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Hydrology and Earth System Sciences

HESS Opinions "The art of hydrology"*

H. H. G. Savenije

Department of Water Management, Delft University of Technology, Delft, The Netherlands

Unesco-IHE, Institute for Water Education, Delft, The Netherlands

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Abstract. Hydrological modelling is the same as developing and encoding a hydrological theory. A hydrological model is not a tool but a hypothesis. The whole discussion about the inadequacy of hydrological models we have witnessed of late, is related to the wrong concept of what a model is. Good models don't exist. Instead of looking for the "best" model, we should aim at developing better models. The process of modelling should be top-down, learning from the data while at the same time connection should be established with underlying physical theory (bottom-up). As a result of heterogeneity occurring at all scales in hydrology, there always remains a need for calibration of models. This implies that we need tailor-made and site-specific models. Only flexible models are fit for this modelling process, as opposed to most of the established software or "one-size-fits-all" models. The process of modelling requires imagination, inspiration, creativity, ingenuity, experience and skill. These are qualities that belong to the field of art. Hydrology is an art as much as it is science and engineering.

1 What is hydrology?

What is hydrology? One would think that this is a trivial question. Hydrology has been long since defined. In my own words, it is the science that describes the occurrence and behaviour of water above, over and through the Earth. It is an earth science. However, depending on someone's background, the interpretation of this definition may vary. People from specific disciplines sometimes have a very particular interpretation of what hydrology is. Some scientists merely look at hydrology from the limited perspective of their own domain. A soil scientist or an agricultural engineer limits it to the hydrology of the unsaturated zone; a geo-hydrologist constrains it to the processes occurring in the saturated zone only.

I once met a geo-hydrologist (who claimed to be a hydrologist) with whom I had an interesting chat about groundwater flow. When I asked him if he was interested in recharge, he answered that this was not his field of interest since he was merely interested in groundwater. I was amazed. It is the same as a catchment hydrologist not being interested in rainfall. Although a true story, it is exceptional. Most hydrologists do look beyond the boundaries of their specialism. Still there are many cases where analysts failed to see the important interactions and feedbacks that become apparent when different domains are involved, and more interestingly, cases where apparent anomalies could be explained by looking beyond the limits of subdisciplines. For instance my colleague Piotr Wolski (Wolski et al., 2006) was the first to explain an "anomaly" in the hydrological behaviour of the Okavango delta, an inland wetland fed by the Okavango river originating in Angola. The word "anomaly" is written between quotation marks because previous authors called this phenomenon an anomaly, whereas it was purely physical behaviour that happened to disagree with their perception. Until then, models consistently underestimated the outflows of the main delta branch during a seven-year period (1974–1981) while performing well during the remaining part of the time (1968–2003). The "anomaly" disappeared when he considered the appropriate surface water-groundwater interaction and the interplay

Correspondence to: H. H. G. Savenije
(h.h.g.savenije@tudelft.nl)

between local rainfall, local evaporation and the floods generated by the Okavango river. Before that, rainfall-runoff modellers and groundwater modellers had not been able to solve this problem. In fact they had created the "anomaly" themselves, by taking a limited perspective of the system (merely looking at surface water flow, or concentrating entirely on the groundwater).

There is another interesting misconception about the Okavango delta. Most scientists believe that the delta, which consists of thousands of islands, is the deposit of the sediments carried by the Okavango river. This is a plausible and obvious misconception, since most – if not all – alluvial deltas in the world have been formed by riverine sediments. However, this is not true for the Okavango delta. The water of the Okavango river does not carry much sediment. The fine sediments that make up the delta have not been brought there by the river in solid form. If that were the case, the flood waters of the Okavango should be muddy, but they aren't. 90% of the catchment of the Okavango river consists of very permeable Kalahari sands, and the Okavango floods are almost completely groundwater generated. The water in the delta is crystal clear, even during floods. There is some bed load transport but this is not sufficient to explain the sedimentation in the delta and cannot explain the formation of the islands.

What has shaped these islands if the floodwaters don't carry sediments? Gumbricht et al. (2004) showed that the islands have a range of sizes that completely fit fractal behaviour, suggesting some self-organising principle for island formation. Gumbricht et al. (2005) came up with an interesting explanation, which comes from yet another discipline: chemistry. The Okavango river carries very small amounts of salts, but considerable amounts of calcite and silica in solution, stemming from the Kalahari sands that it drains. In the delta, the floods feed the islands by a steady groundwater flow. Eventually, the silicates precipitate on the island fringes when the water is transpired by vegetation. This also explains why the island fringes, where the trees grow, are the highest part of the islands. The trees lift themselves up through transpiration. As they transpire, silicates precipitate in their root zones, lifting the trees into the air, at time scales beyond our visibility, of course. I know there are several people who disagree with this idea, but it is clearly a very interesting theory that explains the very low concentrations of solutes in the river water, even though more than 90% of the water evaporates before it reaches the foot of the delta.

Another "anomaly" arising from a limited view on hydrological processes, is the consistent bias that some analysts observed in the runoff prediction of the Meuse river from 1930 to 1970. The Meuse river flows from France through Belgium to the Netherlands. Most of its runoff is generated in the forests of the French and Belgian Ardennes. Modellers fitted the HBV model to a hundred years of data and found that during this 40 year period the model predicted substantially higher runoff than was observed. After compensating for land use change and checking for consistent errors, the bias remained. Most astonishingly, the same bias was seen in the neighbouring Mosel catchment: a mystery not easy to solve when merely looking at rainfall-runoff behaviour.

Until then, people studying this phenomenon had used the well-established HBV model. My student Fabrizio Fenicia (Fenicia et al., 2008a) took a wider perspective. The question to answer was: which process could have been different during this period? Would it be possible that the evaporation process varied over time? The forest of the Meuse and Mosel were intensively exploited for wood production during the period of the bias. It was a period of heavy industrial and mining development in the region. Production forests are known to have a much shorter rotation period (stand age) than the mature forests that nowadays become more prominent. Hence, would it be possible that forest transpiration was measurably larger during the period of active mining? By combining forest hydrology with catchment hydrology, and by developing his own conceptual model (not using a "one-size-fits-all" model), he was able to explain the "anomaly".

These are merely examples of how broadening one's perspective and a multi-disciplinary approach can help to find the solution to an "anomaly" arisen from a too limited view on hydrology. I am sure the reader will have other examples from his or her own experience. So, to come back to the question of what hydrology is, the first and foremost aspect of hydrology is that it is an interdisciplinary science that cuts across earth and life sciences.

2 Hydrology versus hydraulics

Some professions are limited by definition. These we cannot blame for having a limited perspective. Take, for instance, hydraulic engineering. Hydraulic engineers describe the behaviour of water within well-defined boundaries. There is nothing wrong with that. The problem appears when hydraulic engineers start to apply their "physical laws" to hydrology.

Compared to hydraulics, the science of hydrology is fuzzy. Hydraulics takes place within clear, often imposed, boundaries. The interactions with the boundaries are generally parameterised: e.g. the channel roughness, the equivalent grain size, the roughness length. The special character of hydrology is that it describes the movement of water through an ill-defined, often unknown or un-observable medium. The interaction with the medium is strong. In fact the water creates the pathways through which it flows and – as a result – the shape and properties of the medium are implicit in the hydrological equations (e.g. the linear reservoir, the unit hydrograph, the Muskingum method). One could say the same of hydraulics in erodible channels where there also is an interaction between the water and the medium, but here the channel is observable, and as a result often prescribed in large detail. In hydrology, the shape of the medium is not prescribed and seldom observable. As a result, the dominant paradigm of hydraulics is reductionism, or a bottom-up approach (Sivapalan et al., 2003), whereas in hydrology it is (or should be) empiricism and a top-down approach looking for links with fundamental laws of physics. The latter implies that we try to find physical laws that describe the patterns emerging from the interaction between water and the medium through which it flows.

However, reductionism is not the answer to hydrology. The dominant processes in the hydrological cycle only become apparent at larger scales, and these processes are not just the sum of processes occurring at micro-scales. There are numerous scale breaks in hydrology when we move from the micro-scale to the macro-scale, mainly as a result of heterogeneity of the medium through which the water flows. Why do reductionists find this so difficult to see? The answer lies in the human scale. A human being is blinded by the scale at which he observes hydrological processes. We see the water as it drips on the ground, infiltrates, percolates to the groundwater, flows over-land or in streams. As a result, we think we understand the physical processes that generate runoff. What we see with our own eyes, however, is only relevant at the scale at which we observe it: a spatial scale ranging from a few millimetres to maybe 100 m. However, catchments have much larger scales, ranging from a few kilometres to hundreds or thousands of kilometres. The mistake we make is that we think that what we observe at the human scale is similar to the behaviour at river basins or continental scale. Beven (2007) also pointed this out when he said that one of the main challenges for hydrology is to observe hydrological processes at the scale of our models. Our problem is that we are too small. If we were giants we would be better capable of understanding catchment behaviour. This is the "Paradox of the Ant". The ant maybe understands what happens within the ant heap, but it can't see how the ant heap is part of a larger system. Even if billions of ants would join forces, they would still not be able to see the larger pattern which a giant would see at a glance. Only when we zoom out can we see the picture more clearly.

Please don't get me wrong. I don't mean to rank hydrology higher than hydraulics. What I want to bring out is that these are different disciplines that serve different purposes. It is necessary to make the distinction since it has occurred to me that there are many professionals who think that an advanced hydraulic model, 3-D, morpho-dynamic and even including dissolved substances, represents reality and that science has not much to add. Unfortunately practitioners often confuse a mathematical tool (advanced though it may be) with reality. The dominant thought is that if a model can mimic reality, then it *is* reality. In hydrology we know that this is not true. Just think of the discussion on equifinality (Beven, 1993; Savenije, 2001).

Maybe the best example of where hydraulic engineers, through reductionist thinking, developed a complex hydrological model is Mike-SHE. The underlying idea that upscaling physical laws within imposed morphologies will lead to a reliable description of reality is flawed in my opinion. It is based on the perspective of the ant. The concept is wrong and, as we know, has led to serious problems of equifinality and high predictive uncertainty.

We should realise that hydrology and hydraulics are essentially different disciplines. Hydrology has unclear, intertwined and often non-observable boundary conditions. The medium through which the water flows is part of hydrology and has been shaped by the water itself. It uses a top-down and empirical approach to find emerging patterns and organising principles. Hydraulics, on the other hand, has observable or imposed boundary conditions and – as a result – makes use of a bottom-up and reductionist approach. It is a technology rather than a science. It studies a compartment of hydrology without considering the feedbacks and interactions that make it part of the hydrological cycle, and often (except for river morphologists) without considering the interaction with the boundary conditions through which it flows.

In this respect many geo-hydrologists are in fact hydraulic engineers, unless of course they are interested in the interactions with the surrounding compartments and in how the water has shaped the medium through which it flows. Above all they should consider the groundwater as an integral part of the hydrological cycle. A similar mistake is made by hydrologists who consider river runoff as a surface process. Such "surface" hydrologists have an equally limited view of hydrology as the "groundwater" hydrologists who only look at what happens within an aquifer. More often than not, the largest part of the runoff stems from groundwater. In temperate climates even the peak runoff largely consists of "old" water that went through the ground before it joined the river (meaning it was groundwater before it became surface water). Of course the usage of the terms "surface" and "groundwater" is hydrologically flawed. It may be useful for management purposes, but scientifically it is fuzzy to say the least. What do the terms "surface water" and "groundwater" refer to?: where the water is?, where it comes from?, or how it behaves?

3 What is a model?

Related to the question of what hydrology is, is the question of what a model is. From the viewpoint of the scientist, a model is our perception of how a system works. It is a hypothesis of the real world's functioning, codified in quantitative terms: a model of thought reflecting our theory. This hypothesis needs to be tested against empirical evidence. From the perception of the engineer, however, a model is essentially a tool; a tool based on a theory, but still a tool. Both perceptions are needed to solve a problem. As Wolfgang Kinzelbach put it in his invited lecture during the EGU general Assembly (Kinzelbach, 2008): Science and technology are the Yin and Yang of hydrology. They are closely intertwined; they interact, and they need each other for problem solving.

But science and technology are not enough. In developing and testing hypotheses in hydrology there is need for intuition, skill, imagination and creativity; qualities generally attributed to the field of arts. Hydrological modelling requires art, as will be elaborated further down.

On the other hand it is fair to say that also the engineer considers a model as a representation of reality. The difference lies in the interpretation of what a model's purpose is. The scientist realises that all models are wrong. His[1] purpose is to understand where they are wrong, and especially why they are wrong. This will allow him to formulate an alternative and possibly better model. This process, which is the process of scientific discovery, will allow him to advance his understanding. The position of the engineer, instead, is to consider the model as the best representation of reality under the given circumstances. The enlightened engineer knows that all models are wrong, or at least not completely correct. However, he will consider the model as state of the art, and identify it with reality. He uses the model, as the best option he has, for problem solving and decision making.

If we, as scientists, understand that models are wrong, almost by definition, and that our objective is to advance our understanding, then we also understand that the purpose of our research is not to find a "good" model. In fact, there is no such thing as a good model. As hydrologists, we realise that a good model is characterised by an "appropriate" model structure, "good" model performance, and "small" parameter and predictive uncertainty. However, we struggle to give meaning to the words "appropriate", "good" or "small". Instead, the purpose of our research should be the development of a "better" model, that outperforms the one that represents the current state of our knowledge, and that is characterised by a "more appropriate" structure, a "better" overall performance, and "smaller" uncertainty. Hence, we need to see studies that compare models and we need tools that are able to assess the relative merits of different models or model structures.

While these considerations may be trivial, they indicate that much of our research is going the wrong direction. We do not need fixed model structures that can be applied everywhere. We need flexible tools that can evolve sequentially, and adapt to the requirements of a specific situation. This implies that models should never be rigid, as most commercial or established software is. In my view, established models, whatever name they bear, belong to the domain of engineering and not of science. They are primarily engineering tools and not instruments for analysis. The whole discussion about the inadequacy of models (the equifinality and the high predictive uncertainty associated with them) is related to the wrong concept of what a model is. A real hydrological model is a hypothesis to be tested and the tool that reflects this model should be completely flexible, transparent and tailor-made. This makes the "one-size-fits-all" models useless for the purpose of hydrological research. The FLEX model of Fenicia is a good example of a flexible modelling approach (Fenicia et al., 2008b).

[1] I find the politically correct his/her and he/she rather awkward. When I use the pronouns he or his, I mean a gender neutral "he" or "his". It reflects both male and female scientists and engineers.

4 The art of modelling

This brings us to the aspect of art in hydrology. The process of scientific discovery, and the process of hydrological modeling in particular, requires art. The art lies in the ability to reconstruct the architecture of a largely unknown system from a few observable signatures that characterise its behaviour. Hydrology commonly deals with situations where the complex interactions between water and soil and the exchange of mass and energy between the functional compartments of a catchment are not observable. In addition, the medium through which the water flows is highly heterogeneous at all scales. This is the ultimate reason for the failure of the reductionist "bottom-up" approach in hydrological modelling. No matter how "physically based" a model is, parameters will always be effective parameters that reflect averaged process behaviour. The idea that physically based models can do without calibration is based on the erroneous reductionist concept. Calibration of representative parameters is always necessary. Such parameters will only have minimum uncertainty when the appropriate model structure has been chosen.

The correct way to develop a model is first to observe hydrological behaviour, then to hypothesise the dominant mechanisms and test these mechanisms through experiments and data analysis. Subsequently the dominant mechanisms can be codified in alternative model structures, which should be confronted with data to test their performance and calibrate their parameters. The best way to do this is through a top-down approach where alternative model structures are developed on the basis of physical reasoning.

Holism (i.e. top-down thinking) requires art, but reductionism much less. Reductionism in fact, is strongly related to causality, and causality is easier to identify from small to large than in the opposite direction. The operation of piecing together small elements and generating progressively larger elements, which is at the heart of "physically based" hydrological models, may be a more natural operation for the human brain. Thinking in the opposite direction of the causality chain, instead, requires imagination, inspiration, insight, field experience, creativity, ingenuity and skill. These are qualities that belong primarily to the field of art. Modelling is an art.

5 The trinity: science, technology and art

We have seen that hydrology is essentially a multi-disciplinary earth science. Only when we realise that water is the connection between geology, ecology, atmosphere and society, and that it involves basic sciences such as physics, chemistry and biology, are we likely to find breakthroughs in understanding how water behaves in the Earth system. In developing new theories and models of how the water behaves, we need to make use of skill, knowledge and experience that belong to the fields of science, technology and art.

One could argue that, defined in this way, art is implicit in both science and engineering and that emphasising the art in hydrology is trivial. That may be true, but in practice I see a lot of papers, both in review and in print, that do not include elements of art. There are many papers that deal with the application of an existing hydrological model, or that describe automated calibration, or that apply standard statistical methods, without much creativity, empiricism or innovation. It is clear that for finding engineering solutions to water related problems science and technology have to go hand in hand, but when it comes to developing new insights and new approaches, art is an essential element of hydrological research.

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