Geophysical Research Abstracts
Vol. 15, EGU2013-11253, 2013
EGU General Assembly 2013

Self-organization, preferential flow and rainfall runoff behavior - is there a connection?

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In line with the studies of Kleidon et al. (2012) and Zehe et al. (2010) the proposed study analyzes mass flow related flows of free energy in open hydrological systems – hillslopes and small catchments – using thermodynamics methods. Why a thermodynamic treatment? A small part of the kinetic energy input from incoming rainfall is dissipated into heat and to break up soil aggregates. Depending on the partitioning of the incoming rainfall into overland flow and soil water, the remaining part of the incoming kinetic energy is partly transformed into potential energy of surface water and subsequently partly exported as kinetic energy of overland flow from the system; the rest is dissipated by frictional losses. The other part of rainfall infiltrates thereby increasing potential energy of soil water but depleting at the same time (gradients in) capillary binding energy of soil water, which again comprises energy dissipation into heat of immersion. Although, these mass fluxes are not associated with large heat fluxes, they reflect the overall conservation of energy as well as the second law of thermodynamics. They require thus a thermodynamic treatment, because tiny amounts of kinetic energy, surface energy and potential energy are dissipated into heat: this implies irreversibility and explains why water does not flow uphill. Soil hydraulic equilibrium (HE), arising from a balance in potential and capillary binding energy in soil, can be interpreted as a state of maximum entropy in soil. Soil water potential, defined as sum of matric potential and gravity potential, is in HE equal to zero along the soil profile. This corresponds to a state of maximum entropy due to a zero potential gradient, which implies due to Zehe et al. (2010) a state of minimum (Helmholtz) free energy.

Our first main objective is to quantify to which extent connected preferential flow path, in our case vertical macropores and the river network enhance flow velocities at a given driving gradient and thus power in the associated mass fluxes. This implies either an enhanced export of free energy in form of kinetic energy in case of the river net, or an accelerated reduction of potential energy of infiltrating surface water which implies a reduction free energy in form of capillary binding energy of soil water. We hypothesize (H1) that network like structures act as dissipative structures "serving the purpose" of reducing the relaxation time to a state of lower "free" energy in the entire system. This is because they minimize dissipative losses of kinetic energy along their extent. This faster relaxation towards a state of smaller free energy is deemed to be favorable for mechanic stability of the entire hydrological system because a) mass flows perform due to the enhanced export of kinetic energy less work on the system itself and b) mechanical stress from ponded surface water is quickly reduced by fast infiltration and preferential flow.

Our second main objective is, in line with the study of Zehe et al. (2010), the search for thermodynamic optimal hillslope architectures both with respect to the surface density of vertical macropores in soil and with respect to the spatial arrangement of soil types and macropores at the hillslope scale. In line with H1 we suggest (H2) that a hydro-geo-ecosystem is closer to a functional optimum than other possible configurations if it dissipates and exports more of the kinetic energy input from incoming rainfall by redistributing water against internal gradients and exporting water against macroscale geo-potential gradients. Note that H2 does not postulate that functionally optimal hillslope architectures necessarily exist, if they exist H2 implies however that they maximize entropy production and thus reduction of total free energy of the system at a "wisely" selected time scale. The surface density of apparent macropores does for instance control the tradeoff between Hortonian overland flow formation and infiltration, which implies a tradeoff between the amount of kinetic energy input from rainfall that is converted in to power associated with overland flow and power associated with soil water flows depleting gradients in soil water potential. Does this tradeoff imply an optimum surface density of macropores at the hillslope scale in the sense that power in soil water flow is maximized or reduction of free energy is maximized? In case such an optimum hillslope architecture existed, and in case that the evolution of the hydrological systems of interested was indeed in accordance with hypothesis H2, this optimal architecture should allow an acceptable uncalibrated simulation of the systems rainfall –runoff behavior (if the selected model structure can properly represent this

architecture).
We will address these questions and test the main implications of our hypotheses by means of numerical experiments with the physically based hydrological model CATFLOW. We use behavioral model structures as basic model setup, which have been shown to closely portray system behavior and its architecture in a sense that they reproduce distributed observations of soil moisture and catchment scale discharge and represent the observed structural and textural signatures of soils, flow networks and vegetation. Our test areas are the Weiherbach (Germany) and the Malalcahuello research headwaters (Chile), which are located in distinctly different hydro-climatic and hydro-pedological settings. Within the numerical experiments we will simulate the full concert of hydrological processes at the hillslope and headwater scales for meaningful perturbations of the behavioral model structure and compare them with respect to dynamics of free energy and production of power. These perturbations affect a) the river network and the geomorphology of the Weiherbach catchment, b) surface density of macropores in both catchments c) the spatial arrangement of soils and preferential pathways at the hillslope scale in the Weiherbach catchment.

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