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Functional units and lead topologies: a hierarchical framework for observing and modeling the interplay of structures, storage dynamics and integral mass and energy flows in lower mesoscale catchments

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The CAOS Research Unit recently proposed a hierarchical classification scheme to subdivide a catchment into what we vaguely name classes of functional entities that puts the gradients driving mass and energy flows and their controls on top of the hierarchy and the arrangement of landscape attributes controlling flow resistances along these driving gradients (for instance soil types and apparent preferential pathways) at the second level. We name these functional entities lead topology classes, to highlight that they are characterized by a spatially ordered arrangement of landscape elements along a superordinate driving gradient. Our idea is that these lead topology classes have a distinct way how their structural and textural architecture controls the interplay of storage dynamics and integral response behavior that is typical for all members of a class, but is dissimilar between different classes. This implies that we might gain exemplary understanding of the typical dynamic behavior of the class, when thoroughly studying a few class members.

We propose that the main integral catchment functions mass export and drainage, mass redistribution and storage, energy exchange with the atmosphere, as well as energy redistribution and storage – result from spatially organized interactions of processes within lead topologies that operate at different scale levels and partly dominate during different conditions. We distinguish: 1) Lead topologies controlling the land surface energy balance during radiation driven conditions at the plot/pedon scale level. In this case energy fluxes dominate and deplete a vertical temperature gradient that is build up by depleting a gradient in radiation fluxes. Water is a facilitator in this concert due to the high specific heat of vaporization. Slow vertical water fluxes in soil dominate, which are driven by vertical gradients in atmospheric water potential, chemical potential in the plant and in soil hydraulic potentials. 2) Lead topologies controlling fast drainage and generation stream flow during rainfall events at the hillslope scale level: Fast vertical and lateral mass fluxes dominate. They are driven by vertical and lateral gradients in pressure heads which build up by depleting the kinetic energy/velocity gradient of rainfall when it hits the ground or of vertical subsurface flows that “hit” a layer of low permeability. 3) Lead topologies controlling slow drainage and its supply, and thus creating memory at the catchment scale level: These are the groundwater system and the stream including the riparian zone. Permanent lateral water flows dominate that are driven by permanently active lateral gradients in pressure heads. Event scale stream flow generation and energy exchange with the atmospheric boundary layer are organized by the first two types of lead topologies, and their dominance changes with prevailing type of boundary conditions.

We furthermore propose that lead topologies at the plot and the hillslope scale levels can be further subdivided into least functional entities we name call classes of elementary functional units. These classes of elementary functional units co-evolved being exposed to similar superordinate vertical gradients in a self-reinforcing manner. Being located either at the hilltop (sediment source area), midslope (sediment transport area) or hillfoot/riparian zone (sediment deposit area) they experienced similar weathering processes (past water, energy and nutrient flows), causing formation of similar soil texture in different horizons. This implies, depending on hillslope position and aspect, formation of distinct niches (with respect to water, nutrient and sun light availability) and thus “similar filters” to select distinct natural communities of animal and vegetation species. This in turn implies similarity with respect to formation of biotic flow networks (ant-, worm-, mole- and whole burrow systems, as well as root systems), which feeds back on vertical and lateral water/mass and thermal energy flows and so on.
The idea is that members of EFU classes interact within lead topologies along a hierarchy of driving potential

gradients and that these interactions are mediated by a hierarchy of connected flow networks like macropores, root networks or lateral pipe systems. We hypothesize that members of a functional unit class are similar with respect to the time invariant controls of the vertical gradients (soil hydraulic potentials, soil temperature, plant water potential) and the flow resistances in vertical direction (plant and soil albedo, soil hydraulic and thermal conductivity, vertical macropore networks). This implies that members of an EFU class behave functionally similar at least with respect to vertical flows of water and heat: we may gain exemplary understanding of the typical dynamic behavior of the class, by thoroughly studying a few class members. In the following we will thus use the term “elementary functional units, EFUs” and “elementary functional unit class, EFU class” as synonyms.

We propose that a thorough understanding of the behavior of a few representatives of the most important EFU classes and of their interactions within a hierarchy of lead topology classes is sufficient for understanding and distributed modeling of event scale stream flow production under rainfall driven conditions and energy exchange with the atmosphere under radiation driven conditions. Good and not surprising news is that lead topologies controlling stream flow contribution, are an interconnected, ordered arrangement of the lead topologies that control energy exchange. We suggests that a combination of the related model approaches which simplified but physical based approaches to simulate dynamics in the saturated zone, riparian zone and the river network results in a structurally more adequate model framework for catchments of organized complexity.

The feasibility of this concept is currently tested in the Attert catchment by setting up pseudo replica of field experiments and a distributed monitoring network in several members of first guess EFUs and superordinate lead topology classes. We combine geophysical and soil physical survey, artificial tracer tests and analysis of stable isotopes and ecological survey with distributed sensor clusters that permanently monitor meteorological variables, soil moisture and matric potential, piezometric heads etc.
Within the proposed study we will present first results especially from the sensor clusters and geophysical survey. By using geostatistical methods we will work out to which extend members within a candidate EFU class are similar with respect to subsurface structures like depth to bedrock and soil properties as well as with respect to soil moisture/storage dynamics. Secondly, we will work out whether structurally similar hillslopes produce a similar event scale stream flow contribution, which of course is dependent on the degree of similarity of a) the rainfall forcing they receive and b) of their wetness state. To this end we will perform virtual experiments with the physically based model CATFLOW by perturbing behavioral model structures. These have been shown to portray system behavior and its architecture in a sense that they reproduce distributed observations of soil moisture and subsurface storm flow and represent the observed structural and textural signatures of soils, flow networks and vegetation.