Geophysical Research Abstracts,
Vol. 10, EGU2008-A-10230, 2008
SRef-ID: 1607-7962/gra/EGU2008-A-10230
EGU General Assembly 2008

Threshold nonlinearities in hydrological and environmental systems: implications for observability and predictability

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The paper aims to provide an overview of the presence and role of threshold nonlinearities in hydrologic systems and subsystems and their implications for hydrological predictions. While hydrological systems and processes may be very different, on a meta-level they may yet exhibit striking similarities in their behaviour whenever thresholds are involved. One may define threshold behaviour as an "abrupt change" in the dynamics of a system that has more than one "dynamic equilibrium". Abrupt means that the change occurs much faster than the time scales (a) of the process/system itself and (b) of the external forcing of the system. The threshold behavior is triggered when a state variable, which is often called the "control variable" exceeds or drops below a threshold value, and we might observe this sudden change often in the form of an activity or triggering event. Regardless of these common characteristics, available field evidence demonstrates that threshold behaviours at different spatial scales are underlain by different physical (climatic, landscape) controls. For this reason we propose a hierarchy to characterize manifestations of threshold behaviour in the form of: (a) process thresholds: when hydrological processes suddenly emerge/vanish or show a drastic change such as the onset of overland flow and the switch from slow to fast infiltration. The threshold behavior of these processes is strongly determined by the nonlinear interaction of local structures/ properties with the soil moisture state and the rainfall intensity and depth. (b) micro- and meso-scale response thresholds: The fact that a process threshold has been triggered at the point scale is necessary but not sufficient for a larger unit such as an entire hillslope or a catchment to react in the same way. First order controls are attributes of patterns of controlling state variables such as connectivity or spatial coherency of states and forcings.. The complexity of the underlying controls, including that of the associated feedbacks, increases from the first to the last category. This is illustrated through examples of different forms of threshold behaviour taken from recent field and model studies. The examples range from local scale overland flow production and solute transport, hillslope and catchment scale flooding responses, stability of geo-ecosystems and their hydrological functioning in semi-arid regions. Additionally we discuss different approaches to modelling threshold behaviour and demonstrate that there appears to be a common "pattern" of predictability whenever threshold nonlinearities dominate the behaviour of hydrological systems regardless of scale. Predictability is inherently low in the vicinity of the threshold, simply because within the uncertainty of observed initial or boundary conditions we may not confidently predict whether the threshold is going to be triggered or not. In this respect, predictability of threshold driven systems is closely linked to the observability of critical state variables and climatic inputs.