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What are the main research challenges in hydrology?

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The science of hydrology finds itself in a difficult situation. The PUB decade has told us that we are not very good at predicting hydrological behaviour in a data scarce environment. How good is our science if we are so uncertain about our predictions? On the other hand experienced hydrologists may say that we know enough for most practical problems. We can apply standard approaches or models to a variety of situations and if we have enough data we can make reasonable predictions of river flow, groundwater levels or water availability. In the world of applied hydrology we have enough knowledge to design dams, well fields, embankments, irrigation schemes, water intakes, and the like. There are proofs galore of impressive hydraulic works, all around the world.

But for a scientist these accomplishments are hardly satisfying. The fact that a model works is no proof that the theory is correct, or that we understand the processes behind it. A hydrological scientist will rightly point out that there is still a lot that we don't understand. Although we can apply rainfall-runoff models to catchments, we fail to understand how exactly the water behaves, or how long it resides within the different compartments of the system. From a science perspective this is very unsatisfactory, even though engineers may argue that there is no problem as long as the models give reasonable outputs.

So is our science adequate or are we still in the dark and do we fail to understand precisely how our hydrological system functions, much like a clockmaker who can read the time from a watch, but fails to understand how precisely the clockwork works?

Hydrology is about the occurrence and flow of water (or moisture) through the Earth system. In that sense it is similar to other Earth sciences, such a climatology, oceanography or hydraulics. But this similarity is treacherous, because it is different in one fundamental aspect. Unlike other Earth sciences, in hydrology the medium through which the water flows is unknown. This medium is highly heterogeneous at all scales and largely unobservable. Knowing just the basic laws of conservation of mass and momentum is not sufficient because we lack geometrical relationships that define the medium through which the water flows. We often call these equations the closure relations, because they are the equations that we lack to make the system predictable. As hydrologists we know we can measure the characteristics of this medium indirectly by setting up an experiment or by calibration, but these characteristics are scale dependent and hence need to be (re-)calibrated if we move to a different scale. This makes hydrology highly empirical and dependent on calibration.

Other scientists often fail to see this fundamental aspect of hydrology and may blame hydrologists for not being able to forecast the system's behaviour without calibration. They also have closure problems, but having observable system boundaries they have been able to develop scaling laws that allow them to use closure relations for new situations. For instance they developed the Manning equation for the interaction with the river bed, with tabulated coefficients for use in a wide range of hypothetical cases. A similarly simple hydrological equation such as the Darcy equation, however, always requires calibration because we cannot observe or predict subsurface characteristics. And if it is difficult for an aquifer, then we can imagine how difficult it is for a catchment.

By now we know that the reductionist approach, that aims to solve this problem by starting from the smallest element and to upscale to the catchment scale, does not work. Not only because it would require lots of data, but more importantly because it is a flawed concept. It neglects the fact that the hydrological system is organised and that in upscaling there are scaling laws that we need to obey. But what are these scaling laws? That is the fundamental question.

We do know that in hydrology sometimes surprisingly simple laws come to the fore, however complex the hydrological system is. Here lies the opportunity. There are physical processes at play behind the evolution of hydrological patterns. Because the formation of catchments is through erosion of the substratum and the

deposition of its sediments, the formation process is the result of energy dissipation and hence entropy generation. Somewhere the answer lies in applying entropy laws to hydrology and to the characteristics of the substrate.

For me, finding the laws that govern the characteristics of the substrate is the largest challenge for the science of hydrology in the coming decade. It requires that we embrace the Darwinian science of evolution and apply it to catchment formation processes. There is a lot that we can learn from geo-morphologists, geologists, physicists and ecologists. We have to find the laws that are behind the patterns that exist in and under the landscape and subsequently find the causes for the existence of relatively simple hydrological laws, such as the linear recession of a hydrograph, Lacey's equation for the width of a channel, the exponential shape of an estuary, or the predictability of the Budyko curve. And I would be very happy if we could develop the scaling law for the threshold function of the unsaturated reservoir, which can so well be described by a beta-function.

Only if we try to find the physical explanation for these relatively simple laws can we claim that hydrology is a true Earth science, and can we start to make our science a predictive science.