Towards Theories that Link Catchment Structures and Model Structures

Proposal for a Special Issue in Hydrology and Earth System Sciences

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Hydrological research and practice have traditionally been concerned either with predictions of water related hazards such as floods and droughts, or with water resources management. This has motivated us to focus on prediction of **integral systems responses** - mostly stream flow - using **hydrological model structures** that represent the process patterns and redistribution of water and mass inside a hydrological system, based on **parsimonious (and therefore simplified) concepts**. This story of ongoing success seems to require a) a **certain minimum catchment** size so that errors arising from simplified process conceptualisations have the opportunity to average out, and b) **stationarity** of both the climate conditions and of the hydrological system itself. Even when ignoring the challenge of coping with hydrological system change (an increasingly optimistic endeavour these days), we still struggle to provide predictions for systems that exhibit organised complexity at the intermediate scale of 5-200 km^2. Following Dooge (1986), these can be characterized as heterogeneous systems that display “some degree” of organisation, which is both too small to be treated with simple second order statistics and too large for the application of a reductionist, deterministic treatment based on the Darcy-Richards paradigm.

To cut this Gordian knot in hydrology will require the solution of three cardinal problems, which we call: **1**) **the structure problem, 2) the context problem** and **3) the transience problem**.

1) The Structure Problem: This consists of two parts which can be understood as the bottom-up and top-down perspectives.

1a: The structure problem viewed from a bottom-up perspective (i.e., how does catchment structure control integral catchment function/response?)

The surface and subsurface bio-geo-morphic architecture of a catchment system seems to exert the **dominant control** on organization of hydrological process in the **rainfall driven context** (i.e. on storage and on fast **vertical and lateral redistribution** of water, dissolved mass, and energy within the system). This is because it is the geomorphic and pedological architecture of the catchment that determines the volumes of subsurface stores and the topology/connectivity of surface and subsurface **preferential flow** paths (for instance, cracks and pipes acting in concert with biomorphic structures such as animal burrows and root channels). In systems of intermediate complexity the time scales of these fast processes can be of the same order as the timescales of downstream transport in the river system. Consequently, the vertical and lateral transport distances are too small for the central limit theorem to apply and we **cannot assume** fully mixed conditions.

Residence time distributions of water and substances within the catchment are therefore non-Gaussian, and this implies that the higher order moments (beyond mean and variance) of the probability density functions of subsurface flow velocity, as well as information about extremes, and the covariance structure and connectivity of the flow field are necessary to characterize residence time distributions of water and dissolved substances in the subsurface. These characteristics very likely constitute a fingerprint of the heterogeneity of the pore space and the topology of the preferential flow paths that interact with the rainfall forcing. Our understanding of the underlying cause-effect relationships that trigger and control fast non Gaussian flow responses is currently insufficient to predict these processes at scales larger than the 100 by 100 m scale, for at least three reasons: 1) Current technologies do not enable us to observe the underlying structures and fast flow processes *in situ*, 2) We struggle with how to quantify relevant connectivity of fast flow paths and thus how to represent these structures in physically based models of the reductionist type, and 3) We do therefore not understand (in a quantitative sense) which characteristics of the "network of connected flow paths" controls which part of the residence time distribution at larger scales. Consequently, when we observe non-Gaussian residence time distributions at larger scales, we are unable to infer backwards to the underlying structures.

1b: The structure problem viewed from the top-down perspective (i.e., how to infer dominant catchment structures and processes by attempting to reproduce observed integral responses/functions?

At larger scales we can usually observe only the integral effects of catchment heterogeneity and structure, such as residence time distributions of water leaving the catchment - the hydrograph - or (in the subsurface) in form of tracer breakthrough curves. Due to their **integral nature,** such signals are essentially of "low dimension", which has two important implications for the inference problem. The first one relates to the problem of model structure uncertainty. Because the problem of parameter estimation for conceptual hydrological models can become under-determined (except in the case of *very* simple (low-dimension) models), it is generally the case that several sets of model parameters will provide acceptable reproduction of an integral signal (equifinality). While multi-objective calibration (via attempts to reproduce more than one integral signal) can help to better constrain parameter uncertainty, it can be difficult to apply if additional target variables are lacking at the integral scale(s) or, as in the case of residence times, when there is no straightforward approach to link such integral responses to conceptual model states and/or parameters. Of course, another possible cause of equifinality is that part of the indeterminacy may be essentially system inherent, in the sense that several types of architectures of subsurface flow pathways may yield the same integral residence time distribution.

The inherent drawback of conceptual models is that their ability to reproduce an integral function at the catchment outlet does not necessarily imply that the dynamics simulated within the model domain can be expected to be consistent with the "true" process dynamics within the catchment. In particular, conceptual model representations of lateral flow processes within the catchment are typically based on well-mixed reservoirs, even though it is well known that the system is not well mixed. We cannot, therefore, infer backwards regarding many (if not most) of the dominant catchment structures and processes that combine to produce the integral catchment response. But, this ability is precisely what is needed to tackle the hydrologic change problem, because the bio-geo-morphic catchment architecture can be expected to adapt to changes in the system boundary conditions (thereby giving rise to changes in integral catchment function). Even if we ignore the hydrologic change problem, we remain trapped in the standard paradigm. We must move forward – to achieve predictability for ungauged basins (the PUB problem) we must develop methods that take us beyond the traditional problem of hydrograph reproduction.

2) The Context Problem: Addressing catchment function(s) in the context of both energy and rainfall drivers.

Till now, hydrology has focused primarily on describing mass balance at catchment scales, and mainly during rainfall driven conditions. In terms of **catchment functions** this addresses mainly the function of *drainage*, and consequently directs attention to the soil and landscape structures that control drainage. Clearly, this focus is too narrow to facilitate understanding of the many **hydrological functions of a catchment**, particularly when considering its responses to change. In fact, roughly 60% of the water balance worldwide happens in an energy driven context, where evaporation and transpiration are the dominant hydrological processes and those structures that determine drainage in the mass driven context (lateral and vertical preferential flows) are of relatively low importance. In the energy driven context, functional response can depend on vegetation, aspect, slope, capillary binding energy of water in soil, and much more. Further, the functional units may largely operate in parallel due to evapotranspiration being mainly a vertical exchange process that **organizes the exchange of energy** between the catchment and the atmosphere.

We therefore suggest that a new theory of catchment hydrology must link mass and energy balances, simply because the dominant structures in each of these different contexts are different. Vegetation is the key mediator in an energy driven context. We do not understand and are currently unable to predict the transition from energy- to water-limited transpiration of most plants. A key to progress in this respect might be that we understand transpiration in the context of ecological optimality, as recently suggested by Schymanski et al. (2009). Different plants have different strategies to produce biomass, thrive within their “niche”, survive extreme conditions and reproduce. Understanding and predicting transpiration as a “side product” of plants population dynamics is a step towards understanding and predicting change of catchment functions under transient conditions.

3) The Transience Problem: Transient environmental systems and feedbacks to catchment function

The architecture of a catchment – viewed as a closely coupled hydro-geo-eco system – is characterized by typical patterns and structures of topography, soil and vegetation that co-evolve over “long” time scales (since the last ice ages in Europe and since several million years in Australia; Dietrich and Perron, 2006). On the one hand, these structures and landscape attributes “organise” the drainage and energy exchange of the catchment in the present. On the other hand, these structures have themselves been shaped by the same dissipative processes – past flows of water, mass, and energy – in a self reinforcing manner, which must necessarily be true for these structures to persist. Self reinforcement and positive feedbacks imply that certain structures / catchment architectures are “more favourable / closer to being functionally optimal” than other structures. Connected structures can for instance be deemed to optimise “drainage” (at the scale of a river basin (Rodriguez-Iturbe and Rinaldo, 2001) but also at the hillslope scale (Zehe et al., 2010)) in relationship to the intensity of the mass inflow into the system. Structures allow maintaining large volumes/masses to flow at a low driving gradient. This is both favourable for “exporting excess water” while also allowing redistribution of water within the soil profile. It has been suggested that both processes can accelerate the relaxation of a system towards thermo dynamic equilibrium (Zehe et al. 2010)

We suggest that the resilience/dynamic stability of a hydro-geo-ecosystem configuration – the extent of disturbance a system will tolerate without responding with drastic qualitative changes - may be a key to understanding why catchment structures have evolved in an optimality context. To understand systems resilience we must therefore understand the **feedbacks** between biota and abiotic processes in the catchment, and especially the controls they impose on the formation of structures and catchment functions.

To conclude, we believe there is a real need to advance towards a new hydrological theory that treats catchments as organised bio-geo-morphic systems. This is necessary to guide: (i) the study of landscape architecture, (ii) the choice of hydrological model structures, and (iii) current and future approaches to the observation of landscape structures, processes, and catchment responses, all within a flexible and unifying framework that is underpinned by the notion of catchment and ecosystem function. We believe that movement towards such a theory is crucial to (a) re-unify the currently fragmentation within the community (including the artificial distinctions between "theoreticians", "modellers" and "experimentalists"), and (b) prepare and mobilize to face the challenges being posed by hydrologic change. The fundamental challenge is to achieve the right levels of complexity that account for the "grains of truth" that govern how catchment structures impact integral catchment functions, while avoiding both over-simplification and losing ourselves in too much detail.

This special issue solicits contributions that address the following how, what, and why questions at catchment scales ranging from hillslope to lower mesoscale, thereby helping to link the bottom-up and top-down approaches and, in this way, help achieve movement towards unified theories at the catchment scale. Questions of interest include, but are not limited to:

- How to detect and quantify catchment structures, especially in the subsurface?
- How does structure control integral hydrological response at higher scales?
- How to infer model structures in a top-down manner, building on representations of key landscape (or other) units in a more realistic manner?
- What model structures better allow reproduction of the current bio-geo-morphic system architectures (e.g., better reproduction of volumes of surface and subsurface stores and topologies of surface and subsurface flow paths)?
- How do ecological, pedological and geomorphological behaviours control processes and functioning of hydrological systems?
- How to account for the context dependence of process organisation within catchments?
- Why did a system evolve the way it did, in adaptive response to past hydro-geo-morphologic and biotic processes, and what can we learn from this to address future prediction challenges?
- What roles do feedbacks between biota and abiotic processes play in controlling structure formation and in stabilizing catchment functions?

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