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Towards Quantitative Modelling of Landform Evolution through Frequency and Magnitude of Processes: A Model Conception

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Abstract. In recent years, various process-based models for the evolution of regional landform systems have been developed (Coulthard, 2001). Quantitative models have considerable use in applied geomorphology, but also represent a good means we have for testing and developing theoretical models. Nevertheless, there remains a considerable gap between the detailed quantitative representation of individual process behaviour and its integration across spatial and temporal scales that are relevant to landform evolution (Hergarten and Neugebauer, 1999a). A major research issue that must be confronted is the differing frequencies and magnitudes of the various processes that contribute to regional landform evolution. A unifying concept that offers promise is that of the sediment cascade, i.e. viewing geomorphic processes as contributing to the general system of sediment flux through the landscape. In this paper, we present a formulation for modelling sediment flux at the Holocene timescale and at regional spatial scales (3rd/4th order drainage basin, Preston and Schmidt, 2003). The temporally integrated production of sediment from individual geomorphic units is derived through reference to frequency/ magnitude distributions of process behaviour. The model operates at coarse spatial scales, providing a framework for linking individual geomorphic systems as components within a regional scale sediment flux model. The proposed modelling approach combines classical conceptualisation of landscapes into units with process-based flux modelling concepts and therefore represents an upscaling approach for models of landscape evolution. A series of issues with respect to contemporary geomorphologic research are discussed on the basis of the presented model approach.

Keywords: Landform Evolution, Sediment Cascade, Numerical Modelling, Conceptual Modelling, Frequency/Magnitude

INTRODUCTION

Models of landform evolution can be characterised as either qualitative or quantitative (Fig. 1). Qualitative approaches have involved geomorphogenetic and chronostratigraphic reconstruction of former landsurfaces and are often

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based on dating results (Wasson *et al.*, 1998; Lang and Hönscheidt, 1999; Eriksson *et al.*, 2000). Alternatively, in recent years there has been an increase in the number of attempts to simulate landform development using numerical models of varying complexity (Armstrong, 1987; Kirkby, 1990; Willgoose *et al.*, 1991; Braun and Sambridge, 1997; Coulthard *et al.*, 1998; Hergarten and Neugebauer, 1999b). These models use more or less detailed descriptions of individual processes (e.g. gully erosion or fluvial sediment transport) ranging from simple threshold models (Kirkby, 1990) to differential equations describing sediment flux (Coulthard *et al.*, 1998). The individual process models are usually applied using artificial discretisation of the study area in space and time (often fixed grid cells and time steps), the size of which is determined by the maximum required resolution for the used process models and their interactions. Spatio-temporal scales and resolutions to which these models can be applied show a wide range (Preston and Schmidt, 2003).

Qualitative approaches can provide information about the development of small scale features, and insight into the underlying mechanisms. Their use for modelling of regional landform development, however, is limited by the scale transfer problem, i.e., larger scale systems are not simply larger versions of small scale systems. Further, because such reconstructions are often based on simple assumptions of geomorphic processes, they run the risk of being influenced by subjective interpretation. For these reasons, numerical/process-based models are more desirable, which are useful to explore process behaviour beyond the limits of individual locations (e.g. sensitivity studies) and therefore are applicable to large areas.

There are physically-based models for most if not all geomorphic processes and, on a small scale, they do indeed represent components of landform development. However, it is a research issue whether, and how, these models can be applied within the framework of regional landform development (Hergarten and Neugebauer, 1999a). In recent years, various models for the development of regional landform systems have been proposed (Coulthard, 2001). These models range from comparatively simple approaches (simplification of geomorphic processes) to complex models including detailed descriptions of individual processes (Coulthard, 2001; Preston and Schmidt, 2003). Generally, these approaches are based on process dependent formulations of sediment detachment, transport, and accumulation. Whereas the simple approaches of Armstrong (1987), Ahnert (1988), and Kirkby (1990) are based on parametric equations for sediment fluxes, the more complex recently developed models (e.g. Coulthard *et al.*, 1998) use common physically based formulations. However, obvious problems in both cases relate to model parameterisation and validation (see Schmidt, 2001; Preston and Schmidt, 2003). In the first case, the parameters used represent large scale process abstractions (e.g. denudation rates); in the second case, the spatio-temporal model parameterisation is normally impossible with respect to real world conditions. Usually both model types deliver temporal sequences of landform surfaces (either 2D or 3D). A main problem is how to verify these outputs and compare them with real world conditions. Therefore, most of the

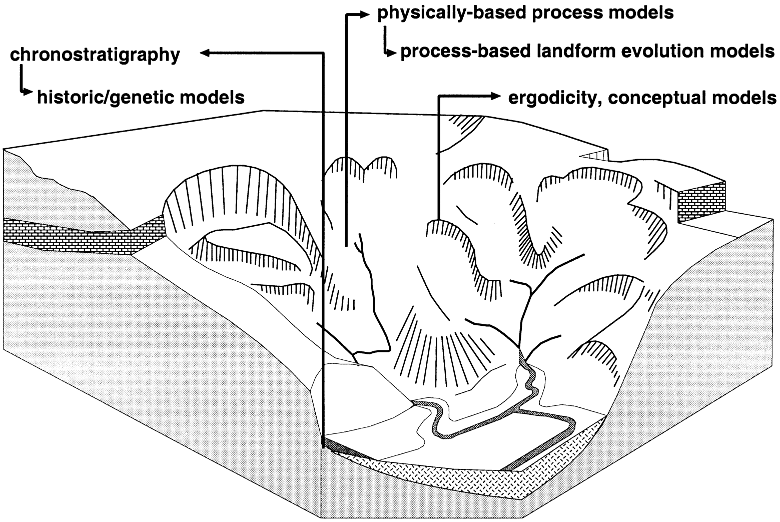

Fig. 1. Evidence and models used in understanding geomorphic systems: These range from detailed and small scale process models, principles and simplified models of landform evolution to singularily available field evidences.

modelling approaches remain speculative and unverified. Another problem relates to the various coupled processes within a landsystem, which operate at different magnitudes and with different frequencies. Understanding the interactions of these processes on longer timescales and the integration of these within landscape evolution models remains an unresolved issue. This present situation leaves a gap between numerical modelling of individual processes on the one hand and general landform evolution models on the other hand (Hergarten and Neugebauer, 1999a). It remains undetermined, if, and to which degree, detailed process modelling can contribute in modelling landform change, a system which acts on a different spatio-temporal scale. Much more research is needed in filling this gap and to come to a more fundamental understanding of landform systems and landform change on a physical basis. In general, it is questionable whether a landform surface, modelled with more or less spatial details can and should be compared with real world conditions; modelling and verifying plausible patterns may well be a more realistic objective of long term modelling (Beven, 1996; Preston and Schmidt, 2003).

Therefore, it might be more appropriate to view a landform as a composite system of landform units and to model their properties and interactions, rather than to model detailed surface development and pixelwise matter fluxes. Preston and Schmidt (2003) therefore argue for a hierarchical approach for modelling regional sediment flux over Holocene timescales. The model concept combines aspects from different scientific directions within geomorphology (Fig. 2). In this paper we present a model formulation of this concept, and the approach is used

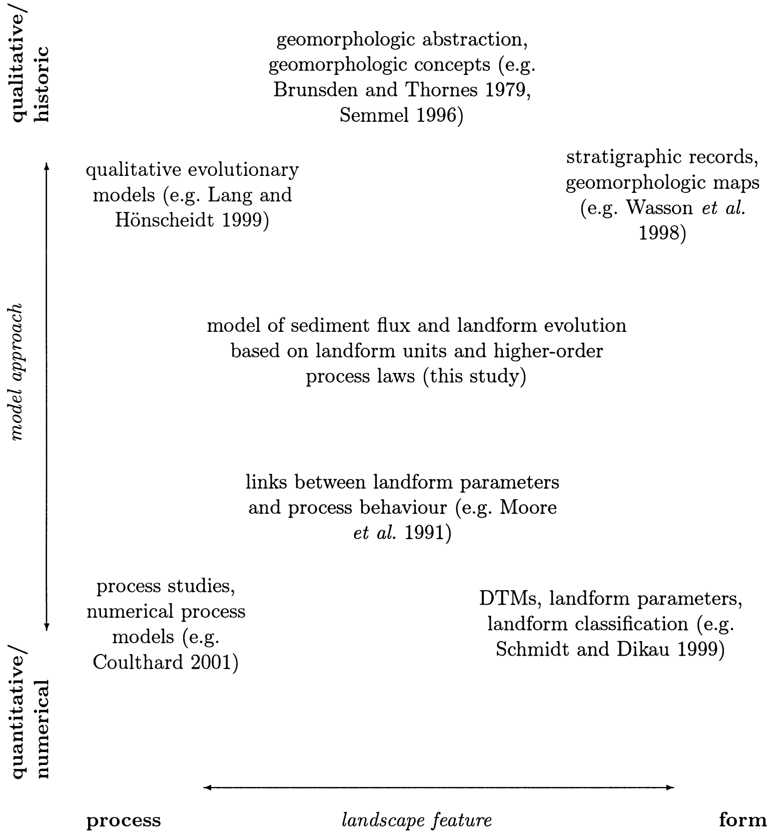

Fig. 2. Scientific position of the proposed model approach within the framework of model concepts (qualitative/quantitative) and modelled features (process/form). Quantitative approaches include process modelling and landform parameterisation. Some efforts have been made to find links between processes and parameters. Qualitative approaches include historic/genetic models, which are often based on stratigraphic records. Qualitative models include high degree of abstraction/expert knowledge. The model presented in this paper aims to find links between these approaches by higher-scale modelling of sediment flux based on a geomorphologic abstraction of land surface.

to discuss some key questions with respect to understanding regional landform systems.

WHAT IS REGIONAL LANDFORM EVOLUTION?

It has to be kept in mind that the *geomorphic evolutionary system* is highly complex, acting on different scales in space and time (Schumm, 1979; Chorley *et al.*, 1984). Therefore, system descriptions on different scales have to be developed. It is the purpose of this paper to introduce a conception and a modelling approach for landform evolution at regional spatial scales (3rd/4th order drainage basins, approx. 10^8 m^2, scale of mesorelief according to Dikau (1990)). Typical landform systems within this respect include the Holocene development of the soft rock hill country on the east coast of New Zealand (Page and Trustum, 1997; Eden and Page, 1998; Trustum *et al.*, 1999) or the development of the Tertiary cuesta region in central Germany (Semmel, 1995; Preston, 2001). These systems, i.e. the related landform components (sediment storages), show residence times in the order of 10^3–10^4 a. Therefore, processes of sediment redistribution and sediment storages varying in timescales of tens to hundreds of years are considered, i.e. hillslope processes (soil erosion, mass movement) and colluvial storages, fluvial processes and alluvial storages. This means that the total timescale of interest is on the order of 10^4–10^5 a, and that the temporal resolution, determined by rates of major process activity, is in the range of 10^1–10^2 a. The typical regional landform system within this respect is illustrated in Fig. 1. It consists of sediment storages on the hillslopes and on the alluvial plains. Hillslope processes are dependent on hillslope form, but also change hillslope form on the other hand by creating erosive and accumulative form sequences (Fig. 1). These processes interact with fluvial processes which are dependent on channel morphology.

As one can see, the described system is a crude simplification of the complexity of landform systems. However, it is the purpose of this study to focus on the dominant forms, processes and interactions which characterise the study objective (Beven, 1996). We believe that this approach can more effectively assist in understanding regional landform systems than focusing on the complexity and possible variations and exceptions inherent in these systems types (Band *et al.*, 1993).

MODELLING LANDFORM COMPONENTS BY SEDIMENT FLUX

Landform is spatially and temporally hierarchical. The temporal scale of interest defines the appropriate spatial scale, and vice versa. Further, landform development involves a hierarchy of processes. While landform evolution occurs through processes of rilling, gullying, creep, landsliding, etc., modelling of these processes per se is not the objective of the present discussion; rather it is their net long term combined effect that is of interest, i.e. the “processes” of slope development and drainage development.

The link between individual processes and the morphologic evolutionary system of landform development is the *cascading* system of regional sediment flux. Chorley and Kennedy (1971) have argued that each process subsystem within the cascading system occurs with a different frequency/magnitude distribution resulting in a complex *process-response* system characterised by equilibrium and transient system stages and thresholds (Schumm, 1979; Preston and Schmidt, 2003). Indeed, it is these system characteristics that are the major focus of interest in modelling regional landform evolution, i.e. this is what can be expected from modelling of regional landform evolution rather than reconstructing the detailed development of three-dimensional surfaces. Modelling of landform evolution by sediment flux requires that a geomorphic system is separated into

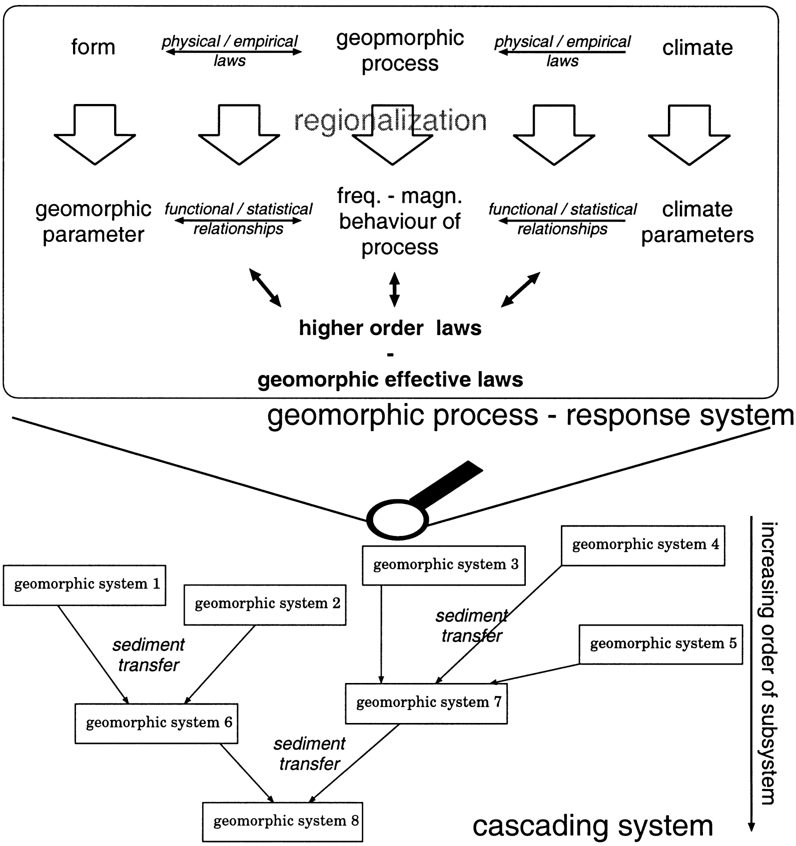

Fig. 3. Cascading system and geomorphic process-response system as parts of a geomorphic sediment cascade. Sediment transfer through the cascade can be easily described, if an appropriate topology of geomorphic subsystems is defined. Calculation of sediment produced by each subsystem is a problem, which cannot be solved in appropriate temporal and spatial scales by applying physically-based models. Hence, simpler geomorphic laws have to be found describing functional relationships between representative parameters and the frequency-magnitude characteristics of the processes.

individual components of the cascading system (and the related geomorphic components). The matter fluxes between the components should be modelled using process knowledge and scale transfer methodologies.

In the approach presented, the cascading system is simplified to a hierachical connected structure of geomorphic subsystems transfering sediment through the geomorphic cascade (Fig. 3). An example would be a system of drainage basins, from zero-order head water basins to the regional base level. Each subsystem can be viewed as a geomorphic process-response system with a geomorphic form, and geomorphic processes mainly determined by climatic regime, geomorphometry and lithology. The subsystems include site-specific process behaviour in terms of form-process interactions and climatic impact on the acting geomorphic processes (Fig. 3). However, one issue considered in this paper is how the complex physical form-process and climate-process models can be simplified to functional relationships between geomorphic and climatic parameters and frequency-magnitude behaviour of geomorphic processes. Therefore, a basic requirement of the proposed model scheme is a discretisation of the continuous landscape into geomorphic components which are linked topologically by net sediment fluxes (Preston and Schmidt, 2003).

1. Model concept

The model structure is illustrated schematically in Fig. 4. It can be characterised as a simple tank model, in which sediment is routed through a series of storage components. The basic aims are to simplify complex landforms using a set of simple landform units and parameters and to describe temporal patterns of their long-term behaviour. This involves regionalisation and parameterisation steps.

- Regional scale landscapes are split up into process subunits (Fig. 3). These components are conceived as geomorphic process units or process domains, i.e. a spatial unit is defined in terms of its dominant geomorphic processes. They can be defined by a specific form-process relationship. These components can be seen as a landform unit producing a specific amount of sediment within a given timestep, related to their internal geomorphic properties, the climatic input, and the landcover conditions. These units can be described as *storage units* and/or *morphometric units*. This procedure can be seen as an analogy to the fixed cell-based discretisation of recent process-based landform evolution models.
- These geomorphic units are *linked topologically* to describe the transfer of sediments through the whole geomorphic evolutionary system and to model the spatio-temporal development of this system.
- A geomorphic unit is described by a set of *geomorphic parameters*. These parameters (i) describe the unit in terms relevant for evolution, and (ii) characterise corresponding *form-process relationships* of the cascading system (Fig. 3). Various landform components have to be considered, i.e. landform morphometry and material. In fact, there are numerous studies on effective geomorphometric parameters available (Schmidt and Dikau, 1999). The major issue is to integrate these within higher scale geomorphic models.
- The influence of climate and form on geomorphic processes can be quantified as functional relationships of geomorphic parameters (see above), climate parameters (see below) and frequency/magnitude characteristics of net sediment transport by geomorphic processes. This means that either (i) geomorphic processes act independently and can be modelled by separate equations or (ii) they have to be replaced by one integral process law. To complete the cascading system, functional *process-form relationships* are required, quantifying the influence of geomorphic processes on geomorphic forms (e.g. simplified sedimentation law).

- So far, only internal behaviour of the geomorphic system has been considered. External forcing processes, i.e. climatic input and landcover changes, are represented using *effective parameters* at timescales relevant for regional landform evolution. In order to simplify the temporal variability of these parameters (which is very uncertain, anyway), it is helpful to divide the continuous timescale into *climatic/landcover regimes* (Schmidt, 2001). These show comparatively high internal homogeneity in terms of their effects on geomorphic processes (which means their effective parameters). However, if the modelled temporal period is short enough (no major climatic variations), it might be reasonable to exclude climatic/landcover regimes from the model.

2. *Model formulation*

A mathematical formulation of the model is presented on the following pages (Fig. 4).

Step 1: Defining initial conditions by geomorphic regionalisation in space and feature scales to geomorphic process units

The continuous landscape is subdivided into n ($i = 1, ..., n$) geomorphic process units (slope units, zero-order basins etc.), where unit i delivers sediment to j:$i \rightarrow j$ (defined by surface topological relationship). Landform can be described by a set of geomorphic landform parameters $\vec{l} = (l_1, l_2, ...)$, which can vary with time t and unit i: $\vec{l} \doteq \vec{l}_i(t)$. These parameters describe dominant landscape characteristics and the sensitivity or susceptibility of a landform unit with respect to acting geomorphic processes (Crozier, 1999). Modern geomorphometric technology provide techniques assisting in these kinds of spatial regionalisation steps, e.g. algorithms for landform analysis (Schmidt and Dikau, 1999).

Step 2: Defining boundary conditions by aggregation to climatic/landcover regimes

Variations in the spatio-temporal continuous systems of climate and landcover are modelled by a set of climatic/landcover regimes, which means time intervals T_k: $t = [t_1, t_2]$, where variability in controlling conditions is relatively low and climate and landcover conditions are relatively homogeneous, i.e. the continuous timescale is discretised to time intervals $t \rightarrow T_1, T_2, T_3, ...$ (Preston and Schmidt, 2003). The time intervals are parameterised by a set of effective climate and landcover parameters $\vec{c} = (c_1, c_2, ...)$, which vary with unit i and time t, i.e. $\vec{c} \approx \vec{c}_i(t) \approx \vec{c}_{i,T_k}$ for $t = [t_1, t_2]$. Therefore the temporal dependency of the effective climate and landcover parameters can be reduced to a relationship between climatic and landcover regime and effective parameter. This step can be seen as a parameterisation of environmental conditions (forcing factors) in terms of their geomorphic effectiveness.

Step 3: Geomorphic process laws using frequency and magnitude

Power laws have frequently been used to describe temporal characteristics of geomorphic processes (Bak, 1996; Boardman and Favis-Mortlock, 1999; Hergarten and Neugebauer, 1999b). Therefore, the frequency-magnitude

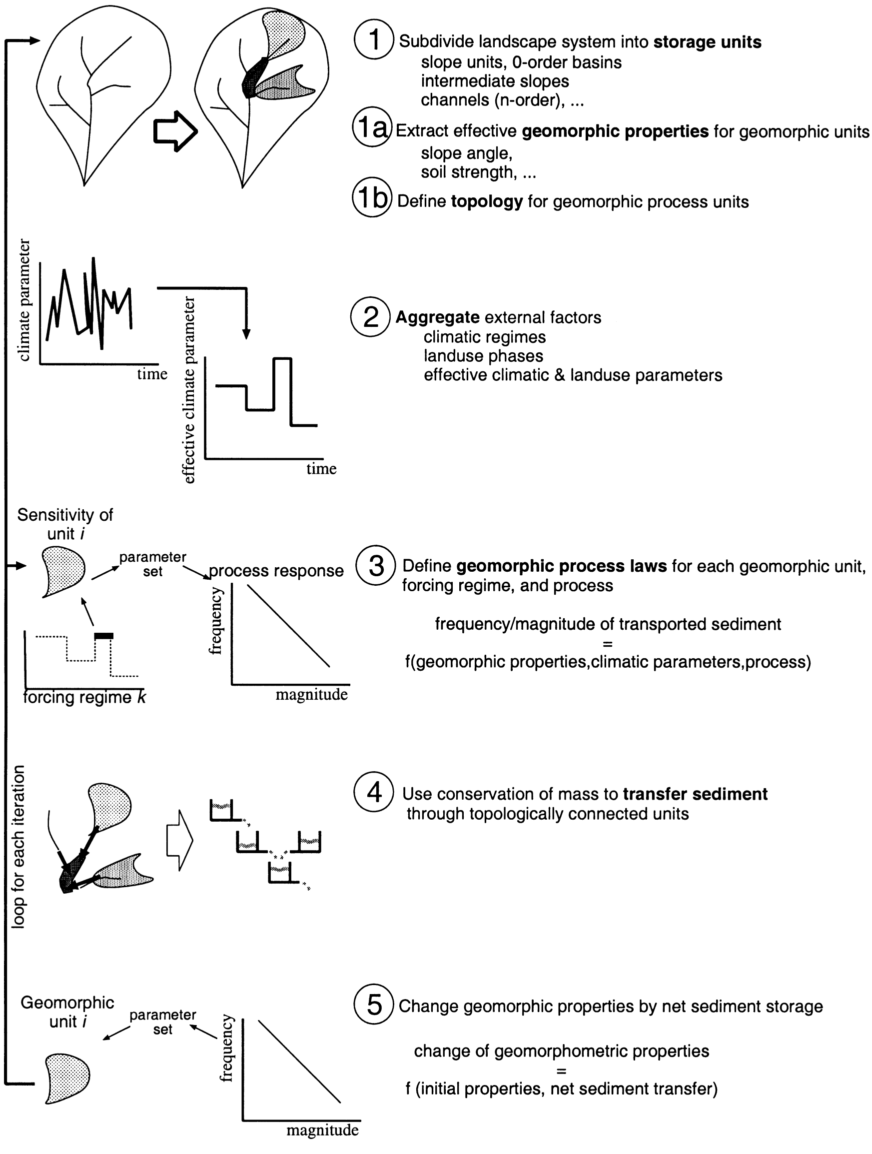

Fig. 4. Concept of a modelling approach for regional scale landform evolution (see text).

distribution of mobilised sediment (that is transfered from unit *i* to the topologically connected units) can be described as a power law between magnitude (unit: mass/time) and recurrence interval. This relation varies with geomorphic characteristics $\vec{l}$ (that means geomorphic unit *i*) and process and climatic/landcover conditions $\vec{c}$ (that means time interval T_k).

$$M = \left[M(R)\right]_{\vec{l},\vec{c},p} = \left[k \cdot R^b\right]_{i,T_k,p} \tag{1}$$

where M, magnitude of process p; R, recurrence interval of process p; k and b, power law parameters; i, geomorphic unit; p, geomorphic process and T_k, time interval.

The assumption is made, that the frequency-magnitude relationship of mobilised sediment is only dependent on (i) the geomorphic parameters $\vec{l}$, (ii) the climatic and landcover parameters $\vec{c}$, and (iii) the geomorphic process p. Therefore the parameters of Eq. (1) can be determined as:

$$\begin{pmatrix} k \\ b \end{pmatrix} = \vec{f}\left(\vec{l},\vec{c}\right)_p \tag{2}$$

where $\vec{l}$, effective geomorphic parameters of unit i, and $\vec{c} \approx \vec{c}_{i,T_k}$, effective climate parameters $\vec{c}$ of unit i for homogeneous time intervals T_k.

This means, the parameters of the frequency-magnitude relationship can be calculated as a function of geomorphometric properties and climate and landcover properties (i.e. landform sensitivity and effectivity of forcing factors).

Step 4: Sediment redistribution per time step

Based on the proposed dependency of frequency and magnitude of sediment production, a sediment flow law is established. This can be done by integrating the magnitude of processes for a given time span. However, finding appropriate time steps to route the sediment through the cascade is one crucial problem for the model solution.

$$V_i(t) = \sum_p \int_t^{t+\Delta t} (M)_{i,T_k,p}\, dt \tag{3}$$

where V_i is the total amount mobilised material in unit i (sediment flux out of unit i) by all geomorphic processes p acting in that unit within time interval t, $t + \Delta t$. The frequency magnitude relationship $M(R)$ can be calculated by Eqs. (1) and (2). However, a problem is identifiying the integral $\int_t^{t+\Delta t} M\,dt$. A possible solution is to estimate the contribution of an event magnitude by $\frac{M(R)\Delta t}{R}$. Then the total amount of sediment flux out of unit i within time interval t, $t + \Delta t$ can be calculated as

$$V_i(t) = \sum_p \int_{R=0}^{R=R_{\max}} M(R)_{i,T_k,p} \frac{\Delta t}{R}\, dR \tag{4}$$

However, because of divergence of the integral (and because of geomorphological considerations), this requires the introduction of a maximum recurrence interval $R_{\max}$ (i.e. exclusion of large events). The sediment budget *S* for unit *i* can be defined by the topology (as defined above) and the continuity equation from the sediment fluxes *V*:

$$S(i,t+\Delta t)=S(i,t)-V_i(t)+\sum_{j:j\to i}V_j(t) \qquad (5)$$

Step 5: Recalculation of geomorphic properties

The change of geomorphic properties $\vec{l}$ for each unit *i* is a function $\vec{g}$ of initial conditions $\vec{l}$, mobilised sediment and sediment input in the system unit.

$$\vec{l}_i(t+\Delta t)=\vec{g}\left(\vec{l}_i(t),\ \sum_{k=i,\ j:j\to i}V_k(t)\right) \qquad (6)$$

These step defines the initial conditions for the next modelling iteration (step 1, see Fig. 4).

DISCUSSION

The proposed model addresses topics that feature within contemporary geomorphologic research. A key problem is to devise methods and techniques in modelling geomorphologic evolutionary systems and to identify the role of process based models within that framework (Hergarten and Neugebauer, 1999a). This paper presented a conception for modelling geomorphic evolutionary systems based on the topology of sediment flux rather than individual process behaviour. To overcome the limitations inherent in raster and TIN based approaches (Coulthard, 2001), which represent an inappropriate spatial resolution for modelling evolutionary systems, it is proposed to represent space as a series of morphologically semantic *landscape units*; and to model landscape dynamics based on the *sediment fluxes*. This leads to models of landform evolution on a higher scale. The uncertainty in modelling landform evolution is treated by modelling evolution of landform structure rather than the height change of a three-dimensional surface. Therefore, configurational aspects in geomorphic systems are emphasised. Moreover, a *multiplicity of processes and related interactions* are modelled rather than details of behaviour of individual processes. Therefore, the proposed model approach simplifies process laws to relationships between frequency-magnitude spectra of processes and the environmental conditions which produce them, i.e. between the sensitivity of landscape units and the effectiveness of forcing factors (Brunsden and Thornes, 1979; Crozier, 1999).

However, the presented model framework also indicates a series of problems and issues related to modelling approaches on higher scales. The approach is based on the modelling of landform structure and topology by storage units or geomorphic process domains. Therefore, a quantitative definition of *geomorphic process domains* has to be derived. Although there exist various specific approaches (e.g. hydrological response units (HRUs) or chemical response units (CRUs)), there is a need for a unifying and more rigorous definition for geomorphic units as a part of the cascading system (see the previous section). On the other hand, the definition of landscape units always involves a certain degree of abstraction and therefore subjectivity. However, this task could be done empirically, i.e. by mapping of process redistribution in association with the controlling factors. With geomorphometric progress this could replaced by semi-automatic GIS-supported expert systems on the basis of the controlling factors (Schmidt and Dikau, 1999).

Another problem relates to the definition of phases (regimes) of relatively homogeneous driving forces and landcover conditions. This involves landuse reconstruction, paleo climate analysis (e.g. using proxies), which is a research field in itself (Pfister and Lauterburg, 1992; Thompson *et al.*, 1993; Glaser *et al.*, 1999).

Another basic issue within the proposed generalised landform evolution model is the formulation of general *geomorphic process laws* based on frequency-magnitude spectra. The geomorphic process law as described in Eq. (2) might be simplified by functional separation of the independent variables into relationships (i) to the landscape sensitivity and (ii) to the effectiveness of forcing factors.

$$\begin{pmatrix} k \\ b \end{pmatrix} = \vec{f}\left(\vec{l},\vec{c}\right)_p \approx \left(\vec{h}\left(\vec{l}\right)\vec{i}\left(\vec{c}\right)\right)_p \qquad (7)$$

Finding a functional separation like this could assist in identifying more generally valid formulations for relationships between the several factors. That means, the different functional relationships are independent and therefore universally applicable. Numerous empirical studies have been carried out, relating *landform properties* and geomorphic processes (Moore *et al.*, 1991; Schmidt and Dikau, 1999). However, universally applicable formulations of geomorphic process laws, as the relationship of process parameters and frequency and magnitude of processes to geomorphic parameters are missing. Geomorphometric parameters have been one major focus of interest (Moore *et al.*, 1991; Schmidt and Dikau, 1999). Moreover, physical process models can assist in deriving these relationships, in particular form-process interactions and effective parameters. Within this respect, various sensitivity studies have been carried out (Schmidt *et al.*, 1998, 2000) and several simple parameters that are currently applied within process models can be used (Beven and Kirkby, 1979). However, much more work is needed to establish more generally valid parameters and geomorphic laws.

Modelling of landform change by processes completes the circle of form-process-form interaction. Whereas the influence of topographic properties on geomorphic processes has been investigated in many studies, a quantification of the impact of processes on landform has been rarely taken into account. Therefore, deriving adequate formulations for Eq. (6) (function $\vec{g}$), e.g. sedimentation laws, remain a problem in the model formulation. Moreover, appropriate iteration intervals for the proposed model approach have to be defined. These should certainly be considered in the context of frequency characteristics of the modelled processes that are thought to be most relevant.

Long-term processes such as weathering and tectonic uplift are not directly included in the current modelling concept. Weathering processes, which are dependent on soil hydrology, soil and bedrock properties, and climate (Cox, 1980) are considered to be spatio-temporal homogeneous for the model scale. However, weathering might be included as a spatio-temporal varying process like any other geomorphic process within the model concept (Eq. (2)). Tectonic activity might be included by adding a constant or varying change in surface height (or the effect of this change on the geomorphic parameters for each domain) and recalculating geomorphic process domains and geomorphic parameters for each timestep. The same issues apply to baselevel change. For highly active areas like New Zealand or Japan it might be appropriate to include details of spatio-temporal variations of tectonic displacements (e.g. to model fault scarps and rift valleys).

Landcover dynamics are treated as external factors, independent of the geomorphologic subsystem. However, in general and especially for specific environments, there are strong relations between these subsystems (parent material, landform, soil, vegetation).

CONCLUSIONS

The presented modelling approach focuses on modelling the regional scale sediment cascade. Individual process details are neglected or simplified. In terms of understanding the evolution of regional scale systems, it is argued that it is more appropriate to model the topology of the sediment cascade system rather that the exact behaviour of the single processes in the cascade, because of their stochastic nature in the context of higher order evolutionary systems. We argue that the inexactness and error in process description on the scale of process-response subsystems are averaged by diffusive effects of the cascading system. Moreover, at this scale interactions between process subsystems acting on different levels of frequency and magnitude may dominate the system. The proposed model offers potential for evaluating these effects using sensitivity analysis. The model structure is one possible solution for the necessary regionalisation step in changing scales from local process scales to scales of geomorphic evolutionary systems. It highlights the need for both detailed individual process studies to model net effects of process-response subsystem on the higher scale, and consideration of system scale by scaled system descriptors in terms of form (landscape units and parameters) and processes (frequency-magnitude spectra).

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