Systems theory in Geomorphology
A challenge

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with 6 figures

Summary. Systems theory in Geomorphology – A challenge. Every scientific observation and explanation is based on theory, and also the respective results are strongly dependent on the theoretical background of the individual researcher. In many cases, if not most, general systems theory builds this theoretical background within geomorphology. However, as a result of the widespread acceptance of geomorphic systems theory and the strong empirical orientation of the discipline, its theoretical foundation as well as the definitions and basic assumptions are rarely (if at all) questioned and analysed. Thus, it is rarely asked ‘What is as system?’ or ‘What are the basic assumptions of geomorphological systems theory and do they still apply to our present knowledge?’ This paper tries to answer these questions by analyzing how geomorphologists conduct their research. Within the geomorphological theoretical framework, geomorphic systems are considered as open, i.e. they have in- and outputs which enable the environment of the system to highly influence the system. At the same time, the openness of geomorphic systems brings with it difficulties in system delineation, and reveals inconsistencies with the concept of equilibrium and cause-and-effect relationships. With the concepts of self-reference, autopoiesis and operative closeness of systems we put first thoughts for a (paradigmatic) re-orientation of the discipline up for discussion.


Keywords: Systems theory, observation theory, systems definition, equilibrium, causality, reductionism, autopoiesis, self-reference

1 Introduction

Due to their competences such as mapping, analyzing, reconstructing and monitoring of geomorphic processes geomorphologists contribute significantly to the debate on Earth System Science and related issues. At the same time, however, neighbouring disciplines – whilst accept-
ing geomorphological empirical work – often question the scientificality, i.e. the theoretical foundation of this research. Thus, a "[...] rarely mentioned methodological conflict exists in physical geography: the relative merits of empiricism and theory. While, in many sciences, the two are seen as complementary but competitive – and practiced separately (experimentalists deride theorists, and vice versa, in physics and biology) – little space exists in physical geography for theorists. As far as I know, all physical geographers engage in empirical work, so much so that theorists in related fields expect geographers to be empiricists. Attempts to construct and analyze simple theoretical models in physical geography are rare" (Malanson 1999: 746 f).

But beside the knock-out argument that science is not scientific without a coherent foundation in theory and epistemology – do we really need theory?

We can approach this question by having a closer look at an example of a landscape which probably is familiar to many geomorphologists (Fig. 1). Geomorphologists instantly realise that weathering takes place, mass wasting and fluvial processes occur, vegetation changes appear, etc. However, it is also obvious that somebody with a different theoretical background perceives completely different things: She or he may classify the landscape using criteria like scenery appraisal, available resources, or tourism potential. Moreover, if A. Penck looked at this landscape, or Gilbert, or Davis they would explain the landscape fundamentally different than any contemporary geomorphologist. Still, the landscape should be the same for all, as it is the same section of reality. How then can these differences be explained? The argument in this contribution is that it is the theoretical background which determines our perception (cf. also Rhoads & Thorn 1996, Elverfeldt 2010). The perceptions themselves, however, cannot be judged as right or wrong, it only is the logical coherence of the theoretical background, the awareness of the limits of our perception and the explanatory power of our initial assumptions which can be assessed.

In summary, there is no observation, no explanation, no research design without theory, and the respective results are strongly dependent on theoretical backgrounds. It is within this context how a landscape is described, analysed and respective conclusions are drawn (e.g. Glade 2003). This contribution attempts to assess the logical coherence and the explanatory power of the initial assumptions within geomorphology. We approach this by analysing the implicit and explicit theoretical foundation of a large part of geomorphological research: geomorphological systems theory.¹

2. Five decades of systems theory in geomorphology

Thinking in systems is not a new concept, indeed the idea of systems is as old as occidental philosophy and can be traced back to Aristotle. Nonetheless, the now widely-used vocabulary of systems theory is relatively new: In the 1950s, the Austrian biologist Ludwig von Bertalanffy

¹ Within the framework of general systems theory, we observe the world in terms of systems. It has to be emphasized, however, that it is only a way to look at the respective objects of interest: Systems do not exist. Therefore, whenever a phrase similar to "the system $\mu$ (open/isolated/ ...)" is used in this paper it does not connote any ontological statement.
(1901–1972) proposed a general systems theory. He understood organisms as open systems that absorb matter from their environment for their metabolism in order to reach a steady state (Bertalanffy 1950b). The basic ideas of his general systems theory were supposed to apply universally to all systems, not only to living organisms, and they should function as fundamental assumptions for constructing models in all sciences (cf. Bertalanffy 1950a, 1950b). Since then, further development of systems theory took place in a multitude of disciplines, so that nowadays different system theories exist rather than one coherent general system theory as intended by Bertalanffy. Therefore, today general systems theory cannot be presented as a consolidated totality of concepts that is universally valid for the natural sciences including physical geography and geomorphology.

Systems as a way of viewing the world have been introduced to geomorphology more than fifty years ago by Arthur N. Strahler (1950, 1952) and John T. Hack (1960). However, its success story only started with Richard Chorley’s USGS professional paper on geomorphology and general systems theory (Chorley 1962) and especially about a decade later with the textbook...
of Richard Chorley and Barbara Kennedy (1971) who adapted Bertalanffy's theory to geomorphology. Soon the potential of systems thinking became obvious, as it necessitates a shift from observing singular features or details to observing relationships between elements of the physical world.

Thus, to date systems thinking is a well established concept within geomorphology. This is also mirrored in the amount of publications which are (more or less implicitly) using systems theory as their framing concept. Search results from the ISI Web of Science suggest a steep incline in the usage of the system concept within geomorphological research in the 1990's and the first 10 years of this century (Elverfeldt 2010).2 Whereas from the 1960s till 1989 the amount of publications referring to 'geomorph*' AND 'systems' was approx. 3% (28 of 903), it reached 27% of total publications (971 of 3656) in the 1990s and 31% (2205 of 7044) within the first ten years of this decade (cf. Fig. 2). Though the validity of the numbers is limited and they thus only indicate a trend, it can be argued that this wide acceptance of the theory, paired with a long and strong tradition of field observations is at the expense of theoretical foundation and enhancement of the theory. For example, it is rarely asked why we refer to nearly all objects in our environment as systems, or if there are any theoretical constraints to this broad application of systems theory, or even what a system in stricto sensu is.

Furthermore, scanning those papers and publications in the field of geomorphology shows that, when using a systems approach, most authors do not define the term system (e.g. Vandenberghe 1995, Snyder et al. 2009, Orford et al. 2002, Hooke 2007). It can thus be hypothesized that as a result of the widespread acceptance of systems theory, its theoretical foundation as well as the definitions and basic assumptions are rarely (if at all) questioned and analysed. This may be intensified by the fact that most of the geomorphological studies and thus publications are empirical, not theoretical. According to Thomas S. Kuhn (1962) this is a classical criterion for a paradigm within the phase of normal science, but it can be questioned in how far Kuhn’s concept can be applied to a scientific discipline with such a strong empirical focus as geomorphology. In our discipline, theory or even scientific philosophy is mostly regarded as not mandatory and subordinate to empirical studies and field experience. Chorley (1978: 1) summarized this attitude by stating: „Whenever anyone mentions theory to a geomorphologist, he instinctively reaches for his soil auger“. Cox (2007: 47) suggests that this statement is still true today and adds: „[…] geomorphological research and the literature it generates remain dominated by empirical case studies“4. Therefore, the lack of theoretical discussions on geomorphological systems theory can be interpreted as the degradation of a scientific theory to an implicit theory5, that is, a combination of assumptions which are no

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2 Those papers which are written within the framework of geomorphological systems theory without mentioning "system" within title, abstract or keywords are not captured. Due to limited data the query only serves as an indicator, not as a proof.

3 In psychology, the notion of implicit theory is defined as personal constructions about particular phenomena that reside in the minds of individuals (Sternberg et al. 1981, Furnham 1988). Assigned to geomorphological research this can be understood as set of presuppositions which we are no longer aware of though working with them continuously.
Systems theory in Geomorphology

longer explicitly addressed nor questioned (cf. EGNER & ELVERFELDT 2009). „In this it was often forgotten that system dynamics are based on a set of rather specific assumptions which may or may not apply in connection with specific geomorphological problems“ (SCHIEDEGGER 1992: 213). Still, this does neither connote that empirical studies are of low scientific value, nor that there has been no progress in geomorphological systems theory at all, especially since the focus shifted from systems in equilibrium towards systems in non-equilibrium with non-linear, complex, chaotic, and/or self-organised behaviour and thresholds (e.g. SCHUMM 1991, PHILLIPS 1992, 1999, 2006, BAK 1996, THOMAS 2001, HEGGARTEN 2002, and also cf. KEILER in this issue).

Thus, it is not surprising that it is rarely asked ‘What is as system?’ or ‘What are the basic assumptions of geomorphological systems theory and do they still apply to our present knowledge?’. Moreover, these questions are devaluated mostly as trivial.

This paper tries to answer these simple questions. We are approaching this aim by analyzing how we as geomorphologists conduct our research (2nd order observation, for details see below and FOERSTER 1984, EGNER 2008a, EGNER & ELVERFELDT 2009), including the discussion of definitions, systems classifications, basic assumptions and the respective theoretical challenges for a geomorphology of the 21st century.

Fig. 2. Search result in ISI Web of Science® for the topic ‘TS = geomorph* and TS = (system OR systems)’ and ‘TS = geomorph*‘, respectively. The topic search includes title, key words and the abstract of the publications. (Note: ISI Web of Knowledge coverage of journal abstracts ca. 70 % from 1991 onwards, listing of conference proceedings from 1990 onwards. Hence, there is a bias in this data. Query date: 19.01.2009).
3 Re-discovering observation

Why talk about observation? Isn’t observation one of the most ordinary things in science?

In his inaugural in Berlin “Beobachtung als Grundlage der Geographie“ (Observation as foundation of geography) ALBRECHT PENCK states that all precise sciences rely on observation, i.e. research is conducted by observation (PENCK 1906: 10). In his eyes, observation has a revitalizing influence on the development of all sciences. By observation PENCK understood empirical studies or ‘being in the field’.

The cyberneticist and mathematician HEINZ VON FÖRSTER has a different view on observation (cf. e.g. FÖRSTER 1984). He defined observation by the two-fold practise of distinguishing and indicating. FÖRSTER drew his insights from studies on the ability of beings to recognize. For example, certain cerebral injuries cause a considerable loss of the visual field – which the person concerned does not realize. However, specific motoric dysfunctions develop, e.g. single-sided loss of arm or leg control. One therapy is to blindfold the patient, so that she or he learns to focus on those inner channels which function properly and which give information about his or her posture. What is most striking here is that the ‘absence of perception’ is not perceived and that the ability to perceive has to be rebuilt by senso-motoric interaction (FÖRSTER 1984: 289).

Another example is an experiment in which a single word is recorded and then the tape is looped so that the word is re-played continuously. After a specific number of iterations of the word, however, the probands suddenly start to hear “another meaningful and clearly perceived word” (FÖRSTER 1984: 290), a so-called alternate. After some more repetitions, this first alternate switches to a second alternate, and so on.

Experiments with cats, where their brain activities have been displayed via micro-electrodes, give a similar picture of perception. In the experiment, in the cage there is a food box which can be opened by a lever. However, the lever functions only when a certain tone rings. Thus, the cat only reaches the food if it realized that it has to press the lever when the tone rings. The brain activities showed that the tone was not perceived as long as the tone was uninterpretable. In other words: As soon as the perception was understood, the whole nervous system immediately started working. Before, the tone has not been distinguished as order from noise. These examples show that something is seen or heard which does not exist, or it is not seen or heard that something exists. What is perceived is thus dependent on internal structures, not on external signals. Therefore, if we want to understand these internal restrictions to perception we have to understand how perception, how ‘seeing’ or ‘observing’ functions (FÖRSTER 1984). For geomorphologists this is of interest, as it may shed a new light on the way we conduct our research.

The most basic statement is that each observer has a blind spot, that is, something that he or she cannot see. To start with, this can be understood as the physiological blind spot of the eye. Most peculiar, however, is not the fact that there always is something which we do not see, but that we do not see that we do not see (something): That is, we do not permanently see a black spot in the centre of our focus, because our brain fills the gap quasi-reasonably (FÖRSTER
1984: 288 f.). In a nutshell, this means that we are blind for the blind spot, i.e. we do not see (FOERSTER 2002: 39), and in this sense every observation is blind (for its own blindness).

Heinz von Foerster, the mathematician GEORGE SPENCER BROWN (1972) as well as the biologists HUMBERTO MATURANA and FRANCISCO VARELA (1987) or the sociologist NIKLAS LÜHMANN (1995a) transform this physiological blind spot to a more theoretical level. Every time we identify an object, a matter, a unit or a being this identification is an act of distinction which separates the identified from a background and thus makes it distinctable. Every observation thus starts with a distinction between something that is indicated and everything else that is neglected. This means that whenever we refer to something we have determined a criterion which specifies its attributes and features as a being, a unit or an object, and this distinction is the basement on which further distinctions are made and thus enables us to gain information about the observed object. At the same time, the observer always is unaware of this very distinction, it can only be risen to awareness in the retrospective. This is an everyday-situation in which we necessarily find ourselves continuously (MATURANA & VARELA 1987: 46).

Transferring this to geomorphological investigations implies that we can only observe the world accordingly to our presuppositions. For example, within geomorphological research we differentiate the landscape based on certain criteria (e.g. form, process, material, scale), but other criteria could be considered as equally important (e.g. hazard potential, scenery appraisal, land development). The choice of one or more of these criteria is our initial distinction which then directs our subsequent research activities and thus our study results. Distinctions in geomorphology relate, for example, to the respective school of thought during academic education, general personal interests and the like, which can be described as the "cognitive conditioning" (in German 'Wahrnehmungsdressur', WARDENGA 2001, also cf. BELL et al. in press) of any researcher. RHoads & THorn (1996: 51) come to a similar conclusion when stating: "A quintessential point to emerge […] is that observation is theory-dependent". For example, if the focus of one's geomorphological education is on landslides, one will also focus on landslides in the field and will also find landslides. If the focus is soil erosion, one will find eroded soils and colluvia. Or, in other words: With the difference of good and evil one can – wherever he or she looks – observe something else than with the distinction of rich and poor, beautiful and ugly, new and old, or healthy and sick (cf. PORKSEN 2002: 34 f.). This clarifies one important aspect: There is no right or wrong in observations, as there is no locus observandi from which reality can completely and impartially be observed (FOERSTER 2002).

In summary, in the very same second that we observe something (that is, distinguish and indicate), we're blind for the distinctions on which our observation is based – it is the blind spot of the respective observation. This is why observation theory distinguishes between first order observation (with the central question "What is observed?") and second order observation, asking "How is observed?" (cf. EGNER & ELVERFELDT 2009). Second order observation thus can be described as the observation of observation. It is this level of second order observation at which the blind spot (i.e. the initial distinction) of an observer can be discovered. However, also second order observations do have a blind spot which can be discovered by third order observation which has a blind spot which can be discovered ... and so on.
Realizing these boundaries to perception brings with it rather profound consequences for sciences: There is no reference point for observation from which the world or reality can be impartially captured. Following the observation theory of Heinz von Foerster, the physiological arguments of Maturana & Varela, and the logical treatises of George Spencer Brown or Niklas Luhmann, every observation or every result has to explicitly address the constraints under which it gains its restricted validity (cf. Bardmann 2001). Whereas we can indeed evaluate the inner logic of a research performance, of a theory or a methodology, we cannot evaluate the trueness of results. It can only be shown which descriptions, results, theories are now viable, i.e. with which now can be effectively worked.

Against this background, we can keep ourselves highly adaptive and advance scientific progress. "The investigation of the Earth surface can indeed be conducted from any position; but certain locations draw the researcher's attention to specific problems and prepossess him with particular ideas so that he starts his investigations from a very specific point of view" (Penck 1906: 9, translation by Elverfeldt & Glade). Second order observation is the tool with which we can make these specific viewpoints and prepossessions visible and thus redirect our attention to those problems which remained unseen so far. Re-thinking Penck's statement (1906: 10) in this new framework one can indeed state that observation has a revitalizing influence on all sciences.

4 Systems in geomorphology

How do geomorphologists currently observe the world? In many cases, if not most, we are observing the world with the aid of general systems theory. By systems, most geomorphologists understand a (complex) whole that exhibits a specific structure of single elements and the relationships between these elements (e.g. Bull 1991, Chorley & Kennedy 1971, Huggett 2003, Werner & McNamara 2007, White et al. 1998). These definitions are more or less identical to the original one by Ludwig von Bertalanffy (1950b: 143): "A system can be defined as a complex of interacting elements $p_1, p_2 \ldots p_n$. Interaction means that the elements stand in a certain relation, $R$, so that their behaviour in $R$ is different from their behaviour in $R'$. On the other hand, if the behaviour in $R$ and $R'$ is not different, there is no interaction, and the elements behave independently with respect to the relations $R$ and $R'$."

Within the geomorphological theoretical framework, geomorphic systems are generally open, i.e. they have in- and outputs. These in- and outputs enable the environment of the system to highly influence the system, because they influence and change the components of a system (Bertalanffy 1950a: 23). That is, the surrounding can affect the structure of a system as well as the connections between the elements and thus determine systems behavior. From this point of view, geomorphic systems are constantly striving towards a balanced interaction with their surrounding. However, it is exactly due to the principle openness of geomorphic systems

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4 The concept of viability in contrast to the concept of 'truth' has been introduced by the philosopher Ernst von Glasersfeld and states that actions, notions and concepts are viable if they suite the purposes and descriptions they are used for (Glasersfeld 1997:43).
that such equilibrium cannot be reached (cf. Elverfeldt 2010). Just as ‘global change’ can be considered as a keyword of earth history, ‘systems change’ is a key to understanding systems behaviour. It’s all about evolution, not stability!

However, equilibrium thinking within the systems framework has been dominant in geomorphology till at least the late 1990s and is still considerably influencing geomorphological research – according to Bracken & Wainwright (2006: 167) “equilibrium continues to be referred to in a wealth of research publications” and “many others include implicit references to the concept”. Equilibrium thinking is framed by the concept of scales, especially the concepts of “graded time” and “steady time” within which equilibria can be described and linear, causal relationships are assumed (cf. Elverfeldt & Keiler 2008). Closely related to the concept of scale is a reductionistic approach to reality, because it is hypothesized that space and time can quasi be sliced into smaller pieces which then can be more easily described and understood. This conflicts with contemporary concepts of nonlinearity, including emergent properties of systems (cf. Keiler in this issue).

These concepts of unity, equilibrium, causality and reductionism and their implications are the challenges and obstacles for the theoretical re-orientation of the discipline towards system evolution and non-linearity.

4.1 Challenges to Unity

As outlined above, systems are seen as a unity or complex whole with specific connections to its surrounding. However, it is rarely discussed how the system differs from its environment, i.e. what are the criteria with which a researcher can disintegrate geomorphic phenomena into ‘system’ and ‘surrounding’? This question becomes even more relevant when the openness of geomorphic systems (only exception: the morphological system, cf. Chorley & Kennedy 1971) is taken into account: “A natural delimitation occurs only if a system is completely closed within itself”, whereas the distinction of open systems is arbitrary (Scheidegger 1992: 213–214). For the analysis of systems, however, one of the most crucial steps is to correctly define the system, i.e. its boundaries. Honig (1999: 2) summarizes this by stating that it “is of the utmost importance to delineate a system adequately and to distinguish it properly from its surroundings. Failure to do this leads to nonsensical and paradoxical results”. But which are the criteria in order to “properly” define a system? Honig suggests “actual physical constraints such as walls, or conceptual designs such as geometric surfaces”. Still, it is not clear how to assess whether a wall belongs to a system or not. Common sense as suggested by Chorley & Kennedy (1971: 23), however, is important for the development of new ideas and concepts (e.g. the idea of Alfred Wegener to compare the coastlines of South America and Africa may be related to common sense), but has its major weaknesses as a ‘scientific method’ for the delineation of systems (as it is neither impartially nor repeatable). Werner & McNamara (2007: 395) suggest that the “boundaries of a system enclose the smallest set of elements that are nonlinearly coupled, with only weak, linear interactions crossing boundaries”. However, in order to accordingly delineate the system, one already has to know the system, i.e. the system has to be analyzed in advance, because the kinds of interactions have to be known afore. It is a circular definition. This cir-
Circularity could be circumvented if the initial description and analysis of the system would be hypothetical, and the hypothesis would be either falsified or verified. However, this is not how geomorphologists seem to usually proceed.

In most cases, geomorphologists would probably agree with Honig (1999: 2) that any study area can be considered as system. For the delineation of these systems, physical properties are chosen which can easily be identified or interpreted as boundary, such as the boundary fluid/solid (like the boundary between a river and a slope) or frozen/unfrozen (as the boundary of a permafrost body) (cf. e.g. Huggett 2003, White et al. 1992). Often, these boundaries are identical with a change of form and/or dominant processes (cf. Fig. 3).

In a nutshell, the delimitation of geomorphic systems follows no coherent guiding principle and is to a certain degree primarily subjective, i.e. dependent on the respective research focus and the expertise of the respective researcher (also cf. Baker & Pyne 1978): The character of a system, its dynamics and its evolution therefore no longer are a property of the object, but dependent on the choice of the location of the system boundary (cf. Elverfeldt 2010). Thus, system boundaries in contemporary geomorphological thinking are spatiotemporal variable. This probably is one of the reasons why geomorphologists perceive the system as strongly interconnected with and determined by the surrounding systems or the “System Earth” at

Fig. 3. The system ‘hillslope’. The boundaries of the system are connected to a visible change in form (interfluve, channel), and to some extent to a change in dominant geomorphic process group (debris transport, debris production). However, the exact boundaries of the system remain somewhat vague and dependent on the research focus. (Source: changed after Huggett 2003: 14).
large. The knowledge-based delimitation of systems is our way of reducing this perceived complexity (i.e. high amount of elements which are non-lineary coupled and which exhibit emergent phenomena (cf. Baas 2007)). The price to be paid is that a coherent scientific method is absent.

The remaining question is whether such a coherent scientific method for the delineation of geomorphic systems does exist and which advantages it would offer. Afore, however, we will have to consider another scientific challenge to geomorphology, i.e. equilibrium thinking, which is closely related to the openness of geomorphic systems.

4.2 Challenges to Equilibrium

"Equilibrium is a central concept in geomorphology" (Bracken & Wainwright 2006: 167) and has a long history and tradition within the discipline. One equilibrium concept is that geomorphic systems can be considered to be in equilibrium when the input of mass and/or energy is balanced by self-adjustment of the elements and variables of a system, e.g. by the change of form or geometry. The debris transfer on a slope, for example, is partly determined by the debris input and slope angle. If the system attains via different feedback mechanisms its specific angle of repose, input and output are balanced and the system is in equilibrium and - on a specific scale - no profound changes occur.

Thus, one has to bear in mind that inputs and outputs do not only influence the system when certain thresholds are exceeded and the system reacts immediately, for example when a rainfall event of a given magnitude triggers a landslide (extrinsic thresholds, cf. Schumm 1979). In contrast, inputs and outputs are continuously influencing the structure of a system and therefore also its inner disposition to react (intrinsic thresholds, cf. Schumm 1979). This can also be described as memory or history of a system.

However, if system inputs and outputs are continuously determining system dynamics, we reach again one of the core problems of geomorphological systems theory: the openness of geomorphic systems. Equilibria can be found in isolated systems, in fact, isolated systems "must eventually reach a state of equilibrium, according to the second law of thermodynamics" (Bertalanffy 1950b: 156, accentuation by the author). In open systems, however, a steady state - which is inherently different from (thermodynamic) equilibrium (Prigogine 1981) - may be attained, which is, however, dependent on the structure and the history of the system. "Then the system appears also to be constant, though this constancy is maintained in a continuous change.

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5 It has to be pointed out that the concept of equilibrium is indeed central to geomorphology, but at the same time there is neither a coherent definition nor a coherent usage of the concept. Phillips 2007 shows that currently there are more than 20 different equilibrium concepts in geomorphology. For a detailed discussion of this problem please refer to Bracken & Wainwright 2006 and Elverfeldt 2010.

6 In his paper on geomorphic thresholds, Schumm (1979) distinguishes between extrinsic and intrinsic thresholds. Extrinsic thresholds refer to those thresholds inside a system, which are exceeded by a change in an external variable, e.g. vegetation cover. Intrinsic thresholds are those thresholds inside a system, which are exceeded without a change in outer conditions. This can be explained by the ongoing in- and output of material and energy which continuously alters the inner disposition of the system to change.
inflow and outflow of materials" (BERTALANFFY 1950b: 156–157, accentuation by ELVERFELDT & GLADE). Furthermore, these steady states have to be in no way stable. Thus, equilibrium thinking is misleading as it mantles the view of the evolution of systems. By introducing free energy to the system, inputs of mass and energy maintain the working capacity of the system as they increase or preserve gradients. One could argue that systems are ‘trying’ to reduce these gradients. Due to their principle openness, however, they will by no means attain a thermodynamic equilibrium, where no change will occur on whatever timescale.

Despite the premise that only isolated systems are striving towards an (thermodynamic) equilibrium, the concept of equilibrium is often applied to open geomorphic systems. BULL (1991), for example, focuses on the ideas of equilibrium and geomorphic thresholds for the description of landscape changes. If perturbations occur, the system starts to react to these changes of outer conditions if certain geomorphic thresholds are exceeded. In BULL’s (1991) example (Fig. 4) the system reacts by a change of streambed altitude with time. After an initial disturbance the system passes the phases of reaction (Ra), relaxation (Rx) (summarized as response (Rt)) and persistence (Ps). At the moment when a threshold is exceeded the reaction phase ends and relaxation begins with the change in the variable. If another perturbation appears

Fig. 4. Scheme showing the change of a geomorphic variable (streambed altitude) depending on threshold-exceeding external perturbations. In geomorphology, the temporary ‘equilibrium’ of one variable is in general seen as equivalent to system equilibrium. (Source: changed after BULL 1991 and DIKAU 2006).
before an equilibrium state is reached, the system is unable to balance the first perturbation and enters a new reaction phase. Thus, in this example, equilibrium is attained when erosive forces are balanced by resistant forces (cf. DIKAU 2006:134, ELVERFELDT & KEILER 2008).

But can such system states really coherently be described as equilibrium? We think that it has only been possible to maintain the idea of system equilibrium in geomorphology because the analysis has been restricted to a single variable in a specific unit of time – as in Fig. 4 streambed altitude. Only then equilibria can be observed – but these are equilibria of a variable, not of a system as a whole and from this it can be in no way inferred whether the system is in equilibrium with its surrounding or not.

Furthermore, Fig. 4 suggests that the system (here represented by a single variable) remains in equilibrium, i.e. input, throughput and output are in balance, unless a threshold is exceeded. However, this balance already does not exist from the moment of profound disturbance onwards – the problem being that we do not directly “see” that it is out of balance. What is here displayed as a straight ‘equilibrium-line’ for a system can be rather considered as a state description of a variable with its measurable or perceivable reactions.

So far we have seen that the concept of open systems brings with it profound contradictions in the inner logic of geomorphological systems theory. The ineligible transfer of concepts which are restricted to isolated systems such as that of equilibria, however, has further implications with respect to a statical or thermodynamical approach to systems and causality.

4.3 Challenges to Causality

Another challenge it is thus to move from the statical, equilibrium-focused approach to a thermodynamical approach to systems with which it can be assessed in how far process and form are mutually accomplishing and mutually depending. This implies a circular relation of process and form, form and process so that cause and effect become indistinguishable. „We believe that distinctions between cause and effect in the molding of landforms depend on the span of time involved and on the size of the geomorphic system under consideration. Indeed, as the dimensions of time and space change, cause-effect relationships may be obscured or even reversed, and the system itself may be described differently“ (SCHUMM & LICHTY 1965: 110). That is, in a dynamical approach to systems any cause can become an effect and vice versa (SCHUMM & LICHTY 1965: 113) and system behaviour becomes non-linear. If form and process are seen as mutually dependent, this circularity becomes the key to system analysis, because systems then will have to be described as being determined by their structure, not by some external variables and forcings. Any existing system then has to be considered as being adapted to environmental conditions (otherwise it would cede existence), regardless of equilibria, disequilibria or non-equilibria, but as not being determined by environmental conditions, and it would have to be considered as a whole, not only its components (cf. SCHUMM & LICHTY 1965). Since the 1990s this perception is reflected in a growing number of publications referring to non-linear, dynamic behaviour of systems as a whole (e.g. HERGARTEN 2002, PHILLIPS 1999, 2006, SCHUMM 1991, THOMAS 2001).
To conclude, systems have a history which is reflected within their structures and thus inevitably determines their behaviour. This also partly explains the perceived unpredictability of many systems, as one and the same impact may trigger different (re-) actions. Examples can be given from landslide research where rainfall events of a given magnitude do not necessarily cause a landslide (cf. Fig. 5). Thus, it is not solely the environment which determines systems behaviour, it is the system itself which sets accordingly to its structure (i.e. the characteristics of its components) whether it reacts or not. This in turn is highly dependent on the history of events, on the way information (here understood as an utilizable pattern of mass and energy) is processed within the system. Seemingly causal relationships like impact-reaction-relations represent an over-simplification of complexity and delimit the discipline's ability to describe systems behaviour. At the same time, it follows from this that the principles of reductionism seem to be largely inappropriate to analyze these kinds of systems, as it implies strong causalities.

4.4 Challenges to Reductionism

The analysis of a single variable synonymous for a system is also a good example for the reductionistic approach within geomorphology. Reductionism is based on the assumption "that even the most complex of systems, when viewed at the 'component level', somehow becomes simpler" (Favis-Mortlock & de Boer 2003: 137). However, how to link the separated components with other components at the same scale or others in order to understand the system as a whole is an open question. This problem is made clear by the physicist Pehr Sällström.

![Diagram of Failure Threshold and Weathering]

Fig. 5. A geomorphological example for information selection by systems (modified after Bell 2007: 14, Schumm 1979: 491). A system might not react on a heavy rainfall event, but due to changes in its internal structure, some time later it does on a relatively small rainfall event. (Source: Egner & Elverfeldt 2009).
(1992) when discussing a drawing of the painter Oscar Reutersvärd ("perspective japonaise", Fig. 6). Having a closer look at the drawing, the seemingly three-dimensional object becomes impossible. But by laying the focus on a sufficiently small part of the drawing, the impossibility and the strangeness vanishes, because any small part seems to be completely coherent. That is, the impossibility and oddness can only be seen with the whole object. Consequently, putting together any number of consistent small parts does not guarantee the consistency of the whole (Sällström 1992). In some way, the very same thing is said by Aristotle’s “The whole is more than the sum of its parts”: Putting together parts does not end up in a whole. Unfortunately, perceiving the oddness of the whole is easy for a drawing like this, but rather impossible for real world phenomena which we perceive as systems.

The success story of reductionism certainly is partly due to one marvelous property of the approach: it is inevitably successful. A system is just as long separated into smaller parts till finally one part of it becomes understandable. However, biological and physical systems behave as a whole, meaning that any change in any element depends on “all the others” (Bertalanffy 1950b: 146) and “that the behaviour of an element is different within the system from what it is in isolation. You cannot sum up the behaviour of the whole from the isolated parts, and you have to take into account the relations between the various subordinated systems and the systems which are super-ordinated to them in order to understand the behaviour of the parts” (Bertalanffy 1950b: 148).

5 Meeting the challenges

Concepts to meet these challenges already exist in other scientific disciplines, such as physics and biology. Among these concepts are those of (1) self-reference, (2) autopoiesis, (3) operative closeness, and (4) structural coupling of systems. Within this publication we will focus on the first three concepts to exemplify their potential as starting point for theory enhancement within geomorphology.
Self-reference:

Self-reference continues the idea of self-organisation (which refers to the structure of systems) and states that a self-referential system is only referring to itself in all its operations and not to another system and its operations (cf. Foerster 1960, Luhmann 1995: 32 ff. and 437 ff.). In this, it simultaneously sets its boundaries and self-reference thus is a prerequisite for system formation. Self-reference does also imply that the processes which lead to the production of elements within the system are dependent only on preceding processes and that they are at the same time the starting point for following processes. This concept does have far-reaching consequences: Because the system is creating itself with all its elements and is also referring only to itself in all its operations, environmental factors cannot determine system behaviour. They are, nonetheless, necessary for the existence of the system. In consequence, self-referential systems are operatively closed (for details see below), that is, the environment cannot directly influence the system via input-output-relationships as it is classically seen in general systems theory and geomorphology (cf. Egner 2008: 55 ff., Egner & v. Elverfeldt 2009). Hence, self-reference and operative closeness does not imply that a system is autarkic (as inputs and outputs are still taking place), but it means that the environment can only irritate the system, i.e. the environment can produce noise. However, it is the system itself which (accordingly to its inner structure) sets which information is selected as order from noise (cf. Foerster 1960).

Autopoiesis:

The concept of autopoiesis has been proposed by the biologists Umberto Maturana and Francisco Varela and describes the self-delineation and self-creation of a biological system, as the system itself produces and reproduces all its elements (Maturana & Varela 1973). Elements which are not produced by the system thus are not part of the system and the unity of the system is such determined. This view differs strongly from the traditional geomorphological perspective, where abiotic systems like a glacier are understood as a (complex) whole with interrelated elements which are generating specific input-output-relationships and where cause and effect can be rather easily distinguished.

What would happen if the concept of autopoiesis was transferred to abiotic systems? First of all, autopoietic systems cannot be understood as one element (with a specific function or role) in the interrelationship of ‘everything’. Rather they can be understood via the analysis of their self-creation, self-organization, self-reference, and momentum (cf. Egner 2008a). For example, each and every single cell of a living system is produced by cell-division resulting from a network of internal operations7 of this system and not by another system or some external impacts (Maturana & Varela 1987). The very same could be argued for example, within geomorphology, for a glacier which produces its constituents – glacier ice –, through metamorphosis, i.e. the transformation of snow to firn and then by further compression to ice. Just as food is a necessary pre-requisite for the cell-division and growth within a human being,

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7 From here onwards, we will use the term “process” synonymously for “operation” as this is much more familiar to geomorphologists and essentially describes the same.
snow is a necessary pre-requisite for the growth of glacier ice. Though one system is biotic and the other is abiotic, both can be considered as being autopoietic, as they are producing their elements themselves. From this it follows, that inputs cannot directly influence the system, they are just a necessary prerequisite for the existence of the system. Thus, systems automatically are adapted to the environmental conditions as long as they exist (Maturana & Varela 1987), but the environment cannot determine systems behaviour as it operates differently (if at all) and therefore cannot directly 'connect' on the basis of the specific process of the system. The only coupling which can occur is on the basis of structure, i.e. structural coupling, and via these well-established associations the environment can then irritate the system (Maturana & Varela 1987). If the irritation triggers an action, the action cannot be causally linked to the trigger, as the action is dependent on the structure of the system. Hence, autopoietic systems are autonomous in that their functioning cannot be influenced (apart from destruction, i.e. glacier retreat), but they are by no means autarkic.

Operative closeness:

The specific mode of operation, i.e. the defining process, can only be found within the respective autopoietic system and nowhere else. Otherwise it cannot be considered as an autopoietic system (Luhmann 1988: 295). Cell division can only be found in living systems, and thoughts only in psychic systems. This is called operative closeness as the structure of the system can only be built by its internal operations and in this sense is independent of its environment - it does not mean, however, that the system does not still rely on environmental conditions, e.g. energy or water. While these environmental conditions are within geomorphology referred to as inputs, within the concept of autopoietic systems they can be externalized. This has the major advantage that it is strictly defined what belongs to a system and what does not. The respective autopoiesis of a system can be utilized not only for the coherent delimitation of systems, but in consequence also for the coherent distinction of systems. Just as life (reproduction of cells) can be considered as unique mode of operation of biological systems, and consciousness as the unique mode of operation of psychic systems (cf. Luhmann 1995b), ice metamorphosis could potentially be considered as the process unique to glacial systems.

On the one hand, we would thus have to re-think currently existing system definitions and the respective boundaries (for example, a human being thus exists of at least two

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8 Note: In contrast to the understanding in geomorphology, within the concept of autopoiesis the environment (or “nature”) itself is not a system, because it does not have a specific (unique) mode of operation. What belongs to a system and what to the environment can only be determined by the system (cf. Egner & v. Elverfeldt 2009). Although the environment can, for example, consist of different systems, these do not act as a unified ‘supersystem’ as the systems do not share the mode of operation.

9 Emphasis has to be laid on the term “operative” in front of closeness. Operative closed systems are inherently different from the traditional closed systems within geomorphology. Operative closeness does not deny the existence of “inputs” or “outputs”, but it externalizes their influences by stating that systems are either adapted to environmental conditions – or not. Thus, “inputs” are a prerequisite, not a determinant. For example, human beings also need sufficient nutrition to stay alive, and this is completely comparable to geomorphic systems which of course are not cut off any material and energy flows. However, neither nutrition nor material and energy flows will ever change the way in which the respective autopoietic system operates.
different autopoietic systems: life (the body) and psychic (the consciousness) which are strongly interrelated, but still indeterminable by each other). On the other hand, we would gain a coherently and comprehensively applicable method for the definition and delineation of systems. However, it has to be emphasized that potential ‘physical’ autopoietic systems as indicated above are first ideas and not fixed results. It represents the state of the art in our discussion and theoretical process, but some doubts do currently remain. For example, the proposed autopoiesis of glaciers, i.e. ice metamorphosis, may be also seen as a combination of different physical processes (nivation, firniation, sintering, and regelation) each of which can be found as single process outside of glaciers – only the combination of the processes is unique to glaciers. But this seems to apply also to the original concept of autopoiesis as proposed by Maturana & Varela (1987), as this also is a complex of processes (of interaction, production, transformation, and destruction) (Zeleny 1980). Hence, this paper is intended as a contribution to a hopefully emerging theoretical discussion within geomorphology, and is not intended to provide results.

As explained in the introducing chapter on observation we can only perceive something if it is distinct from something else – in the case of geomorphic systems, there has to be a difference between the system and its environment. Only through this difference the system becomes discernable. As stated above, within geomorphology this perceived difference is dependent on the expertise of the researcher, her or his school of thought (i.e. which definition she or he applies), the study focus or on common sense, but not on an approach which can be ‘universally’ applied to any geomorphic system. The concept of autopoietic systems offers such a broadly applicable methodology.

The consequences of adapting the concept of autopoieses to geomorphology are manifold (also cf. Egner & Elverfeldt 2009, Elverfeldt 2010):

(1) The role and influence of the environment is sharply diminished, because the environment is only capable of “irritating” the system. These irritations, or “triggers”, are not capable of determining or directing system behaviour, because this information is processed within the system accordingly to its internal structure. Thus, any action of a system depends on the way the specific system is structured in the moment of irritation. Therefore, irritation always means self-irritation. Our previous example on landslides may help clarify this aspect: The plot shows that a slope may not react to one or more heavy rainfall events, but some years later it might react to a comparatively smaller event and fail. Geomorphologists usually explain this observation with a threshold which has been reached, for example due to weathering, and which has increased slope instability (cf. Fig. 5). Thus, this shows how a system which is determined by its inner structure processes information of its environment and cannot be regarded as being determined by environmental factors. So far, geomorphologists often refer to the changing susceptibility of the slope which tends in the same direc-

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10 It has to be stressed that this is a mere didactical example. It does not imply that a slope is an autopoietic system, as (at least to the authors) the specific process (mode of operation) which is unique to slopes has not (yet) been determined.
tion of limited external influence. However, there is no theoretical framework which supports these findings, and this framework is offered by the concept of autopoiesis (and/or self-organisation, cf. Elverfeldt 2010).

(2) The observation of systems is facilitated: The focus can be laid on congruently defined specific systems, with their structure, processes and functioning.

(3) Reduction of complexity: The (self-) creation of a system implies a reduction of complexity as a system creates order, because the system is always less complex than its environment (cf. Egner 2008b). Additionally, the observer can focus on a system which stays the same irrespective of the changing respective study focus. Thus, environment always stays environment and system stays system, and the coupling in-between the two can congruently be focussed.

6 Conclusions

In the previous chapters we focussed on the challenges of geomorphic systems theory and offered first thoughts on autopoiesis, self-reference and operative closeness in geomorphic systems as a basis for further discussions. What would be the advantages of such a view on systems?

Firstly, the delineation of systems would follow a coherent principle, i.e. the (self-)delineation of systems via a system-specific process which can only be found within the respective system. Secondly, autopoiesis, self-reference and operative closeness are strikingly minimizing the (determining) influence of the environment on geomorphic systems as inputs and outputs are externalized as pre-requisite for the existence of the respective system. As this perceived determination can be seen as one of the biggest challenges of contemporary geomorphic research (because it forces us to perceive the world as an interconnected ‘whole’ where everything depends on everything else) autopoiesis and the related concepts offer a completely new perspective: The environment can by no means determine systems behaviour. Actions can be triggered, but it is the system which determines itself if, how, and when it acts whenever it processes information from the environment through its structure. In consequence, our research focus would be directed towards inner-systemic processes instead of studying the behaviour of single elements and/or the ‘metabolism’ of a system.

Equilibria are non-existent in the concept of autopoietic systems. Furthermore, the concept of autopoiesis inherently acknowledges circular processes which prohibit cause-and-effect relationships and thus automatically accounts for non-linearity. Of course, with its focus on the difference between a system and its environment and on the unique mode of operation, the concept of autopoietic systems also is reductionistic. Concluding from Foerster’s theory of observation, this cannot be avoided, because any observation generates blind spots, i.e. certain aspects are not considered and reality is thus always reduced. However, the kind of reductionism and the awareness of it can be chosen.
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