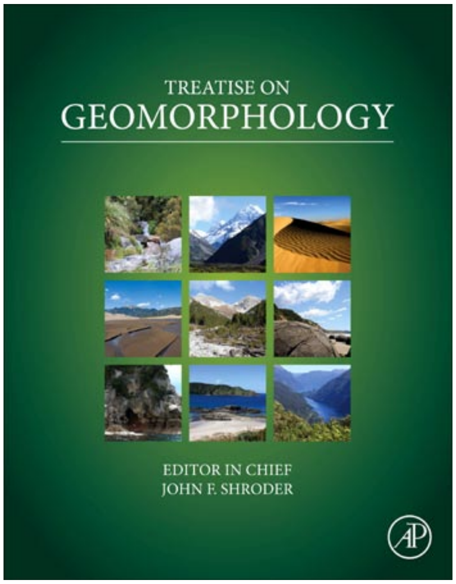

Temme A.J.A.M., Schoorl J.M., Claessens L., and Veldkamp A. (2013) Quantitative Modeling of Landscape Evolution. In: John F. Shroder (ed.) Treatise on Geomorphology, Volume 2, pp. 180-200. San Diego: Academic Press.

2.13 Quantitative Modeling of Landscape Evolution

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Glossary

Conceptual model A set of equations describing the processes relevant for the evolution of a particular landscape.

Descriptive model study A model study focussed on the geomorphic evolution of landscapes in general, often using synthetic Digital Elevation Models. When using real Digital Elevation Models in these studies, the simulations are not compared with field data but with general geomorphic theory.

Perceptual model A set of ideas about the processes relevant for the evolution of a particular landscape.

Postdictive model study A model study focussed on the correct simulation of past landscape evolution in real landscapes, often using model calibration.

Predictive model study A model study focussed on the correct simulation of future landscape evolution in real landscapes, using a calibrated landscape evolution model.

Procedural model study A model study focussed on the experimentation with model equations and formulations or with input data characteristics (such as resolution) instead of the simulation of landscapes.

Procedural model Computer-coded equations describing the processes relevant for the evolution of a particular landscape.

Abstract

This chapter reviews quantitative modeling of landscape evolution – which means that not just model studies but also modeling concepts are discussed. Quantitative modeling is contrasted with conceptual or physical modeling, and four categories of model studies are presented. Procedural studies focus on model experimentation. Descriptive studies use models to learn about landscapes in general. Postdictive and predictive try to correctly simulate the evolution of real landscapes, respectively in the past (with calibration) or in the future (with calibrated models). The geomorphic process is a central concept in landscape evolution modeling. We discuss problems with the field-based definition of these processes from a modelling perspective. After the classification of 117 landscape evolution studies in these categories, we find that descriptive studies are most common, and predictive studies are least common. In the remainder of the chapter, we list and review the 117 studies. In procedural studies, attention has been focussed at production methods for digital landscapes, spatial resolution and the role of sinks and depressions. Descriptive studies focussed mainly on surface–tectonic

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Temme, A.J.A.M., Schoorl, J.M., Claessens, L., Veldkamp, A., 2013. Quantitative modeling of landscape evolution. In: Shroder, J. (Editor in chief), Baas, A.C.W. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 2, Quantitative Modeling of Geomorphology, pp. 180–200.

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interactions, sensitivity to external forcing, and the definition of crucial field observations from model results. Postdictive and predictive studies operate mainly in time-forward mode and are sometimes validated (postdictive studies of soil redistribution over centennial to millennial timescales). Finally, we look ahead to the future of landscape evolution modeling, arguing for a larger role for complexity research, predictive studies and uncertainty analysis, process definition and feedbacks to and from other fields (including ecology).

2.13.1 Introduction

This chapter reviews the quantitative modeling of landscape evolution. Therefore, it focuses not only on landscape evolution models *per se*, but also on some of the concepts that underlie such models.

Quantitative modeling of landscape evolution is considered here as the dynamic and spatially explicit calculation of landscapes and landscape changes through time by means of computer programs. In that sense, it differs from two alternative categories of landscape evolution modeling: the conceptual modeling of landscape evolution and the physical modeling of landscape evolution.

Conceptual, or qualitative, models of landscape evolution are aptly described by Tucker and Hancock (2010) as ''word-picture(s) describing the sequential evolution of a landscape over geologic time.'' Before the advent of modern computing techniques, such conceptual models provided the visual illustration of – sometimes intense – debates about the nature of landscape change. William Morris Davis' geological cycle (Davis, 1899) has become the best known of these models, although its validity has been contested (Orme, 2007). For more information, the reader is referred to Pazzaglia (2003), who included a discussion of conceptual models of landscape evolution in his review of landscape evolution models.

The other alternative, physical modeling of landscape evolution, is the act of mimicking the processes that operate in landscapes on a typically smaller spatial and temporal scale. Downscaling landscapes and landscape activity is a difficult task because it requires the reproduction of correct ratios between material properties and forces on a smaller scale (Pazzaglia, 2003). Nevertheless, significant progress has been made with physical models of landscape evolution. An important case in point is the seminal physical modeling work by Schumm (1973) that resulted, among others, in the conclusions that ''some geomorphic anomalies are, in fact, an inherent part of the erosional development of landforms and that the components of a geomorphic system need not be in phase'' (1973, p. 300). With these words and in his work, Schumm introduced the now-famous concepts of geomorphic threshold and complex response.

Our subject in this chapter, the quantitative modeling of landscape evolution, currently receives more attention from researchers than its two alternatives and offers possibilities that neither conceptual nor physical models do. For this chapter, we divide these possibilities into four broad categories.

As a start, modern models of landscape evolution allow an unprecedented easy and detailed visualization of the spatially and temporally explicit results of wide ranges of assumptions about process behavior and process interactions. In that sense, quantitative models have replaced conceptual models of landscape evolution as the main method for the description of ideas and hypotheses about landscape evolution (Coulthard, 2001; Tucker and Hancock, 2010). They have become the geomorphic laboratories of choice.

Second, when observations on the evolution of a particular landscape are available – for instance, in the long term through the presence of river terraces in an incising valley (Tucker, 2009) or in the shorter term through measurements of radionuclide redistribution (Schoorl et al., 2004) – models can be calibrated and model outputs can be tested. Under some conditions, conclusions can be drawn about the validity of underlying equations (Beven, 2009). Model outputs used for such tests are postdictions, that is, predictions of something occurring in the past (and typically ending in the present) about which we have quantitative information.

Third, quantitative models of landscape evolution can be used for the detailed prediction of future landscape change. This requires confidence in model equations and outputs, and is typically preceded by model calibration in postdictive studies. Predictions are an important goal of numerical landscape evolution models (Istanbulluoglu, 2009b), but they are rarely made because of limited confidence in predictive ability. As discussed later in the chapter, recent research even suggests that at least some types of landscape change may be inherently unpredictable, due to their self-organized criticality (Coulthard and Van De Wiel, 2007).

A fourth category of numerical landscape evolution modeling studies of interest in this chapter is best called procedural studies – studies that are focused on learning about models rather than learning about landscapes. Studies that present new model algorithms (e.g., Coulthard and Van de Wiel, 2006; Temme et al., 2006) or that focus on the effects of model resolution (Claessens et al., 2005; Schoorl et al., 2000) belong to this category. Procedural studies are of particular interest because they expose to scientific inquiry the nontrivial computer programming decisions that can otherwise remain hidden or even unknown behind model interfaces (e.g., Nicholas, 2005).

The four categories of numerical landscape evolution studies, procedural studies, descriptive studies, postdictive studies, and predictive studies, will serve as the highest-level structure of this chapter. However, it must be noted that many quantitative landscape evolution modeling studies contain elements of two or more categories. In particular, studies commonly combine descriptive and postdictive elements, for instance, when an existing landscape is used as a template landscape for descriptive studies (e.g., Ellis et al., 1999). Also, many descriptive or postdictive studies have procedural elements when a model is first introduced or tested and then used (e.g., Claessens et al., 2007).

To assess the prevalence of these different categories in the body of literature on quantitative modeling of landscape evolution, we selected 117 studies that present landscape

Table 1 Categories of landscape evolution modelling studies

Category	*Focus*	*Papers*
Procedural	Learning about models, presenting new algorithms	17
Descriptive	Possible mechanisms of landscape change, what-if analysis	63
Postdictive	Model calibration or validation using landscape change information	35
Predictive	Prediction of future change	2

Table 2 Overview of recent reviews of landscape evolution modelling

Authors	*Year*	*Title*
Coulthard	2001	Landscape evolution models: a software review
Bras et al.	2003	Six myths about mathematical modeling in geomorphology
Pazzaglia	2003	Landscape evolution models
Martin and Church	2004	Numerical modelling of landscape evolution: geomorphological perspectives
Whipple	2004	Bedrock rivers and the geomorphology of active orogens
Willgoose	2005	Mathematical modeling of whole landscape evolution

evolution modeling results. Although we attempted to be complete in our search, no guarantee to that effect can be given. We ventured to assign one of our four categories to each of the studies (**Table 1**) – realizing that this occasionally did not do justice to the width of individual contributions. We found that 17 studies are mainly procedural, 63 are mostly descriptive, 35 have a strong postdictive focus, and only two are clearly predictive. In our further discussion, we merge the postdictive and predictive categories for practical purposes.

In the remainder of this chapter, we first give an overview of existing reviews of landscape evolution models. Then, we look in somewhat more detail at general properties of modern landscape evolution models and discuss some shared concepts and definitions. In particular, the concept 'geomorphic process' will receive attention because of its growing importance in modern, multi-process landscape evolution models. Third, the body of landscape evolution model studies will be reviewed and discussed. Finally, we venture a look into the future of landscape evolution modeling and explore research opportunities.

This chapter is distinct from previous chapters in this volume mostly through the larger spatial and temporal extents that are associated with landscape evolution, as opposed to soil erosion or hillslope evolution. At the very least, landscapes are larger than hillslopes, and typically include more than one of the following elements: hillslopes, river channels, drainage divides, and plains. These landscape elements may be arranged regularly or irregularly, with implications for the connectivity between them (e.g., Hooke, 2003). The inclusion of these different landscape elements requires that landscape evolution models at least combine erosion and deposition, in contrast to soil erosion models.

At this larger spatial extent, landscape evolution is typically studied over longer timescales than soil erosion or hillslope evolution. In addition, modeling studies of the temporal extent of individual landscape evolution is strongly linked to the type of study: procedural, descriptive, postdictive, or predictive. Over timescales of millions of years, studies are almost exclusively descriptive – illustrating what landscape evolution could look like under a range of assumptions and almost in the absence of observations (Ellis et al., 1999). Only at smaller timescales, for example, smaller than several ten thousands of years, when more detailed information about paleo-landscapes and other model inputs is available, do studies become typically postdictive (Tucker, 2009). Finally, studies predicting future evolution of a particular landscape have temporal extents that are typically smaller than the postdictive studies that are used to calibrate the models for prediction (Temme et al., 2009; Willgoose and Riley, 1998). In keeping with their nature, procedural studies do not entail a typical temporal extent.

We do not consider analytical solutions to landscape evolution problems in this chapter because their application has hitherto been – and conceivably remains – limited to idealized cases (e.g., Tucker, 2004) or cases with simple boundary conditions. Readers interested in analytical solutions are best referred to a recent volume that includes an excellent overview of analytical solutions to landscape evolution equations (Pelletier, 2008).

2.13.2 Recent Reviews of Quantitative Landscape Evolution Modeling

Two early reviews of models that focus on landscape evolution are by Mike Kirkby (1988, 1993). These reviews partly reflected the descent of such models from the hillslope and erosion models that are the subject of earlier chapters in this volume.

The years since 2000 have seen more reviews of landscape evolution modeling, summarized in **Table 2**. Pazzaglia (2003) took the widest view and discussed quantitative, conceptual, and physical models of landscape evolution.

The most practically and procedurally oriented reviews are Coulthard (2001) and Tucker and Hancock (2010). Coulthard (2001) reviewed four landscape evolution models from the user point of view, comparing model characteristics such as runtime and type of inputs and outputs. Tucker and Hancock (2010) reviewed the entire chain of assumptions, choices, and solutions used in contemporary landscape evolution models. These two reviews are useful starting points when planning a quantitative landscape evolution study – along with more general modeling works like Beven (2009).

Bras et al. (2003) wrote an elegant and personal defense of landscape evolution modeling against different criticisms, arguing why such models have value even when they do not pass the most stringent mathematical and physical tests. Martin and Church (2004) focused on the appropriate level of detail in process descriptions in landscape evolution models as a function of spatial scale – ranging from mechanistic (Newtonian) modeling at small scales up to generalized, cellular automata at larger scales. At the same wide range of spatial scales is Willgoose's (2005) review, which covers both geomorphic and computer issues.

Both Codilean et al. (2006) and Bishop (2007) reviewed landscape evolution models at the largest spatial and temporal extents, where tectonics and topographic processes interact. Whipple (2004) took a somewhat smaller focus and discussed the modeling of bedrock rivers in different tectonic settings.

2.13.3 Quantitative Models of Landscape Evolution: Concepts and Definitions

2.13.3.1 Landscape Evolution

Clearly, this text requires a broad definition of landscape evolution. One of the first sentences of this chapter gives this definition: landscape evolution is the change of landscapes over time.

The word evolution suggests both slow and (very) long-term change – but by no means rates of change that are constant over time. The notion of constant rates – uniformitarianism – is outdated (Gould, 1965). In fact, relatively sudden events such as extreme floods, volcanic eruptions, major debris flows and lahars, or large rock falls can have huge impacts on landscapes that may persist over many millennia (e.g., Lamb and Fonstad, 2010; Maddy et al., 2007). All geomorphic change has a feedback through relief change, causing path dependency that makes constant rates even more unlikely.

2.13.3.2 Landscape Evolution Models

At their core, modern landscape evolution models calculate the (possibly combined) effects of geomorphic and tectonic processes on the landscape, driven by topography, lithology, and climate. In mathematical terms, they are sets of equations operating on a digital representation of a landscape. The model setup scheme in **Figure 1** (adapted from Beven, 2001) helps to structure a short introduction to such models and related concepts and definitions.

In the scheme, the setup of landscape evolution model studies proceeds from choosing the objectives through making perceptual, conceptual, and procedural models to model calibration and model validation. For now, we focus on the first four steps – where the model is built – rather than on the last two steps – where the model is used.

The choice of objectives determines the spatial and temporal extents of a quantitative landscape evolution modeling study. It also determines the type of output that is required: a digital representation of a landscape or alternatively a landscape metric, such as mean elevation or drainage network configuration (e.g., Rinaldo et al., 1993). Models that simulate landscape metrics are sometimes called surrogate models (Pazzaglia, 2003) to distinguish them from more traditional landscape evolution models. The objectives of a study also determine whether it is procedural, descriptive, postdictive, or predictive.

In the perceptual model phase, choices are made about the processes included in the model. For our purposes here, two choices are particularly important because they strongly impact on model structure.

First, whether to use multiple processes or one process only? When it is decided that multiple processes are relevant for a study, decisions regarding their interaction must be made during the next steps in model setup that are otherwise not necessary. Such decisions include the use of homogeneous or heterogeneous spatial and temporal resolution for the processes (Temme et al., 2011).

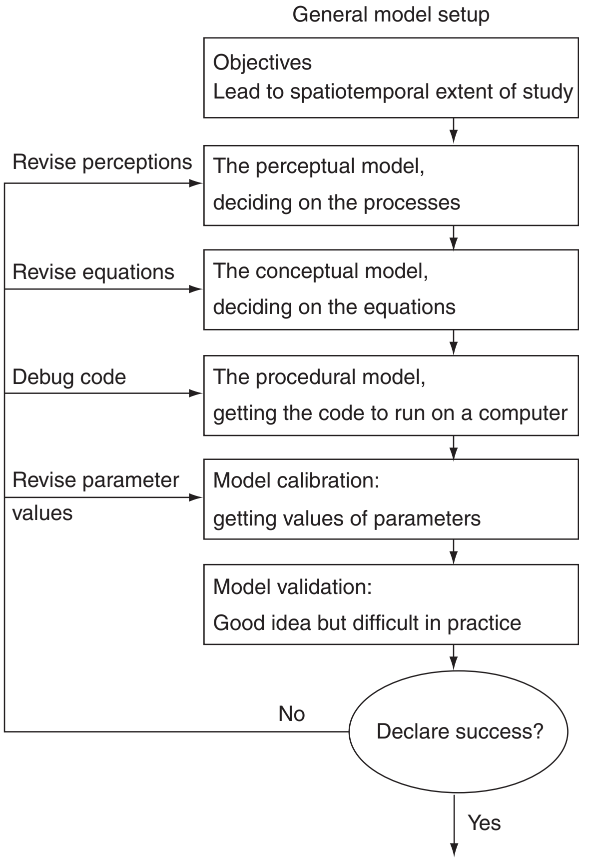
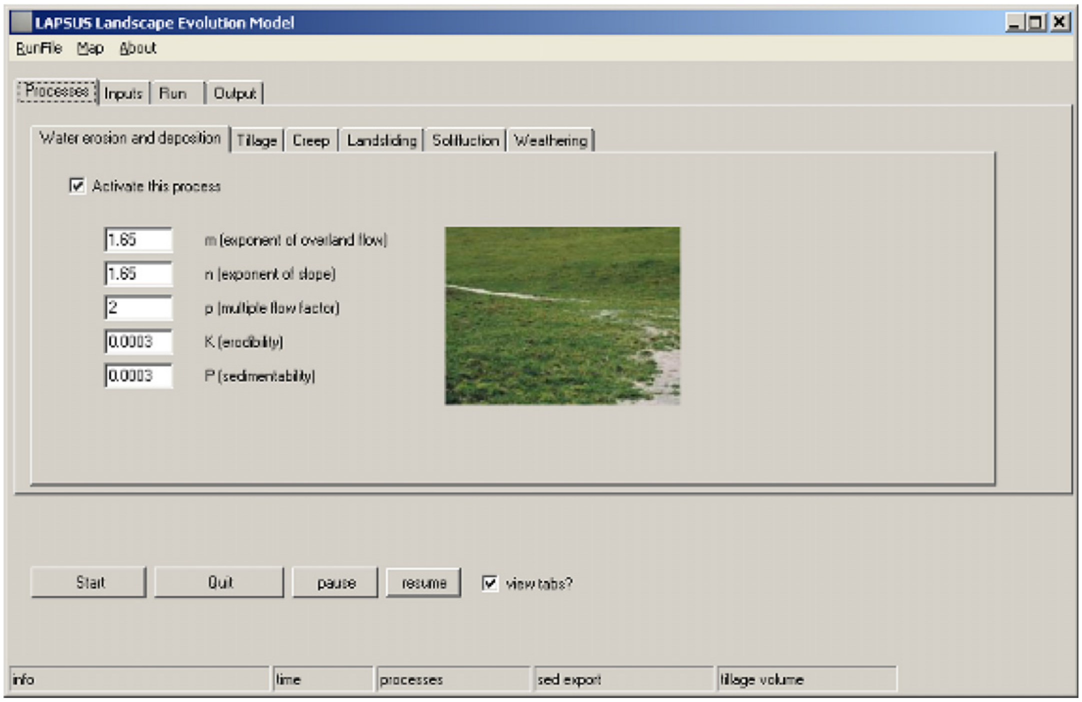


Figure 1 Beven (2001)'s model setup scheme. Reproduced with permission from Beven, K., 2001. Rainfall-Runoff Modelling: The Primer. John Wiley & Sons, Chichester, 361 pp.

Second, and more specifically, is whether or not to include tectonics. At timescales shorter than hundreds of thousands of years, tectonics are not usually included in landscape evolution models. Therefore, these models are sometimes called surface process models (e.g., Codilean et al., 2006).

In the conceptual model phase, decisions are made about the equations that describe each process in the model. Typically, choices are placed along an imaginary axis ranging from fully mechanistic (Newtonian) approaches to fully descriptive (regression-based) approaches (like the Universal Soil Loss Equation-type hillslope erosion models (Renard et al., 1991; Wishmeier and Smith, 1978). Mechanistic models need limited calibration at the expense of strong computing and data demands. As a result, (nearly) mechanistic models are used only at short timescales and for small study areas – for instance, to study evolution of reaches of large-boulder rivers (Hodge et al., 2007). Because of their lack of use in whole-landscape studies, we disregard them in this chapter.

Descriptive models offer ease of use at larger temporal and spatial extents at the expense of larger calibration needs. All landscape evolution models are descriptive to some extent,



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1.65 m (exponent of overland flow)
1.65 n (exponent of slope)
2 p (multiple flow factor)
0.0003 K (erodibility)
0.0003 P (sedimentability)

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Figure 2 Landscape evolution model LAPSUS interface.

most of them strongly so (Brasington and Richards, 2007). Common simplifications of the mechanistic St. Venant equations in the modeling of running water are first the assumptions that flow has steady speed within a time step (quasi-steady state, the gradually varied flow approximation), then that inertia of water is negligible (the diffusion-wave approximation), and, finally, that water pressure effects on water flow are negligible (the popular kinematic-wave approximation), where flow is determined by topography only (Tucker and Hancock, 2010; Van De Wiel et al., 2011).

Note that descriptive models are not the same as descriptive studies. The former designation gives information about the type of formulas used in models; the latter designation gives information about the use of models in a particular study. Mechanistic models can be used in descriptive studies and descriptive models can be used in nondescriptive studies (in fact, many studies in this chapter use descriptive models for procedural and postdictive studies).

In the procedural model phase, decisions are made about the translation of equations into computer code. This is no trivial step, at least because decisions include a choice for the discretization of the landscape. The two most popular discretizations are the digital elevation model (DEM) and the triangulated irregular network (TIN). In DEMs, the landscape is represented as a regular grid of square cells with uniform altitude. In TINs, the landscape is built up of Delaunay triangles. This choice is generally followed by the choice for an algorithm for the flow of water over the surface, based on the kinematic-wave approximation – if the geomorphic processes under consideration are dependent on the amount of water. Many water flow algorithms are available, most of them reviewed and tested in Freeman (1991) and Murray and Paola (1997). In the resulting calculation framework, equations are translated into computer code (Pelletier, 2008).

From the setup scheme, it can be argued that every new landscape evolution modeling study (with new objectives) should lead to a new model formulation. However, existing models (and their set of underlying perceptual, conceptual, and procedural choices) are often reused in later research with minor or no changes. This reuse is defensible as long as the assumptions underlying the initial model are not violated, but making that assessment requires a more intimate knowledge of the model than is usually possible from studying the interface and the documentation alone. This leads to frequent doubts about model validity.

Models or model frameworks that allow individual users to choose among a range of perceptual, conceptual, and procedural choices minimize this problem. Some of such choices have been included in the interfaces of modern landscape evolution models (e.g., LAndscape ProcesS modelling at mUlti dimensions and scaleS (LAPSUS), **Figure 2** and CAESAR) – although especially procedural choices remain unavailable to the model user. Recent projects, such as the Community Surface Dynamics Modeling System (CSDMS; Voinov et al., 2010), which offer advanced facilities to combine and adapt models, are instrumental in opening up the range of model setup options to the inexperienced modeler.

2.13.3.3 Geomorphic Processes

As shown above, a central concept in geomorphology and geomorphic modeling is the geomorphic process. This concept has not been critically discussed in the reviews mentioned before, although it has been the topic of philosophical work by, among others, Rhoads (2006).

Geomorphic processes have been recognized since the birth of the discipline as the activities leading to the formation and maintenance of different landforms (e.g., Press and Siever, 1994). For instance, wind erosion and deposition lead to dune formation, glacial activity leads to characteristic moraine and subglacial landforms, and solifluction leads to lobate forms on hillslopes. Born in the conceptual age of landscape evolution modeling, these form–process relationships (or, if one is more critical, narratives) have been at the base of geomorphic thinking ever since. At that point, landforms were thought of as the result of single processes and were described in mono-genetic terms. As we shall attempt to show below, this categorical way of thinking is fundamentally at odds with modern numerical multiprocess models where a landscape changes and hence landforms result from the activity and interaction of multiple processes.

It can be argued that what are seen as processes are sets (or categories) of landscape activity defined in a multidimensional space of material properties (including resistance) and affecting forces. It can also be argued that it is not ensured that our traditional definition of these sets of activity – by means of the landforms that they supposedly create – is objective or correct. Consider **Figure 3** for a simplified two-dimensional (2D) illustration of this concept and its problems.

In the landscape, gravity is the main force. Additional forces depend on the case study setting and may include the force that flowing water or blowing wind exerts on a substrate, the force that a flowing glacier exerts on bedrock through scouring, or the uplifting force for an entire orogen (cf. Phillips, 2009). Material properties of relevance to **Figure 3**, depending on geomorphic setting, on spatial scale and on model complexity may include, for example, bulk density, cohesion, shape, wetness, size, lithology, or crustal elasticity.

The categories of activity that we call processes may, problematically, overlap (**Figure 3(a)**) or leave space in between – underlap (**Figure 3(b)**) – in the numerical process space. Consequently, this could cause multiprocess landscape evolution models using these process definitions to calculate geomorphic activity twice (a) or not all (b). As an example, imagine process descriptions that calculate creep, solifluction, mudflows, and landslides in the same landscape evolution model. There is no intrinsic guarantee in our field- or landform-based definition of processes that the descriptions of creep and solifluction, or of mudflows and landslides, do not overlap and model the same activity, nor that they cover the whole space of activity. Commonly used thresholds, below which process activity is zero, do not solve this problem – although their extension into multiple dimensions (forces) could.

An interesting figure to discuss in relation with **Figure 3** is a figure in Carson and Kirkby ((1972), p. 100). This figure (**Figure 4**) is a visualization of the relation between hillslope processes, as a function of the relative amount of flow, slide, and heave that they display. The triangular area in which the processes are placed shares important properties with the process space in **Figure 3**.

Figure 4 is a concrete example of the ideas in **Figure 3** for hillslope processes. However, processes are not occupying an area in process space, but are merely points. Assigning processes to points instead of to areas avoids – instead of solves – the overlap – and underlap issues raised above. It leaves unanswered questions such as: When does landsliding change into earth flow? Which geomorphic activity happens between solifluction and mudflows – have we considered that activity in our studies?

As mentioned above, multiprocess numerical landscape evolution models that combine processes that suffer from overlap and underlap would *ab initio* calculate some geomorphic activity twice and some activity not at all. Since overlap and underlap cannot be avoided with our current set of process definitions, this is not merely a problem of academic importance.

It may seem that (in postdictive studies) these problems can be solved in the model calibration step (**Figure 1**). Indeed, it is not unthinkable that calibrating – tuning – parameters in the equations for the different processes can cause the model

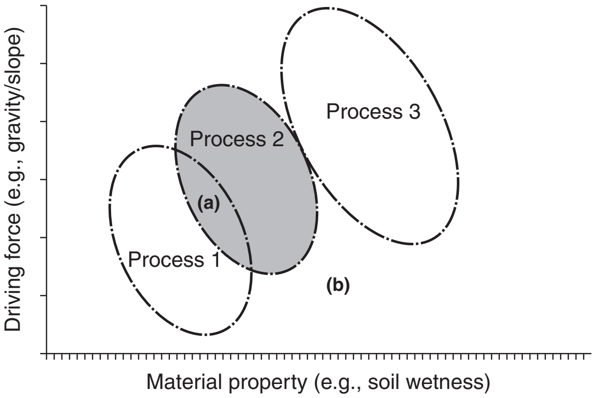

Figure 3 Geomorphic processes, recognized and defined from form–process relations, do not by definition cover the complete process space. Form-defined processes may overlap (a) or not cover process space (b).

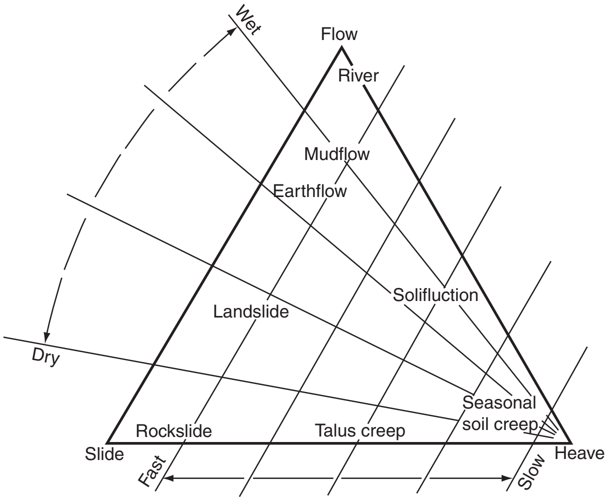

Figure 4 Kirkby and Watson's classification of mass movement processes. Reproduced with permission from Carson, M.A., Kirkby, M.J., 1972. Hillslope form and process. Cambridge Geographical Studies, 3, Cambridge, UK, 100 pp.

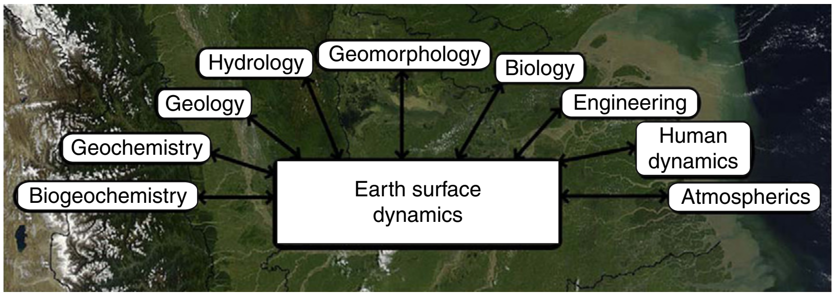

Figure 5 A visualization of the interdependence and interactions between fields related to landscape evolution. Reproduced from Murray, A.B., Lazarus, E., Ashton, A., et al., 2009. Geomorphology, complexity, and the emerging science of the Earth's surface. Geomorphology 103(3), 496–505.

to calculate an output that is in agreement with a set of observations. However, this would be unsatisfactory because the correct output would have been calculated with the wrong model – causing problems in validation (**Figure 1**) and prediction.

The multiprocess problem is all the more alarming because our common focus seems to be shifting toward the study of the interaction between processes. Recent reviews and white papers (Murray et al., 2009; Paola et al., 2006; Reinhardt et al., 2010) call for a more holistic view of landscape change, accounting for the many interactions between and among geomorphic processes, hydrology, vegetation (ecology), and perhaps human activity (**Figure 5**).

If our models with individual, over- or underlapping geomorphic processes have been calibrated to calculate the correct output for the wrong reasons, then individual process activities or volumes are wrong. Therefore, interactions between them will also be calculated wrongly.

This means that although process overlap and underlap are not currently seen as major problems in landscape evolution modeling, their effects may become more important as we continue to integrate our models with more geomorphic processes and with models from other environmental or socioeconomical sciences (Claessens et al., 2009) – resulting in new feedbacks and interactions that are at risk. Solutions to these problems must come from a clear definition of individual processes, which may differ between studies.

2.13.4 Landscape Evolution Model Studies

Below, we discuss the landscape evolution modeling literature; categorized on the type of study as procedural, descriptive, postdictive, or predictive.

2.13.4.1 Procedural Studies

A large portion of procedural studies focuses on the digital representation of the landscape. As mentioned above, there are essentially two options in landscape evolution modeling: regular grids (DEMs) and TINs. Taking DEMs as a starting point, three issues are focused on in LEM literature: (1) the effect of production or gridding method, (2) the effect of DEM resolution, and (3) the effect and role of sinks and depressions.

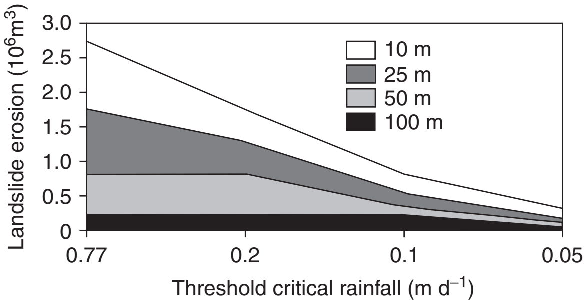

Figure 6 Total amounts of landslide erosion for different critical rainfall thresholds and DEM resolutions. Reproduced from Claessens, L., Heuvelink, G.B.M., Schoorl, J.M., Veldkamp, A., 2005. DEM resolution effects on shallow landslide hazard and soil redistribution modelling. Earth Surface Processes and Landforms 30(4), 461–477, with permission from Wiley.

Hancock (2006) has shown that DEM-derived topographical or hydrological properties may show (subtle) differences between different gridding methods. However, over large temporal extents, SIBERIA landscape evolution model outputs are not significantly different between these gridding methods – suggesting that the choice of gridding method is not of particular importance for their landscape evolution model study.

Resolution does matter however. Compared to the large volume of work on DEM resolution effects in hydrology, there have been only few tests of the effect of resolution on results of landscape evolution models. According to Schoorl et al. (2000), DEM resolution has a strong effect on soil redistribution and especially redeposition rates: the coarser the spatial modeling resolution, the less re-deposition their LAPSUS model predicts. Claessens et al. (2005) found a similarly strong effect of DEM resolution on shallow landslide hazard and soil redistribution modeling (**Figure 6**), also using the LAPSUS model (Claessens et al., 2007). These results can serve as illustrations of the fact that there is a danger involved in changing the resolution of the digital landscape: process descriptions may be invalid for resolutions that they were not designed for.

Both Temme et al. (2006) and Hancock (2008) have studied depression removal in landscape evolution models. Depressions are an important issue when dealing with the hydrological correctness of input DEMs. Depressions (or sinks) may be either spurious (due to errors in DEM production or due to too coarse resolution) or natural (e.g., karst

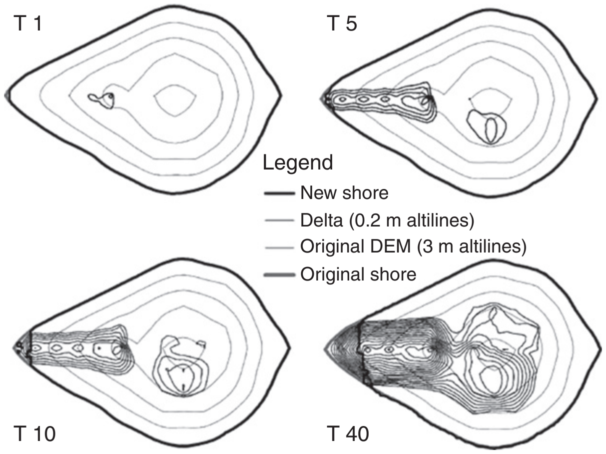

Figure 7 The building of a delta in a hypothetical depression with sediment from upstream erosion (not shown) using the algorithm of Temme et al., 2006. Reproduced from Temme, A.J.A.M., Schoorl, J.M., Veldkamp, A., 2006. Algorithm for dealing with depressions in dynamic landscape evolution models. Computers and Geosciences, 32(4), 452–461.

depressions, lakes, and postglacial kars). Hancock (2008) found that initial sediment export rates of a catchment differed considerably between DEMs with and without depressions, but that the difference was negligible at timescales longer than a thousand years. Arguing the other way around (landscape evolution models should be able to deal with natural depressions to study the interaction and incorporation of sink-causing processes), Temme et al. (2006) designed an algorithm that allows LEMs to deal with large and small depressions as natural landscape elements that can be filled in, enlarged or fragmented (**Figure 7**). Using this algorithm for a research area in South Africa, they also found a decreasing importance of sinks in input DEMs as runs progressed – and argued that it was as an argument against removing such sinks from input DEMs.

The use of TINs in landscape evolution modeling was pioneered by Braun and Sambridge (1997), who listed some advantages and disadvantages of working with TINs and DEMs. The Tucker et al. (2001) the channel-hillslope integrated landscape development (CHILD) model uses a set of routing and transport equations designed for use in a TIN environment. Using the CHILD model, Clevis et al. (2006) proposed an algorithm for dealing with the problem of linking TINs and raster discretization schemes and illustrated its applicability in river meander and subsurface fluvial architecture modeling (**Figure 8**).

When not focusing on the digital landscape, descriptive studies typically focus on the effects of different process formulations (i.e., different conceptual models). Within fluvial landscape modeling, one of the most important issues is the representation of channels and processes at different scales in the landscape. To differentiate between process rates in channels and at basin scale, Birnir et al. (2001) proposed two different spatial roughness coefficients. These two scaling exponents are interpreted as reflecting distinct physical mechanisms. Alternatively, Stark and Stark (2001) suggested a subgrid scale parametrization. Using this parametrization in a simple geomorphic model, they demonstrated that channel disequilibrium may play a significant role in the dynamics of mountainous landscapes.

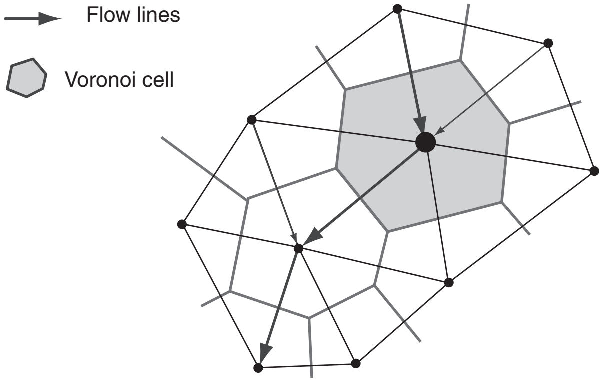

Figure 8 Landscape evolution modeling with TINs: example of steepest descent flow routing.

Adding functionality to the CAESAR model, Coulthard and Van de Wiel (2006) extended existing braided river functionality and designed a cellular model of river meandering. Van de Wiel et al. (2007) incorporated reach-scale alluvial dynamics, to allow for nonlinear geomorphological response.

Nicholas and Quine (2007a) proposed to subdivide reduced complexity models of rivers into high-resolution cellular and section-averaged approaches. Combining these types of models, they show that internal feedbacks play an important role in controlling river response to environmental change. However, uncertainties in parametrizations show that channel responses to external forcing may vary considerably between the models because of internal feedbacks and thresholds.

2.13.4.2 Descriptive Studies

Most of the descriptive studies that we reviewed can be subdivided into three broad categories. The first category contains work that focuses on experimentation with the interactions between tectonic and surface processes. The second category contains a set of studies that apply some sort of sensitivity analysis to explore landscape reaction to a range of variables and processes. A third category of landscape evolution model studies focuses on the use of models to define field observations that can help decide between competing equations for geomorphic processes.

In the first category, Kooi and Beaumont's (1996) seminal work investigated the response of a landscape evolution model to tectonic forcing at spatial scales ranging from slopes to series of basins. Densmore et al. (1998) used a numerical landscape evolution model combining a detailed tectonic displacement field with a set of physically based geomorphic rules including bedrock landsliding, to generate synthetic landscapes that closely resemble mountainous topography observed in the western US Basin and Range. Similarly, in Western Nepal, Champel et al. (2002) used a landscape evolution model combining uplift, hillslope diffusion, and landsliding to demonstrate the dynamics of fault-related fold propagation. In south-eastern Australia, Van Der Beek and Braun (1999) used a similar model to assess controls on

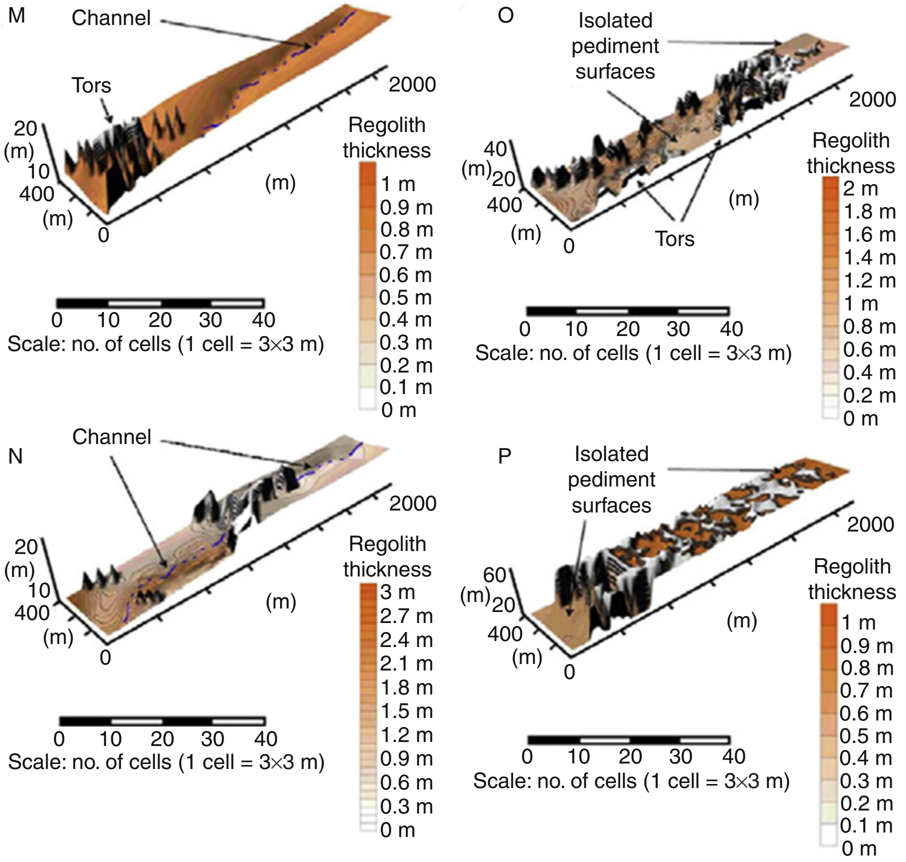

Figure 9 Different landforms resulting after 5-Ma simulations of high-intensity storms in humid environments with 0.1-mm yr^{-1} incision, initial slope of 5° and rainfall increasing from 20 cm yr^{-1} (M) to 152 cm yr^{-1} (P). Reproduced from Strudley, M.W., Murray, A.B., 2007. Sensitivity analysis of pediment development through numerical simulation and selected geospatial query. Geomorphology 88(3–4), 329–351.

landscape evolution and denudation history. Studying extensional relay zones with a similar model, Densmore et al. (2003) concluded that the geomorphic evolution of such zones is an interplay between the timescale over which the fault array develops, and the timescale over which the footwall catchment fan systems are established.

Miller and Slingerland (2006) and Miller et al. (2007) used landscape evolution modeling to suggest an explanation for the fact that drainage basins along opposite flanks of mountain ranges are aligned and commonly similar in planform. Their model, with tectonics, detachment-limited stream incision, and linear hillslope diffusion, shows such advection of topography where valleys are incised and bedrock moves laterally. In a simpler tectonic setting – uniform vertical uplift – Pelletier (2004) showed that drainage migration (as opposed to stable drainage networks) occurs only when steepest-descent water routing is abandoned in favor of bifurcation routing (or presumably other more complicated routing schemes). Snyder et al. (2003) showed that the presence of a stream threshold for bedrock incision, combined with a probabilistic model of storm and flood occurrence, has first-order implications for the dynamics of river incision in tectonically active areas.

In the second category (sensitivity analysis to explore landscape reaction to a range of variables and processes), Flores-Cervantes et al. (2006) developed a model of headcut retreat of gullies resulting from plunge–pool erosion and did a sensitivity analysis for flow discharge, upstream slope, surface roughness, and headcut height. Using similar sensitivity analyses, Strudley and Murray (2007) and Strudley et al. (2006) studied pediment formation and properties as a function of rock type, base-level history, style of sediment transport, and rainfall rate (**Figure 9**). They found that uniformity of thin regolith mantles in pediments is governed by a negative feedback between weathering rate and regolith thickness (cf. Minasny and McBratney, 2006). Evaluating different types of transport equations (linear vs. nonlinear), Jimenez-Hornero et al. (2005) showed that different conditions might result in the same hillslope morphology. This is an illustration of the concept of polygenesis, which we have discussed in greater depth for postdictive studies.

Focusing on signatures of climate in landscapes, Rinaldo et al. (1995) illustrated that both landscapes in equilibrium with current climate and landscapes with relict signatures of past climates are possible. Heimsath et al. (1999) further explored the issue of equilibrium landscapes through a model that predicts the spatial variation in thickness of soil as a consequence of the local balance between soil production and erosion. Using two independent methods, they confirmed that soil production varies inversely with the thickness of soil and apply this assumption in the model, comparing modeled soil thickness with measured field data and finding good agreement. Using a deterministic model, Fowler et al. (2007)

presented a channel equation for the formation of river channels that admits a global steady state. Hancock and Willgoose (2001) showed that the SIBERIA landscape evolution model can correctly simulate experimental model landscapes in declining equilibrium. Their simulations are sensitive to the (nonuniform) spatial distribution of rainfall and DTM errors.

In steeper soil-mantled landscapes in Oregon and California, Roering et al. (2001a) and Roering et al. (2007) compared the effect of nonlinear and linear transport processes, finding that the timescale of hillslope adjustment is shorter with nonlinear transport. The differences between timescales of damming events and erosion are the most important controls on river incision and landscape evolution, according to Ouimet et al. (2007), who used an area in the eastern margin of the Tibetan plateau as a template.

At larger spatial scales, Roe et al. (2003) found a strong effect of orographic patterns of precipitation and temperature on 1D river profiles. In 2D, Huang (2006) studied the role of groundwater movement in long-term drainage basin evolution for a catchment in Pennsylvania. In dune landscapes, Baas and Nield (2007), Nield and Baas (2008a, 2008b) used the DECAL model to focus on the interactions between dune formation and vegetation (e.g., **Figure 10**). They found a strong effect of vegetation type (with corresponding geomorphic effect) on the type of predicted equilibrium landscape – something they called an attractor state.

Similarly focusing on the effect of vegetation on geomorphic processes, Istanbulluoglu and Bras (2005) found that a runoff erosion-dominated landscape, under none or poor vegetation cover, may become landslide dominated under a denser vegetation cover. They also substantiate the effects of vegetation disturbances by geomorphic events and wildfires on the landscape structure. D'Alpaos et al. (2007) proposed ecomorphodynamic modeling of the interplay between vegetation, erosion, and deposition in tidal landscapes to investigate different scenarios of sediment supply, colonization by halophytes, and changing sea level.

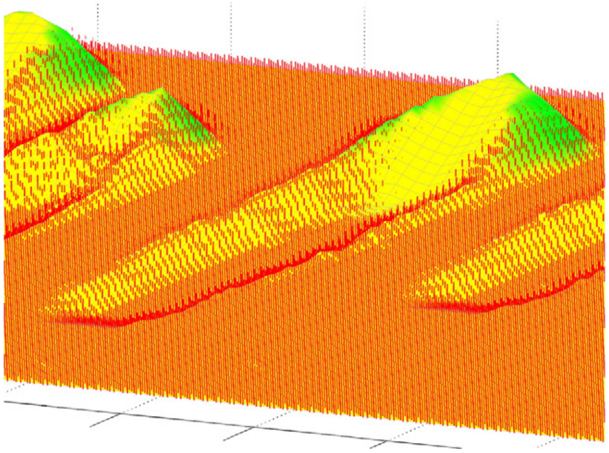

Figure 10 Parabolic dune development in the DECAL model. The green gradation indicates grass density (vegetation effectiveness), the spacing and size of red sticks indicate woody shrubbery density. The model started from a flat, fully vegetated surface with a few bare circular patches. Transport direction is from lower left to upper right (unidirectional). Reproduced from Baas, A.C.W., Nield, J.M., 2007. Modelling vegetated dune landscapes. Geophysical Research Letters 34(6), L06405, with permission from AGU.

Coulthard et al. (2000) and Coulthard and Macklin (2001) applied their CAESAR model to an upland catchment in the UK to separate the effects of land use and climate change on channel formation. Looking at tectonic and climatic forcing, Tucker (2004) developed analytical solutions for average rates of stream incision and sediment transport in the presence of an erosion threshold for flood flows. Results imply that nonlinearity resulting from threshold effects can have a first-order impact on topography and patterns of dynamic response to tectonic and climate forcing.

In glacial environments, Dadson and Church (2005) studied the evolution of an idealized glaciated valley during the period following retreat of ice using a numerical model including landsliding and fluvial sediment transport. Model results are compared with those from a deterministic linear-diffusion model and predict a rapid rate of fluvial sediment transport following deglaciation with a subsequent gradual decline. Tomkin (2009) presented a numerical model incorporating glacial slide-based erosion that simulates the evolution of glaciated mountain landscapes and shows an application with generic parameters and another one with parameters from the Southern Alps of New Zealand (**Figure 11**).

The model predicts that current rates of sedimentation are higher than the long-term average, and that several tens of thousands of years are required for the landscape to adjust to a change in the dominant erosional forcing. He concluded that, therefore, glaciated orogens are unlikely to achieve topographic steady state over Milankovitch timescales. At larger temporal extent, MacGregor et al. (2000, 2009) used a numerical model of glacial erosion and headwall retreat driven by the past 400 thousand years of variable climate to explore the development of the longitudinal profiles of glaciated valleys.

In a tropical setting, Fleurant et al. (2008) simulated the formation of cockpit karst landscapes. Varying the spatial pattern of subsurface dissolution, they concluded that an anisotropic dissolution pattern results in simulated landscapes that better resemble a reference karst landscape in Jamaica than an isotropic dissolution pattern. Kaufmann (2009), using the KARST model, focused on the subsurface evolution of a karst aquifer, although a surface landscape was used as well.

Focusing on hillslopes and river channels, Willgoose et al. (1990, 1991a, 1991b) proposed and applied an early influential drainage network and hillslope evolution model that combined hillslope surface processes with drainage network development. Using sensitivity analysis, they found that the (imposed) amount of flow where hillslope conditions and equations change into channel conditions and equations strongly affects drainage density. The form of a channel network is very sensitive to initial topographic conditions, but physical statistics such as drainage density are only slightly affected by these conditions (cf. Rinaldo et al., 1993). Willgoose et al. (1991c) described the results of this model in more detail. They found that the model performs well ("desirable behaviour," p. 237), both during transient periods and during dynamic equilibrium. Willgoose et al. (1992) used the same model to study how the hillslope and drainage network scale interact in river catchments.

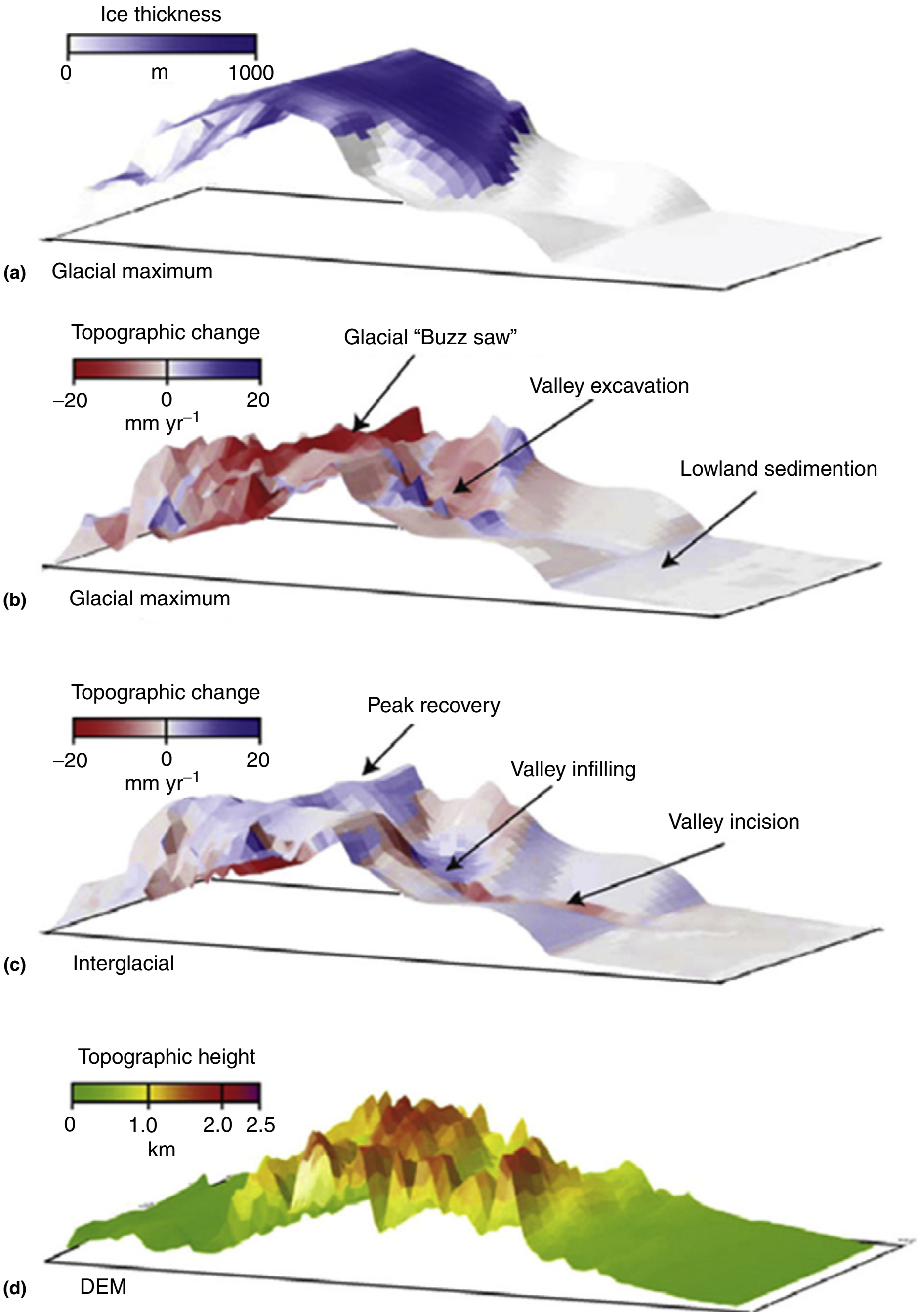

Figure 11 Perspective plots of ice thickness at glacial maximum (a), topography and net topographic change at a glacial maximum (b), and topography and net topographic change during an interglacial (c) produced by the Southern Alp simulation model. The area displayed measures 150 km by 20 km, with a vertical exaggeration ratio of 15:1. (a, b) Represent 4.40 Ma of evolution; (c) represents 4.43 Ma of evolution. Net rates of topographic change are averaged over 10 ka. (d) A 150 km by 20 km transect of the central Southern Alps. Reproduced from Tomkin, J.H., 2009. Numerically simulating alpine landscapes: the geomorphologic consequences of incorporating glacial erosion in surface process models. Geomorphology 103(2), 180–188.

Schneider et al. (2008) used landscape evolution models and morphometric data to illustrate how the ratio between sediment transport on hillslopes and in channels influences landscape and channel network morphologies. Headwaters of fluvial- and debris-flow-dominated systems are characterized by rough, high-relief, highly incised surfaces with a closely spaced channel network, whereas where landsliding is important they are characterized by a low channel density and by rather straight and unstable channels and smooth topography. Willgoose and Hancock (1998) used the SIBERIA catchment evolution model to explore the role of hypsometry as an indicator of geomorphic form and process. They showed that hypsometry can reflect runoff and erosion processes, and is also strongly dependent on channel network and catchment geometry.

Hancock and Anderson (2002) used a 1D channel-evolution model, including sediment transport, vertical bedrock erosion limited by alluvial cover, and lateral valley-wall erosion, to explore whether and how temporal variations in sediment and water discharge can generate terrace sequences. Sobel et al. (2003) developed models of channel defeat to examine the threshold conditions required to fragment the channel network of large, internally drained areas and concluded that channels persist indefinitely when uplift overwhelms the fluvial systems and defeats the preexisting channel network.

Studying network morphology, Rinaldo et al. (1993) used a landscape metric model to simulate optimal channel networks (OCNs, Rodriguez-Iturbe et al., 1992) from a range of random topographies, and compared fractal statistics of the results (Tarboton et al., 1988, 1989) to those of real river networks. They concluded that both sets of statistics are indistinguishable – meaning that river networks conform to their assumptions of minimum energy expenditure. Finally, they suggested that OCNs are spatial models of self-organized criticality (Rigon et al., 1994; Rinaldo et al., 1993).

Wainwright (2008) explored an agent-based approach to simulate the dynamic interactions of people and animals with their landscapes and demonstrated the value of this approach in simulating the vulnerability of landform evolution to anthropic pressures (**Figure 12**). More traditionally, Schoorl and Veldkamp (2001) and Schoorl et al. (2002) applied the LAPSUS model to explore the impacts of land use and vegetation changes on both on- and off-site landscape and soil properties. Two scenarios of fast and gradual land-use change were simulated for a study area in south Spain and different erosion rates and patterns as well as contrasting on- and off-site effects were found (**Figure 13**).

Looking at soil more in detail, Rosenbloom et al. (2001, 2006) applied an LEM that focuses on the redistribution of soil texture and soil carbon along a hillslope in response to geomorphic transport processes. The model results suggest that sandy soils are more likely to differentiate downslope with respect to soil texture than clayey soils and that this redistribution will lead to disproportionately broad areas of predominantly coarse-grained particles on upper slopes.

The conclusions of work in this second category have resulted in strong attention for the complex-system properties of landscapes, caused by nonlinear cause–effect relationships. Self-organization patterns result from models of fluvial (De Boer, 2001) and aeolian landscapes (Baas, 2002) and chaotic behavior is simulated in aeolian landscapes (Baas and Nield, 2007). Moreover, as for instance, Nicholas and Quine (2007b) concluded, dramatic and persistent landscape change (in their case, fan entrenchment) may occur in the absence of external forcing such as tectonics and climate. Using CAESAR, Coulthard and Van De Wiel (2007) took this concept further: in their study, similar amounts of rainfall or runoff produce strongly different amounts of erosion and deposition – they argued that this indicates self-organized criticality in fluvial environments. Supported by similar results by others (Pelletier, 2007a), they pointed out (Van De Wiel and Coulthard, 2010) that such results are at odds with traditional thinking that interprets the sedimentary record as a function of tectonic or climatic forcing. The conclusion that seemingly minor differences in floodplain morphology can cause widely differing reactions to controls is a message of strong interest to the geomorphological community, and is likely to reverberate in the coming years.

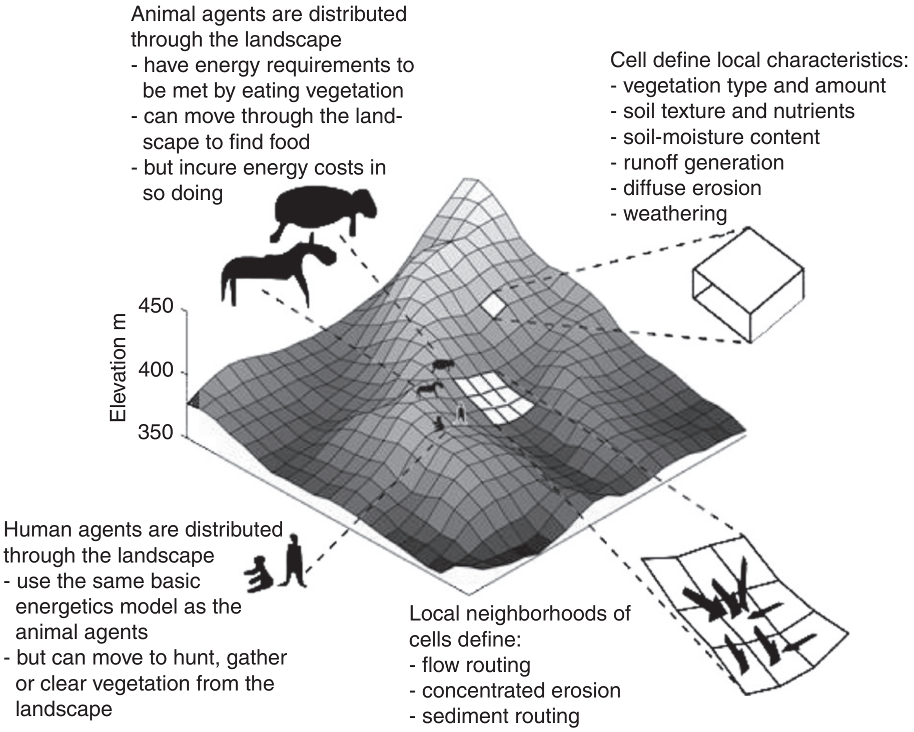

Figure 12 An overview of agent-based model combining human, animal, and geomorphic effects. Reproduced from Wainwright, J., 2008. Can modelling enable us to understand the role of humans in landscape evolution? Geoforum 39(2), 659–674.

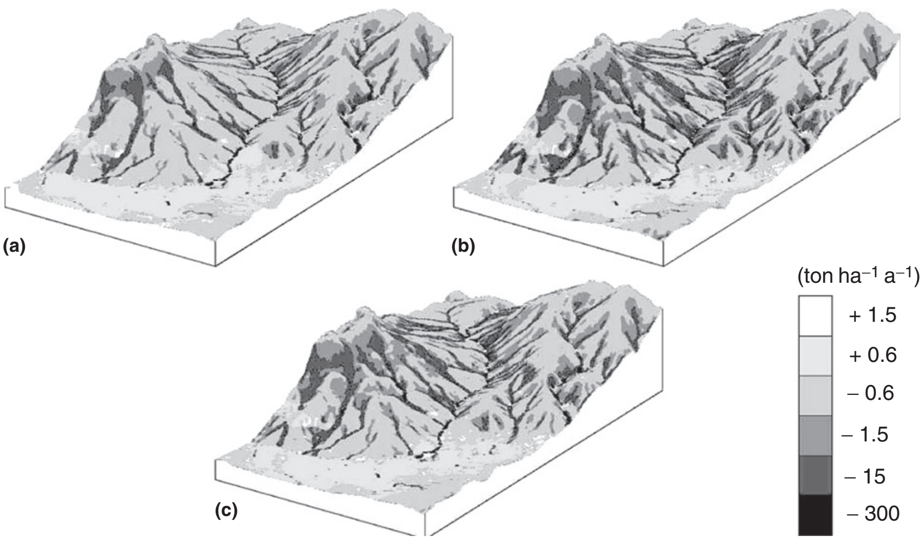

Figure 13 Erosion and deposition outputs (10 years) of the LAPSUS model for three scenarios of land-use change (Schoorl and Veldkamp, 2001). Scenario (a) corresponds to no land-use change, scenarios (b) and (c) correspond to different speeds of olive orchard abandonment. Reproduced with permission from Schoorl, J.M., Veldkamp, A., Bouma, J., 2002. Modeling water and soil redistribution in a dynamic landscape context. Soil Science Society of America Journal 66(5), 1610–1619.

The third category of landscape evolution model studies is about the use of models to define field observations that can help decide between competing equations for geomorphic processes. Tucker and Slingerland (1994) presented a nonlinear, 2D landscape evolution model that is used to assess the necessary conditions for long-term retreat of erosional escarpments of rifted continents. Of all the conditions, high continental elevation is common to most rift margin escarpments and may ultimately be the most important factor. Tucker and Whipple (2002) examined the topographic implications of two leading classes of river erosion models, detachment-limited and transport-limited, in order to identify diagnostic and testable differences between them. Their findings indicate that given proper constraints, it is indeed possible to test fluvial erosion theories on the basis of observed topography. Whipple and Tucker (2002) analyzed the implications of various sediment-flux-dependent river incision models for large-scale topography to identify quantifiable and diagnostic differences between models that could be detected from topographic data and to explain the apparent ubiquity of mixed bedrock–alluvial channels in active orogens. Herman and Braun (2006) showed that for soil-mantled hillslopes, linear and depth-dependent creep constants can be constrained by simple geomorphometric measurements, such as the distribution of soil thickness on the landform and its relationship to surface curvature. Using a similar approach, Wu et al. (2006) concluded that using drainage area as a surrogate for channel discharge in the stream power erosion law has important shortcomings and suggested using it together with the geomorphoclimatic instantaneous unit hydrograph.

2.13.4.3 Postdictive and Predictive Studies

Although some of the studies in the descriptive category use existing landscapes as a template or comparison for their experiments, they were not classified as postdictive because their objective was experimentation rather than the correct simulation of landscape development. In this section, studies are discussed that do have correct simulation as an objective.

Almost all postdictive and, by definition, all predictive landscape evolution model studies calculate forward in time, from a more or less well-known paleo-landscape to another landscape (often the present).

The conceptual and mathematical problems of backward modeling are well known. Equifinality, the notion that different paleo-landscapes may result in one present landscape, and polygenesis, the notion that different processes may be responsible for the formation of a landscape, are at the root of these difficulties (Beven, 2009). However, if processes are well known, and if the landscape does not structurally change within the temporal framework under consideration, then these problems may be small. This was illustrated by Peeters et al. (2006) for a catchment in Belgium. They found that differences between forward and backward modeling with their Water and tillage erosion model long term (WaTEM LT) model are minor, both in terms of total amount of erosion and in terms of spatial distribution of erosion.

Nevertheless, forward modeling remains the method of choice for postdictive studies. Many of those studies focus on the redistribution (erosion and deposition) of soil over hillslopes and small catchments, at decadal to millennial timescales. First, we discuss several such studies that validate the postdictions of calibrated models.

Desmet and Govers (1995) innovatively used information from soil maps to assess the validity of the outputs of their hillslope erosion model for an agricultural catchment in Belgium. Hancock et al. (2000) used the SIBERIA model in Australia to postdict known 50-year erosion from a man-made mine waste rock dump. The model correctly simulated the geomorphic development of gullies on the dump. Later, Hancock and Willgoose (2002) and Hancock et al. (2002)

compared model predictions with physical landscape evolution model results and with a natural catchment on the basis of landscape metrics such as hypsometric curve, width function, cumulative area distribution, and area–slope relationship. Van Rompaey et al. (2001) calibrated and validated the sediment delivery model SEDEM using data sets for several dozens of small catchments in Belgium, achieving an average accuracy of 41%. In New Zealand, Roering (2002) used the thickness of (bioturbated, creeping) soil over a 22.6-thousand-year-old tephra layer as a data source to calibrate a transport model. Peeters et al. (2008) used short-term erosion data to calibrate the WaTEM LT erosion model in Belgium and then successfully postdicted millennial-scale soil erosion known through profile truncation (**Figure 14**). They achieved a model efficiency factor (MEF; Nash and Sutcliff, 1970) of 0.92 (the maximum MEF value is 1).

Van Oost et al. (2004) similarly evaluated a soil redistribution model that uses multiple texture classes. Braun et al. (2001) used observations of soil thickness to evaluate a hillslope transport model.

When assuming that hillslope profiles are in equilibrium, postdictive models of steady-state landscape evolution can be tested by comparing them directly with existing profiles. Roering et al. (1999) made this assumption for a number of catchments in Oregon and tested postdictions of a hillslope transport law using measured high-resolution profiles. It must be noted that the equilibrium assumption has attracted criticism on theoretical grounds (Phillips, 2010), and that, in many settings, hillslope profiles and catchments are clearly in disequilibrium (e.g., Densmore et al., 2003; Tomkin, 2009). At the very least, use of the equilibrium assumption must be clearly defended.

Radionuclides are a quantitative source of erosion and deposition data. In particular, a cesium isotope – Cs^{137} – has been popular. This anthropogenic radionuclide was deposited worldwide after nuclear tests in the 1960s and has a half-life of about 30 years. When making assumptions about initial spatial distribution (usually uniform) it is therefore well suited to characterize decadal-scale soil redistribution. Govers et al. (1996) used the technique to measure soil redistribution rates in two catchments in Great Britain and compared these to model postdictions. The modeling of diffusive processes gave the best postdiction: $r^2 = 0.43$ and 0.41 for the two catchments. Later, Quine et al. (1997) used the same technique to study the relative influence of tillage and water erosion at sites in Belgium and China. Schoorl et al. (2004) successfully used the technique with LAPSUS in a more challenging steep and rocky natural area in Spain. Heuvelink et al. (2006) also used the technique with LAPSUS to postdict tillage redistribution for an area in Canada ($r^2 = 0.39$).

In other studies, validation data sets were not available. Calibrating a landslide model, Claessens et al. (2006) used a sediment record at the outlet of a catchment in New Zealand – to assess the postdicted volumes of landslide deposits delivered to rivers. Roering et al. (2001b) calibrated a nonlinear hillslope soil transport model with results of a laboratory study of a hillslope of granular material. Roering and Gerber (2005) later used field measurements of post-fire and long-term critical slope gradient (above which flux increased rapidly) to calibrate a soil redistribution model in Oregon. On a much longer timescale, Gilchrist et al. (1994) used landscape evolution models to study post-Gondwana geomorphic evolution (denudation) of southwestern Africa, resulting in several postdictions that are consistent with large-scale field observations.

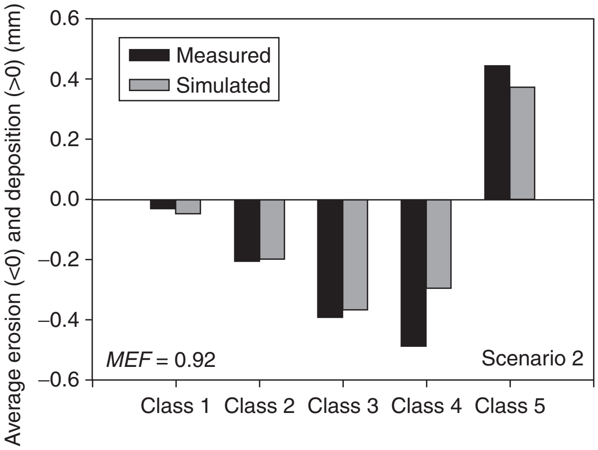

Figure 14 The Peeters et al. (2008) comparison of measured and simulated (postdicted) long-term soil redistribution (in mm) for a landscape divided in five classes – using a landscape evolution model that was calibrated with short-term erosion data. Reproduced from Peeters, I., Van Oost, K., Govers, G., Verstraeten, G., Rommens, T., Poesen, J., 2008. The compatibility of erosion data at different temporal scales. Earth and Planetary Science Letters 265(1–2), 138–152.

In fluvial environments, postdictive studies use network morphology or incision histories (mainly in bedrock reaches) or streambed morphology (mainly in alluvial reaches) to calibrate and validate models.

Tomkin et al. (2003) invoked the equilibrium assumption – using terrace sequences to argue for stable incision – to evaluate six competing bedrock incision models in Washington State. None of the models successfully accounted for the observations. Brocard and Van Der Beek (2006) used field observations from several dozens of combined detachment- and transport-limited rivers in the French Alps to calibrate a model for the development of valley flats (in transport-limited reaches). In the Austrian Alps, Anders et al. (2009) used a combined vector-based longitudinal profile incision model and a grid-based surface process model with a 1-m spatial resolution DEM to realistically simulate development of a catchment from the late glacial to present.

Working in alluvial reaches, the Coulthard et al. (1998) CAESAR model concentrates on the simulation of floodplain morphology. Working at 1-m resolution in a catchment in Great Britain, CAESAR realistically postdicted formation of bars, braids, terraces, and alluvial fans (Coulthard et al., 1998). In another catchment, where rainfall input data for the last 9200 years were prepared, CAESAR was used to postdict landscape development of a reach with an alluvial fan. Fluvial postdictions reacted to climatic and land-use changes as expected, but fan postdictions indicated no clear link with climate or land-use history (Coulthard et al., 2002). Lancaster and Bras (2002) designed a model of river meandering, which compared well with meanders observed in nature. At larger spatial scale, van Balen et al. (2010) modeled the response of the Rhine–Meuse fluvial system to known climate fluctuations at postglacial timescales, confirming among others that terraces are diachronic features: they were formed earlier – and are older – upstream than downstream. Results of this 2D study extended the conclusions of an earlier 1D profile study (Tebbens et al., 2000).

Combining tectonics and surface processes, Van Der Beek et al. (1999) postdicted the landscape evolution of the south eastern Australian highlands – providing a new hypothesis for their formation. Similarly, van der Beek et al. (2002) postdicted denudation history of the South African Drakensberg and compared model results with apatite fission track data. In tectonically active western Nepal, Champel et al. (2002) used a similar model to postdict a drainage pattern that compared well with observations. Pelletier (2007b) modeled the Cenozoic geomorphic history of the Sierra Nevada, comparing postdictions with known uplift history.

A general note is in order about the value of goodness-of-fit indicators in postdictive studies. In many studies, goodness of fit is indicated qualitatively (e.g., 'correctly', Hancock and Willgoose, 2001 and 'good', Heimsath et al., 1999). Where possible, a quantitative expression of model performance is to be preferred. Cell-by-cell comparisons, comparisons of moving-window averages, or of landscape-class averages can, for instance, be expressed as coefficients of determination (r^2, Govers et al., 1996), root mean square errors (RMSEs), or MEFs (Peeters et al., 2006). Results are typically better where overall landscape forms do not change much and form–process feedbacks are limited (for instance, soil redistribution studies) than where landscape form is very dynamic. This means that it is difficult to compare even quantitative goodness-of-fit indicators between study sites.

Only two predictive landscape evolution modeling studies were found. Willgoose and Riley (1998) predicted the 1000-year evolution of the Ranger Uranium Mine in Australia, to assess whether government-imposed requirements for containment were met (**Figure 15**). Temme et al. (2009) also extrapolated their earlier 50 000-year postdictive modeling efforts (Temme and Veldkamp, 2009) in a small catchment in South Africa for 1000 years into the future. Uncertainty was taken into account by varying LAPSUS model parameter values in a Monte Carlo setup. They found that – accounting for this uncertainty – in most subzones of their catchment, landscape evolution under predicted changing climate differed significantly and substantially from landscape evolution under stable climate.

2.13.5 The Future of Landscape Evolution Modeling

Below, we venture a look into the future of landscape evolution modeling and point out a few directions for future research that we deem particularly important.

2.13.5.1 Self-Organized Criticality

As discussed above, recent modeling work has resulted in the suggestion that some geomorphic activity (sediment export from rivers, Coulthard and Van De Wiel, 2007, or fluvial network density, Rinaldo et al., 1993) displays self-organized criticality: the variable (e.g., sediment export) is independent from the external forcing (e.g., rainfall and discharge). This idea is a major threat to conventional interpretations of sedimentary records being caused by driving factors such as climate and land-use change. Building on contributions from conceptual modeling (cause–effect narratives) and physical modeling (complex response), this major theoretical contribution can be uniquely attributed to quantitative modeling studies.

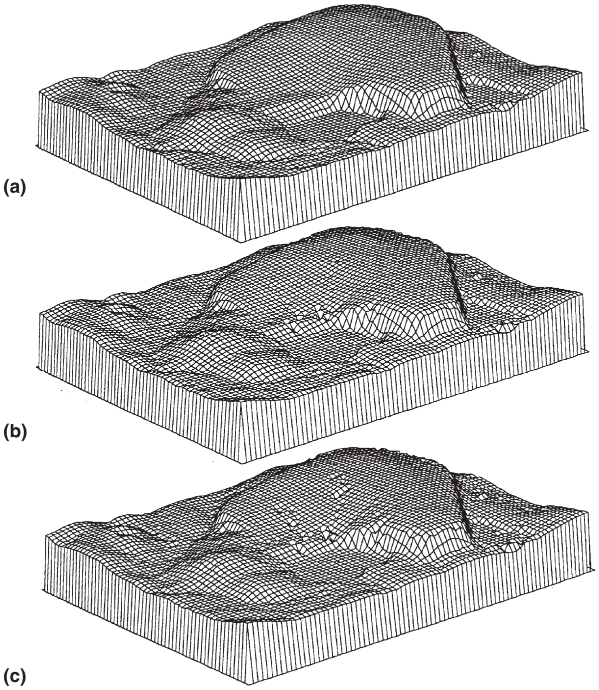

Figure 15 Simulated morphology of Ranger Uranium Mine dump after 0 (a), 500 (b), and 1000 (c) years. Reproduced from Willgoose, G., Riley, S., 1998. The long-term stability of engineered landforms of the ranger uranium mine, Northern Territory, Australia: applications of a catchment evolution model. Earth Surface Processes and Landforms 23(3), 237–259, with permission from Wiley.

It is important to find out to which degree the simulation of self-organized criticality is a model artifact. If not, we must find out in how many geomorphic environments and variables it exists, and how significant its effect is over larger temporal and spatial timescales (Van De Wiel and Coulthard, 2010). Landscape evolution modeling is poised to play a large role in answering these crucial questions through its ability to simulate wide ranges of processes, environments, and timescales.

2.13.5.2 Predictive Studies and Uncertainty Analysis

The increasing availability of decadal, centennial, and millennial scale data sets for landscape evolution model calibration makes it possible that our models of landscape evolution at shorter timescales are used less descriptively and more predictively. Therefore, their results may become more useful for policy makers (Korup, 2002). This requires clarity about the value of predictions.

For this purpose, sensitivity analysis and uncertainty analysis are becoming more important. Beven (2009) argued that uncertainty analysis is one of the directions in which most is to be gained for environmental models in general – perhaps more than from model improvement. We agree with that assertion, and, moreover, we argue that the procedural level of models should be included in such sensitivity and uncertainty analyses (Temme et al., 2011). Commonly, procedural decisions are hidden behind interfaces, making them inaccessible to users (as opposed to easy variation of model parameters).

This is not the case with models that lack an interface. The use of such models requires intimate knowledge of, and supposedly implies agreement with, procedural choices. However, models without interface are generally used less often. The inclusion of procedural options in interface-based models would allow a wider appraisal of the sensitivity of model outputs. Procedural options in sensitivity analyses could include the type of digital landscape (DEM/TIN), the type of flow routing, and the method of dealing with sinks and flats. The development and sharing of models that offer these advanced sensitivity analysis opportunities, through programs such as CSDMS (Voinov et al., 2010), are something to work toward in the years ahead.

Varying parameter values to assess their effect on model outputs or goodness-of-fit indicators is often easily done through Monte-Carlo analysis. In Monte-Carlo analysis, many (sets of) parameter values are randomly drawn from their (joint) probability distributions – and the model is run repeatedly with these (sets of) parameters. If no information about distributions is available, a uniform distribution is often used. Monte-Carlo analysis is computationally intensive due to repeating model runs, but has a great potential in quantifying model uncertainty (when uncertainty of parameters is known) or model sensitivity (when uncertainty is not known).

Another possible contribution toward clarity about the validity of predictions is a more thorough exploration of the validity of boundary conditions and process descriptions when using models in environments or at spatial and temporal scales other than what they were designed for. End-user knowledge of such validity domains is an important objective and could be realized through model meta-information.

2.13.5.3 Multiple Processes

Our discussion of the geomorphic process led to the conclusion that studies of interactions within and between geomorphology and related fields will experience the negative effects of ill-defined processes when multiple processes are modeled. Such problems would certainly have to be solved (for instance, in an as-yet imaginary global pan-process landscape evolution model where an enormous range of process equations would have to interact over a range of differing environments).

An unambiguous definition of processes that remains usable at the spatial and temporal scales of global landscape evolution remains a topic of interest to the authors, and perhaps others in the years ahead. It is conceivable that new, accurate, and large-scale observations of landscape activity, such as those offered by repeated terrestrial laser scanning, offer a road toward such definition for surface processes. Such large data sets of individual micro-events of landscape activity could be used in principal component analysis to arrive at a neutral, independent classification of processes.

2.13.5.4 Feedbacks to and from Other Fields

Feedbacks from traditional geomorphology to vegetation currently receive much attention (e.g., Baas and Nield, 2007; Buis et al., 2010; Istanbulluoglu, 2009a; Istanbulluoglu and Bras, 2005; Tucker and Hancock, 2010). These feedbacks form a crucial field of investigation that will likely grow in future years. It is likely that nonlinear interactions of vegetation with geomorphic processes will increase our understanding of the complex-system properties of landscapes, and perhaps of the predictability of landscape evolution.

Feedbacks can be found elsewhere, too (Murray et al., 2009; Paola et al., 2006). Wainwright's (2008) agent-based work offers an interesting road to quantifying the role of humans as land users and constructors at the large spatial extents where inevitable small-scale probabilistic effects of his approach can be lumped together. Land-use change models may offer an additional way of accounting for human activity on the landscape and on vegetation (e.g., Verburg and Overmars, 2009). Interactions between large-scale land use and landscape have already been explored (Claessens et al., 2009) and have strong potential.

2.13.5.5 Validation with Whole-Landscape Data Sets

Finally, it remains crucial to focus on calibration and validation of landscape evolution models. Calibration and validation data sets that combine different types of data (for instance, total altitude change at a number of sites, sediment export from a catchment as a whole through time, and the current rate of erosion of the water-divides) offer exciting opportunities for validation. This has long been recognized as an important issue, and calibration and validation data sets at the millennia and shorter timescales are – although rare – becoming available for model tests, also through smarter selection of case studies in landscapes that offer validation opportunities (Tucker, 2009). Millennia-scale postdictive studies are currently rare, but as more data sets become available, such studies will increase in number – conceivably leading to better models.

At the shorter timescale, a crucial role will likely be played by the critical zone observatories that are currently being installed in the United States and some comparable observatories in Europe. The wealth of landscape process, vegetation, meteorological, and other data that will be available from such observatories will also lead to an increase in model calibration and validation studies – especially because the observatories are situated in a wide range of environments. The importance of the role that such observatories can play in our understanding of landscape evolution at the larger timescale is still unknown and may be limited where and when evolution is slow or rare events play large roles.

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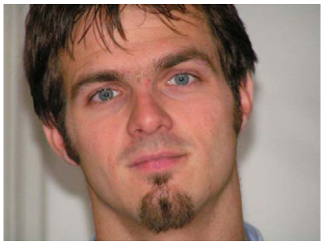
Biographical Sketch



Arnaud Temme works at Wageningen University in the Netherlands. He has experience in the dynamic spatial modeling of landscape and land-use change, working primarily in the conceptual and technical development of the LAPSUS model. He added process descriptions for soil creep, solifluction, and biological and frost weathering, as well as an algorithm for dealing with natural depressions to the LAPSUS framework. Working in South Africa, he studied late Quaternary landscape development using various stratigraphical and dating techniques and simulated that same development with several LAPSUS versions. He also worked on other landscapes in the Netherlands, Belgium, Poland, Spain, Croatia, and Turkey. In land-use change modeling, he developed a method to map the spatial distribution of agricultural land use of different intensities for the whole of Europe.

Lieven Claessens has extensive experience in the spatial analysis and modeling of soil–landscape–land-use systems. At Wageningen University, he developed the LAPSUS-LS landscape process model, a spatially explicit methodology for predicting landslide hazard and quantifying associated soil redistribution (erosion–sedimentation). LAPSUS-LS forms part of the LAPSUS framework, a landscape evolution model simulating multiple processes (water erosion by runoff, tillage erosion, and landslide erosion) in the context of current and future environmental change. The model has been explicitly linked to methodologies addressing ecological processes and land-use changes to assess interactions and feedback mechanisms between landscape, land use, and land cover, and has been applied in study areas all over the world. In addition, he has experience in digital soil mapping, integrated assessments of agricultural systems, and land-use change modeling. His current research at CIP (International Potato Center) focuses on interactions between biophysical and socioeconomic processes from household to regional scale levels. Within the Tradeoff Analysis (TOA) framework, case studies are conducted in Kenya, Uganda, Ethiopia, Peru, and Ecuador. Integrated assessments of the sustainability of the agricultural systems are performed with an emphasis on testing adaptation strategies, specifically alternative technologies, and policies in potato- and sweet potato-based systems, in the context of climate change.

Dr. Jeroen M. Schoorl is currently an assistant professor at the chair of Land Dynamics at Wageningen University (Netherlands). He has extensive experience in geomorphological modeling and characterization of integrated soil, landscape, and land-use systems. He carried out several international and national research projects on geomorphology and landscape–soil interactions in Europe (Spain, Greece, France, and Turkey) as well as some preliminary investigations in Latin America, Africa, and Asia. He has founded and currently leads the LAPSUS group, a team of researchers working at modeling landscape processes at multispatial and temporal dimensions and scales. In addition, he has experience with land-use change modeling and digital soil mapping. He has authored or co-authored over 68 papers in national and international proceedings, refereed journals, and books (28 peer reviewed).

Prof. Dr. Ir A. Veldkamp obtained an MSc in Soil Science (1987) and a PhD in Agriculture and Environmental sciences (1991) at Wageningen University. In 2002, he became a full professor and chair in land dynamics at Wageningen University. Since 2010 he has been dean/rector at University of Twente, of the faculty ITC of geo-information science and earth observation. His research topics involve earth system analysis and modeling. He developed several spatial explicit models on landscape development and land use change.