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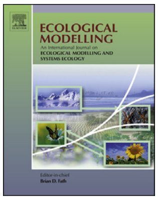

What we see now: Event-persistence and the predictability of hydro-eco-geomorphological systems

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ABSTRACT

What we see now in the landscape is the result of a long history of events with varying degrees of persistence. We have only limited access to much of that history and we know that many current events have only a minimal impact on what we see. Even rather extreme events may have impacts that are not very long-lasting but can have the effect of changing the antecedent states for future events. That means that sampling of sequences of events might be important in understanding the evolution of the catchments. In some cases, however, extreme events can have an impact on the system that persists over hundreds or thousands of years. Any evolution of the landscape is then constrained by those past events, however much it might be also constrained by self-organisational principles. It might be difficult to verify those principles given the epistemic uncertainties about past histories and system properties that are generic to the studies that are possible within a research project or career. These arguments are investigated in a simple slab model of landslip failures in a hillslope hollow subject to stochastic forcing over long periods of time. The complementarity of an event-persistence approach to hydro-eco-geomorphological systems is captured in suggestions for future research questions.

1. Introduction

Landscapes are structured. They show spatial organisation that is the result of their development over time. In that landscapes are open systems, with a throughput of mass and energy, that development is necessarily evolutionary, even if certain aspects of pattern and form might appear (at least for certain periods of time) to be in some steady or quasi-equilibrium state consistent with the distribution of external forcing. That external forcing has, for much of geological time, been due to natural agents but in the anthropocene, man has had an increasing influence on both process and pattern in the landscape. Until the anthropocene, the landscape was, necessarily, self-organising in ways that have led to some general emerging patterns (climatic zones, river basins, natural vegetation patterns) but now there is a co-evolution of man and the landscape that leads to new emergent structures (and subjects of research as reflected in the concept of ecohydrology, sociohydrology and the new IAHS Panta Rhei decadal programme; Sivapalan et al., 2012; Montanari et al., 2013; Ehret et al., 2013; Lane, 2014).

The landscape we see now, both in our qualitative interpretation of form and process, and in the patterns of measurements we might make in space and time, is an integration of past temporal and spatial processes and events, with different time and space scales of effectiveness and impact. The system is open and the dynamics are nonlinear, even if we have to close the system and specify both initial and boundary conditions for a particular period of study. It has therefore been rather attractive to borrow from the concepts of nonlinear systems and apply concepts such as self-organised criticality to environmental systems. In brief, systems that tend to evolve to critical states are unpredictable in that small forcing events might, in the right circumstances, lead to significant and rather unpredictable consequences or emergent properties, in particular resulting in power law magnitude-frequency relationships. Such concepts have proven useful in explanations of environmental systems, including the fractal nature of river networks and catchments, the magnitudes of earthquakes, the form of debris cones, and the areas of forest fires. This form of explanation has been advocated as providing behavioural principles that govern environmental systems and should be included in environmental models

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(Schaefli et al., 2011) but also criticised as a general form of explanation (e.g. Frigg, 2003) and in specific applications.

One of the features of this approach is that history is important, which makes closure somewhat problematic if what we see now depends on unspecified initial and boundary conditions from the past. As systems evolve towards critical states, the ordering of events becomes important in that the sensitivity of the system to significant change will depend on the rather arbitrary occurrence of external forcing events in space or time (e.g. Beven, 1981). Significant change might be triggered at a particular point in time (or not) dependent on the current state of the system and the magnitude of the event. Thus, history is important, but its effect might be indeterminate. We can see now only the net effect of sequences of events, some of which might be seen as having persistence in what we see now.

Herein lies one of the problems with explanations based on self-organisation. Simulation models show that in order for the characteristics of the self-organisation to become fully apparent, a very large number of critical events are necessary in part because the different realisations of events will develop in different ways, even if they have a tendency to similar self-organisational forms. This requires time and a very large number of potential sites in space (as, for example, in earthquakes and river basins). Thus, even if there is a tendency towards self-organised criticality in such systems, will it be apparent in what we see now given this requirement, or will we see only transient characteristics when changes are occurring more rapidly than sufficient critical events can occur? Such changes might themselves be the result of self-organised criticality operating on some other processes at some other scale (see examples below). How does what we see now reflect this balance of changes within the overall evolution of the system and what are the implications for the predictability of the system of interest?

Here we would like to suggest that another viewpoint is richer in explanatory power. This is not to deny that concepts of self-organisation do not provide valuable insights but what we see now is, in very many landscapes, the result of past events that have had the effect of resetting the initial conditions for the processes currently operating. This can happen frequently in some systems; and at Holocene or orogenic scales for others. What we see now is a (non-linear) superposition of the effects of distributions of events that have occurred at different time scales into the past (including anthropogenic events) and of the dispersion of the effects of those events into different parts of the system that defines their persistence under the forcing of particular sequences of events in time at any particular site in space.

There is then a question of what self-organised criticality means in this situation (except in some rather trivial sense that an event necessarily has consequences). That depends very much on how sensitive a system is to small forcing events having large consequences, i.e. how close that system is to criticality or how quickly it moves towards criticality after an event. But that is not what we see in many systems. We certainly see history resulting from evolution in the nature of soil profiles, in the succession of vegetation communities, the form of river basins etc. but that history seems to be rather easily reset by external forcing events rather than internal organisation. What we see is in evolution but with evidence of the persistence of some past extreme forcing events that did have a dramatic effect on the nature of the system, changing the initial conditions for the time evolution at that site. We shall avoid the use of the word relaxation following such a critical event (e.g. Anderson and Calver, 1977; Culling, 1986; Ahnert, 1994; Calver and Anderson, 2004; Phillips, 2009) because, even if there might be a return to some particular quasi-stationary form, the system is not actually stationary in any way. What we see now (over the limited time scale of a typical research project or research career) will then be a particular state in that evolution, as dependent on a particular sequence of events when the ordering of events might be important. Lacking data from the past, origins beyond that time scale are necessarily the stuff of speculation. Hence, the attraction of finding general concepts and theoretical principles for extending our knowledge and understanding over those longer time scales.

It has always been thus, of course. We naturally tend towards generalised theories, but the drive today is to find theoretical principles that have quantitative utility, rather than only qualitative explanatory power. The questions that consequently arise include how far it is possible to distinguish between competing explanations in the light of limited data and the particular contingencies of individual events (and anthropogenically induced change) in shaping what we see now. For the hydrologist this is an extension of the continuing discussion of equifinality of models and testing models as hypotheses (e.g. Beven, 1996, 2002, 2006; Clark et al., 2011; Beven et al., 2012). For the geomorphologist it is an extension of the discussion of the concepts of equifinality, equilibrium, and non-linear dynamics to landform systems (Culling, 1957, 1987, 1988; Culling and Datko, 1987; Phillips, 1997; Renwick, 1992; Ahnert, 1994; Beven, 1996; Phillips, 1997, 2011). For the ecohydrologist it is an extension of the discussion of behavioural principles to the landscape (Schaefli et al., 2011).

There is an interesting aspect to the original concept of equifinality in geomorphology (see Culling, 1957; and his later discussion in Culling, 1987, 1988) that has relevance here. That is that looking backwards into the past, it is impossible to know all the details of the events and processes that formed a particular landform feature. Thus there might be an equifinality of explanation. This is a form of epistemic uncertainty that will hold for any open system under study within which history and sequences of events are important. But, it is particularly severe for all those events and processes that do not have persistence to the state we see now. Where self-organised criticality offers something new in this respect is to extend the concept of persistence to the net effect of long sequences of events producing recognisable organisation in the landscape that may not have its origin in some extreme event. Where it does not necessarily help is in shedding light on the impacts of events in producing that organisation. We are limited to seeing the effects of events that have persistence extending to the period of study or what we see now.

Thus, the palimpsest of landscape will be the result of an evolution that includes a variety of different forcing events. In general, the effects of large events will have longer persistence, and the effects of small events will dissipate more rapidly, but there is the possibility that for systems close to some critical threshold, a small event will induce some impact with persistence such that the ordering of events will be important; a form of conditioning and triggering (Phillips, 2009). All events contribute to the throughput of energy through the system, and consequently the evolution of the system, that may be gradual, punctuated by sudden changes rather than demonstrating some dynamic equilibrium. These features of nonlinear open systems now seem conceptually uncontroversial. It should also then not be controversial that what we see in the landscape is the persistence of events that have changed the boundary conditions for smaller scale processes.

2. Turbulence: organisation and boundary conditions

Many fluxes of water and air in and above the landscape are turbulent. Turbulent flows are often cited as an example of nonlinear dynamics and self-organisation in practice, albeit one in which it has proven impossible to resolve completely (hence the resort to various closure schemes in predicting turbulent flows). Turbulence shows complex structures in both air and water, such as the horseshoe vortices that have been studied in rivers, and the boundary layers that build up around obstructions and changes in local internal boundary conditions for the flow domain of interest.

For the case of homogeneous turbulence, far from any obstruction or boundary, the complete description of turbulence remains unresolved. Even direct numerical simulations of the Navier–Stokes equations need some closure scheme for how momentum dissipates at the level of the Kolmogorov length scale (e.g. Meneveau and Sreenivasan, 1987). The issue is worse for inhomogeneous turbulence induced by boundary condition effects (Hunt et al., 2006). The length scales over which changes in boundary conditions can have an impact can be very long. But the effects of changes in boundary conditions in time and space will be partly organised by the flow itself (as in dune and other features in mobile bed rivers) and partly imposed on the flow by totally independent factors (such as geological structures in bedrock rivers and large boulders from rock falls or glacial deposition). There is a range of intermediate scales from gravel bars to flood plain meanders within which the organisation will depend on a sequence of external forcing events. The effects of such events may be more or less persistent dependent on the magnitude of that event and the integral effect of the subsequent effects that create what we see now.

3. Forcing events and self-organisation – when does evolution become a change in boundary conditions?

This is just one example of how landscape systems are only partly self-organising because of their dependence on external forcing events that drive the evolution of the landscape by changing the constraints on smaller scale processes. In fact, it could be suggested that self-organisation is really only a part of the mechanism for dissipating the effects of such singular events. This is quite clear when we look at the landscape in many parts of the world. What we see now is clearly a reflection of the past and, in particular, the result of glacial and periglacial events and processes. These have had long persistence in the forms of hillslopes and catchments and, less obviously, in soil structures and the occurrence of landslides and debris flows in moraine and head deposits that have been “waiting to fail” for thousands of years.

This is a modern form of a long time discussion in geomorphology between catastrophist and dynamic equilibrium views of landscape evolution. The balance between the two views depends on the magnitude of a forcing event relative to the rate of dissipation of the impact of that event. Extreme events, such as the last glaciation, can change the constraints for the dissipative processes to such an extent that the effects of such an event are persistent. The effects of small events will dissipate much more quickly, but might still be persistent to the observer depending on when the observations take place. The occurrence of events, including anthropogenic events, might be quite arbitrary even if contingent on the overall evolution. The balance is then complicated further by the dependence of the response to an event on the antecedent state of the system and the possibility that dissipative processes might act to make the system more sensitive to smaller events (including the instigation of catastrophic events at larger time scales). The occurrence of shallow landslides and debris flows are an interesting example in that respect.

4. Event-persistence concepts and contingency

Thus, in an event-persistence view of hydro-eco-geomorphological evolution, how the system responds depends on the antecedent states and the nature of the event in space and time. The persistence of that event will have an effect on the antecedent conditions for the next event. After an event the system continues to evolve in ways that might make it more or less sensitive to future events.

Consider the case of the occurrence of a shallow landslip or debris flow. Debris flows can have locally dramatic effects on hillslides and valley bottoms, and any communities and human activities that they impact. In July 2007 a small debris flow occurred in the Mallerstang Valley, Cumbria, UK as a result of intense rainfall over Mallerstang Edge resulting in the transport of large amounts of sediment into the Outhgill Beck and the River Eden, blocking of the channel and road bridge in the hamlet of Outhgill. Fortunately the debris flow only caused damage to some field boundary walls; the channel and bridge were soon cleared; no properties were damaged or lives lost (although a lot of coarse sediment deposited upstream of Outhgill is still being transported in later events). Elsewhere in the world the impacts of debris flows have been much greater (e.g. Carrara et al., 2008).

In this case, the debris flow originated from glacial lateral moraines left high on the sides of the valley. There is evidence of similar failures elsewhere in the valley and similar locations in the UK. They are, however, rather arbitrary in occurrence, contingent on a combination of local occurrence of intense rainfalls and antecedent conditions (and possibly long term evolution of the cohesion of the materials at a site). In other small tributaries of Outhgill Beck, less than 100 m from the impacted channel, there was no sign of erosion or major change. There was, however, another similar debris flow that blocked a bridge on another tributary to the River Eden on the same day some 3 km downstream. In this location, the combination of circumstances producing such events seems to be rather rare in both time and space.

Once such a flow has occurred of course, it might have persistence in a number of different ways: visually as a qualitatively distinguishable feature of the landscape; in making sediments available from stream transport; in delaying the potential future occurrence of a debris flow at that same site for long into the future (relative to what we see now). Newson (1980) reports on a similar complexity of response from 2 events at the Plynlimon experimental catchments in mid-Wales. Both events were estimated to have return periods of the order of 100 years (although they were rather different in their rainfall patterns) but occurred within 5 years in 1973 and 1977. The first event was characterised by a landslide and debris flows; the second by transport of sediments in the river network. Effectively the first event changed the antecedent conditions for the second. Similar coupling sequences have been described for the Howgill Hills in Cumbria by Harvey (2001) with some evidence that there have been a number of distinct periods of hillslope activity in the last 2500 years (Chiverrell et al., 2008).

Clearly, once a slope has failed it will generally require a period of time to evolve towards being a potential failure site in the future (e.g. Fig. 1). This will also depend on the sequence of events in relation to the accumulation of soil at the site. Where a debris flow has exposed a bedrock surface then subsequent events might actually keep this clear of soil for significant periods of time. In Nelson County, Virginia, the scouring of valley bottoms to granite bedrock by debris flows during Hurricane Camille in 1969 has had decadal persistence (Bechtel, 2006). How quickly soil and vegetation starts to build up again will depend on geology and the surrounding topography and soils. Vegetation developing at a site will help retain soil and later, root strength will help maintain stability relative to the magnitude of forcing events. The non-occurrence of a failure, and subsequent increase in soil depth might also reduce the potential for failure. A change in rainfall regime with an increase in rainfall intensities might increase the potential for failure, depending on the development of the system states between events. Anthropogenic events, such as forest clearing, might change the potential for failure significantly (e.g. Montgomery et al., 2000). This is one example where the ordering of events at a site might

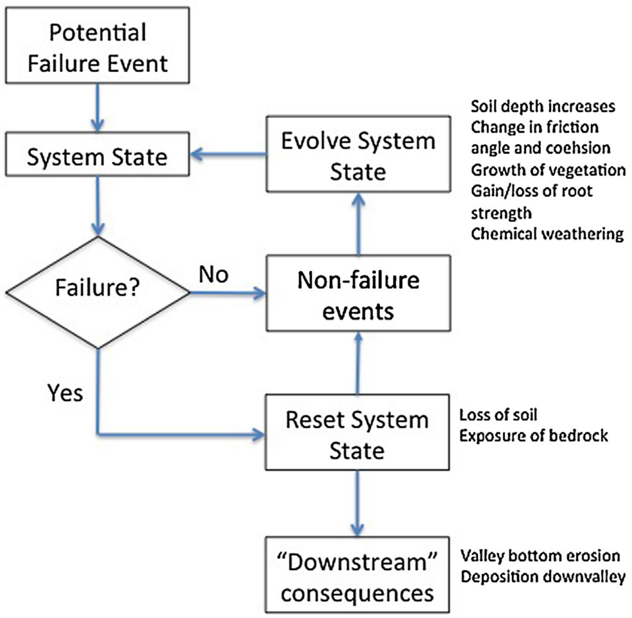

Fig. 1. Simple event-relaxation concepts for a potential debris flow site.

be important on whether a failure occurs or not (Beven, 1981). Prediction of such events remains difficult, if only because of lack of adequate rainfall data in time and space, lack of adequate soil property data and the persistence of effects from past failures (e.g. Casadei et al., 2003).

Some attempts have been made to look at the long-term implications of debris flow events in time and space on catchment morphology (e.g. Benda and Dunne, 1997; Stock and Dietrich, 2006). This change of scale reduces the focus on individual sites, to the integral effect over long periods of time. We do not then know, of course, what the particular distribution of events in the past might have been, nor generally what the past impacts of man might have been. What we see now is the persistence of (some) individual local events in the past superimposed on long term evolution which provides an antecedent condition for the local; to "see" the integral effect requires some theoretical interpretation and some auxiliary assumptions about distributions of events and their impacts.

5. Organising principles and quantitative prediction

Perhaps more controversial is what new concepts can be introduced within this framework that will result in additional insights, over and above information gained from purely empirical study of local persistence. Here again we should distinguish between qualitative concepts, such as self-organised criticality, that can be demonstrated on simple theoretical systems but which might be much more difficult to verify as hypotheses in a complex landscape because of the sheer number of degrees of freedom and uncertainties inherent at landscape scales (Frigg, 2003); and those that might be useful as deductive quantitative constraints of system behaviour. Within the first category we can include concepts such as the complex attractor, bifurcation and chaotic behaviour, dynamic equilibrium and nonequilibrium, and self-organised criticality. Within the latter category are principles of fractal scaling, maximum entropy production, minimum energy dissipation, maximising boundary energy gradients, and dissipation of Helmholz free energy (see Rodriguez-Iturbe and Rinaldo, 2001; Kleidon and Schymanski, 2008; Schymanski et al., 2010; Zehe et al., 2010; Schaefli et al., 2011; del Jesus et al., 2012; Kleidon et al., 2012).

As Reggiani et al. (1998, 2000) and Kleidon et al. (2012) amongst others have pointed out there has often been a lack of rigour in applying physical principles in studies of environmental processes and landscape. Such systems are subject to the requirements of thermodynamics and the conservation of mass, energy, and momentum. In particular, Kleidon et al. (2012) emphasise the open nature of such systems and the way in which the free energy supplied as net boundary fluxes must be dissipated according to the laws of thermodynamics (see also Porada et al., 2011). This has suggested to some that these types of organisational principles can provide constraints on models that might be useful in making predictions (Schaefli et al., 2011). Similar arguments have been made by Bejan (2007, Bejan and Lorente, 2010) in his theory of constructal networks. These are, however, purely theoretical conjectures that we have little hope of proving unequivocally because of the limitations on how we can account for mass, energy and momentum in any complex system (Beven, 2002, 2012). Similar points have been made more generally by the philosophers Morton (1993) and Cartwright (1999). Cartwright suggests that such principles might be better perceived as potential *capacities* rather than quantitative constraints. Indeed, she suggests that even the thermodynamic laws must be treated in this way when applied to any particular system.

These principles are generally quantified and deemed applicable by empirical back-calculation of coefficients. This type of determination of empirical calibration is, of course, traditional in hydrology and other environmental sciences. Many other process representations were developed and continue to be justified in this way. Equivalent roughness lengths at a flow boundary can always be calculated given a velocity profile (even if in some circumstances that calculation yields values orders of magnitude greater than the sand grains that Nikuradse's original experiments involved, e.g. Babaeyan-Koopaei et al., 2002). Darcy's law will hold when a hydraulic conductivity can be back-calculated from observations of profiles of soil water tension and moisture content, even where preferential flows would mean that it is not the appropriate theoretical framework (Beven and Germann, 2013).

The application of theory where it is not appropriate is clearly not new (even if it should be considered as bad practice) and in many areas of environmental modelling the aphorism of George Box that all models are wrong but some might be useful is generally accepted. It might then be helpful, however, to have some indication of the types of conditions under which certain theoretical concepts might be useful in this sense. In the case of the organisational principles discussed above, this would appear to depend on some balance between the rate at which the potential towards observable organisation evolution takes place and the persistence of boundary controls that apply at different time and length scales.

Consider the development of river networks. Rodriguez-Iturbe and Rinaldo (2001) argue that water draining from the land will take a path of least resistance and will consequently minimise energy dissipation in developing a drainage network and patterns of slope and catchment areas. The result is a set of fractal relationships characteristic of self-organised processes with exponents in the range found by the empirical analysis of actual networks. Bejan (2007) extends this optimisation argument to explain channel-cross sectional areas and flux in other tree forms, Kleidon et al. (2012) to critical zone fluxes, and Sidle et al. (2000, 2001) to drainage networks within hillslope soils.

Drainage networks develop over time under the influence of a (changing) distribution of events large and small. There are critical event thresholds at a variety of scales, from the initiation of motion of individual sediment particles, to the collapse of undercut banks, to the cut-off of river meanders and to major avulsions of channels from one position to another. The way in which momentum is dissipated in the network will depend on the capacity of the stream to erode and transport the material of the bed and banks, which itself will depend on the magnitude of a particular spate event and the disposition of the sediment prior to that event (bed armouring and the way in which phytoplankton, macrophytes and bankside vegetation locally affect the supply, cohesion, mobilisation, and deposition of sediments). As noted earlier, what is available to be transported by an event, might depend on past events. Transport within an event might be transport limited in some circumstances and supply limited in others, even at the same site. There may be a scale effect as well, in that persistent events at small scales might lead to the breakdown of scaling laws apparent at larger scales (e.g. Moody and Kinner, 2006).

This will be cases, however, where what we see now at the local scale will often show little in the way of clear persistence from past events. Where a major event has stripped vegetation and reworked gravel deposits then the persistence will be greater (and can sometimes be dated from vegetation ages, etc.). Even then, however, the channel modifications are largely constrained by what was there before, representing the integral effect of all past events.

It is clear that even in this case the network cannot be entirely self-organising. Persistence is still often apparent in prior landforms, the influence of underlying geology and the effects of changing base levels, etc. This will be most evident at the external links to the network when the uniqueness of particular places comes most into play (Beven, 2002). It will be less evident at the scales where a river is reworking its own past alluvial deposits. At smaller catchment scales, the scope for arbitrary effects and contingencies is greater.

One particular example of this is the effect of the outbreak of chestnut blight in the southern Applachians in the early part of the 20th Century. Although it is thought that this was introduced to the US by the importation of Asian chestnut trees around 1900, by 1940 some 4 billion trees had been lost. In parts of the Appalachians 25% of the trees were chestnuts. Many of the affected trees were cut for timber, some after damage or toppling by wind. The blight has been suggested as a major reason for the expansion of gully systems in the southern Appalachians in the 1930s that persist to this day. Fire (Moody and Kinner, 2006) and blowdown due to wind have also been invoked as forms of contingent events (Phillips et al., 2008; Phillips and Park, 2009). In Virginia, in October 1979, an early snowstorm led to about 30% of trees in some places in Shenandoah National Park falling over. The arroyo expansion in the American south-west in the late 19th century might also have an anthropogenic origin with the introduction of cattle grazing. In this case, there may have been earlier, more “natural” periods of gullying induced by occasional droughts (Antevs, 1952; Tuan, 1966; Pelletier et al., 2011). There is clear persistence, but less information about causes, initial conditions and changes.

6. Preferential flow in soils

Another consequence of chestnut blight in the Appalachians was the death and decay of root channels resulting in significant networks of preferential flow pathways through the soil. In this case a critical event has had a consequence, but in this case it is far more of an arbitrary event external to the preferential flow process. There are other factors that affect preferential flows, such as worms and burrowing animals, and cracking during drought periods, that are also external to the preferential flow process. Such processes might actually create opportunities for preferential flow where there was little or none before, even though there may be little change in the hydrological regime. Other external processes, such as the use of ploughing rather than no-till agricultural management, might reduce the opportunities for preferential flow. These external effects are changing the boundary conditions for the preferential flow process, rather than being the product of self-organisation of the flow process itself. What we see now at any site, clearly depends on the rather arbitrary occurrence of such events and their time scale of persistence. But they may have persistence over long periods of time. Beven and Germann (2013) note that, even in the case of cracking in a clay soil, the cracks may persist as preferential flow pathways even after a wet winter (in part due to roots that lie on cracked ped surfaces rather than penetrating the clay). It is therefore difficult to believe in the general validity of the suggestion that where there is “excess water” on hillslope a fractal preferential flow network will develop so as to evacuate that water (e.g. Sidle et al., 2000, 2001; Weiler and McDonnell, 2007).

It is interesting to think through the concept of excess water on hillslopes. There is a long history of such a concept. Robert Horton (1933) suggested that the soil surface was a separating surface, causing water in excess of the infiltration capacity of the soil to become surface runoff (though his concepts were actually somewhat more sophisticated, see Beven, 2004). He recognised that cracks in the soil could be important, but concentrated on the downslope movement of excess water through crack systems or “sun checks” which he called “concealed surface runoff” (Horton, 1942; Beven, 2004). Later, Dunne and others introduced the concept of saturation excess surface runoff (Dunne, 1978) and Sidle et al. (2000, 2001) have suggested that preferential flow lines could develop in the soil to deal with water fluxes in excess of storage in the matrix. The generality here is that water in excess of what can be stored locally finds some way of finding its way downslope towards a recognisable channel. In some cases, of soils that are easily dispersed or eroded, that may cause a feedback into the development of subsurface pipe systems, rills or gullies with a consequent increase in the effective drainage density. Where the flow can have a direct effect on developing the flow pathways this can be a form of self-organisation, similar to that which leads to dendritic drainage patterns in general. It is not so clear, however, that this would be evident in cases where the soil surface is not easily eroded and the hillslope simply sheds any excess water as surface runoff, except perhaps in the most extreme events or after the surface has been disturbed by anthropogenic action.

It is also not so clear in the case of preferential flow within the soil, when the flow pathways due to roots, fauna, drying and other causal mechanisms that are largely independent of preferential flow of the water itself. The water might still locally take a path of least resistance, and some of the networks in the soil that are self-organisational (such as root networks, mycorrhizal mycelial networks and cracks and fissures) might have fractal scaling characteristics (e.g. Van Noordwijk et al., 1994; Deurer et al., 2003; Boddy and Donnelly, 2008). It might also be the case that some flow pathways might be enhanced over others, for example by the translocation of clay particles and build-up of cutans on the surfaces of some preferential flow pathways, or long-term chemical weathering. This is also thought to happen in the shallow pipe networks in peat soils found in the UK and elsewhere (Chappell, 2010; Jones, 2010). These networks appear to have their origins in cracking in rare drought summers, but then parts of the network are enhanced over others by the flow process itself. The network can also be changed by roof collapse and blocking (Gilman and Newson, 1980). On balance, however, this would appear to be one case where an event-persistence concept might dominate self-organisation in controlling the local boundary conditions for the flow.

7. Vegetation productivity and drought

Another example of this balance between event persistence and organisational principles is provided by the organisation of vegetation patterns. One issue in looking at vegetation patterns is that

Table 1
Parameters of the simple soil depth model.

Parameter	Symbol	Base value	Units
Initial soil depth	d_o	0.1	m
Slope angle	α	0.36	rad
Effective upslope contributing area	A_c	1000	$\mathrm{m^2\,m^{-1}}$
Density of water	ρ_w	1000	$\mathrm{kg\,m^{-3}}$
Density of soil	ρ_s	1500	$\mathrm{kg\,m^{-3}}$
Density of bedrock	ρ_s	2500	$\mathrm{kg\,m^{-3}}$
Maximum cohesion of soil	C_o	1	kPa
Maximum cohesion of roots	C_r	3.5	kPa
Time constant to reach maximum cohesion of roots and equilibrium soil depth	T_e	50	y
Depth at which root cohesion reaches a maximum	a	0.8	m
Rate parameter in logistic root cohesion function	b	50	y
Equilibrium soil production rate over upslope contributing area	C_p	0.001	$\mathrm{m\,y^{-1}}$
Friction angle	θ	0.576	rad
Minimum effective event specific discharge	q_{min}	25	$\mathrm{m\,d^{-1}}$
Maximum effective event specific discharge	q_{max}	300	$\mathrm{m\,d^{-1}}$
Beta shape parameter 1 for effective specific discharge	B_1	1	–
Beta shape parameter 2 for effective specific discharge	B_2	12	–
Minimum inter-event time	I_{min}	0.01	y
Mean inter-event time	I_{mean}	0.5	y
Transmissivity at soil depth of 1 m	T_o	150	$\mathrm{m^2\,d^{-1}}$
Power of soil depth/transmissivity function	f	5	m
Surface erosion coefficient	C_e	0.025	$\mathrm{d\,m^{-3}}$
Excess pressure coefficient	C_x	0.1	–

there are very few vegetation communities that have not been affected by man, either directly or (as in the case of chestnut blight) indirectly or (as in the case of beetle infestations following the impacts of acid rain on trees in the north of the Czech Republic) both. Self-organisational principles have been invoked to explain some vegetation patterns, such as the banded patterns of the "tiger bush" in the semi-arid Sahel region of Africa as a response to limited water supply (Galle et al., 1999; Valentin et al., 1999). Banded vegetation patterns are also found elsewhere (e.g. Dunkerley and Brown, 2002; Pelletier et al., 2012).

An interesting example is the suggestion that more generally natural vegetation is adapted to maximise net carbon profit within the constraint of maximising entropy in the local energy and moisture regime. Schymanski et al. (2007, 2009, 2010) have shown how maximisation of entropy might be used as a quantitative constraint in models of evapotranspiration processes. The interaction of vegetation, atmosphere, and the hydrological regime has been explored in some detail as a problem of nonlinear dynamics, including the possibility that changes in one area might have consequences in another area at distance. Such consequences might be part of the overall non-equilibrium response but would be seen in the affected area as a change in boundary condition with some degree of persistence.

However, consider the piñon pine–juniper community found in areas of the American south-west. This community has been the subject of significant research (e.g. Huffman et al., 2012; Limousin et al., 2013). In 2002–2003 an external forcing event, in this case and extended drought, caused the death of many of the piñon trees, at sites that had already suffered mortality in the 1996 drought (Mueller et al., 2005). Such events are persistent. Other contingent events such as fire can also have a significant impact on water use and productivity, even where the area is recolonised by the same species, such as in the Mountain Ash (*Eucalyptus regnans*) that is found in the water supply catchments for Melbourne, Australia. In these catchments it has been suggested that the effects of fire on the water yield of these catchments can have a persistence of over a century (see Jayasuriya et al., 1993; Watson et al., 1999). What we see now is the persistence of individual contingent events.

In these particular cases the impact and persistence of an event can often be distinguished by aging the vegetation using tree rings or other techniques. Where trees survive, a history of fires and droughts can sometimes be distinguished at a site (McBride, 1983; Swetnam, 1993; Buechling and Baker, 2004; Li et al., 2006; Liang et al., 2006). Such studies have also shown that death can be a function of the stand characteristics and local soil properties (e.g. Ogle et al., 2000; Floyd et al., 2009; Peterman et al., 2012) and might also involve other mechanisms such as increased sensitivity to insect damage (Clifford et al., 2008). The occurrence of contingent persistent events is not necessarily inconsistent with some organising efficiency or optimality principle applying at different stages during regrowth, but it must do so under continuously, and sometimes dramatically, changing constraints.

8. A simple case study: surface erosion and shallow slope failure in a hillslope hollow

We can illustrate some of these issues by a simple model of soil accumulation and erosion in a single hillslope hollow where soil cohesion is a function of vegetation succession with increasing soil depth, and surface erosion is also affected by the vegetation cover (as in Fig. 1). To keep the example very simple we assume that the infinite slab model of shallow landslip failure holds (e.g. Montgomery and Dietrich, 1994; Borga et al., 2002). In this case, the slope will fail if the ratio of water table depth to soil depth satisfies the inequality

$$\rho_s dg \sin\alpha \cos\alpha > C + (dg\rho_s - hg\rho_w - h_e g\rho_w \cos^2\alpha \tan\varphi) \quad (1)$$

where d is soil depth (m), h is the water table depth above the base of the soil (m), h_e excess pressure head (m), C is the total cohesion of the soil, (kPa) and the other variables are defined in Table 1.

The water table depth will depend on the effective discharge from upslope and a transmissivity function that we will assume to be a simple power law that is constant in time. Implicitly therefore we assume that as the soil depth increases the transmissivity increases as a result of root and other channels in the soil as the vegetation develops on the site. Thus:

$$T = T_o d(i)^f \quad (2)$$

where T_o ($\mathrm{m^2\,s^{-1}}$) is the transmissivity at a scaling depth of 1 m and f controls the nonlinearity. In a similar way, cohesion due to roots

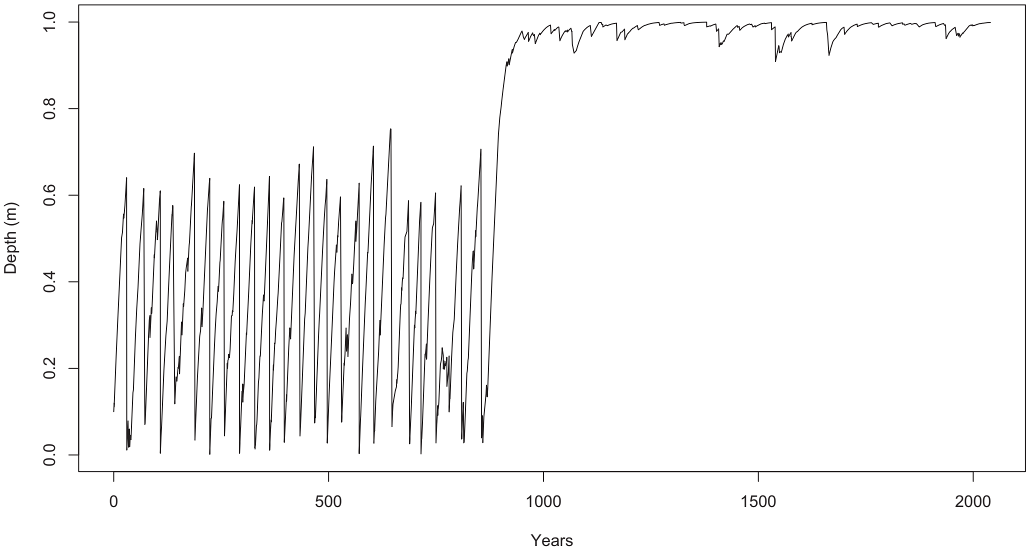

Fig. 2. The evolution of soil depths over time at a hillslope hollow failure site for one realisation of the base parameter values of Table 1.

be a logistic function of soil depth, reaching a maximum strength at a soil depth a, reached at a time scale of b years.

$$C = C_o + \frac{C_r}{1 + \exp(-b\left\{d - a\right\})} \tag{3}$$

Once the slope has failed, we assume that the soil depth starts to increase as a function of both weathering and the dispersive transport of soil from the same effective contributing area upslope. It will, however, take time to reach an equilibrium soil depth. The accumulated soil depth is specified as a function of the rate of soil production over the upslope catchment area, the current soil depth and time to reach an equilibrium soil depth as:

$$d(i) = d(i-1) + \left(\frac{\rho_r}{\rho_s}\right) d_e \left(1 - \frac{d(i-1)^2}{d_e^2}\right)\left(\frac{I(i)}{T_e}\right) \tag{4}$$

where $d(i)$ is the soil depth (m) prior to event i after an event inter-arrival time $I(i)$ (years) and d_e is the equilibrium soil depth due to supply from the upslope contributing area of $A_c\ C_p$ (m^2). Potential failure events are generated randomly with effective event magnitudes of specific discharge over the upslope area generated as a beta distribution with specified minimum and maximum values, and event inter-arrival times as an exponential distribution, shifted by a minimum event inter-arrival time.

Where the discharge supplied from upslope exceeds the downslope flux capacity of the current soil depth then it is assumed that there is some potential for surface erosion. This is represented as a simplified form of the Morgan–Morgan–Finney model (Morgan, 2001; Vigiak et al., 2006; Morgan and Duzant, 2008) as:

$$G = C_e(q(i) - q_o(d))^2 \sin\theta; \quad q(i) > q_o(d) \tag{5}$$

where $q(i)$ is the specific discharge for event I, and $q_o(d)$ is the maximum specific discharge at the current soil depth, d. The effects of bedrock fractures on the potential for excess pore water pressures in inducing failures is often revealed only after an event, (e.g. as at the Coos Bay site, see Montgomery et al., 2002) but might be important in controlling the occurrences of failures. This has been included here also in a very simple way by making excess pressure proportional to the excess water depth (as predicted by an extrapolation of the transmissivity function) over the soil depth as:

$$h_e = C_x\left(q(i) - q_o(d)\right); \quad q(i) > q_o(d) \tag{6}$$

The model considered here allows for the evolution of soil depth over time but considers only potential failures at that site and not potential failures at other sites in the same drainage, i.e. we assume we have chosen the most critical site in that drainage. However, it already requires a large number of parameters to be specified (Table 1), it assumes that those parameters are constant over time, and it shows rather complex behaviours (Fig. 2) that are sensitive to both realisation effects (Fig. 3) and changes in parameter values (Fig. 4). In Fig. 3, the only difference between runs is the random seed that starts the sequence of events. In Fig. 4 only the value of the parameter b has been changed, all other parameters and the sequence of events is the same. While this simple landslip model could be further complicated (e.g. by introducing state dependent parameters) this would not fundamentally change the inferences that can be drawn from the complex simulated responses.

This is undoubtedly a very simple model of soil depth evolution at a site. Similar models have been employed to assess the potential for failures in space (Montgomery et al., 2000) and, in some cases have been linked to equilibrium soil depth models (Dietrich et al., 1995), but many factors have been left out. It does not take any account of the effects of man or disease on the soil and vegetation characteristics and consequent cohesion at the site (e.g. Montgomery et al., 2000); it does not allow for the effects of geology and climate on weathering rates; it does not take any explicit account of the effects of vegetation changes on flows and antecedent conditions in the upslope contributing area; it does not allow for the effects of wetting and drying sequences on weathering and soil creep from upslope; and it does not allow for any non-stationarity of the parameters of the functional relationships incorporated in the model.

The time scales of these plots are long. What we see now at a site will depend on where we are on the trajectory at that site. We might see a site that is sensitive to failure with relatively shallow soil depths; we might equally see a site that is resistant to failure. Fig. 5 shows the evolution of the factor of safety for one run of the model, at the point where there is a transition from a reduction of the factor of safety as soil depth increase, to where increasing soil depth results in an increasing factor of safety if a failure event does not occur (for those particular parameter values). The system exhibits a change in the mode of behaviour at this point. What we see now will depend very much on whether observations are made on one side of that transition or on the other.

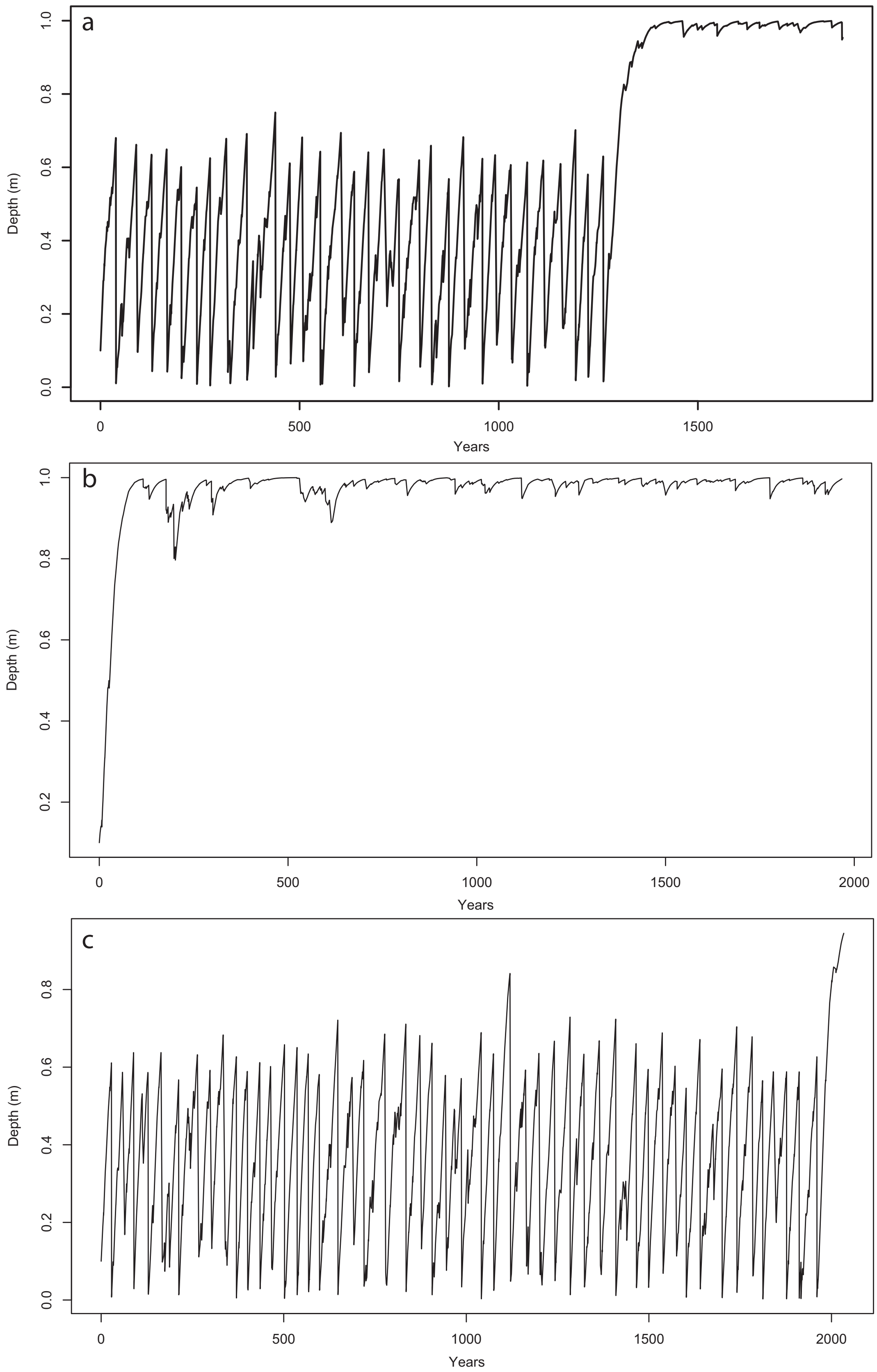

Fig. 3. Different realisations of the evolution of soil depths over time in the slope failure model for the same base parameter values shown in Table 1. The runs vary only in the random seed used to initialise the forcing events.

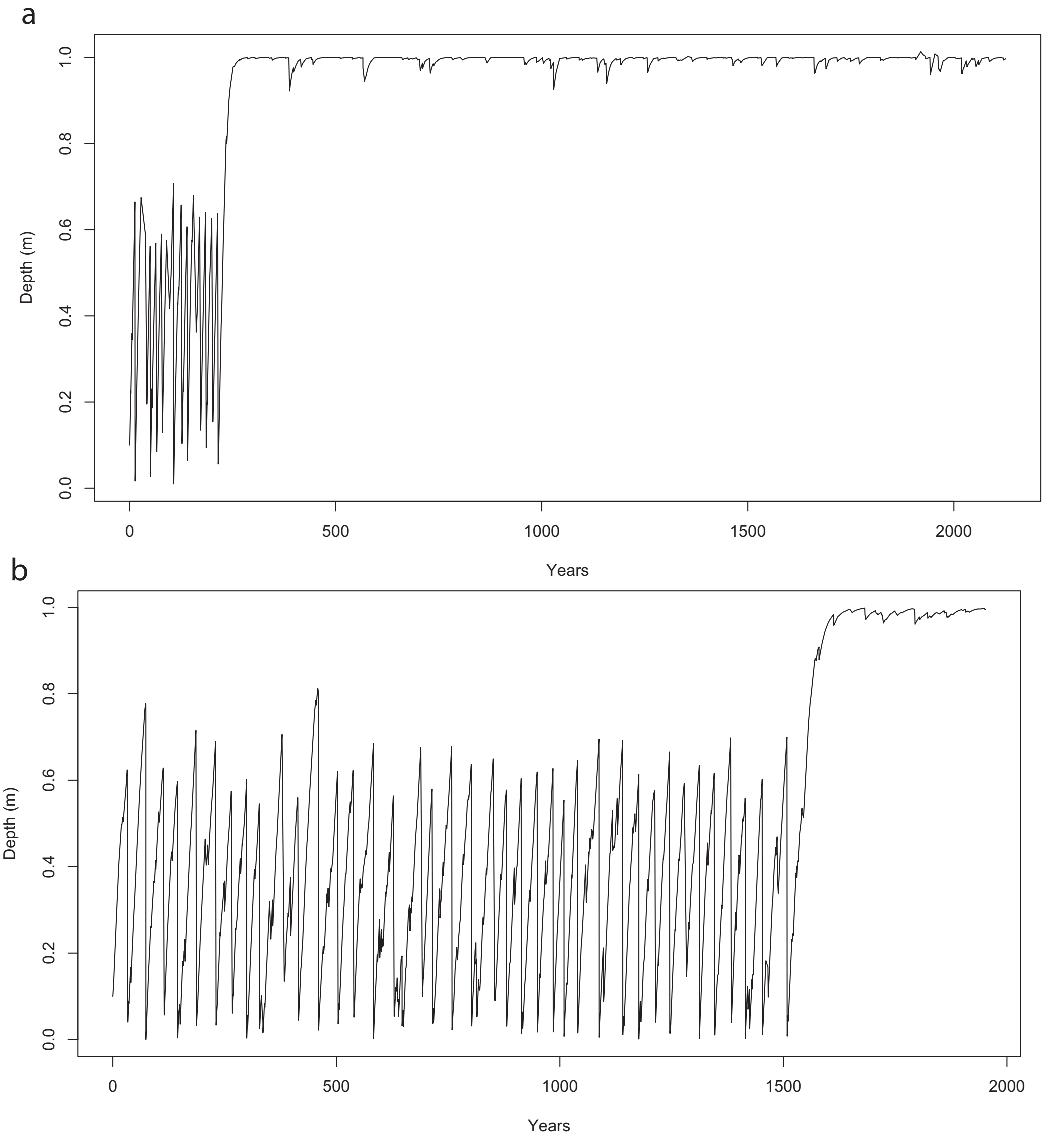

Fig. 4. Different runs of the slope failure model for different values of the soil depth increase time scale parameter. Upper panel: $b = 25$ years; lower panel: $b = 50$ years. All other parameters as in Table 1.

An ergodic argument could be made at this point in that consideration of multiple sites in space might give a better reflection of the underlying nonstationarity and variability in the processes by reflecting the potential distribution of expressions of soil depth in any time window. This is clearly true to some extent, but there is also the potential for variability of basic parameters between sites, as well as other contingent auxiliary conditions that would increase the potential dimensions of the joint distribution to be considered. The number of sites required for robust inference might take on the magnitudes of samples needed to estimate a fractal dimension with precision (see Theiler, 1990; Gallant et al., 1994).

9. Mediating models in understanding and predicting the future

The point of all these examples is to show that it is not always possible to apply general constraining principles to explain the local detail of what we see now, nor to validate those general principles on the basis of short periods of observation. An event-persistence approach to explanation is not, of course, inconsistent with organisational principles that integrate over time or space, but both might contribute to a complete explanation of what we see now. This is analogous to the discussion of dynamic equilibrium and nonequilibrium in geomorphology (see for example, Renwick, 1992, and the simplexity arguments of Phillips, 1997) and more recent state and transition modelling methods that recognise the historical contingencies of system evolution (e.g. Phillips, 2007, 2009, 2012, 2013).

This is clearly the case with landscape and the environment. We have little reason to question the principles or capacities of mass balance and thermodynamics, but given the limitations of measurement techniques it is really not possible to disaggregate those balances or apply thermodynamical principles in any other than a very approximate way subject to significant uncertainties. The models that we use then will be mediating models, mediating between theory and observations, and subject to many auxiliary assumptions that may not be verifiable (Morton, 1993; Gooding and Addis, 2008). I have argued elsewhere that in many systems, including catchments, it may then not be possible to distinguish between different models as hypotheses about system function (e.g. Beven, 2002, 2006, 2009, 2012).

So there is scope for different types of mediating models, including false models. Some of the current (sometimes conflicting)

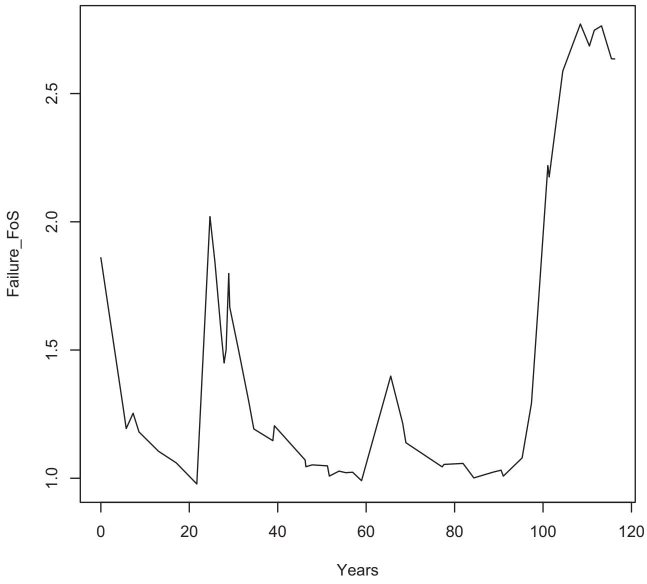

Fig. 5. Factors of safety for part of a model run showing a transition from sequences of failures to relative stability once depth exceeds about 0.7 m.

organisational constraints that have been suggested might fall into this category. This is not necessarily a bad thing. As Frigg (2003) points out in his discussion of self-organised criticality concepts, false models can act as useful ways of changing entrenched thinking: "*to think differently about certain problems, motivate new questions, shed a different light on some issues, and finally make it easier to adopt an altogether different point of view. In doing so, the model acts as an antipode to stagnant assumptions, undercuts too readily accepted hypotheses, and helps to defamiliarise deeply entrenched styles of reasoning. In short, a false model can indicate alternative ways to deal with a phenomenon*" (Frigg, 2003).

The question that then arises, of course, is how best to test models given limited boundary condition and evaluation data that are subject to epistemic as well as statistical error. This is particularly important if we wish to use those models to make future predictions on which decisions will be based. Once it is accepted that epistemic errors are a significant constraint on model evaluation, it means that it is very difficult to make predictions associated with a realistic probability or likelihood that can be incorporated into risk-based decision making (Beven, 2012; Beven and Young, 2013). We might then need to develop some non-statistical methods of model evaluation, such as in the latest applications of the GLUE methodology (Beven and Binley, 2013; Beven and Smith, 2014). Global climate models are of this type; it is of some concern that they have not generally been rigorously evaluated even for short term decadal projections (Suckling and Smith, 2013). In this case, recognition of the epistemic uncertainties associated with the scenario projections might lead to decisions being made in different ways (Beven, 2011) but, this may not necessarily be a sufficient protection against an arbitrary future surprise (Beven, 2013).

Summary: the contingent, the arbitrary, and what we see now

What we see now in the landscape is the result of a long history of events with varying degrees of persistence. We have only limited access to much of that history and we know that many current events have only a minimal impact on what we see. Even rather extreme events may have impacts that are not very long-lasting but can have the effect of changing the constraints for future events. That means that sampling of sequences of events might be important in understanding the evolution of catchment hydro-eco-geomorphology. In some cases, however, extreme events can have persistence over hundreds or thousands of years. Any evolution of the landscape is then constrained by the effects of those events, however much it might be also constrained by self-organisational principles at shorter time scales. It might be difficult to verify those principles given the epistemic uncertainties that are generic to the studies that are possible within a research project or career. Such uncertainties also imply that it might therefore be difficult to test different models of development as hypotheses about how catchments and landscape systems function and even more difficult to assess future evolution when that might be dependent on arbitrary events in the future that could then have persistence. We search for general principles and theories that will support predictability but should recognise that what we see now may be subject to the effects of such contingent persistent events that may instigate new organisational structures.

Consequently predictability will be an issue for time scales between the very long, where organisation is integrated over many such contingent events, and the very short, in between contingent events that modify the short term local organisation that integrates over many small non-persistent events. The evidence presented by persistence in the landscape suggests that this situation is not uncommon such that an event-persistence conceptual framework might often be useful.

As the results presented in this paper show, however, we can also conceptualise that we might see rather different modes of behaviour at different points in the time trajectory of a sequence of events. Multiple sites might also be in quite different modes of behaviour at any given time, making it difficult to generalise and demonstrating a certain of uniqueness of place that is a result of both spatial and temporal variations (see discussion of Beven, 2000). Drawing general inferences in such situations might be difficult but we can at least propose some interesting topics for further study. This should include:

- What are the scales of persistence in any hydro-eco-geomorphological system?
- How far is any short term process organisation dependent on the effects of past persistent events?
- What are the potential future events, including anthropological interventions, that might have the effect of changing the organisation of those processes?

These questions suggest a promising line of research that should be considered as complementary to the type of self-organisation and short-term behavioural principles of such systems being advocated elsewhere.

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