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The hydrological system as a living organism

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Abstract. Hydrology is the bloodstream of the terrestrial system. The terrestrial system is alive, with the ecosystem as its active agent. The ecosystem optimises its survival within the constraints of energy, water, climate and nutrients. The key variables that the ecosystem can modify are the controls on fluxes and storages in the hydrological system, such as: the capacities of preferential flow paths (preferential infiltration, recharge and subsurface drainage); and the storage capacities in the root zone, wetlands, canopy and ground surface. It can also, through evolution, adjust the efficiency of carbon sequestration and moisture uptake. Some of these adjustments can be made fast, particularly rootzone storage capacity, infiltration capacity, vegetation density and species composition. These system components are important controls on hydrological processes that in hydrological models are generally considered static and are determined by calibration on climatic drivers of the past. This leads to hydrological models that are dead and incapable to react to change, whereas the hydrological system is alive and will adjust. The physical law driving this evolutionary process is the second law of thermodynamics with the Carnot limit as its constraint. This physical limit allows optimisation techniques to explore the reaction of the hydrological system and its components to change in climatic drivers. This implies a new direction in the theory of hydrology, required to deal with change and addressing the Unsolved Problems in Hydrology.

Keywords. UPH 19; ecosystem-based hydrology; new theory

1 Introduction

Physical processes in the atmosphere, the hydrology, ecosystems, and geology are interconnected, influencing each other with numerous feedbacks at a wide range of temporal scales. This was realised as early as the 18th century by Alexander von Humboldt who did empirical research in many parts of the world and came to the conclusion that all these processes were connected (Wulf, 2015). In present times, in the science of hydrology, specialisation and reductionism has forced us towards fragmentation and focus on laboratory processes instead of system-wide and interdisciplinary research. This has led to wide applicability of laboratory scale-based methods that have been erroneously upscaled to catchment level. The most well-known examples are the Richards and Darcy equations which, supported by ever stronger computational power, are applied at scales for which they are not fit. They may give reasonable answers, but not for the right reasons, demanding numerous calibration parameters at different scales. At catchment-scale, these concepts are flawed.

The main problem with these lab-scale-based methods is that they neglect preferential flow patterns that are dominant in nature. Wherever water moves through a medium, fractal-type patterns appear. These are omnipresent in nature: in the veins of leaves, in branches and root systems, in rills of overland flow, in alluvial vans, in seepage of water, in soil infiltration, in sub-surface drainage patterns, in the shape of river networks and in the veins of our own body. Although hard to observe, these drainage patterns are also present in the groundwater system, which is the cause of the mismatch between the travel times of dissolved substances and the water in predominant groundwater models.

These patterns are formed by different processes at different time scales. They evolve over time and are not static. The speed of pattern formation in geo-morphological processes depends on the erodibility and consistency of the medium through which the water flows and often has long time scales. Biological processes of pattern formation are much faster.

But although these processes are dominant, main stream hydrological models don't take them into account.

Instead, traditional models: (1) split-up the Earth in small fragments, destroying patterns, preferential pathways and system behaviour; (2) consider the substrate and ecosystem static; (3) are dead and don't consider the ecosystem as an active agent which can adjust to change; (4) are unnecessarily complex; and (5) rely heavily on calibration. This goes against what we observe in nature and there is an urgent need for a new hydrological theory that considers the hydrological system as a living organism (Savenije and Hrachowitz, 2017). Catchments are alive!

2 Towards a new theory of hydrology

The ecosystem, as the most active agent in the natural system, manages the water. It does this for a simple evolutionary purpose: to optimise survival. If an ecosystem had not managed its water resources well, it would simply no longer be there. People, who also manage the water system, obey similar laws of survival, by trial and error. But in the head waters of a catchment, the ecosystem is dominant and has a high potential for adaptation under existing climatic, landscape and geological constraints. With the ecosystem as the active water manager, the hydrological system is alive and able to adjust to changing climatic or human-induced circumstances (e.g. Nijzink et al., 2016). But although the ecosystem-atmosphere-hydrology-geology interaction is very complex, surprisingly, hydrological laws we observe in nature, such as the linear reservoir, resistance to flow, Budyko's curve, Darcy's equation, etc., are often described by simple equations (e.g. Dooge, 1986, 1997; McDonnell et al., 2007). How can this be explained?

The only physical law that has a unique direction in time is the second law of thermodynamics, which functions at all scales, and which states that entropy can only increase. The Earth is a "dissipative structure" that exchanges low entropy for high entropy. It does so at Maximum Power, close to the "Carnot limit" of a dissipative engine (Kleidon, 2016). The ecosystem that has the potential to evolve, appears to operate close to the Carnot limit, the most efficient way in which free energy can be converted into work. It appears that maximizing the Power of a natural process often leads to surprisingly "Simple Laws" (Kleidon et al., 2013).

Hydrology is the bloodstream of the ecosystem. There are several ways in which the ecosystem manipulates the hydrological system. The canopy interception not only provides immediate feedback to the atmosphere maintaining atmospheric moisture, it also channels water to dominant dripping points and stemflow, directing the water to places where infiltration is facilitated and preventing surface runoff. Through preferential patterns this infiltration recharges the root zone moisture and percolation to the groundwater. If there is too much water, then the excess moisture is evacuated through preferential sub-surface drainage patterns that are formed under the root zone. In addition, the ecosystem creates sufficient storage in the root zone to overcome critical period of drought. Hence, the ecosystem stores and partitions the precipitation to its advantage and in doing so determines the parameter values of hydrological models.

The root zone storage capacity is a crucial parameter in all hydrological models, which is normally calibrated, but which can be predicted by a simple water balance method similar to the way in which engineers size a reservoir (Gao et al., 2014a). Considering hydrological systems as a living, evolving ecosystem holds the key to independent determination of model parameters, such as the root zone storage capacity (De Boer-Euser et al., 2016; Wang-Erlandsson et al., 2016), and its spatial distribution (Gao et al., 2019), but can potentially also be applied to interception, infiltration and drainage capacity.

3 How should we model catchments?

The essence of hydrological modelling is to translate what we observe in the actual environment to the model space. From our real-life observations, we formulate a perceptual model, followed by a conceptual model and a model structure, and finally mathematical equations that quantify these processes (Beven, 2011). Each of these steps is equally important, but – in the process – we should take the following in consideration:

1. Accounting for landscape in the model structure. The landscape reflects different formation processes that have developed over longer time scales, but which have different dominant runoff processes, such as surface runoff, sub-surface runoff, groundwater recharge, groundwater seepage, freeze-melt cycles, etc. (e.g.: Savenije, 2010; Gharari et al., 2011; Gao et al., 2014b).
2. Accounting for the geology in relation to model structure, defining model structure and slow groundwater processes (Fenicia et al., 2014).
3. Accounting for land use, since different land covers will have different phenology and evaporation, storage and runoff characteristics.
4. Considering the ecosystem as the active agent that manipulates the hydrological processes to optimise its survival (Savenije and Hrachowitz, 2017).
5. Using the 2nd law of thermodynamics to try to find the laws and parameters that govern the energy transitions, by maximizing the power of transferring free energy to work (the Carnot limit).

Although the last item is a deeper item for research, the first four are very practical and can be applied readily (Mao and

Liu, 2019; Bouaziz et al., 2020). This ecosystem-centred approach has the potential to lead to more robust equations with physical parameters, which reduce the need for calibration and enhance our capacity to predict hydrological behaviour in ungauged basins.

4 Tipping points and the limits of ecosystems to adjust

A good illustration of how ecosystems adapt to climatic drivers and of transition points that occur when an ecosystem is no longer capable of meeting atmospheric conditions is provided by Singh et al. (2020). In a number of transects through Africa and South America they showed how ecosystems adapt their root zone storage capacity to the occurrence of drought and dry spells, indicating the point where evergreen rainforest gradually switches to less dense (often deciduous) forest, such as the African Miombo forest, until a maximum root zone storage is achieved, after which a transition occurs to savannah and dry land vegetation. These tipping points are crucial because they are often strengthened by positive feedbacks, such as in the transition of rainwater harvesting tiger bush to barren land.

5 How to deal with human interference

One may question whether the ecosystem-centred approach also applies to parts of the world that are strongly influenced by human interventions. Clearly in hydrological modelling it is required to take into account land use. If the use is a monoculture, whether covered with forest of agricultural crops, then it is important to distinguish between annual or multi-annual crops. A multi-annual single-species crop will obey the same survival rules as a natural ecosystem, although adjustment to change is different. In a landcover with a wide range of species, adjustments can occur not only by species adaptation but also by invasion of more fit species, changing the composition of species. In all cases it is important to take into account the ecosystem traits. Evergreen forest will have to store enough water to deal with dry spells or dry seasons, catering for a dry period with a longer return period for survival (e.g. once in 20–30 years). Deciduous forests have an additional option. They can shed their leaves earlier than normal in case rains stop early in the wet season; this happens for instance in the African Miombo forest. In the Miombo, some trees can even tap into the deeper groundwater. The return period can thus be shorter than for evergreen forest (e.g. once in 10–20 years). Grasslands have even more options. They can go dormant, stopping evaporation until the next rainy season starts. As a result, they cater for within season droughts with a return period of about once in 1–2 years. Single year crops act in much the same way as grass land, catering only for within year dry spells. Finally, irrigated crops react again differently, whereby the human being aims at a crop survival of about once in 5 years, depending on the value of the crop. In urban areas, one should look at the vegetation cover and apply the approach to the vegetated part only.

Of course, it still requires creativity of the modeller. The essence is the different frame of mind, putting the ecosystem at the centre of the approach; popularly said: “try to think like an ecosystem”. Ask yourself the question “if I were the ecosystem, what would I do to improve my survival and reproduction?”.

6 Conclusion

UPH #19 of the 23 unsolved problems in hydrology reads: “How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics?” (Blöschl et al., 2019). This paper offers a promising new venue for addressing this question. Considering the hydrological system as a system that can adapt itself to changing climatic and human circumstances, while trying to optimise its conditions for survival, is a way to discover parameter values that agree with an unknown future. Instead of confronting a calibrated model, tuned to the past (i.e. a dead model), to changing atmospheric drivers, one should use a living and adaptable model that corresponds with these changing circumstances. Partly that can be done by evolving parameter values, and partly by “exchanging space for time”, i.e. by lending the ecosystem characteristics from other parts of the world where these climate conditions already exist (e.g. Bouaziz et al., 2022).

Dealing with a world that is continuously changing is the main challenge of the coming decades (Sivapalan et al., 2012; Montanari et al., 2013) and the ecosystem-centred approach may be a promising way to address this challenge.

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