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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