# 12 Equifinality and Uncertainty in Geomorphological Modelling

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ABSTRACT

Recent experience in modelling hydrological systems has revealed that good fits to the available data can be obtained with a wide variety of parameter sets that usually are dispersed throughout the parameter space. This problem of *equifinality* of different model structures or parameter sets is discussed in the context of previous uses of the term in geomorphology. The consequences of equifinality are uncertainty in inference and prediction. Recognition of such uncertainties, however, may suggest ideas for hypothesis formulation and testing by creative experiment and monitoring that will lead to the elimination of some of the possible model scenarios.

## INTRODUCTION

The availability of increasingly powerful computers has made possible the study of complex environmental systems by numerical experiment. Prime examples are the advances made in numerical weather forecasting and the scenario modelling of the atmosphere and oceans for the prediction of the effects of possible climate change resulting from anthropogenic pollution. There has also been a recent flurry of research publications on models of geomorphological development (see p. 301).

In most environments, the geomorphological development of the landscape and processes of erosion, deposition and weathering, are dependent on the flow of water. Consequently the modelling of geomorphological processes must necessarily depend on the modelling of hydrological processes with all its complications of dynamic surface and

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subsurface contributing areas forced by an unpredictable sequence of events of different magnitude. In turn, the modelling of hydrological processes must necessarily depend on the form of the landscape, with its control over convergent and divergent flow paths, soil and vegetation development. This interaction of hydrological and geomorphological processes will shape the development of the landscape over long periods of time within the context of climate change and tectonic change.

In what follows we will first consider the implications for geomorphology of recent studies in hydrological modelling. This has a long history, driven by the needs of prediction for water resources management. Over the last 10 years, the increases in computer power have been used in two main ways. The first has been to create ever more complex models of both hillslopes and river flows, with the aim of introducing as much physical understanding of the processes as possible (see for exarnple Bates and Anderson 1993; Bathurst et al. 1995; Refsgaard and Storm 1995). In this way the hydrologist is attempting to emulate the atmospheric modeller but in a system that is less amenable to study in such ways because of the lack of knowledge of the subsurface part of the hydrological cycle. The second approach has been to use the computer power to make many thousands of runs of simpler models to explore the different predictions in the 'parameter space' and, in particular, how well different parameter sets fit the observed data. The results have been revealing. It has been widely found for both hydrological and geochemical models that many different models are *behavioural,* i.e. fit the data to an acceptable level, with the behavioural parameter values dispersed widely through the parameter space.

This chapter is primarily concerned with the implications of this *model* (rather than system) equifinality. It will be shown that geomorphological models should be expected to exhibit similar model equifinality, resulting in uncertainty and limitations on geomorphological predictability. Equifinality also leads to problems of inference where parameter values are determined by calibration, since such values will be conditional on the values of the other parameters in the model. Discussion of the problem of equifinality leads to the conclusion that progress in geomorphological modelling will depend on creative hypothesis formulation and testing by experiment and monitoring that will lead to the elimination of some of the feasible models.

## MODELLING WITH DATA - THE HYDROLOGICAL EXPERIENCE

Only recently have coupled models of hillslope hydrology and sediment production and transport and of channel form, discharge and sediment transport started to appear (e.g. Bathurst et al. 1995). In virtually all hydrological analysis and models that take some account of catchment topography, the 'landscape' element (catchment characteristics) are considered to be fixed (e.g. Beven et al. 1995; Refsgaard and Storm 1995). No feedbacks between hydrology and geomorphology are generally considered (despite the continuing requirement for the hydrologist to re-evaluate rating curves for the conversion of stage to discharge, particularly after extreme events). This has been partly due to a lack of computer power in the past, partly because of a lack of measurement techniques and data, but is primarily attributable to a lack of interest of hydrologists in sediments. The problem has been that the prediction of stream discharges and modelling of water flow pathways assuming everything else constant has been sufficiently challenging. In fact, only relatively recently have the topographic controls on flow pathways been reflected in the model structures used by hydrologists (see for example Stephenson and Freeze 1974; Beven and Kirkby 1979; O'Loughlin 1981; Abbott et al. 1986; Beven et al. 1995; Ambroise et al. 1996).

The hydrologist has, however, had some major advantages in modelling flow processes over the geomorphologist wanting to model sediment transport processes. One is simply that the time scales of interest to the hydrologist are more compatible with dissertation, research grant and research career time scales, rather than the generally longer scales needed to integrate the effects of processes to a level of significant geomorphic change. The time scales of hydrological process theories are also short, and are not, in fact, amenable to application over long periods of time. In addition, because of the importance of water resources management, considerably more effort has been expended by both researchers and government agencies in hydrological data collection. The data are still limited but there are many sites for which rainfall, discharge and evapotranspiration data are available; fewer sites where limited internal state data such as soil moisture or water table information are available; and just a few sites where detailed measurements of the spatial patterns of flows have been undertaken using tracers and detailed sampling of state variables.

At well-gauged sites, therefore, it has been possible to examine the magnitude-frequency characteristics of hydrological events directly and to calibrate models of flood and drought frequencies, monthly water balances, and lumped and distributed models of groundwater and river flows, and lumped and distributed models of catchment hydrographs both for individual events and continuous (discrete time step) simulation. Hydrological models are now used routinely for flood forecasting, sometimes with real-time updating, surface and groundwater reservoir management and design, predicting the effects of land-use and climate change on runoff and flow extremes, pollution incident prediction and a range of other purposes. There is a vast literature on model structures (see Wheater et al. 1993 and Singh 1995, for recent reviews of available models), ranging from the purely functional unit hydrograph, still used to advantage in modern transfer function form (see Duband et al. 1993; Jakeman and Homberger 1993; Young and Beven 1994), to the solution of stochastic differential equations for flow in a heterogeneous soil or groundwater system (e.g. Jensen and Mantoglou 1992).

Hydrological models are, in fact, a particularly interesting class of environmental models. At the small scale, the theory of water flows as embodied in the Navier-Stokes equations is relatively well understood. These equations are, however, very difficult to solve: in general because of the nonlinearity of the equations and the problems of closure associated with the velocity fluctuations in turbulent flows; and in specific applications because of the poor knowledge of boundary conditions, both locally and for the flow domain as a whole. Thus, it has been normal in developing model structures to resort to semi-empirical physical theory of surface and subsurface flows (Darcy's law, Richards' equation, the St. Venant equations, or more functional representations at larger scales). Some processes are quite well represented (at least locally) by the resulting descriptions; for others (such as evapotranspiration from a vegetated surface) the descriptive equations may be only poorly developed. For each process, however, this introduces parameters of the model that must be calibrated for individual applications, either by direct measurement, some indirect relationship with some characteristics of the catchment, or by adjustment to fit model predictions to observed responses. Where direct or indirect measurement of such parameter values is possible, it has often revealed that the parameter of such models cannot necessarily be assumed constant in space or time, leading to further difficulties of calibration for general applications.

A recent review of techniques for the calibration of parameter values has been presented in the context of hydrological models by Sorooshian and Gupta (1995). The availability of observed output discharges in hydrology for comparison with model predictions makes such calibration possible. It is, indeed, necessary since it has proven very difficult either to measure or estimate the parameter values of hydrological models a priori, even for the most 'physically based' hydrological models (see discussion in Beven 1989). This is in part because the scales of measurement of parameter values tend to be very different from the scale at which the model requires 'effective' parameter values to be specified. It has been known for a considerable time that calibration of hydrological models by comparison of observed and predicted variables is fraught with difficulties, because of model nonlinearities (particularly those associated with threshold parameters), interaction between parameter values, insensitive parameter values and the effects of error in the observations. Where a quantitative measure of goodness of fit is used to assess model performance, these effects can result in very complex 'response surfaces' in the parameter space, with flat areas and multiple local optima that creates considerable difficulties for automatic optimisation techniques (see Blackie and Eeles 1985; Duan et al. 1992; Beven 1993).

It might be expected that improving the theoretical basis of model structures would help in this respect. It is now recognised, however, that this is not necessarily the case (see Beven 1989; 1993; Grayson et al. 1992; Jakeman and Hornberger 1993). There are a number of reasons for this. Increasing the physical basis of a model will usually increase the number of parameter values that must be supplied to a model while the data available for calibration may not increase commensurately. Even the simplest hydrological models tend to have more parameters than can be justified by the data available for calibration; they are *overparameterised* in a systems identification sense (see for example Kirkby 1975).

In addition, even the most physically based theory available has been developed at small scales for 'homogeneous' systems. Some processes, such as flow through structured, macroporous soil and extraction of water by root systems, are not adequately described at application scales by the available equations; heterogeneities and time variability within such a nonlinear system may mean that it may not be possible to relate local measured values to the effective parameter values required at the model grid scale; while many of the boundary conditions required may be essentially unknowable (Beven 1995a, b).

As a result, it has been suggested that all hydrological models can easily be invalidated as descriptions of reality and that even the most 'physically based' models must be considered as merely conceptual descriptions as used in practice (see Beven 1989), and not very good descriptions at that. The process of modelling is then saved by the process of calibration; the models normally have sufficient degrees of freedom in their parameters to be able to fit the observed data with an acceptable degree of accuracy, at least provided our standards of acceptability are not too high.

Confirmation of such models by prediction of another period of data (a split-record test) is a relatively weak test. A much stronger confirmation test would be independent check of the predicted *internal* states of the system. This is also problematic, however, since most internal variables have to be measured at scales much smaller than the grid or catchment scales of the model predictions. Predictions and measurements will then refer to different *incommensurate* quantities, making validation difficult. Concepts of validation, verification and confirmation of models have recently been much discussed in the hydrological literature (see Konikow and Bredehoeft 1992; Oreskes et al. 1994).

One interesting feature of hydrological models that has been revealed recently by computationally intensive explorations of parameter response surfaces is that, for most models, there may be many combinations of parameter values that will provide almost equally good fits to the observed data (see for example Duan et al. 1992; Beven 1993). For any given calibration period and chosen goodness-of-fit measure there will be one set of parameter values that gives the global optimum. There will, however, be many other parameter sets, in many cases from very different parts of the parameter space, that give almost as good fits. A little thought will suggest that this should not be unexpected, due to the problems of parameter calibration outlined above, together with the effects of error in the model structure, in the input and boundary data that drive it, and error in the observed variables themselves. Changing the calibration period or the goodness-of-fit index will give a different ranking of parameter sets in fitting the observations. In short, there is no single parameter set (or model structure) that can be taken as characteristic in simulating the system of interest; there is consequently a degree of model equifinality in reproducing the observations with model predictions.

This problem is, in fact, worse since one result of the lack of an adequate hydrological theory is that there may also be competing model descriptions of a catchment system, as well as competing parameter sets within a given model structure. They may differ in conception in one or more elements, the details of approximate solution techniques (such as different base functions for finite element solutions) or have totally different bases and parameter definitions. Even a cursory examination of the literature will reveal a plethora of models in hydrology with no clear basis for making a scientifically reasoned choice between them. Choice is more normally made for *ad hoc* reasons: the model is already on the computer; it is in the public domain; it is not too expensive to run; I have experience of previous applications; it can make use of the soil and topographic data already loaded on the geographic information system (GIS); the model has been used in this type of environment/for this type of problem before; it is the model I developed. The latter reason normally takes precedence over other considerations.

The problem can be compounded if the interest is not in the hydrology alone but in variables and processes that depend on the hydrology (weathering, solute, sediment and pollutant transport). This introduces additional model components with additional parameter values, all with the same problems of measurement scales, spatial and temporal heterogeneity, dependence on the model structure, together with the possibility of interactions between the hydrological parameters. This will generally increase the possibility of many different parameter combinations being able to fit the available measured data, especially when the available measurements are few. Figure 12.1 shows the results of comparing the predictions of the PROFILE soil geochemistry model (Warfvinge and Sverdrup 1992) to measurements at the C2 catchment at Plynlimon, mid-Wales (Zak and

Beven 1995). PROFILE is an equilibrium geochemistry model that treats the soil as a sequence of soil horizons in series from top to bottom. It requires 35 user-defined parameter values, 26 of which are allowed to vary by soil horizon, normally resulting in the order of 100 parameter values to be specified. A Monte Carlo experiment was carried out using 10 000 randomly selected sets of parameter values, chosen from qualitatively feasible ranges for a restricted number of parameters. The other parameters were kept constant at reasonable values. Each simulation was compared to the measured values of the integrated weathering rate, and the pH and BC/Al ratio of the Bs3 horizon (which dominates the soil geochemistry at this site).

Each plot in Figure 12.1 demonstrates the combined goodness of fit to all three measures for some of the varied parameters. Each point on the plots represents one of the 10,000 Monte Carlo sets of parameter values. It is clear that for most of the parameters, there are combinations of parameter values that give better fits to the observations across the whole of the parameter range considered. The only parameter in the model that shows any strong sensitivity is the reaction coefficient for gibbsite which controls aluminiurn solubility in the model with a consequent strong effect on pH. This reaction is used widely in geochemical models, despite the fact that there is little or no gibbsite in temperate soils, including the soils at C2. In addition, it was found in this study that none of the combinations of parameter values could simulate the estimated weathering rate at C2

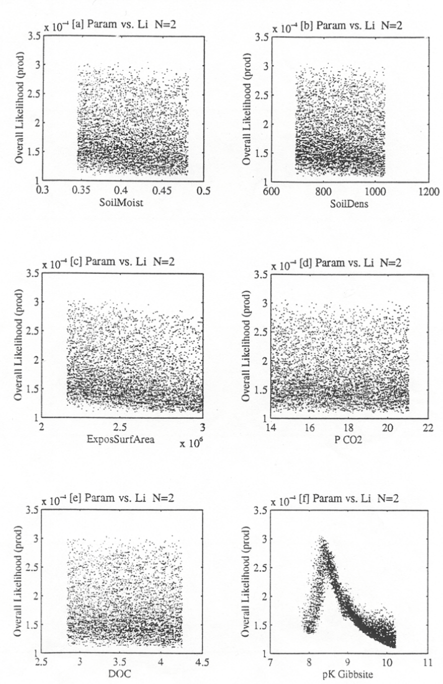


Figure 12.1 Results of fitting the PROFILE geochemical model to data from the C2 catchment in mid-Wales for six of t the PROFILE model parameters. Each point represents a run of the model with randomly chosen parameter values. The higher the likelihood value for a given run, the better the fit to the observations (after Zak and Beven 1995)

adequately. The implication in this case is that the model should be rejected (but PROFILE is being used to estimate critical loads for acid deposition in many areas of Europe and North America).

## EQUIFINALITY AND UNCERTAINTY IN HYDROLOGICAL MODELLING

It is suggested therefore that model equifinality may be axiomatic of environmental modelling where highly parameterised models requiring calibration are fitted to limited data that integrate the response of the system of interest over time and space. Equifinality implies that any parameter values determined by such calibration will be conditional on the other values of the model parameters such that any physical interpretation of the values must be made with care. Equifinality also implies uncertainty. Different model structures or parameter sets that are considered acceptable simulators will, in general, produce different predictions. Beven and Binley (1992) have applied a Bayesian methodology (generalised likelihood uncertainty estimation-GLUE) for estimating this predictive uncertainty based on associating a likelihood weight with each simulation. Their application uses Monte Carlo simulation of multiple randomly chosen parameter sets within a single model structure as the basis for estimating the uncertainty (see also Beven 1993; Romanowicz et al. 1994; Freer et al. 1996). Extension to multiple model structures is straightforward.

The GLUE approach rejects the idea that there may be some optimal model or parameter set. Models can only be evaluated in terms of their relative likelihood of being an acceptable simulator of the system of interest or rejected as being non-behavioural. Such a view seems to lie somewhat uneasily between several rather different philosophical viewpoints on the structure of science. Most environmental scientists will agree that model/theory confirmation is a matter of degree of empirical adequacy (van Fraasen 1980; Oreskes et al. 1994); the point here is that adequacy may be limited or conditional, requiring further tuning or modification of ancillary conditions as more or different types of data become available. This would appear at first sight to result in a purely relativist attitude to the problem of modelling complex environmental systems, in keeping with the views of Feyerabend (1975) on the development of scientific thought (see Beven 1987, for a discussion in relation to hydrology). The estimation of likelihoods is certainly consistent with a relativistic philosophical stance which does not require any necessary or strong correspondence between theory and reality.

The problem can, however, be viewed from within other traditions as a problem of model/theory falsification. It is now well recognised that falsification is fraught with difficulties, but we use it here in a weak sense in respect of the declaration of certain models as 'non-behavioural' in simulating a particular system of interest. There may indeed be many models that are behavioural or acceptable simulators, but an important part of the process of modelling is then the rejection of some of those models on the basis of existing or new evidence. This does not necessarily imply that there is any correspondence between those models retained and reality; nor that rejection of a model in one application implies that a model may not be a useful predictor elsewhere. Indeed the very fact that there may be multiple models or competing hypotheses retained does not encourage such views.

However, whilst recognising the difficulties associated with the concept of falsifiability, in this context it raises some interesting possibilities. It may be possible to design testable hypotheses and associated experiments that would allow model structures or parameter sets to be designated as non-behavioural, i.e. a certain class of models or parameter sets will be deemed falsified. The resulting studies might represent a very different approach from the experimental work associated with modelling carried out at present in which the concern tends to be with the measurement of parameters or state variables at small (but manageable) scales. Such an experimental design may not be the most cost-effective approach to refining the likelihood associated with individual models and consequently to constraining the set of behavioural models and consequent predictive uncertainty. Such an approach has much in common with the Bayesian methodology espoused by Howson and Urbach (1989). Rejection of all the models tried on the basis of some reasonable criteria will suggest a serious lack of predictive capability.

Why has this approach not already been adopted widely in hydrological modelling? One reason is that it is actually too easy to falsify the currently available models on the basis of either their assumptions or their performance relative to observations. The modelling process is then saved by the adoption of less stringent criteria of acceptability or recourse to ancillary arguments which allow that it may not be possible to predict all the observations all of the time (arguments of scale, spatial heterogeneity, lack of time variability in parameter values, uncertainty in theoretical descriptions of the processes, etc.). In this context, relativism is commonly practised - albeit using qualitative rather than quantitative measures of performance and without explicit recognition of the process. I have suggested elsewhere that the result is more akin to prophecy than to prediction (Beven 1993).

In what follows the implications of these conclusions for geomorphological studies and modelling will be considered.

## EQUIFINALITY, EQUIFINALITY AND EQUIFINALITY

The use of the term 'equifinality' has had a somewhat different content in geomorphology compared with the usage above, stemming from the principles of 'general systems theory' outlined by von Bertalanffy (1951, 1962) and introduced into geomorphology by Culling (1957) and Chorley (1962) (see Haines-Young and Petch 1983). The concept in this context is used to denote the possibility of similar landforms being derived from different initial conditions in different ways by possibly different processes. Haines-Young and Petch (1983) provide a critical review of the concept, suggesting that the unthinking resort to equifinality in explanation of landforms is a failure of methodology. They suggest that if similar landforms can truly be shown to be the result of different processes then equifinality is an empty problem. They particularly object to the link with the method of multiple working hypotheses made in the work of Cooke and Reeves (1976). Cooke and Reeves interpret equifinality in the sense that it may not be possible to distinguish between several different theories for the formation of a particular landform. Haines-Young and Petch (1983, p. 466) by contrast argue that

> if two or more theories cannot be distinguished on the basis of the predictions that they make about landform character *then they are poor theories. To* describe those features as 'equifinal' does not detract from this situation. Use of the term merely encourages the maintenance of those theories in an *ad hoc* and uncritical way. The aim of the geomorphologist should be to develop those theories so that they can be tested *against each other.* Only then, through the process of experiment and observation can the geomorphologist hope to eliminate any false conjecture.

They further suggest that the only valid use of the term is the much more restricted sense used by Culling (1957) who suggests that in open systems the operation of similar processes will, over time, tend to produce similar forms from a range of initial conditions. Culling suggests that graded streams may be considered 'equifinal'. A link with the gradualist concept of dynamic equilibrium may be discerned here, but the use of the term in this way was later criticised by Culling (1987, p. 68) himself in the light of more recent work on nonlinear dynamic systems theory and chaos. He notes:

> The ubiquity of noise means that all stable systems are transient.... It is now known that transients can exhibit chaotic behaviour and that these chaotic transients may have extremely long lives ($\sim 10^6$ iterations). Chaotic transients can only compound the difficulties of recognising chaotic behaviour in the landscape. Despite all these difficulties, however, it is known that chaotic motion and strange attractors into the heartland of physical geography for turbulent flow is irregular, intermittent, self-similar and whether we like it or not ubiquitous.

Culling's (1987, p. 69) conclusion is that equifinality is a vague and transient concept that will ultimately be subsumed into the well defined apparatus of abstract dynamical systems. Geomorphological systems are nonlinear and subject to random forcings of events of different magnitudes. Similar to other nonlinear systems they should be expected to show significant sensitivity to initial conditions and random perturbations. He distinguishes between equifinality *sensu strictu,* where a perturbed system will eventually return to its original form, and weaker forms of equifinality which imply only persistence of some property, i.e. stability in some sense. He defines a number of ways in which properties may exhibit local (small perturbation only) or Lyapounov stability (return to a similar form) or, in a weaker sense, ergodic or topological persistence. The application of nonlinear dynamical theory to geomorphological systems has been further explored by Culling (1988), Malanson et al. (1992), Phillips (1993, 1994) and others.

The experience of model equifinality in hydrology suggests that there is, in fact, little incompatibility between all these views when it comes to *practical* geomorphological explanation. If there are, indeed, many models that may be compatible with the geomorphological evidence, they should include those models that exhibit equifinality in the senses outlined by Culling (1987). Haines-Young and Petch (1983) note that part of the attraction of the concept of equifinality may come from the fact that landforms present extremely difficult objects to study. As a result it may be very difficult to obtain the necessary data over sufficient periods of time and sequences of events to decide between multiple working hypotheses (or models). That does not mean that they are necessarily poor hypotheses, only that the problem is currently undecidable within the limitations of currently available models and data. If information was available to determine that the hypotheses were poor, they would normally be rejected.

If indeed, geomorphological systems are sensitive in their nonlinear dynamics to initial conditions and random forcings then it follows that much of the history of particular landforms may now be lost from view. This is not inconsistent with the fact that in many environments some effects of past geomorphological processes and climatic regimes are readily distinguished, even after long periods of time. Geomorphological systems are indeed transient, they should be expected to show the remnant results of past and present processes, but the possibility of chaotic behaviour means that the *trajectory* of their development may be undecidable on the basis of present-day evidence alone. Thus, the consequences of understanding from dynamical systems theory suggest that equifinality may not be an indication of poorly developed methodology but may be implicit in the nature of geomorphological systems.

One practical consequence of this equifinality is in the application of geomorphological models which represent a (more or less) rigorous way of formulating practical hypotheses about geomorphological systems. As in the case of hydrological models described above, geomorphological models require necessary simplifications and abstractions to be tractable and involve parameters that must be calibrated in some way. The models are nonlinear and may demonstrate chaotic behavior (Phillips 1993). Within such a model framework there may then be many combinations of initial conditions, model behaviours and parameter sets that are consistent with the limited observations available about a particular class of landform. They are then equifinal in some sense, indeed in a very similar sense to that used by Cooke and Reeves (1976) and criticised by Haines-Young and Petch (1983). This analysis would suggest that there may be very many situations in geomorphology where equifinality stems not from an inherent property of the system but from an inherent property of the process of study of the system.

At first sight this would appear to be a very unhealthy situation for geomorphological science, as expressed in the concerns of Haines-Young and Petch (1983). This is not necessarily the case; equifinality of hypotheses and models today, when properly recognised, can lead to the formulation of experimental and analytical methodologies that may allow rejection of some of the competing explanations in the future. One suspects, however, that there will be an irreducible set of possible explanations and that equifinality will, itself, exhibit persistence.

In summary, equifinality would appear to remain a valuable concept in geomorphological studies as a result of the inherent limitations and constraints on understanding both the genetic evolution and modelling of landforms. It expresses, in shorthand form, the impossibility of distinguishing between many possible histories from different possible initial conditions and different possible process mechanisms on the basis of the available evidence.

Qualitative reasoning to argue for one trajectory rather than another has ultimately to depend on faith. Quantitative reasoning, based on model predictions, will result in many different sets of model structures, initial and boundary conditions and parameter values that will be compatible with the available data. However, it is hoped that recognising this equifinality may lead to a more robust approach to testing the viability of different model explanations, leading to the rejection of some but, undoubtedly, to the retention of many. The class of retained models may, of course, be inherently interesting in themselves. Similarities and differences may lead to improved understanding.

The next section explores the background to model equifinality in geomorphological explanations, starting from the geomorphologist's perceptual model of the processes that are her/his concern.

## EXPLANATION IN GEOMORPHOLOGY - THE PERCEPTUAL MODEL

In geomorphology, as in hydrology and all other environmental sciences, there is a difference between a scientist's perception of how the system of interest operates and what is included in the working models being used. Since the work of Popper and Bachelard, it has been recognised that both are socially conditioned; that both theory development and interpretation of experimental and other evidence are carried out within a social and historical context of interaction and competition between research groups, individual scientists, teachers and students. Geomorphology has not been subject to the detailed sociological scrutiny as some other areas of science (e.g. Knorr-Cetina 198 1) but there has been a succession of reviews of the status of the subject that allow the framework for a perceptual model to be assessed, both in terms of the philosophy of the science (e.g. Haines-Young and Petch 1983; Richards 1990, 1994; Rhoads and Thorn 1993, 1994; Bassett 1994; Rhoads 1994) and the subject-matter itself (e.g. Brunsden 1985, 1990; Scheidegger 1987).

The perceptual model is not, of course, written down. It is individual to each geomorphologist depending on her/his teachers and training, his/her field experience of different environments, the literature and conference presentations s/he has been exposed to, and day-to-day discussions within a research group. Putting a perceptual model into writing will necessarily require simplification (but also perhaps useful critical review and formalism). The important thing here is that any perceptual model will recognise complexities and multiple possible explanations of landforms in a way that cannot be included in the mathematical descriptions that form the basis for any predictive capability. The perceptual model is inherently qualitative, but conditions both responses to experimental evidence and decisions about the dominant processes and representations of those processes to be included in quantitative models.

For certainly decisions must be made. Quantitative models are necessarily crude approximations of our perceptual understanding of what is important. There are many processes for which we may understand the governing principles in detail but cannot apply those principles at scales of interest because of lack of information about characteristic parameter values or boundary conditions that are only poorly known or too complex to be feasibly known. There are other processes for which we do not have an adequate description at any useful scale. These decisions are constrained by the current perceptual model and considerations of feasibility in terms of mathematical tractability, computing and data requirements. There is also, perhaps, a competitive edge to the process, observing and improving upon what is being done elsewhere (or at least doing something a little different).

Consider then a perceptual model for a particular area of geomorphology, the development of a hillslope/river network system. This is an area that has recently been the subject of significant (and competitive) modelling activity. A (simplified) perceptual model of the controlling processes will involve the following elements. The primary driving forces for hillslope and channel development are gravity and the hydrology, which largely controls erosion, deposition, chemical weathering and removal of material by solution. The balance of hydrological processes of surface and subsurface flows and 'losses' to evapotranspiration will affect the pattern of geomorphological development and may lead to important seasonal differences in geomorphological processes (e.g. Schumm 1956; Howard and Kerby 1983; Harvey 1994). There is a feedback between hillslope form and flow processes that will control the dynamics of surface and subsurface contributing areas for runoff and the concentration of flows and resulting shear stresses.

Over long periods of time, there may be important feedback mechanisms between vegetation cover, soil development, weathering processes, erosion and deposition with different constraints in different environments. Man can have an important impact over short periods of time. Extreme events (floods, droughts, mass movements or volcanic eruptions; e.g. Starkel 1976; Baker 1978; Newson 1980; Dunne 1991; Howarth and Ollier 1992; Nott 1992) can also have important impacts over short (and sometimes long) periods of time. We assume that uniformitarianism holds in the sense that the physical and chemical dynamics of the processes involved will not change, but the boundary conditions and values of controlling parameters may change over time. The relaxation time of the system to such short-term disturbances will control how the system is perceived as being in some 'dynamic equilibrium' and how far the magnitude-frequency of system responses can be related to the magnitude-frequency characteristics of the external forcing in terms of concepts such as the 'dominant' or 'formative' event (Wolman and Gerson 1978; Brunsden 1985,1993; Dunne 1991). Some systems may be perceived as apparently continually in disequilibrium (e.g. Stevens et al. 1975). In some circumstances, the sequence of events may be important as well as the magnitude-frequency distribution, particularly where some threshold phenomena control the response (Anderson and Calver 1977; Beven 1981). Sediment transport depends on complex thresholds for the initiation of motion and erosion and may be transport limited or supply limited (perhaps at different times or different locations within the same system, e.g. Newson 1980; Coates and Vitek 1980; Campbell and Honsaker 1982).

Thresholds (for example, for shallow mass movements or surface erosion at a point) may evolve over time, and might also vary spatially with vegetation or soil patterns. The exceedance of thresholds may depend on spatial patterns of rainfall intensity and antecedent conditions that may depend on hillslope form as well as vegetation, soil and preceding weather patterns. The analysis of nonlinear dynamic systems suggests that perturbations of the system might, in some circumstances, lead to switches in the mode of behaviour and associated processes, without necessarily any relaxation back to the original system state. Geomorphological systems show some evidence of self-organisation in patterns of dendritic rill and channel networks, meandering channels, and slope-area relationships (see Hallet 1990; Rinaldo et al. 1993; Rigon et al. 1994; Rodriguez-Iturbe et al. 1994; Ijjasz-Vasquez and Bras 1995).

The operation of these processes is set within a historical context of changing external forcing associated with climate change and tectonic effects (e.g. Thornes and Brunsden 1977). Both will be expected to show irregular rates of change over time. The residual features of previous climatic regimes and geomorphological processes may still exert important controls on current landforms and processes (e.g. Fried and Smith 1992), for example in those temperate areas that were subjected to successive periods of glacial and periglacial processes in the last ice age. It is generally impossible to know the initial conditions for slope development (except for some laboratory and man-made systems). It is also impossible to know in any detail the parameters that control the process responses, particularly those of the subsurface. Biotic controls on soil permeability and soil strength through root growth and decay and the effects of soil fauna may be very difficult to assess. Soil physical characteristics can generally only be determined on a small number of samples that may be a poor representation of the soil mass as a whole. There may also be considerable heterogeneity of processes associated with the nature of the surface and its vegetation cover (e.g. Dunne et al. 1991) in ways that may be very difficult to understand (see for example Hawkins 1982; Hjelmfelt and Burwell 1984).

So much for the (simplified!) perceptual model. In summary: 'the key-words of modern geomorphology are: mobility, rhythm, flux, instability, adjustment, sensitivity, complexity and episodicity' (Brunsden 1985, p. 52). To this must now be added the possibility of chaos and strange attractors (Culling 1987, 1988; Phillips 1993, 1994). Modelling such systems is clearly very difficult. We can conclude that in addressing the modelling problem we will generally have no information about the initial conditions, little information about the changing nature of the external forcing (both climatic and tectonic) over time, poor information about the effects of man except in the very recent past, little knowledge of how the physical and biotic characteristics of the system have changed over time, and relatively poor mathematical descriptions of the processes of development at the scales of interest.

How is the modeller to proceed in the face of such uncertainty? One answer is certainly deductively; it saves having to come too close to reality and address the need for and prediction of real data.

## MODELLING WITHOUT DATA - DEDUCTIVE GEOMORPHIC REASONING

Deductive reasoning has a long and prestigious history in science. It allows the consequences of a given theory and set of assumptions to be enumerated and in many cases tested. There have been a number of well-documented cases of deductive predictions in science that have later been confirmed by observation. The implication is then that the assumptions of the theory are a good approximation to reality and from a strong realist viewpoint, that the variables embodied in the theory are real variables. It is not necessary to make such claims for quantitative geomorphological theorising, which is incomplete, based on empirical expressions and recognised as approximate. The process is more normally referred to as modelling.

Quantitative geomorphological modelling has been growing rapidly in popularity as an indoor sport in recent years (e.g. Ahnert 1976, 1977, 1987; Armstrong 1976; Cordova et al. 1976; Kirkby 1985; Roth et al. 1989; Willgoose et al. 1991a, b, c, 1992; Chase 1992; Howard 1994; Moglen and Bras 1995). These models solve partial differential equations of mass conservation for water and sediment coupled to various semi-empirical erosion and transport laws, mostly of the general form

$$R = (K_1 + K_2C)C^pD^m \sin^n \alpha - K_3) \tag{1}$$

where R is the rate of transport, D is the local value of discharge, sin $\alpha$ is the local value of slope angle, and C is the local soil depth, $K_1$, $K_2$ and $K_3$ are coefficients and *n, m, p* are exponents which vary with the nature of the transport process (splash, viscous flow (creep), plastic flow (debris flows and slides), suspended wash transport and fluvial transport; see Ahnert 1977). For each process included in the model, the six coefficients and exponents must be specified. Even if the slope and channel process parameters are assumed to be stationary in time and space, potentially there are 30 parameters to be specified for these five processes, although many are normally set to zero. There may be additional parameters associated with weathering processes (e.g. Ahnert 1976, 1977, who uses a two-parameter formulation), while running the model requires a field of initial elevations and boundary conditions in terms of net runoff rates and a field of rates of tectonic uplift in the area of the simulation.

These 'laws' are empirical-causal idealisations which, in themselves, have little explanatory power in terms of the underlying mechanisms, and have parameters that may require calibration for particular applications. Rough ranges of these parameters are known from experimental and previous modelling experiences (e.g. Figure 12.2 from Kirkby 1990), although it has been suggested that no general agreement exists on the powers *n* and *m* (Kooi and Beaumont 1994, p. 12-207). The nonlinearity of the transport laws necessitates approximate numerical solutions, in most models using finite difference approximations on a regular square mesh, and values of $m > 1$ imply that the magnitude-frequency distribution of events may be important. All the models produce dissected landscapes that have some similarity to real landscapes, despite being gross simplifications of the perceptual model described above. In all these cases, the forcing due to external variables is continuous and steady with no allowance for extreme or catastrophic events or periods of 'relaxation' between major events. Time derivatives in the equations are usually treated explicitly and, in most cases, little study is reported of the stability constraints on the solution of these nonlinear equations.

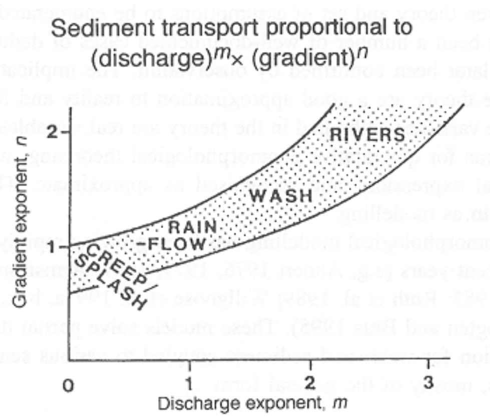


Figure 12.2 Range of parameters *m* and *n* for different processes (after Kirkby 1990)

These are examples of what Morton (1993) calls 'mediating models'. They mediate between an underlying theory, which in geomorphology is developed largely in rough qualitative terms (the perceptual model), and the quantitative prediction of landscape development. They have the general characteristics revealed by Morton's analysis: they have assumptions that are false *and known to be false:* they are not, however, arbitrary but reflect physical intuition; they tend to be purpose specific with different (and possibly incompatible) sets of assumptions and auxiliary hypotheses for different purposes; they have real explanatory power but may never (nor are they expected to) develop into full theoretical structures. They also have a history, in that successful modelling techniques tend to be refined and inherited by later models (see Schrader-Frechette, 1989, for a hydrological example).

The predictions of such models are valid only within the context of the model structure itself. This will necessarily include any effects of the solution algorithms used, for example the effects of numerical dispersion within a finite difference scheme, meaning that the approximate solution may not be convergent with the original differential equations, despite the fact that the numerical solution may remain stable throughout. In addition, these are dissipative nonlinear discrete time systems; depending on the nature of the attractors of the solution, model predictions may be sensitive to initial conditions (for geomorphological examples see, for example, Willgoose et al. 1991b; Ijjasz-Vasquez et al. 1992; Howard 1994) while slightly different models applied to the same set of boundary conditions may result in significantly different predictions. Deductive inference then refers to the model; any inference about the behaviour of real systems is likely to be tenuous.

What is clear is that both landscape and models belong to a class of systems that produce dendritic structures. This arises out of the simple feedbacks between flow, erosion and sediment discharge. Various arguments have been advanced in the literature for the constraints that lead to a dendritic network for shedding water and sediment, including asymptotic efficiency arguments for the form of particular networks in particular circumstances (e.g. Woldenberg 1966; Rodriguez-Iturbe et al. 1992; Ijjasz-Vasquez et al. 1993), where the parameters of that particular system can be specified.

Consider, however, if we wish to use such models to deduce (or perhaps more correctly *abduce)* the development of particular landforms where the initial conditions, transport laws and historical boundary conditions are not well known. There are a number of problems in trying to do this. Each of the models quoted above, albeit gross simplifications of the real processes, requires the specification of a gamut of parameters. Thus, in similar fashion to the hydrological models discussed earlier, there may be many different sets of parameter values within a number of different model structures that will be equally consistent with some statistical measures of goodness of fit between modelled and real landforms. In addition, it is known that model predictions may be sensitive to their initial conditions and precise values of parameter values (see for example Moglen and Bras 1995). Thus, for any given model, there may be many different initial conditions that are equally consistent with the chosen measures of fit. In addition, the history of the boundary conditions in terms of the magnitude, frequency and sequence of events is equally unknowable; there may be many sequences that, when interacting with the parameter values and initial conditions, will be equally acceptable as simulators of today's landforms, particularly if those forms are close to an attractor in the solution space. In short, model equifinality should be an expectation in geomorphology.

The inference from this analysis is not that it is not possible to simulate today's landforms using geomorphological models. The problem is rather the contrary, it may be all too easy to produce statistically similar landforms (especially if the statistics are not too discriminating since it is very difficult to characterise precisely all the characteristics of a landform in terms of a few statistical indices or fractal dimensions which may be limited in discriminatory power). Thus there may be many model 'explanations' of the landform, equally valid given the information available but all known to be false through being based on modelling with all its limitations. Many factors have been knowingly glossed over or ignored in these first modelling studies, due to lack of knowledge and computing power.

Will further refinements of the models or data help in this respect? Again, experience from hydrological modelling suggests not a great deal. It is almost an aphorism that refinements of models within the normal development of a science tend to introduce complexity and require additional parameter values and boundary conditions. Increasing the dimensionality of the parameter space in this way leads to further identifiability problems, unless those parameter values can be estimated quite independently of the model (unlikely in geomorphology). Consideration of the nature of specific landforms requires consideration of their unique as well as generic characteristics. The unique characteristics include the heterogeneity of characteristics and parameters and previous history, all of which are essentially unknowable.

## GEOMORPHOLOGICAL PREDICTABILITY - COMPARISON WITH REAL LANDFORMS

Pure deduction requires validation only for internal and numerical consistency. Models for geomorphological development, which may or may not be internally and numerically consistent, can also be compared with real landforms. Current models can produce a wide range of landforms, similar to the wide range of landforms seen in different real landscapes (e.g. Howard 1994). A variety of landform modelling studies have reported qualitative assessments of the realism of the simulated landscapes; the difficulty comes in comparing model simulations with particular landforms with their own unique characteristics of underlying geology and history, including the persistence of effects from past events or tectonic or climatic regimes. There have been very few studies that have attempted to do this. The examples below will illustrate some of the problems involved.

One early study was that of Ahnert (1970) who compared a simple slope profile model predicting both bedrock profile and overlying waste thickness with data on waste cover collected from three short profiles on gneiss bedrock in North Carolina. Two other, longer, profiles were eliminated from the analysis because of irregularities in slope and waste cover that are probably due to local variations of rock resistance (Ahnert 1970, p. 93). The model was purely deterministic based on a simple exponential relationship between weathering and soil depth and a transport rate that is directly proportional to slope angle. It appears to have required two parameters (a weathering rate scaling parameter and transport rate scaling parameter) and an initial slope profile. Slope development was predicted using explicit time stepping. It was found that the model could explain of the order of 86% of the field-measured waste thickness values when 'a profile similar to the field slopes was singled out for comparison'. Ahnert (1970, p. 96) concludes that 'the close agreement between the properties of the model slope and those of the field slopes indicates that the theoretical model is very probably a valid representation of conditions and processes on real slopes'.

This early study, albeit limited in scope, neatly illustrates the general problems of model validation. With the considerable benefit of a current viewpoint, it might be suggested now that, even within the framework of Ahnert's simple model, there might be a number of different representations that would produce results consistent with these field data, while a general explanatory model that would include the other slopes excluded from the validation exercise would require more complexity and parameter values and consequently data to be collected. It is worth re-emphasising that model equifinality raises problems about the physical significance of parameter values determined by calibration. Such values may only have significance within the context of the particular model structure used and will be conditional on values of other parameters. This, by extension, includes parameter values determined by calibration reported in the literature.

Since the time of Ahnert's study, the formulation of geomorphological models has indeed become generally more complex with more parameters to be specified. In addition, it is possible to compare the complete field of predicted values with the real topographic characteristics. Nobody, however, would suggest that a geomorphological model could predict a landscape in precise detail. The tendency therefore has been to compare generalised *indices* of behaviour. One example is the study of Willgoose (1994) who compares area-slope-elevation plots of both model and real landscapes (Howard 1994 shows a similar comparison). For the modelled landscapes, earlier work had shown that such plots show consistent (but different) shapes for the two cases of dynamic equilibrium (when uplift rate is equal to erosion rate) and 'declining equilibrium' (the fixed base level case when normalised hillslopes show a characteristic pattern). Effective parameter values were calibrated by fitting the field data to the characteristic relationships for each form. Some 40% of the variance of the field data was explained for the dynamic equilibrium case and 55% for the declining equilibrium. Confidence limits on the fitted parameters varied up to ± 10% (with the base level for declining equilibrium being particularly well calibrated) while it was found that data from individual subcatchments in the field area showed slopes on the plots considerably different from the aggregated data (perhaps due to different effective base levels). Willgoose (1994, p. 158) notes that while these results show 'that the area-slope and area-slope-elevation relationships can be consistent with observed field data, this does not constitute a validation'. He suggests that a proper validation would require field data collected of total load sediment transport at a range of catchment areas at an 'undisturbed' site. Even then, assumptions of statistical homogeneity of catchment and erosion characteristics would be required. This study makes the difficulty of separating parameter calibration and model validation quite clear.

Mogelen and Bras (1995) have also tried to calibrate a model to whole landscape characteristics using an extension of the Willgoose SIBERIA model. To do so, they have assumed that the landscape is in steady state with erosion in equilibrium with uplift and that the values of $m$ and $n$ in equation (1) can be specified for different processes. They use the observed cumulative area distribution and slope-area curves to calibrate the parameters of the model which include a parameter that controls the heterogeneity of the resistance of the soil to erosion. Two free parameters are fitted to the cumulative area distribution for two catchment areas of different topography using nonlinear least squares. They suggest that the inclusion of heterogeneity is important in reproducing the observed cumulative area distributions. Their model uses a linear law for creep on the hillslopes; elsewhere it has been suggested that linear diffusion is inadequate to reproduce the temporal pattern of scarp degradation (Andrews and Bucknam 1987) and that a nonlinear diffusion law (with at least one extra parameter) is necessary. Although these studies are still very much in their early stages, the attraction of adding complexity and parameters to 'explain' observed landscape features is already apparent.

By concentrating on the 'equilibrium' characteristics of both modelled and field landforms the Willgoose (1994) and Moglen and Bras (1995) studies avoid the problem of persistence of features from past events and regimes of tectonic uplift or climate. In fact, Willgoose notes that his study does not address the interaction between the time of adjustment to uplift events and time between uplifts. Brunsden (1993), in a general discussion of the problem of persistence, uses a framework in terms of *formative events* and *relaxation times*. Ahnert (1987) discusses the relaxation time towards dynamic equilibrium within the context of a distributed slope development model in an application to simulate the slopes of the Kall valley in the northern Eifel. The Kall valley exhibits a Tertiary denudation surface of low slope in its upper reaches, with an increasingly incised channel downstream, thought to be the result of Quaternary headward erosion with slope development affected by periglacial processes. The model used, SLOP3D, is an extension of the hillslope model cited earlier, and in this study is used to simulate the progressive development of a single slope with an initial condition taken as a current profile on the Tertiary surface. Six other profiles from further down valley were compared with the model predictions assuming that the history of the valley allowed for spatial variation in the field to be replaced by temporal variation in the model. Note that this allows an additional degree of freedom in choosing which time step to compare with each field profile. In the Kall valley, profile 7 which is considerably further downstream than profile 6 is compared with a simulated profile at about half the time of that for profile 6.

The version of the SLOP3D model used appears to require nine parameters to be fitted. Of these, Ahnert (1987, p.5) notes that the four controlling suspended load wash 'keep the regolith from becoming too thick but have little effect of the shapes of the profile'. A threshold slope parameter for the occurrence of debris slides 'equals approximately the maximum angles of waste-covered slope found in the Kall valley' (Ahnert 1987, p. 5). The remaining parameters control the rate of fluvial downcutting at the base of the slope, the slow mass movement rate and the weathering rate. These are all assumed constant. Ahnert (1987) comments on the effects of climatic fluctuations that no specific morphological traces of the effects of fluctuations remain. 'Apparently they caused merely intensity variations during the continuing slope development but not any significant changes in the direction of that development' (Ahnert 1987, p. 6), even though Ahnert calculates that the time required for the development of the model slopes is of the order of 1 million years. The relaxation time to equilibrium for this area is estimated as of the order of 5 million years, a time scale within which both climatic and tectonic fluctuations have been significant.

Ahnert (1987, p. 6) shows that, 'after many attempts with different combinations' of parameter values, a simulation was obtained that fits the observed field profiles well. He suggests that this match is not obviously due to equifinality in the sense of similar forms arising from different process representations. Some model runs produced 'qualitatively similar forms. However, in quantitative terms all of these deviated more from the natural Kall valley slope profiles' (Ahnert 1987, p. 6). Interpreting this conclusion in terms of the equifinality concepts described above, Ahnert is clearly suggesting that the range of possible models consistent with the field data is highly constrained despite the uncertainty in the history of these slopes and the appropriate parameter values for both weathering and transport (see also Kirkby 1984). An investigation of just how constrained the feasible parameter sets are, in this and other situations, would be of great interest. Measures of model performance also require further study, but experience with hydrological models suggests that Ahnert's conclusion is optimistic. If it proves correct, however, it will be of great significance for geomorphological reasoning and prediction.

## THE PROBLEM OF FUTURE HISTORIES - UNKNOWABILITY AND UNCERTAINTY

This chapter has attempted to clarify the different notions of equifinality associated with geomorphological theorising and modelling. The potential for equifinality in modelling particular landforms has been emphasised, although one of the few comparisons of modelled and field hillslopes (Ahnert 1987) suggests that the range of parameter values giving simulations consistent with field data may be highly constrained. This is likely to be optimistic, however, since equifinality should be expected as a general characteristic of the limitations of models that are false and of data that are generally inadequate for model parameter identification and in some cases unknowable. The consequences of equifinality are uncertainty in inference and prediction.

There is, however, a need and a market for geomorphological predictions in such areas as the design and near-term future development of erosion on landfill sites (e.g. Riley 1994) and making the long-term safety case for radionuclide repositories (e.g. United Kingdom Nirex 1995). The initial conditions for such predictions will be known in broad scope (either a design or actual current landform) although the heterogeneity of current slope and channel characteristics will be difficult to define precisely. Future boundary conditions, however, are clearly the stuff of speculation even in the relatively short term. Longer-term climate predictions using global climate models (GCM) cannot be considered reliable, being subject to 'flux corrections' and poorly validated at the regional scale even for mean monthly predictions. There will be even more uncertainty about the changing probabilities of extremes under changing climatic conditions which may be important in geomorphological development, particularly for threshold-controlled processes. Perhaps the best strategy towards future prediction is to consider what might happen under different possible scenarios of boundary conditions with a view to identifying those scenarios that might prove application critical.

Thus, there will be uncertainty arising from different possible models and parameter sets and uncertainty arising from different scenarios of possible boundary conditions. The possibilities are numerous and it may be difficult to assess or assign any probability of occurrence or likelihood to each possibility except in some subjective way (as in the case of the first Intergovernmental Panel on Climate Change (IPCC) report (Houghton et al. 1990) on future climate and sea level changes). This is a particular problem for application critical predictions. Decision analysis can make use of some estimate of the risk of occurrence of critical events, given the uncertainties in the prediction process, if it could be made available. It is possible to assess such risks within either Bayesian likelihood or fuzzy set frameworks but it will be clear from the discussion above that assessment of the likelihoods of both models and scenarios will be inherently subjective, even given some 'validation' of models in predicting current landforms.

There is one way in which this concept of multiple scenarios for acceptable models might be used as a proper tool for geomorphological investigations. Consider a sample set of viable models produced by Monte Carlo simulation within ranges of parameter values and conditions considered feasible in a particular situation that reproduce (to some appropriate level of similarity) the nature and historical development (as far as it is known) of real landforms. That range truly reflects the uncertain knowledge about landscape development within the limitations of the modelling process, but may also contain information about competing modes of behavior within the model structures used. If so, it suggests that a process of hypothesis testing (as discussed earlier), in which critical and perhaps novel analyses are used to eliminate certain model scenarios from the current viable set, may be a valid way of improving model structures. Limitations in knowledge, data, and lack of experimental techniques for discriminating between model scenarios, should, however, be expected to lead to a degree of irreducibility of the set of feasible models and consequently to uncertainty in inference and prediction.

This suggests two requirements for work in the future. The first is for creative experiment: collecting measurements that will allow for different hypotheses and assumptions to be tested in a way that eliminates some of the set of possible behavioral models. This is not a simple task, in that failure in a test can often be avoided by the simple addition or refinement of auxiliary assumptions (such as heterogeneity of parameter values) that allow underlying model structures to be protected and that many of the possible measurements may not have great power in discriminating between models and parameter sets. The second is for continuing monitoring of sites so that the likelihoods associated with particular scenarios can be refined as time progresses. It probably remains an open question as to whether this strategy, as it evolves in symbiosis with model development and improvement, will increase or decrease the uncertainty in predictions of future geomorphological change.

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