in Ecuador and Italy, but critical information about data accuracy, file type, and map projections were unavailable and had to be inferred by making point-by-point comparisons between digital files and printed paper maps. Also, unbeknownst to us at the time, the DEMs did not show a recently constructed motorway embankment that could potentially divert lahars descending several of the drainages that entered Quito. The second challenge involved identification of prospective lahar source areas and volumes. Local and USGS scientists used historical accounts of volcanic ash accumulations from previous Pichincha eruptions, as well as their knowledge of the geology and hydrology of the upland watersheds adjacent to Quito, to estimate probable and maximum credible volumes of lahars. We used these estimates as a basis for computing sets of nested hazard zones that depicted a range of possible inundation limits, thereby accounting for uncertainty in both the model and the initial conditions.

When local scientists recognized that the maps generated by LAHARZ did not account for possible lahar diversions by the new motorway embankment or by structures on densely populated fans, they revised the forecasts without guidance from any model. As a result, the hazard maps constructed from the LAHARZ model were not directly used in delineating hazards, but played a useful, if preliminary, role in developing maps that guided hazard-mitigation strategies.

Local officials wanted maps with definitive hazard-zone boundaries, not the uncertain boundaries generated by LAHARZ. In the midst of a pending public safety and economic crisis, it was difficult to communicate that limitations in both input data and model accuracy had stretched the capability and credibility of LAHARZ to its limits. Enhanced use of LAHARZ results would have been facilitated by prior communication among data providers, modelers, and decision makers, with an emphasis on communicating the limitations of model input and the inherent uncertainty of model forecasts.

Subsequent to the Pichincha crisis, use of LAHARZ has been largely in the context of long-term hazard forecasting. The model has been used to update and unify USGS assessments of lahar hazards at numerous Cascades volcanoes in the western United States (e.g., Mts. Rainier, Baker, Hood, Jefferson, and Three Sisters), and it has been used extensively by government and academic scientists in Mexico, Nicaragua, Guatemala, and El Salvador. Others are now using LAHARZ to extend assessments of volcano hazards in Canada and New Zealand. To date, these efforts have been effective and fruitful, as sufficient time has generally been available to train participating scientists and educate prospective users about model uncertainty and limitations.

Application of the Shallow Landslide Model SHALSTAB (William E. Dietrich and David R. Montgomery)

Shallow landslides represent a major source of sediment to mountain channel networks and a hazard to streams, structures, and people in both urban and rural areas. Prediction of the location of landslides and landslide-prone slopes is complicated by the fact that landslide occurrence depends on a complex interplay among a wide range of variables, including slope gradient, drainage area, bedrock geology, soil thickness, precipitation, runoff mechanisms and pathways, vegetation, and land use. Regional slope stability assessments have tended to focus on empirical relations among subsets of these factors or on simple slope thresholds that do not account for the role of topographic form or position on the potential for slope instability. Traditional engineering analyses of slope stability have focused on detailed predictions for specific sites, an approach that is impractical for making management decisions that depend on an understanding of landslide potential over broad areas. With the advent of digital elevation models (DEMs), it has become possible to develop spatially explicit predictions of landslide initiation potential over large areas.

We developed a physically based model (available as SHALSTAB, http://socrates.berkeley.edu/~geomorph/) for predicting areas at risk of shallow landsliding for use in understanding landscape evolution and natural hazards in steep terrain. The model combines a simple steady state hydrologic model and an infinite-slope limit-equilibrium slope stability model with a DEM to estimate the critical steady-state rainfall intensity necessary to trigger slope instability at any point in a landscape [*Dietrich et al*., 1993; *Montgomery and Dietrich*, 1994]. The output is presented as a map of critical values of rainfall intensity (or the ratio of rainfall to soil transmissivity), with lower values indicating less stable portions of the landscape. Tests of the model have shown that shallow landslides preferentially occur in areas with low critical rainfall [see *Dietrich et al*., 2001 and *Montgomery et al*., 2001 and references therein]. The model is intended to identify areas of a landscape with a high topographic potential for shallow landslide initiation.

SHALSTAB is most useful as a planning tool at the watershed scale, where it can identify potentially unstable terrain for which subsequent detailed site-specific hazard assessments might be warranted. The actual rates of landsliding associated with high hazard categories vary widely among drainage basins, and therefore the model requires local calibration for risk assessment [*Montgomery et al*., 1998]. In watching applications of SHALSTAB by government and industry in the US, Brazil, Argentina, and Italy, we have observed three important issues concerning its use by managers and their advisors.

First, the scope and purpose of model predictions can be misconstrued. SHALSTAB predicts the relative potential of shallow landsliding, but not deep-seated landslides, rock avalanche, landslides from undercutting, and a multitude of other landslides types. It is not an all-purpose landslide model. Yet some geologists, and consequently the managers they advise, infer that SHALSTAB predictions are meant to provide a complete forecast of landslide potential. The potential for other landslide types requires other models or field investigation by trained individuals, as does the verification of any landslide prediction. A model such as SHALSTAB is meant not to replace geologists or fieldwork, but to serve as a tool in a complete and efficient investigation. Misunderstanding of the appropriate application and predictions of the model has caused some geologists to oppose using the model for any purpose. Conversely, managers have been tempted to rely solely on models and forego costly, time-intensive fieldwork. Neither approach will lead to effective landslide forecasts and land management.

A second common misunderstanding concerns prediction uncertainty. Understandably, the desire is for landslide models to predict exactly where and when a landslide will occur. Although some managers (and a surprising number of resource scientists) expect certainty at high spatial and temporal resolution, no landslide model can do this because of the practical unknowability of subsurface conditions that dictate pore-pressure evolution and material strength. Nonetheless, a model such as SHALSTAB can be used to delineate areas where shallow landslides are most likely and preventive measures can be taken even though it is not possible to say which site will fail in a given storm. In our experience, we have found that managers can understand the utility of identifying potentially hazardous areas, even if the hazard likelihood remains highly uncertain.

Third, in our experience managers tend to prefer and trust forecasts that are expressed in a probabilistic fashion, e.g. the likelihood that a shallow landslide will occur at a specified site is 1 in 1000 in the next thirty years. Some landslide models, such as SINMAP [*Pack and Tarboton*, 1997; *Pack et al*., 1998], introduce stochastic forcing functions to produce probabilistic forecasts. We find that, because of the typically high degree of covariance among the governing variables, the lack of extensive data to define the forcing functions for specific locations, and the remaining uncertainty in the topography and local rainfall, such probabilistic approaches provide no new insight and may mislead managers into thinking that risks are far better constrained than would be prudent to conclude based on available data.

Forest Management in Oregon: The CLAMS Experience (Gordon E. Grant)

Threatened and endangered native communities of resident and anadromous fishes have particularly high political, social, and ecological profiles. The effects of forest management on these fish are the subject of on-going debate and concern in the U.S. Northwest region. Efforts to directly model fish community response to alternative forest practices are still rather primitive, due in large part to limited population data and unresolved biological complexities associated with fish whose multiyear life histories take them from headwater channels to the ocean. Instead, models typically focus on linkages between forest practices and fish habitat, including wood and sediment composition, volume, and distribution in stream channels, pool size and abundance, and structure and composition of riparian zones that contribute wood, shade, and litter to streams.

The Coastal Landscape Analysis and Modeling Study (CLAMS; www.fsl.orst.edu/clams/) is a joint research effort of the USDA Forest Service, Pacific Northwest Research Station, Oregon State University, College of Forestry and the Oregon Department of Forestry. The overall goal of CLAMS is to evaluate the ecological and socio-economic consequences of different forest management strategies. The goal of models within CLAMS is less "prediction" of what will happen at-a-site than it is an understanding of how different management strategies regarding timber harvest and stream protection might affect key geomorphic elements of fish habitat over large areas and timescales of decades to centuries.

CLAMS has been an informal science and policy based effort, rather than a program specifically mandated to provide predictions for managers. It remains primarily a research effort in that many of the models and approaches are still rather formative and experimental. Although there has been little transfer of CLAMS models to managers, the models are being developed as a decision-support tool within land management agencies and the process brings to light some issues that have broader interest.

Three general approaches to geomorphic modeling have emerged within CLAMS, each with distinct advantages and disadvantages. The first uses empirical models relating fish habitat and channel conditions to hillslope and watershed factors, such as extent of forest cutting, landslide susceptibility, and geology [*Burnett*, 2001]. The empirical basis of this approach limits its ability to reliably extrapolate results to other locations or to the future, but has the advantage of demonstrating relations based on real observations. The second modeling approach simulates landscape behavior through time using “rule-based” algorithms defined from empirical relations and probabilistic distributions. In this approach, stochastically generated precipitation and fire are linked to landslide and debris flow occurrence on a digital elevation model (DEM), using rules governing debris flow behavior as defined by network junction angles and topography [*Montgomery and Dietrich*, 1994; *Benda and Dunne*, 1997]. The combination of a dynamic model with stochastic drivers allows forecasts to be made for large drainage basins over long time scales, although the accuracy of the forecasts cannot be directly tested and is limited by a static topography and by process formulations based on contemporary data. The third modeling approach is similar to the second, except that the algorithms for the geomorphic processes are more detailed and derived from the basic physical conservation laws [*Lancaster et al*., 2001]. This provides greater opportunity for testing elements of the model forecasts and increases confidence in extrapolations to regions with no direct observations. These advantages come at the expense of much larger computational demands, more complex forecasts, and greater sensitivity to uncertainties in model input.

An issue of primary concern to the model developers is that of model choice. The three modeling approaches within CLAMS are quite different in formulation, input, and the type and scale of forecasts. Direct comparison of the models is difficult because they operate on different spatial scales and forecast different habitat properties, and because there is no agreed-upon standard (as there might be in the case of hydrologic models) as to what a good or valid prediction should be. Although of paramount importance to modelers, the differences between models may be largely opaque and even irrelevant to those responsible for making land management decisions. Our discussions with managers suggest that distinctions between the models are viewed as incidental to the larger goal of predicting the outcome, which, in turn, is largely incidental to the goal of interpreting the model results in terms of specific management actions. In other words, from the managers' perspective, a statistical model indicating that riparian protection zones increase wood loading to streams is as good as an empirical or process-based model that shows the same thing. The relevant management issue is simply that riparian protection zones are established as important.

Managers' acceptance of a model or its predictions can depend on factors other than its theoretical basis or the degree to which it is tested. An important influence is likely to be the manager's perception of the credibility of the modeler, particularly when the manager has limited ability to directly evaluate the model. It is difficult to say what constitutes "credibility" from a manager's perspective. Contributing factors include: an established working relationship, a certain aura of a model as being "scientific" (e.g., equations help, even if they're not fully understood), and model predictions that do not stray too far from a manager's own experience and biases. Models that support one or another point of view in contentious policy debates may be seized upon without rigorous testing by either advocates or detractors. Because personal and political factors can influence the acceptance of model predictions, it is incumbent on the modeling community to clearly explain the advantages and disadvantages of the modeling options and, where appropriate, to make recommendations with a full explanation of the consequences.

Our experience with developing CLAMS highlights two model/manager issues that focus on clear and unbiased communication. When researchers take the lead in initiating model development, it is the obligation of modelers to demonstrate the role of models in supporting decisions and sufficient time must be allocated for this educational task. When there are multiple models or modeling approaches (as is typically the case), it is imperative that modelers provide clear, unbiased and comprehensive direction regarding the merit and consequences of all different models.

Sediment Transport Modeling for the Menomonee River Watershed, Wisconsin
(Martin W. Doyle and DeWitt Dominick)

A sediment-transport modeling study of the Menomonee River watershed (a 350 km^2 urbanizing watershed in Milwaukee, Wisconsin) was conducted for the Milwaukee Metropolitan Sewerage District (MMSD). The goal of the project was to provide tools to guide planning for flood control, channel stabilization, and channel rehabilitation activities within the watershed. Using the model forecasts, MMSD intended to shift its approach of river management from reactive to proactive to allow long-term planning and strategic capital investment rather than simply responding to small-scale erosion or sedimentation problems. The primary application of the project to date has been the prioritization of reaches for stabilization and rehabilitation.

Channel surveys and sediment sampling were used to support standard hydrologic and hydraulic modeling using HSPF and HEC-RAS [*Johanson et al*., 1980; *HEC*, 1995]. Sediment budgets were developed for individual stream reaches, including predictions of aggradation/degradation and channel widening using SAM [*Copeland et al*., 1998]. The model predictions were then used to score channel segments on an ordinal scale of 1 to 5, where 1 is extreme degradation, 5 is extreme aggradation, and 3 is "geomorphically stable". Field assessments were then used to evaluate the final score for each reach. Where the model and field assessments differed, the field assessments were given priority. All data collected and model results were compiled in a comprehensive Geographic Information System (GIS), which currently acts as an information link, providing a mechanism to review, store, update, and share watershed data [*Dominick et al*., 2001].

Although MMSD was initially more comfortable with the field assessments than the numerical modeling, the explicit corroboration between the two helped to increase management confidence in the utility of the modeling. MMSD has been pleased with the insight gained from the combined effort and is now conducting similar modeling efforts in other watersheds and is including an expanded geomorphology component to their watercourse projects.

MMSD found that two critical components influenced its decision to incorporate modeling in their watershed management. The first was the education of managers via short courses on the geomorphic system and the modeling program. Managers were able to understand the context for the erosion and sedimentation problems in the watershed, the purpose for modeling, the reasoning behind watershed scale (rather than traditional reach-scale) forecasts, the methods for data collection, and the interpretation of the final results. The second critical component was the field assessment and data collection. MMSD managers felt that the field assessments provided valuable corroboration of the modeling results, thereby increasing their confidence in the modeling. The field assessments also provided information for areas of the watershed where the model was not applicable. Further, the data collected for the modeling study, as well as sub-components of the modeling (e.g., hydrologic and hydraulic analysis) are now available for future work by MMSD.

The model was not as detailed as initially envisioned by MMSD in that some expected a cookbook, or black-box model able to produce detailed results (e.g. 2 meters of right bank erosion on bend #25). Instead, the modeling process provided results on a semi-quantitative ordinal scale and indicated broad-scale trends of erosion or sedimentation throughout the entire watershed. Detail of prediction was sacrificed for field-verified certainty and to accommodate the size of area modeled. MMSD now feels that this is the best approach for their purpose, as finer-scale, reach-based approaches would have greatly limited the potential for long-term planning on the watershed scale, which was the overall goal of the project. More detailed modeling can now be concentrated at prioritized sites based on the results of this project.

DISCUSSION

The five vignettes represent two typical applications of geomorphological models: hazard forecasts and natural resource management. Both have implications regarding land-use planning and zoning, another management issue to which geomorphology contributes. The context of the model/manager interaction is different in the two cases. Hazard forecasts lead to a difficult trade-off between the protection of life and property and the social and economic costs of false alarms. Policy makers are likely to be keenly aware of the need to understand model accuracy and uncertainty. Successful model/manager interactions hinge not only on model accuracy, but also on the ability to communicate uncertainty and to provide model predictions in a timely fashion. In natural resource management, the immediate stakes can appear less urgent (but may often be more widespread), the relevant time frame may be much longer, and the opportunity to evaluate the accuracy of predictions is weaker, making the success of the model/manager interaction more difficult to evaluate objectively. Effective communication of geomorphic predictions may spur management agencies into action, which could be interpreted as a successful model/manager interaction, even though the accuracy of the predictions and the effectiveness of the actions are not known.

All the models described in the vignettes combine some physical basis with empirical observations. The relative reliance placed on reductionist vs. empirical prediction varies, and the empirical information is both quantitative and subjective. All the models produced uncertain forecasts. The uncertainty is accommodated in the model output as explicit ranges in predictions (LAHARZ), frequency of events (CLAMS), or statement of risk (LWS) or by making forecasts on a relative basis (SHALSTAB) or an ordinal scale (MMSD). Although the spatial scale of the predictions varied, all involved predictions at a scale much larger than an individual hillslope or channel reach, such that uncertainty due to unknown local variation of geomorphic properties was common in all cases.

Success of the Model/Manager Interactions

Complexity of the geomorphic processes, the policy context, and the response of managers and the public makes the success of these (or any other) model/manager interactions difficult to evaluate in any simple way.

The LWS could be considered a success in that it provided landslide warnings under conditions producing debris flows. Public response to these warnings—the other component of risk reduction—is hard to evaluate and is poorly known, although no deaths occurred during the times and locations where these warnings occurred. With continued government support and advances in precipitation monitoring, the LWS could be operating with increased reliability today. As with land development in other hazard zones (e.g. floodplains and coastal areas), the most appropriate public response may be relocation and avoidance of hazardous areas, but historical settlement patterns and development pressures lead to riskier behavior for which hazard warnings are needed. One clear success of the LWS was that it heightened awareness of debris-flow hazards, which can potentially increase public support for land use regulations more consistent with the existing hazards and can increase the chance that people will act when a warning is issued. This awareness evidently contributed to the decision to spend approximately $5 million on hillslope restoration following the Oakland Hills fire of 1991. Such public commitment is not an assurance of effectiveness, however. *Booker et al*. [1993] indicate that the restoration methods, developed for conditions in Southern California, were inappropriate for the Oakland Hills, suggesting that the large expenditure of public funds was largely unnecessary.

In the case of the LAHARZ application, success cannot be directly evaluated because a lahar did not strike Quito. The model/manager interaction can be viewed as a success in the sense that the model provided a focused prediction that addressed the management problem, and as a partial failure because the prediction did not provide the certainty that the managers wanted. Application of the model helped to identify data necessary for making useful hazard predictions in the future. This can be considered a success if it leads to efforts to develop the data and the model structure needed to respond to future emergencies. Because certainty in predictions of lahar inundation is unlikely, the necessary remedy in this case is improved education of managers about making planning and emergency decisions given the uncertainty of natural hazards. Again, the most prudent course is likely to be appropriate land-use regulation in hazardous locations, although this has proven difficult to achieve and, in some parts of the developing world, faces immense constraints. It is worth emphasizing that certainty in model predictions is not necessary to instigate appropriate land-use regulation, if public support is sufficient.

The active use of SHALSTAB in management applications can be considered an indication of success, but also serves to illustrate some of the pitfalls of model application. Misunderstanding of the scope of the model predictions and their appropriate application can lead to unsuccessful interactions with managers and their advisors, emphasizing the importance of clear communication of not just the operating rules of a model, but of its underlying philosophy and assumptions and of the appropriate role of modeling in guiding land-use decisions. The ultimate success of the model/manager interaction in hazard assessment requires a time scale long enough to permit a joint evaluation of the accuracy of model predictions and the long-term response land-use agencies.

Success, in a complete sense, is not possible in the CLAMS application because the primary management objective (restoring fish populations) is not directly addressed by the model output (landslides, sediment production, habitat changes). This is a common predicament when policy and management decisions are geared toward protecting fish and wildlife, but the strongest available predictions address only one element of their survival: habitat. The problem can become particularly acute when the target of protection is a charismatic species such as salmon, rather than an overall ecosystem, leading to a focus on narrow solutions, such as fish ladders, rather than the full suite of essential ecosystem elements. CLAMS predictions can clearly be useful in guiding land management decisions, but future success will require management collaboration and the development of management objectives that may be addressed by a model.

The Menomonee watershed model was judged a success by both modelers and managers. Elements contributing to this success were (1) the final level of prediction precision and detail was modest and appropriate to the management goal (prioritization of future stream stabilization/rehabilitation locations), such that the forecasts were able to successfully satisfy the management request; (2) both modelers and managers supported an education program that allowed managers to understand the context, methods, and application of the model; (3) subjective field assessment of model results were conducted and took priority over model results, helping management accept the outcome; and (4) the model output was put in an accessible format that the managers found usable. Within the context of this volume, an interesting aspect of this application is that it was judged a success, even though the final forecasts depended on approximate models and were translated into semi-quantitative results that were subject to override by follow-up subjective evaluations. The combination of a focused, achievable management objective and strong management collaboration was sufficient to allow the model forecasts to be put to practical use.

ELEMENTS OF MODEL/MANAGER INTERACTION

In a review of case studies of the interaction between prediction and policy in environmental management, *Herrick and Pendleton* [2000] suggest that the nature of the model/manger interaction can be organized according to (1) the complexity of the environmental problem, (2) the characteristic time of the problem and its associated scientific information relative to the management time frame, and (3) the maturity and focus of the science supporting the predictions. Most geomorphic models represent complex open systems, modeled only approximately, with considerable uncertainty in initial and boundary conditions, leading to the calculation of a potentially very large range of variables or metrics. Because policy tends to deal better with discrete choices, rather than a continuum of possibilities, complex predictions, dependent on multiple assumptions and scenarios, are likely to be reshaped into simpler pieces in order to fit the policy context [*Herrick and Pendleton*, 2000]. Although model development must often fit into a 1 to 3 year time frame corresponding to a management needs, the geomorphic events or change being modeled usually operate over longer time periods. In these cases, it is difficult to maintain continuity in management decisions and there is a reduced opportunity for recognizing and correcting incorrect predictions. Although the ability of geomorphologists to make and communicate predictions has advanced considerably over the past two decades, there remain a wide variety of approaches and little well formed basis for evaluating a best or most useful prediction.

Success in model/manager interactions is most likely if management objectives are defined in a form that can be effectively and efficiently predicted by a geomorphic model, and if the assumptions, limitations, and uncertainty of the model and its predictions are thoroughly communicated to decision makers. Accordingly, we emphasize objectives and communication in our discussion of the elements of the model/manager interaction.

Developing Common Objectives

It could be argued that if environmental management is the objective, then model objectives should be identical to the management objectives. A variety of reasons, arising from the different constraints and cultures within which modelers and managers operate and from the complexity of the management context and environmental issues, militate against a simple marriage.

In some cases, management and modeling objectives diverge because the policy or legal context demands a precision in model predictions that the available knowledge cannot support. For example, the law governing water rights in the American West specifies that allocations for in-stream water uses must claim the minimum amount of flow necessary to achieve the regulatory purpose. Although water scarcity makes the practical motivation behind this legal mandate clear, it requires a precision that cannot be satisfied by geomorphic and ecological models. Stream habitat models [e.g. *Reiser et al*., 1989] or sediment transport calculations [e.g. *Andrews and Nankervis*, 1995] can be used to specify flow requirements, but the results have considerable uncertainty that cannot be effectively incorporated in the decision process. Similarly, the law requires precise delineation of flood hazard areas, but information about flood magnitude and frequency, as well as future land uses, limits the precision with which accurate forecasts can be made.

A second conflict between modeling and management objectives arises because resource and hazard management would be best served by predictions that are more spatially and temporally explicit than is typically possible or practical. Modeling in support of forest management would be most useful if it were able to predict stream habitat change at specific locations and times following logging. Landslide and lahar modeling would be most useful if it could identify the exact location and timing of the hazard. In practice, geomorphic predictions are likely to indicate broad trends driven by hypothetical scenarios or probabilistic predictions at a specific point and time. For example, predictions of landslides and sediment delivery to streams in response to logging practice are likely to be more accurate on a basin-wide scale than at any specific location at a given time. Similarly, the overall likelihood of landsliding in the San Francisco Bay area can be forecast as a function of precipitation patterns, whereas the ability to predict landsliding at any individual location will be much weaker.

If the existing science can predict only general trends over broad areas of landscape or probabilistic predictions at individual locations, models do not provide the certainty that may be immediately demanded by managers. In such cases, it may be possible to revise the management alternatives, if not the underlying policy objectives, in order to make effective use of the predictions that can be reliably made. Although hazard predictions from flooding and landsliding cannot be precise, probabilistic forecasts can support revised zoning that reduces risk. In the case of the Menomonee River, managers were willing to accept an imprecise, but achievable model outcome as the basis for planning stream rehabilitation works. Erosion control for highway and suburban construction is based on engineering practices designed within broad limits to reduce sediment delivery to streams [*Wolman*, 1964]. Management objectives or alternatives cannot always be revised to fit the predictable. An inability to predict the exact location and timing of a landslide or the population response of an endangered species does not reduce the mandate to protect life and property or the essential elements of an ecosystem. In some cases, action without prediction is required.

Another alternative is to explore modeling strategies that are more consistent with management requirements. Some geomorphological models provide reliable predictions at a fine spatial and temporal resolution, but their predictions are highly sensitive to initial and boundary conditions and the information requirements are too demanding for practical application. For example, accurate and precise predictions of flow, transport, and channel change are possible for small river reaches if the effort is made to collect the necessary information on channel geometry and the composition of the bed and banks. If the objective is to manage streams throughout a watershed, or to estimate channel response to revised forest management policy, the information requirements of such models far exceed that which can be practically obtained. Rather than high resolution, sensitive models that provide certainty when boundary conditions are accurately specified, there is a need for low resolution, robust models that provide just enough certainty to warrant management action under a range of conditions [*Wilcock*, 2001].

The development of shared model/manager objectives can be influenced by the complexity, maturity, and contentiousness of the management context [*Herrick and Pendleton*, 2000]. An established and focused policy regime can influence the type of model developed and the type of predictions made. If management demands are clear, a probabilistic model, or one with incomplete or even incorrect input, can be usefully applied if no more precise model is available. The potential for such an application is evident in the lahar hazard assessment and could have been realized had the emergency officials in Quito been able to make decisions under model uncertainty. If the policy context is incomplete or contentious, without an established management framework, no geomorphic model can resolve the issue, although models can play a role in informing discussion and shaping policy. For example, during the modeling of acid precipitation in the American northeast, significant policy changes were made (e.g. on emission trading) before the air quality modeling was completed [*ORB*, 1991; *Herrick*, 2000] and global climate models are informing policy debate on controlling greenhouse gas emissions [*Brunner*, 1996; *Rayner*, 2000; *Herrick and Pendleton*, 2000].

Water resource policy in the United States is now grappling with the dilemma of avoiding floods in order to protect life and property while also requiring the ecological services of floods for the maintenance of healthy ecosystems [*Haeuber and Michner*, 1998]. Models that predict flooding are needed to support this debate, but cannot resolve the policy action that follows. In a contentious management context, policy advocates can pick and choose among the science pieces in order to support their case, particularly if the science base is also developing. The obligation of science in such cases extends beyond honesty to completeness, such that the full range of available knowledge, including assumptions and limitations, is available to the public and to managers in making value-based decisions [*Schmidt et al.*, 1998].

Another factor that strongly influences the development of shared objectives is the complexity of most environmental problems and the uncertainty in the model results. Predictions in geomorphology are inherently uncertain because of our inability to forecast future driving conditions (particularly of precipitation and runoff), to identify the relevant geomorphic mechanism, and to specify initial and boundary conditions for the models. Predictions that appear accurate over the short time frames associated with most research may become increasingly inaccurate at longer time scales. Within an appropriate policy context, managers may be able to accept uncertainty and variability at a local scale if model output indicates with some reliability that a management action provides a net benefit at the large scale. For example, zoning decisions can be made without certain predictions of geomorphic hazard, if the risk is large and public support is sufficient. Forest management decisions can be made based on broad scenario modeling, if the broad-scale predictions can be demonstrated to be reliable.

Communication, Education, Transparency

Education, the second key element in the model/manager interaction, is a shared obligation. Modelers must clearly communicate model assumptions and limitations and the uncertainty in model results. With the advent of widely available, elegant, and user-friendly computer interfaces, it has become easier to convey complex information to managers. At the same time, polished presentations can obscure uncertainty, error, and irrelevance in the underlying models. This increases the obligation of modelers to clearly explain model limitations in order to balance the persuasive appearance of model output. The success of the Menomonee River project emphasizes the importance of diverse and comprehensive education of managers. Misapplication or rejection of SHALSTAB predictions arises from a misunderstanding of the purpose and appropriate application of the model.

The obligation of managers is simply to make the effort required to learn the limitations, pitfalls, and virtues of models. This may be a daunting and impossible task in some cases. At minimum, policy makers and managers require competent technical staffs to assist in the analysis of model predictions. Collaboration with modelers in developing objectives can increase acceptance by decision makers and the public. As priorities in environmental management extend beyond traditional objectives such as optimizing resource development and protecting lives and property to include broader values of environmental protection and restoration, the role of scientists shifts from prescriptive to advisory such that education and collaboration become as important as technical solutions [*Church*, 2001].

Some geomorphic models are clearly too complex for use by anyone other than the modelers themselves. Application of such models in a management context imposes particular demands on the modeler to develop an effective interface or to recast the model results in a form accessible to managers. In either case, it requires an investment in educating the managers such that they understand the essential features and limitations of the model.

Unambiguous communication of model results also increases the likelihood that incorrect predictions will be recognized and acted upon, whether in the form of amended management directives or revised models. The widespread acceptance of weather forecasting stems not only from the importance society places on the prediction, but also from the abundant opportunities to test the accuracy of the predictions, allowing users of the predictions to adapt their behavior according to the forecast as well as to their perception of its reliability. The long time scale or lack of spatial and temporal resolution of many geomorphic predictions do not provide this opportunity. Even when post-prediction evaluations are possible, however, the opportunity is often not taken [*NRC*, 1992]. Although modelers typically move on to other problems and locations and liability concerns can motivate this lack of testing, an opportunity is lost to investigate how predictions may be made more accurate and useful.

The uncertainty typical of most geomorphic predictions imposes important demands on both modelers and managers. Many geomorphic predictions are appropriately given in probabilistic terms, but error bars or an explicit statement of event probability do not directly provide predictive accuracy. Misidentification of governing mechanisms or controlling boundary conditions can make a probabilistic prediction as inaccurate as a deterministic one. In addition to developing means of incorporating probabilistic predictions into policy and management decisions, managers need to incorporate this broader uncertainty in their deliberations and it is the obligation of modelers to convey it as clearly as possible.

Decisions concerning the type of model to use—or even whether to model—are not purely abstract, but can involve financial consequences for those who apply models and develop designs based on model predictions. Public enthusiasm for some environmental works, such as stream restoration, remediation following fire and floods, and mitigation for wetland takings, can cause management priorities to override the best available science. In these cases, clear and complete communication of model capabilities is needed to support effective public decision-making and to balance a potential conflict of interest for geomorphologists seeking financial and social opportunity.

Curiously, the attributes of a model that are the primary focus of the modeler (e.g. strong and consistent theoretical basis, critical testing, demonstrations of accuracy) may not be the attributes that matter to the manager or that substantially increase the success of the model/manager interaction. Acceptance of a model by managers may hinge on factors such as past experience with the modeler, a perception that the model appears scientific, or model results that are consistent with the manager's perception or needs. Thus, an important obligation of the modeler is to fully disclose the demands, limitations, and uncertainty associated with a model (and any competing models), so that scientists and managers can evaluate and appropriately use the model results.

Alternatives to Prediction

We often think that the primary model product is a prediction. Such predictions might be specific (a site restoration plan, a flow recommendation), or probabilistic (chance of landslide), or quite general (optimum forest cutting practice). Such predictions may lead to hazard avoidance or to specific land management actions. However, prediction is not essential for a model to be useful in environmental management. The exercise of model development, especially when managers have ongoing input, serves as an educational tool (e.g. demonstrating the elements, linkages and contingencies in natural systems) and models can serve as a decision-making tool that incorporates both uncertainty and tradeoffs among disparate items. For example, an adaptive management program concerning the operations of Glen Canyon Dam on the Colorado River in Arizona must consider the effects of alternative dam operations on a wide range of resources and attributes, including native and nonnative fish, endangered snail and bird species, camping beaches used by rafters, sites of archaeological, cultural, and religious significance, the nonuse value of preserving the Grand Canyon in a natural state, along with traditional resources such as hydropower, water storage, and flood control. Specific and compatible predictions of the effect of future dam operations on all these resources are clearly not possible [*Schmidt et al.*, 1998], although the development of a general ecosystem model [*Walters et al.*, 2000] has helped to educate managers about the ecosystem, to identify gaps in the current knowledge, to allocate scarce research dollars for future work, and to define plausible management scenarios that merit further evaluation.

Where the management context is poorly defined or the modeling capability is weak, development of a predictive model may be premature or disruptive. In such cases, the appropriate role of science may be to develop a monitoring plan, or to reconstruct the environmental history. For many decades, channel control and maintenance on the Rio Grande have used different channel designs, structures, and materials to control erosion. With careful observations over time, the effectiveness of alternative designs and/or structures in achieving channel stability provides the basis for management action [*Task Committee*, 1965].

Adaptive Management and Adaptive Modeling

Although the use of observations to test and revise a model might seem normal and necessary for modelers, such flexibility is more difficult to incorporate into the management process. Managers are often constrained by regulatory or legal mandates to make a binary decision to either do or not do something. Only recently has an adaptive element become an accepted part of the rhetoric of resource management and policy [*Lee*, 1993; *NRC*, 1996, 1999]. The role of models in educating managers and supporting policy discussions suggests that there may be a use for a modeling equivalent to adaptive management. *Adaptive modeling* can be defined as a process wherein the objectives, mechanisms, and tolerances of a model may be adjusted interactively in an ongoing model-manager dialogue. An adaptive approach to modeling suggests that modelers acknowledge that different management objectives may require different modeling approaches and fully disclose the range of modeling options with their associated uncertainty. In such a framework, modelers can help policy makers evaluate management objectives and explore alternatives whose performance can be predicted or reliably tested over a time scale that is consistent with policy mandates. Initial models might focus on developing reliable predictions at a broad scale, which can then serve to demonstrate possible states and controls of the system. Based on public/manager response to this information, subsequent models might be developed at a more detailed scale where both precision and data requirements are greater. Both the CLAMS and Milwaukee applications demonstrate the potential for such an interaction. An adaptive modeling process can promote the development of trust between modelers and managers and facilitate the education of the managers regarding the environmental context and the influence of scale and uncertainty on the decision-making process.

CONCLUSIONS

There are, of course, no universal rules for human interaction, including that between scientists and decision makers. Each must want to understand the other and take the time to do so. On either side, not everyone is interested in trying. Scientists may escape from the process; managers may ignore modelers or seek those who are willing to provide a specified prediction. Moreover, policy objectives and the decision-making process may be obscure (whether intentional or not). What is clear, however, is an ever-increasing need for both modelers and scientists willing to work at the interface of science and policy. This is particularly true because the environmental policy questions being asked nearly always demand answers at or beyond current knowledge in the supporting sciences.

In as much as the success of the model/manager interaction is a shared obligation, we conclude with observations for both sides. A number of elements of success can be defined for models and modelers:

To be useful in management, models must address management objectives

The basis for a model and its results, the uncertainty in model forecasts, and the range of alternative approaches, must be clearly communicated

Nonpredictive science may provide a superior contribution to a management objective

Because managers often have a different set of constraints and objectives than modelers, development of models for management application can require modelers to adopt a different point of view. Rather than answering the most interesting, general, or challenging question, it becomes necessary to provide the best answer to an existing question. In some cases, it may be more appropriate to develop an historical narrative or institute a monitoring program rather than develop a predictive model. Modelers may need to work adaptively with managers to define a common set of objectives that meet management and model requirements. Such collaboration requires an effort and a perspective that modelers may not anticipate or be willing to adopt.

The educational obligations of modelers for a successful model/manager interaction will also require effort beyond that required to, for example, present results at a scientific meeting. Peer review, a standard part of scientific communication but not always an important part of the model/manager interaction, can play an important role in emphasizing the relevance of the modeling and evaluating uncertainty in the model forecasts. Clear communication is likely to be as important as technical rigor in assuring a successful model/manager interaction. It also increases the likelihood that incorrect assumptions and predictions will be recognized. Clear communication of model capabilities becomes particularly important when management demands more of the models than they can immediately provide, in which case honest and comprehensive information about all available modeling options is needed to support effective public decision-making.

Although common objectives can emerge from modeler/manager interactions and modelers may be required to enumerate the implications of different management options, it is important for modelers to remember that the final management or policy decision inevitably includes value judgments and must be performed by the managers, as representatives of the public and other stakeholders.

Elements of a successful model/manager interaction can also be defined for environmental managers:

Management objectives must be formulated in a manner that can be addressed by a model.

Managers must have sufficient interest, motivation, and confidence in the modeling process.

Managers must be willing to understand essential features of the geomorphic system, its representation in a model, and the appropriate application of model output, including uncertainty in the forecast.

These elements are largely a mirror image of those for the modeler. In some cases, they may be difficult to achieve. For example, in large-scale, multi-stakeholder, multi-objective, and contested problems, clear management objectives may not be possible. It can be productive for modelers to work interactively with managers to define objectives that can be addressed with models, a process that can also increase the likelihood of management support and the willingness to learn the essential elements of the model.

Unsupportive managers, or an ill-defined or contested management context, can independently assure a poor model/manager interaction. That success can be unilaterally determined by the managers is not always an easy thing for modelers to accept. Modelers tend to have a reductionist spirit and develop models with the objective of finding clear answers. They may be accustomed to having their models challenged on technical grounds, but, it can be difficult for a modeler to accept that the forecast may be judged irrelevant, or unimportant, or simply ignored. This is a risk of doing business, although the potential benefit (and to some, obligation) of applying science to societal use balances the cost.

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