Hydrol. Earth Syst. Sci. Discuss., 5, S2706–S2712, 2009
www.hydrol-earth-syst-sci-discuss.net/5/S2706/2009/

Hydrology and Earth System Sciences Discussions

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5, S2706–S2712, 2009

Interactive Comment

Interactive comment on “Threshold behavior in hydrological systems and geo-ecosystems: manifestations, controls and implications for predictability” *by* E. Zehe and M. Sivapalan

E. Zehe and M. Sivapalan

Received and published: 15 May 2009

HESS Review paper on threshold processes by E. Zehe and M. Sivapalan Stefan Uhlenbrook (SU), E. Zehe and M. Sivapalan (EZ&MS)

SU: This is a long review paper on threshold behavior in hydrological systems, i.e. concerning processes occurring at the plot/hillslope and small catchment scale. The topic is very interesting and the authors introduced ideas on classifying threshold processes at different levels. However, before acceptance of the paper I suggest that this review paper should be somewhat more complete (see below) and a couple of points need to be clarified. The research objectives (P3252) are excellent, but I suggest modifying

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them such that the focus on small scales gets clearer from the beginning, and moving the second part of objective 4 to the front. I think the paper does not answer question 2 (‘...conceptualize different forms of threshold behavior ....’) as much as the others.

EZ&MS: We sincerely thank SU for his patient reading of this admittedly long paper and for his constructive comments and criticisms. We considerably streamlined the paper (cut down 20 pages) by omitting unnecessary details and rearranged the paper around 5 key questions as explained at the end of section 1.

SU: I stress the clarification of the focus of this paper on the small scales, as new processes and controls are coming in at larger scales that are not discussed in this paper. All examples are from the hillslope and headwater catchment scale (<5 km2; incl. 2.4.2 which examples could almost all fit to 2.1 Process-level). Processes like the space time variability of hydro-climatological variables or stream flow routing processes play a much larger role at larger scale, but are not really discussed in this review paper. The text at 3264 top is also not clear on this and needs clarification.

EZ&MS: We disagree slightly with SU on the question of scale: Indeed 5 km is not "large" in a spatial sense. However, complexity peaks at this scale as the system is too large for deterministic approaches but too small for conceptual approaches. Maybe this is the scale of "intermediate" complexity Jim Dooge is talking about in his famous paper 1986 WRR, rather than just the small scale or the mesoscale (which is now explained in section 2.3).

The revised manuscripts highlights that this paper is not about "scale in space" but about "scales" or better levels of complexity. We try to be very precise in distinguishing elementary hydrological processes, responses of hydrological systems - that refer to a specific problem context (flooding or erosion) - and hydrological functioning of an environmental system. We provide multiple evidences that threshold behavior occurs at each of these "levels" and complexity of the underlying controls increases when mov-

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ing from the process, over the response to the functional levels. Threshold behavior at the level of hydrological processes is controlled by the interplay of local soil characteristics and states, vegetation and the rainfall forcing. We selected overland flow formation, particle detachment and preferential flow as examples to discuss this idea in detail. Threshold behavior in the response of systems of intermediate complexity - for instance runoff response or sediment yields - is controlled by the redistribution of water and substances in space and time. This response is controlled by the topological architecture of the system that interacts with system states and the boundary conditions. Crossing the response thresholds means to establish connectedness of surface or subsurface flow paths to the systems boundary. We select subsurface stormflow in humid areas, overland flow and erosion in semi-arid and arid areas as illustrative examples, and explain that crossing local process thresholds is necessary but not sufficient to trigger a system response threshold. The third form refers to changes in the "architecture" of human geo-ecosystems, which experience disturbances around the world. We suggest that a substantial change in hydrological functioning of a system is induced, when disturbances exceed the resilience of the geo-ecosystem and discuss recent examples from savannah ecosystems, humid agricultural systems, mining activities affecting rainfall runoff in forested areas, badland formation in Spain and the restoration of the Upper Rhine river basin as a historical example (at least this is not a small scale example).

SU: The functional scale discussion should be illustrated with better examples of catchment scale phenomena (not the macropore discussion again). I found the discussions about the functional level (e.g. 2.4) generally not so good. Beside the dominant focus on small scales, I missed the importance of the human impacts at this scale. Most of the catchments around the world are not pristine but heavily influenced in their dynamic behavior through man. The authors mention land use impacts, but there are also many others like reservoirs, abstractions (i.e. irrigation in semi-arid environments!), channel works, other water uses etc., which are not discussed in this paper.

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EZ&MS: SU points out correctly that our tea "vessel" analogy is limited, as boundary conditions in hydrological systems change. However, changing the temperature of the hot plate means a change in boundary conditions. We now provide a much wider range of examples to explain the ideas about functional thresholds, (as explained above). T human aspect comes into play for the case of Savannah ecosystems (which are heavily used for producing life stock), the Rhine rectification and the example of the Schaefertal. We still start with the two examples from eco- hydrology because the idea of function and ecosystem resilience stems from ecology and because these systems are simple and clear enough to explain the idea and the consequences. As recommended we reduced our earthworm example to a minimum and discussed additional consequences of a dye back of earthworms for instance for production of organic matter and degradation of substances.

SU: The repeated tea-pot analogy is generally good and helpful for the reader, but it should be clarified that in the pot only the external force (heating energy) is changed and this triggers a switch of processes. However, the boundary conditions remain the same at the tea pot, but usually change completely for threshold processes in real-world hydrological systems. EZ&MS: As mentioned already, we do agree that this is a somewhat limited analogy. However, boundary conditions and external force mean the same in this case. In systems theory it means that we specify the value of a state variable at the boundary (temperature) or its normal gradient (energy flow here). This acts as forcing for internal dynamics (no forcing -> steady state). We will add a statement in the revised manuscript to clarify this point. In a thermodynamic sense, rainfall can be argued to be also an input of energy into the catchment, since the input of water mass changes the chemical energy in the system, which is explained.

SU: 1) Too much of the paper is focused on reviewing own recently published studies. Other literature is referenced to some extent, but almost exclusively all examples refer to own work of the authors. I think a review paper should be somewhat wider in scope. 2) I suggest rewording the title to “threshold behavior in small-scale

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hydrological systems: manifestation, controls and predictability”. The part on geoecosystems is small, not complete in its present form and – as far as I understand – beyond the scope of the paper.

EZ&MS: Good point. We reduced our own work to the necessary minimum, and added various illustrative examples form hydrology, geomorphology and eco hydrology.

SU: 3) P3250, 13: Why an ‘empirical’ threshold value?

EZ&MS: Threshold values are often empirical: the critical Reynolds number for occurrence of turbulent flows has to be determined empirically for different geometries, freezing temperature is an empirical value. Onset for turbulent convection is determined by the Richardson number, the threshold has to be determined empirically. We added a statement in section 1.

SU: 4) 3252, bottom: the hydrosphere is missing. EZ&MS: True, we fixed this the revised manuscript.

SU: 5) The paper is so long as it is partly repeating things, see example at p. 3255 bottom. I think the paper could be shortened by 20 %. EZ&MS: Indeed we managed to cut down 20 pages of the original manuscript.

SU: 6) 3258, 4: define ‘ human time scale’.

EZ&MS: We picked up this idea from Klemes (1983), maybe we should call this time scale of human thinking (e.g., 5-10 years, duration of a research project). However, we deleted this statement.

SU: 7) 3258, bottom: The response at larger scale might look even simpler or even linear, as significant ‘ averaging out’ could happen at that scale. Thus, the complexity at local scale does not matter that much anymore – at least if total response (e.g. stream at a catchment outlet) is studied. This should be mentioned and discussed further here.

EZ&MS: We are not sure what SU means. This part is about functional thresholds i.e. changes in systems behavior triggered by disturbances that exceed ecosystem resilience.... The examples we provide won't average out (the over-grazing example might lead to a collapse of runoff-runon systems, if anecic earthworm will vanish from the Kraichgau, overland flow behavior and sediment yields will change as this is a Hortonian landscape). The effect of the Rhine correction did also not average out, neither in the landscape (dropping groundwater tables) nor downstream (constructive interference of Neckar and Rhine floods, River bed erosion).

SU: 8) 3261, bottom: It is not clear why the energy dissipation is more efficient through macropore flow. Reword this part and add 2-3 sentences. Define ‘ capillary energy’.

EZ&MS: Matric potential/ suction is an energy density in soil. Wetting /drying means just decreasing/ increasing this part of total free energy in soil (we name it capillary energy and it is chemical energy in thermodynamic language). Macropore flow allows a fast flow of water towards locations of lower potential energy and an efficient redistribution of water to drier parts in deep soil. This is a process of dissipating incoming energy (Kleidon and Schymanski, 2008). We will explain this line of thinking better in section 6.2.4 of the revised manuscript. SU: 9) In some subsection titles (e.g. 2.1.3; 2.2.3) you have ‘I’, but it is not clear why.

EZ&MS: Fixed.

SU: 10) 3263, bottom: I do not see the tea-pot analogy here, as only the energy (external force) was changed but not the boundary conditions (see above).

EZ&MS: Change of external energy inflow means changing the boundary condition (see above).

SU: 11) P 3267: This paragraph is not very clear. What is the trigger for sub-surface storm flow? Why can so much isotopically old water discharge so quickly (see $>$ 150

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studies on hydrograph separation in different environments)? Which thresholds are at play here?

EZ&MS: We revised the part on subsurface flows, provided key references and discussed possible controls in section 4.1

SU: 12) I would find it at many places throughout the paper clearer, if the authors would use ‘state’ instead of ‘regime’; e.g. 3270, bottom.

EZ&MS: Maybe we have to explain this better: with regime is a range of initial and boundary conditions where the system shows the same macroscopic behavior: turbulent flow, preferential flow. River hydraulics, for instance, speaks of different flow regimes. We think the new manuscript explains this much better.

SU: 13) There seems to be an error in the section numbering at 2.3 EZ&MS: Fixed.

SU: 14) 3289, top: This paragraph is not clear. I suggest deleting it or expanding on this. 15) 3292: Define ‘functional architecture’.

EZ&MS: The new section of functional threshold does better explain what we mean with catchment architecture.

SU: 16) Figure 4 rather indicates gradual changes but no switches giving evidence for catchment scale threshold behavior. Did all storms at figure 5 have the same rainfall intensity such that only the total rain amount dominates?

EZ&MS: We disagree. In fact we showed that a simple to level threshold model reproduces exactly the same kind of plots, when properly accounting for uncertainty regarding the initial states (Zehe et al, 2007 WRR). (see new figure 4). This corroborates our claim that this study offers novel aspects on predictability in respect of threshold-driven phenomena. In this case all the storms had the same intensity, but Lehmann investigated the effect of different intensities in his study-

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