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State of Science

Thresholds, mode switching, and emergent equilibrium in geomorphic systems

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ABSTRACT: Landform and landscape evolution may be convergent, whereby initial differences and irregularities are (on average) reduced and smoothed, or divergent, with increasing variation and irregularity. Convergent and divergent evolution are directly related to dynamical (in)stability. Unstable interactions among geomorphic system components tend to dominate in earlier stages of development, while stable limits often become dominant in later stages. This results in mode switching, from unstable, divergent to stable, convergent development. Divergent-to-convergent mode switches emerge from a common structure in many geomorphic systems: mutually reinforcing or competitive interrelationships among system components, and negative self-effects limiting individual components. When the interactions between components are dominant, divergent evolution occurs. As threshold limits to divergent development are approached, self-limiting effects become more important, triggering a switch to convergence. The mode shift is an emergent phenomenon, arising from basic principles of threshold modulation and gradient selection. As an example, the relationships among flow concentration, erosive force, and channel incision in fluvial systems are examined in the context of mode switching and thresholds. The commonly observed divergence in channel growth and fluvial dissection and network development, eventually transitioning to a stable, convergent configuration, is an emergent outcome of gradient selection and threshold modification, and does not imply any goal functions of balancing mass fluxes or limiting change. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: thresholds; mode switching; divergent evolution; convergent evolution; emergence; geomorphic systems

Introduction

Convergent and divergent development are fundamentally different modes of evolution in Earth surface systems. Convergence results in decreasing amplitudes of variations, increasing isotropy, and progress towards more spatial uniformity. Examples include topographic evolution involving decreasing relief; pedogenesis towards zonal, mature, or climax forms; and weathering processes that lead to smoothing of rough, irregular rock surfaces. Divergence, by contrast, involves an increase in average amplitudes of variations, exaggeration of initial differences, and increasing spatial variability. Examples include relief-increasing topographic evolution, erosional dissection of initially more uniform surfaces, and diversification of soils and regoliths over time. The purpose of this essay is to develop, propose, and test some general principles for the prevalence of divergent or convergent evolution in geomorphic systems, and shifts between the two. Steady-state, with no net convergence or divergence, may also occur in some geomorphic systems. Steady-state is, like convergence, associated with dynamical stability, or is a transient condition. Further, convergent development is often assumed to be toward a steady-state condition. Thus for purposes of this paper steady-state will be lumped with convergence.

Discussions over divergent vs. convergent evolution are perhaps as old as geomorphology itself, as evidenced by the classic debates on the increase or decrease of relief during topographic evolution. However, these problems have rarely been expressed explicitly in terms of convergence/divergence or similar language. An exception is Johnson and Watson-Stegner (1987) and Johnson *et al*. (1990), who (drawing on Hole, 1961) distinguished between proisotropic and proanisotropic processes of pedogenesis, and assigned the associated progressive and regressive pedogenetic pathways comparable significance in soil and landscape evolution. This was significant in large measure because soil geomorphologists and pedologists had traditionally viewed progressive, proanisotropic pathways as 'normal,' and regressive, proisotropic pathways as unusual disturbances or aberrations from the norm. Scheidegger's (1983) instability principle of geomorphology recognized that increasing variability and irregularity over time (as opposed to inevitable convergence or steady-state) is common, and other studies showed that divergent, relief-increasing forms of topographic evolution may occur even with no tectonic uplift (Twidale, 1991; Gunnell and Louchet, 2000). From the 1990s onward, a number of studies of deterministic chaos, dynamical instability, and other forms of nonlinear complexity in geomorphic systems showed that divergent development occurs frequently in a variety of geomorphic phenomena, and at a range of spatial and temporal scales (reviews by Phillips, 1999, 2006; Sivakumar, 2000, 2009; Elverfeldt, 2012).

The definition of convergence and divergence in geomorphology can be expanded as suggested in Table I. That is, they can be defined or conceptualized with respect to the statistical variance of a key indicator such as elevation or aspect; the general spatial heterogeneity of the landscapes (e.g. soil cover, landform types); and the presence of single vs. multiple possible end-states or developmental pathways. Thus, decreasing variability of regolith thickness, increasing homogeneity of hydraulic or geomorphic units along a river, and observed or hypothesized progression towards a particular slope profile geometry are all examples of convergent evolution. Likewise, increasing variance of regolith thickness or heterogeneity of streamwise geomorphic units, and development of more than one stable slope form, are all examples of divergence.

Many conceptual models of convergent development have been (and continue to be) highly influential, and have enjoyed near-canonical status. These include steady-state equilibrium theories in fluvial and soil geomorphology; Davisian downwasting; soil development toward mature, zonal, or climax soils; and ecological succession of vegetation communities. By contrast, other conceptual frameworks based on evolutionary concepts analogous to Darwinian biological evolution lead to predictions (or at least possibilities) of increasing divergence over time (cf. Ollier, 1979; Thornes, 1983; Johnson and Watson-Stegner, 1987; Huggett, 1995, 1997; Phillips, 2006, 2007).

Both divergent and convergent pathways are common in real landscapes – sometimes occurring simultaneously in very similar landscapes, and sometimes during different periods in the same landscape. Given that divergence and convergence have fundamentally different implications for interpreting and predicting geomorphic forms, processes, histories, and trajectories – and for resource management and restoration – it seems worthwhile to investigate general principles or tendencies that govern or influence these pathways.

Geomorphic Systems

To illustrate the role of positive and negative feedbacks, consider the simplest and most general possible geomorphic system, consisting of two components, *X1* and *X2*. These are linked by feedback relationships, a_{12}, a_{21}, representing the positive or negative influence of *X1* on *X2*, and vice versa. Self-effects (a_{11}, a_{22}) reflect self-limiting or self-reinforcing properties of the components. Positive relationships, e.g. $a_{12} > 0$, indicate that a change in *X1* results in a change in *X2* in the same direction. Thus, for instance, an increase or decrease in the frequency of overbank flooding in an alluvial river leads to a corresponding increase or decrease in vertical floodplain accretion rates. Negative relationships, e.g. $a_{12} < 0$, show change in *X1* leads to a change in *X2* in the opposite direction. For example, a reduction in vegetation cover might result in an increase in soil erosion, and vice versa.

Earth surface systems may include components with positive self-effects, but negative self-effects are more common, and often reflect threshold modulation and/or inherent limits on development. For example, fluvial incision is limited by base level, chemical weathering is limited by depletion of weatherable minerals, and filling of sedimentary basins is limited by accommodation space. We consider here only cases where $a_{11}, a_{22} < 0$.

With negative self-effects, if a_{12}, a_{21} have opposite signs the system is stable, and development is convergent. For instance, weathering at the bedrock interface positively influences regolith thickness, while in many situations thicker regolith cover reduces the weathering rate. If these are the only significant factors influencing thickness and weathering (and both are self-limiting), then the system is stable, converging on a steady-state regolith thickness. This is indeed the conceptual basis of many models of soil, regolith, and landscape evolution (Braun *et al*., 2001; Furbish and Fagherazzi, 2001; Riebe *et al*., 2004; Saco *et al*., 2006; Burke *et al*., 2009; Dixon *et al*., 2009; Gabet and Mudd, 2009; Phillips, 2010; Fu *et al*., 2011).

Interactions are often mutually reinforcing ($a_{12}, a_{21} > 0$) or mutually damping ($a_{12}, a_{21} < 0$). In either of those cases the system is unstable if the interactions (a_{12}, a_{21}) are stronger than the self-effects, and stable if the self-effects prevail. If regolith thickness promotes weathering (i.e. has a positive relationship), as sometimes occurs with relatively thin covers, then there is no convergence to a single steady-state thickness. Rather, the system is unstable to disturbances, and may experience pseudo-random changes in regolith thickness anywhere between zero and the threshold at which thickness inhibits rather than promotes bedrock weathering (Furbish and Fagherazzi, 2001; Phillips, 2010).

The stability conditions described above are based on the Routh–Hurwitz criteria, where the necessary and sufficient conditions for dynamical stability are $F1, F2 < 0$, where

$$F1 = a_{11} + a_{22} \tag{1}$$

$$F2 = a_{12}\ a_{21} - a_{11}\ a_{22} \tag{2}$$

Convergence and divergence

The representation of geomorphic systems above can be generalized to n components x_i, $i = 1, 2, \ldots, n$, such that

$$dx_i/dt = f(d\mathbf{x}/dt) \tag{3}$$

with $\boldsymbol{x}$ indicating a vector of all x_i. The system state at time t of this set of coupled nonlinear dynamical equations is given by

$$\boldsymbol{x}(t) = \boldsymbol{C}\ \boldsymbol{x}(o)e^{\lambda} \tag{4}$$

Table I. Examples of convergent and divergent evolution in geomorphology

Phenomenon	Convergent evolution	Divergent evolution	Convergent example	Divergent example
Statistical variance of key indicator variable	Decreasing	Increasing	Decreasing variability of regolith thickness	Increasing variability of regolith thickness
Spatial heterogeneity	Decreasing	Increasing	Transition from patchy spatial mosaic of geomorphic units to more uniform distribution	Increasing patchiness of geomorphic units
Attractors, end-states, or stable states	Single	Multiple	Smoothly concave river longitudinal profile	River profiles of varying concavity/convexity

where the bold terms are all vector quantities. $\boldsymbol{C}$ represents the constants for the n equations of the system, $\boldsymbol{x}(o)$ represents the initial conditions, and $\boldsymbol{\lambda}$ are the n Lyapunov exponents of the dynamical system, $\lambda_1 > \lambda_2 > ..\lambda_v$ The system is dynamically stable if and only if all $\lambda_i < 0$. Thus $\lambda_1 > 0$ is a necessary and sufficient condition for instability; and $\lambda_1 > 0$ for stability.

The relationship between in(stability) and convergence/divergence can be illustrated by considering the mean difference of randomly selected points or locations within the landscape represented by the geomorphic system with respect to some indicator of system state (e.g. elevation, sediment thickness, water table elevation, etc.). The mean separation or difference at time t is

$$\delta(t) = C \ e^{\lambda_1} t \tag{5}$$

where C indicates the initial separation. This can be rewritten as

$$\lambda_1 = ln \ \delta(t) – lnC \tag{6}$$

Rosenstein *et al.* (1993) used Equation (6) as the basis for determining the largest Lyapunov exponent from empirical data, and Phillips (2006) reviewed the use of this approach in geomorphology. The relationship between the increasing or decreasing (mean) differences over time is also the basis for the relationship between Kolmogorov entropy and the Lyapunov exponents (Oono, 1978; Culling, 1988).

Equation (6) shows how dynamical stability, indicated by λ_1 is directly related to the convergence or divergence of the system as reflected in the mean difference or separation. Thus, for example, if elevation is the variable of interest, during relief-increasing evolution the mean elevation difference between randomly selected locations in the landscape is increasing, and λ_1 in Equation (6) is positive. Downwasting, by contrast, leads to a decrease in the mean elevation difference and $\lambda_1 < 0$. At steady-state, $\lambda_1 = 0$.

Mode switching

The analysis above shows that a given system characterized by mutually reinforcing or competitive interactions will be dynamically unstable if the interactions between system components are dominant (i.e. $a_{12}\ a_{21} > a_{11}\ a_{22}$), and stable if/when the self-limiting effects become dominant. This also applies to larger ($n > 2$) systems where stability is contingent on the relative strength of negative self-effects ($a_{ii} < 0$) versus loops representing interactions between system components ($a_{ij}\ ...\ a_{ji}$).

Commonly (though by no means always) the mutual interactions are predominant during earlier stages of geomorphic system development, and the self-effects in later stages – not least because the latter often represent thresholds or limits in the development of a system component. This results in the phenomenon of mode switching, with unstable divergent evolution until the limits of one or more components are approached, whereupon there is a switch to a stable, convergent (or at least non-divergent) mode. Several examples are given below.

During fluvial dissection of a plateau, mutually reinforcing relationships between weathering and erosion may be dominant initially, resulting in divergent, relief-increasing topographic development. Eroding valleys collect ever more runoff and shear stress, and increasingly expose fresh rock to weathering (maximum weathering may occur either with bare rock or under a minimum critical regolith cover, depending on the situation). However, eventually fluvial incision approaches local base levels, and/or factors other than exposure limit weathering rates. Then a switch to a convergent mode may occur, with subsequent relief reduction. Phillips (2005) indicated this sequence of events for the Cumberland Plateau, Kentucky, with local base level control of fluvial incision the main factor triggering the switch to convergent evolution. The same mode-switch is implied wherever there is evidence of transition from so-called youthful stages of increasing relief to mature and old age stages of declining relief (Figure 1). While this terminology is from the long out-of-favor cycle of erosion model of WM Davis (1902, 1909), the validity of denudation chronologies indicating a change from relief-increasing (youthful) to relief-declining (mature) topography is not contingent on the cyclical interpretation, provided the evidence justifies the interpretation (Penck, 1924; Brunsden, 1963; Summerfield, 1991; Ollier and Pain, 2000; Twidale and Campbell, 2005).

Another example concerns chemical weathering at the scale of a pedon or weathering profile, as shown in Figure 2. Initial variations in weathering susceptibility (due to structure, lithology, mineralogy, microtopography) are often exaggerated due to positive feedbacks (Torrent and Nettleton, 1978; Nahon, 1991; Twidale, 1991, 1993; Pope *et al.*, 1995; Taylor and Blum, 1995; Turkington and Phillips, 2004). This divergent evolution enhances the weathering contrast until weatherable minerals are depleted in the more rapidly weathered zones, and geochemical kinetics rather than moisture availability becomes the major control on weathering rates. This switch to a self-limit results in eventual convergence of weathering rates and the degree of weathering. In addition to the examples above, Phillips (2001, 2005) explicitly analyzed this phenomenon in the context of dynamical stability.

An example involving competitive, negative relationships rather than mutual positive feedback is the interaction between erosion and vegetation cover first explored in a dynamical systems context by Thornes (1985). Vegetation cover inhibits soil erosion, and vice versa. The relationship is dynamically unstable, so that small changes in either soil loss or plant cover result in a shift to one of two stable states: completely eroded with little or no vegetation, or maximum vegetation cover with no erosion (Thornes, 1985). In the first two examples above the divergent phase is characterized by increasing variance and heterogeneity with respect to, for example, topography or weathering state, and the convergent phase with decreasing trends. In the third the switch is from divergent potential development in at least two directions (vegetation cover or denuded, eroded surface) to convergence toward a single state.

It is tempting to attribute mode switches to faster-to-slower transitions that occur due to deceleration of geomorphic system response to perturbations, and to depletion effects – that is, as potential energy, weatherable minerals, transportable material, etc. is depleted, rates of change may slow. These decelerations are indeed common, and frequently occur in conjunction with some of the phenomena described above. However, the convergent stage is not necessarily slower than the divergent mode. An example is the phenomenon of karst breakthrough (Gabrovšek and Dreybrodt, 2001; Dreybrodt and Gabrovšek, 2002). Early in the development of karst conduits, interactions among water flow, dissolution rates, dissolved calcium concentrations, and rock fissure dimensions are dominant. These produce slow solutional widening as a propagating front along the fracture, and divergent evolution in the form of differential widening. At breakthrough (dissolutional widening of the fissure reaches the outlet) both flow rates and dissolution increase rapidly, and further widening is more-or-less constant along the fissure (convergence). At breakthrough, the rate of dissolution kinetics (a self-limiting effect) becomes the limiting

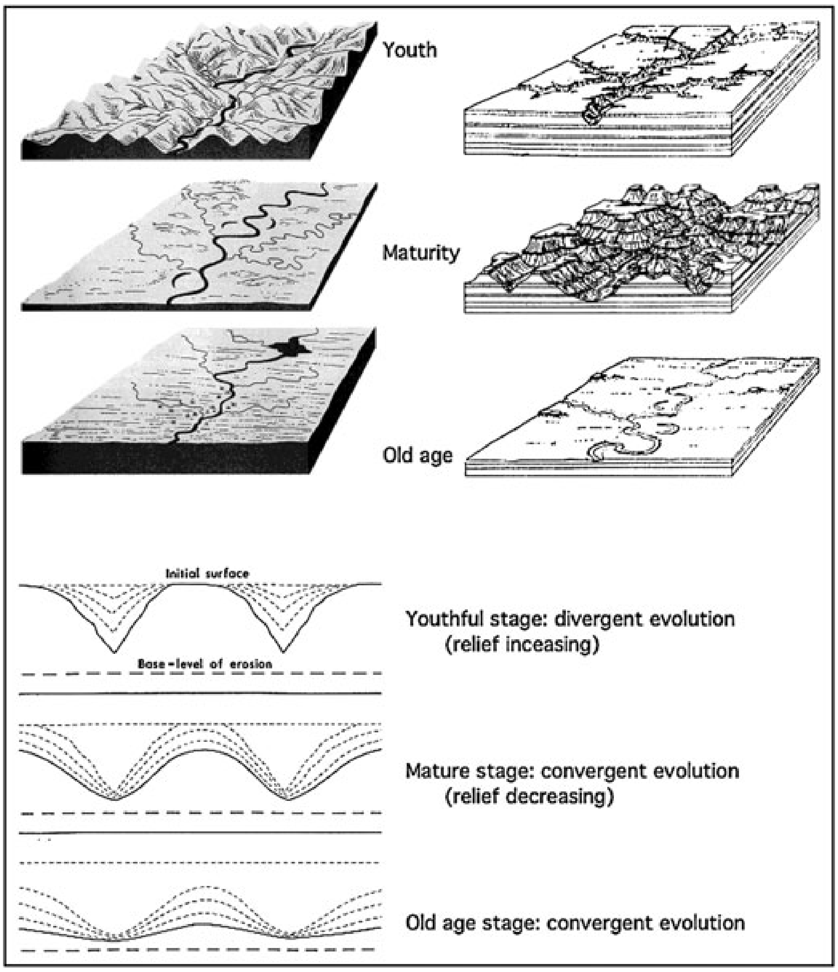

Figure 1. Three different graphical depictions of the youthful, mature, and old age stages of W.M. Davis' cycle of erosion. The diagrams are adapted from the Association of Polish Geomorphologists (http://www.staff.amu.edu.pl/~sgp/gw/wmd/wmdfig.html) which are in turn based on Davis' published drawings.

factor, rather than flow rates, determined by the interactions among system components. Thus in this case the divergent-to-convergent mode switch involves an increase rather than a decrease in rates of change.

An almost *de rigueur* caveat in many geomorphological studies is the issue of scale dependence, and the study of mode switches is no exception. That is, whether a particular phenomenon is (or is observed or perceived as) convergent or divergent may depend on the spatial scale. Thornes (1985), for example, showed that the competitive relationship between vegetation cover and soil erosion in semi-arid areas leads to a tipping of the unstable system to a bare, eroded, unvegetated state or to a fully vegetated, noneroding state. Once established, these tend to be stable, as factors other than erosion and plant cover become the primary controls. Subsequent work, however, shows that these unstable transitions generally occur at a local, patch scale, resulting in an increasingly divergent mosaic of vegetated, fertile 'islands' in a 'sea' of bare, eroded soil. Thus convergence at the patch scale is often associated with divergence at the landscape scale. This also applies to karst example above – what is convergent at the scale of an individual solutional feature could be viewed as divergent at the landscape scale, as the larger conduits grow at the expense of the dissolution of the rest of the rock body.

Switches from divergent to convergent modes could be – and have been – interpreted in terms of stages in a cycle or as progress towards some (often loosely defined) 'equilibrium' state. Davis' cycle of erosion, for one well-known example, involves a divergent, relief-increasing youth stage switching to convergent stages with declining relief (Davis, 1902, 1909). Geomorphic responses to change or disturbance are always finite, and often decelerate as threshold moderated limits are approached, resulting in the phenomenon of relaxation time equilibrium (RTE; Phillips, 2009). RTE is much more akin to a falling rock coming to rest or a clock running down than to any sort of tendency towards steady-state or balance.

Fluvial Channel Evolution

Geomorphologists have long studied the evolution of fluvial channels and channel networks (Abrahams, 1984). These phenomena, though researched from multiple perspectives, have often been viewed in terms of channel or network development proceeding until a steady-state is reached between sediment production and transport or between typical flows and channel conveyance capacity, or until there is an approximate match between surface runoff to be drained and the capacity of networks to drain it (see reviews and syntheses by Abrahams, 1984; Jones, 1987; and Rinaldo *et al*., 1998). This assumption is evident in recent and contemporary work as well (Moglen *et al*., 1998; Rinaldo *et al*., 1998; Bledsoe *et al*., 2002; Collins and Bras, 2010; Solyom, 2011; Hawley *et al*., 2012). Here we explore an alternative possibility, not necessarily antithetical to these notions in terms of predictions about system evolution, but attributing the latter to emergent properties rather than progress toward a normative equilibrium state.

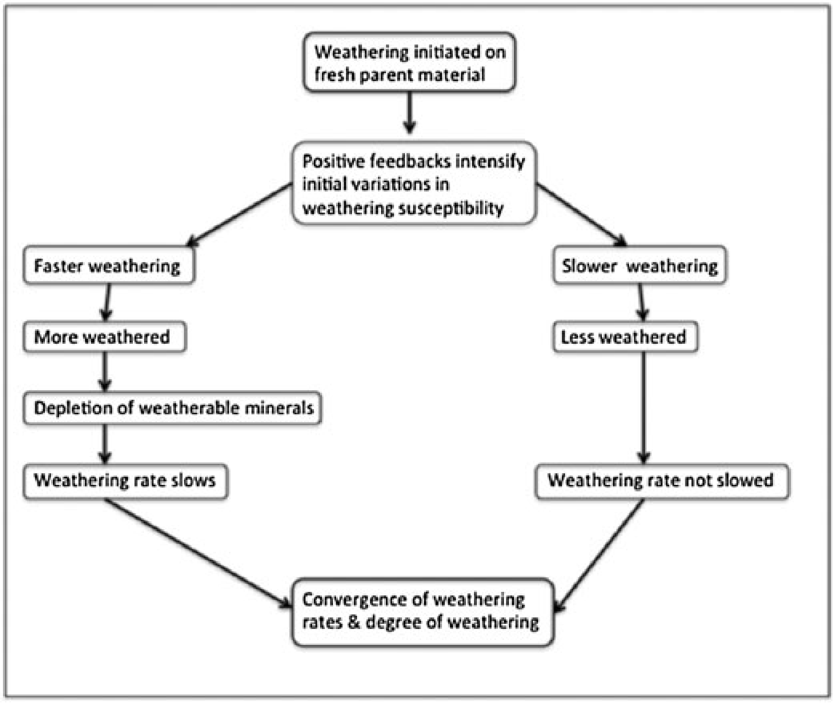

Figure 2. Divergent and convergent evolution in chemical weathering.

Consider the relationships between surface runoff concentration, shear stress, and fluvial erosion, as shown in Figure 3. The interactions between system components are all positive. Runoff convergence increases mean depth (hydraulic radius), and thus increases shear stress. Convergence also increases mean velocity and stream power. Assuming that thresholds of erosion and transport are at least occasionally exceeded, increased shear stress (and stream power) promotes fluvial erosion. Where this erosion incises channels, the channels further promote flow concentration.

The positive feedback cycle of fluvial channel incision, flow convergence, and shear stress cannot continue indefinitely, however. All three components have important negative self-effects or inherent limits. Depth and velocity of converging flow is ultimately limited by a finite supply of effective precipitation and by constraints imposed by slope and flow resistance. Shear stress is a function of slope as well as depth, and is limited by the former, as well as by finite water input. Fluvial downcutting, even if not limited by resistant layers encountered during incision, cannot continue much below the local base level. The phenomenology of this generalized model is consistent with more specific models of drainage evolution (Tarboton *et al.*, 1992; Hancock and Willgoose, 2003; Solyom, 2011).

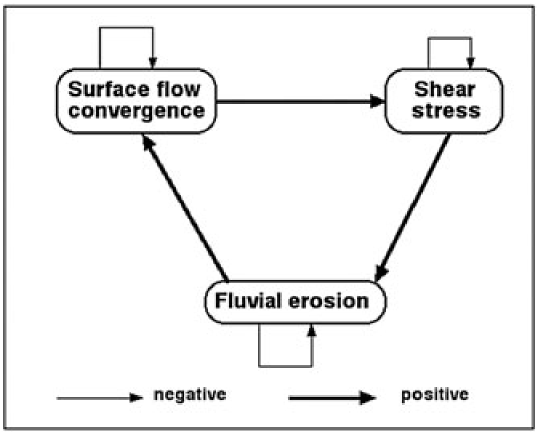

Figure 3. Interactions among flow convergence, shear stress, and erosion. See text for explanation.

The positive interactions in Figure 3 will be dominant, and the system unstable and divergent, in situations where the channels are well above local base level, in the earlier stages of channel and network development (i.e. where limits of maximum drainage density are not yet approached), where shear stress > shear strength (i.e. erosion thresholds are sometimes exceeded), and where moisture supply is not climatically limited. The negative limitations will prevail, and the system will be stable when and where fluvial incision is approaching base level, in later stages of channel and network development, if shear stress is less than critical thresholds, and where moisture supply is climatically limited. The stable phase may be associated with convergent development of drainage basin topography, or with steady-state.

Thus the initiation of channels – and subsequently networks – in humid climates on erodible materials should typically be marked by a divergent period of channel enlargement and network extension, followed by a phase of stable dimensions and extent, with possible periods or episodes of channel infilling. This is exactly the trend often observed in experimental studies, inferred from the geologic record, and occasionally directly observed in the field in rapidly-developing channel systems (Schumm, 1956; Howard, 1997; Pelletier, 1999; Manville, 2002; Wallace *et al.*, 2005; Yue *et al.*, 2007; Vandenbruwaene *et al.*, 2012).

The emergent perspective views the stable phase not in terms of any physical necessity to progress toward a balance between fluvial morphology and material fluxes, but rather as an emergent outcome of system relationships that lead to divergent-to-stable mode switching. The difference perhaps matters little with respect to predictions of fluvial development, as the outcome is independent of an emergent view vs. a notion of balance. The difference is significant, however, if the question is *why* the steady-state or convergent phase occurs. The idea that geomorphic systems seek to achieve some form of balance or stability is fundamentally different from that of a switch in dominance from mutually reinforcing (in the example above) or mutually limiting interrelationships to threshold limits in the development of system components. Fundamentally, the first implies that divergent development is a precursor to inevitable steady-state or convergence, or the result of disturbance or abnormality. The emergent view sees convergence and steady-state as common emergent outcomes, but does not see divergence as (necessarily) a precursor stage or as a result of disturbance.

As discussed in more detail elsewhere (Phillips, 2011) the emergent behavior arises from basic principles of gradient selection and threshold-mediated modulation. Mass and energy fluxes occur along the steepest gradients of concentrations or potentials. The principle of gradient selection is simply that geomorphic features associated with these gradients tend to persist and grow. The related principle of resistance selection is that features that are more resistant relative to applied forces or drivers of change are selected for preservation, while less resistant components are preferentially modified or removed. Gradient selection for water flow results in flows along paths of least resistance, and selection of concentrated vs. diffuse flow paths.

As channels develop they often bifurcate or intersect, prompting development of branching flow networks. Branching networks are favored by hydraulic selection, because these represent the optimum means for simultaneously maximizing total energy dissipation in a fluid flow system and equalizing total energy expenditure within the system (Woldenberg, 1969; Kirkby, 1971; Woldenberg and Horsfield, 1986; Rodriguez-Iturbe and Rinaldo, 1997). As long as the force of flow at least occasionally exceeds the resistance of the substrate, these networks tend to grow in total length. Gradient selection principles thus explain why surface redistribution of excess moisture typically takes the form of branching channel networks that grow over time (until limited by ability to erode the substrate).

The principle of threshold-mediated modulation (TMM; Phillips, 2011) states that thresholds limit development as either positive or negative mass balances increase, and that exceeding the threshold may initiate development in the opposite direction. TMM also applies to trends of aggregation or disaggregation (i.e. concentration or dispersion) of fluxes. With respect to the fluvial system as outlined above, TMM may occur in several different ways. As channel networks expand and drainage density increases, a threshold is reached regarding the minimum flows required to maintain channels (given a finite moisture supply), limiting expansion beyond this point. Within a given region, stream power necessary for channel incision depends on runoff production (a function of drainage area) and slope. As drainage areas per unit channel become smaller, the threshold necessary for incision may be transgressed, limiting channel network growth. Downcutting is ultimately limited by local base level, and channel size by thresholds associated with critical bank heights or width/depth ratios.

The divergence of channel growth and fluvial dissection and network development, eventually transitioning to a stable, convergent or steady-state configuration, can therefore be viewed as an emergent outcome of gradient selection and threshold modification, with no need to invoke any tendency toward tuning transport capacity to sediment supply or other forms of presumed balance.

Mode Switching and Emergence

As in the example above, mode switching from divergent to non-divergent development is an emergent property of many geomorphic systems. This is only a tendency; not a law or universal principle (though the importance of gradient selection and threshold modulation may be more general). The emergent behavior arises from (1) a common (but not universal) structure of geomorphic systems, involving mutually-reinforcing or competitive loops between system elements, and negative self effects associated with threshold limits, plus (2) a tendency for self-effects to increase in relative importance in later stages of a developmental pathway.

The divergent-to-convergent transition also depends on our tendency to view periods of rapid change or geomorphic divergence as starting points. This is partly an inevitable byproduct of studying how geomorphic systems respond to changes and disturbance. Landforms and landscapes undergo constant (or at least chronic and repeated) change, however, and convergent modes of development are also inherently limited. More-or-less homogeneous systems resulting from extended periods of convergent evolution can transition to divergent development by clock-resetting events such as tectonic uplift or subsidence, major climate changes, or catastrophic hydrological, meteorological, or biological events. Smaller, localized disturbances can also precipitate divergence due to unstable growth of disturbance effects. A pattern of mode switching in both directions is a more accurate long-term view of geomorphic systems, with the switches accompanying shifts in the relative importance of interactions between system components (mainly associated with gradient selection) and self-limits (largely attributable to threshold modulations).

To what extent does an emergent view of convergence and divergence differ from existing interpretations? Both the perspective of mode switches and other existing views are likely to predict the same general outcomes in many cases, and unlikely to differ with respect to the key processes and environmental controls. The epistemological and ontological differences may be profound, however, and the different meanings and interpretations attached to the same phenomena may make crucial differences in both theoretical and applied geomorphology.

Consider three interpretations of a shift from relief-increasing topographic evolution to downwasting, recognizing that a number of implicit or explicit assumptions about, for example, spatial and temporal scale, boundary conditions, etc., would also influence interpretations. A Davisian cycle-of-erosion viewpoint sees this as an inevitable stage in a cycle, leading ultimately to a peneplain, which will presumably remain until another episode of uplift occurs. Varieties of 'dynamic equilibrium' or steady-state perspectives lead to interpretations of progress toward a characteristic equilibrium form, or the seeking of a new steady-state topography or mass flux following a change in boundary conditions. The perspective in this paper views the switch as the result of a change in dominance from interactions among system components to inherent limits on the development of those components. In the absence of changes in boundary conditions, the mode-switch view would predict the downwasting to continue until threshold limits are reached, with a possible transition to a new divergent trend. Thus, while the observations are readily accommodated in all three perspectives, the long-term predictions differ completely.

Fundamentally, the way we understand these mode switches also profoundly influences applied geomorphology and environmental management. If steady-state or convergent, stable modes are viewed as a goal function of geomorphic systems rather than an emergent happenstance, then unstable, divergent modes may be viewed as atypical episodes in geomorphic history, or as aberrant, undesirable conditions from a management perspective – even though the latter may be in many cases as common and 'normal' as stability and convergence. An additional management/perception issue with a view of convergence as a normative behavior and divergence as aberrant is that divergent evolution may produce ecological and societal benefits such as greater geodiversity, and associated biodiversity and habitat variety. If the importance or normality of divergent vs. convergent modes is based on their relative frequency of occurrence and duration, those in turn depend on the time spans of dynamically unstable or stable development. For example, for how long is a channel network expanding, as opposed to a period of stability or contraction? The latter will depend in turn on the occurrence of clock-resetting environmental change, or localized disturbances – or even on what happens to be occurring during a period of observation or a time span for which information or inferences are available.

The term 'goal function' is used here as a shorthand here for perspectives that assume, hypothesize, or standardize progression toward a single, stable end-point or idealized condition, and does not imply teleology. The term thus includes notions of development toward, e.g. climax vegetation communities or soil types, characteristic (variously defined) equilibrium forms, critical states, or steady-states.

The idea of goal functions includes classic cyclical ideas in geomorphology and notions of optimality, but is not restricted to these, and does not necessarily imply adherence to any cyclical or optimal concepts. For example, the assumption of steady-state topography is an implicit goal function in many studies of the evolution of mountain belts and features within them (Montgomery, 2001; Whipple, 2001; Willett and Brandon, 2002; Stolar *et al.*, 2007; Cheng *et al.*, 2012; Roden-Tice *et al.*, 2012). Many of these authors acknowledge the limitations of the concept, the rarity of demonstrated steady-state at all but the broadest scales, and the limited conditions under which topographic steady-states may occur. Still, the condition of constant elevation due to the achievement of an approximate balance between rates of uplift and denudational lowering is the assumed condition the system will evolve toward, given enough time and limited disturbance or change in boundary conditions.

If the steady-state goal function is treated strictly as a simplifying assumption or constraint for modeling or analytical purposes (as it indeed often is, though more often implicitly than explicitly), there are not *necessarily* any strong implications for field interpretations or conceptual frameworks of landscape and landform evolution. Also note that the literal existence of steady-state topography is not necessary for the utility of the concept as a model constraint or benchmark condition. If, on the other hand, topographic steady-state is treated as a truth statement on the way geomorphic systems function, the ontological and epistemological implications are significant.

This type of implicit goal function is common in contemporary geosciences. Another example is the assertion that soil or regolith thickness evolves toward a steady-state where surface removals are balanced by weathering additions at the weathering front (Braun *et al.*, 2001; Furbish and Fagherazzi, 2001; Riebe *et al.*, 2004; Saco *et al.*, 2006; Burke *et al.*, 2009; Dixon *et al.*, 2009; Gabet and Mudd, 2009; Fu *et al.*, 2011). This has previously been discussed with respect to the practical, epistemological and ontological issues above by Phillips (2010) and Dethier *et al.* (2012).

The emergent interpretation also has important implications for the study of geomorphic system evolution. It implies, for example, that predicting the eventual end of a divergent episode should not be based on how some sort of steady-state or adjusted, equilibrated condition can be reached, but rather on the point at which thresholds and limits come into play. The latter is hardly without difficulties, but seems a much more tractable problem.

Finally, at least thinking about geomorphic systems in terms of emergent behavior or other alternatives to goal functions such as steady-state is consistent with broader conversations in the sciences. These include debates over succession, assembly, and multiple stable states in ecology, and the role of goal functions in evolution of ecosystems and biospheres (cf. Fath *et al.*, 2001; Lapenis, 2002; Reynolds, 2002; Huggett, 2006; Volk and Pauluis, 2010). An emergent approach may also facilitate studies of coevolution of landforms and climate. Recent and contemporary studies of climate history and evolution present a straightforward (if often complex, incomplete, and sometimes contradictory) picture of climate as an entity in continuous flux at a variety of scales (Huggett, 2006; Cronin, 2009; Uriarte, 2011). Climate history is rife with mode-switches (for example, glacials and interglacials). Climate states are constrained by thresholds and limits, and process dynamics are governed by universal laws of physics and chemistry. However, other than an acknowledged human value-based preference for conditions characteristic of the late Holocene, climatology is not otherwise burdened by normative notions of climate goal functions (i.e. there is no assumption of any single state toward which climate tends). The emergent perspective suggests that this is an appropriate mindset for geomorphology as well.

Conclusions

Many geomorphic systems are characterized by a structure typified by mutually reinforcing or competitive interrelationships among system components and negative self-effects. In many cases unstable interactions among geomorphic system components tend to dominate in earlier stages of development, while stable limits often become dominant in later stages. This results in mode switching, from unstable, divergent to stable, convergent development. The shift to convergence in such systems is an emergent property arising from basic principles of threshold modulation and gradient selection. The mode shift is a type of emergent equilibrium (or perhaps pseudo-equilibrium), and does not imply or require any inherent tendency toward steady-state or other specific conditions.

The relationships among flow concentration, erosive force, and channel incision in fluvial systems is one of many geomorphic phenomena exhibiting mode switching and emergent pseudo-equilibrium. The commonly observed divergence in channel growth and fluvial dissection and network development, eventually transitioning to a stable, convergent configuration, is an emergent outcome of gradient selection and threshold modification, and does not imply any goal functions of balancing mass fluxes.

The perspective outlined here differs from other approaches mainly with respect to interpreting the meaning of geomorphic changes and evolution, rather than 'what' and 'how' questions. However, the interpretative differences are critical for contextualizing specific results relative to landscape and Earth system evolution and Earth surface system behaviors, integrating geomorphology with related sciences, and evaluating environmental changes in a management context.

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