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A random walk on water (Henry Darcy Medal Lecture)

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Randomness and uncertainty had been well appreciated in hydrology and water resources engineering in their initial steps as scientific disciplines. However, this changed through the years and, following other geosciences, hydrology adopted a naïve view of randomness in natural processes. Such a view separates natural phenomena into two mutually exclusive types, random or stochastic, and deterministic. When a classification of a specific process into one of these two types fails, then a separation of the process into two different, usually additive, parts is typically devised, each of which may be further subdivided into subparts (e.g., deterministic subparts such as periodic and aperiodic or trends). This dichotomous logic is typically combined with a manichean perception, in which the deterministic part supposedly represents cause-effect relationships and thus is physics and science (the "good"), whereas randomness has little relationship with science and no relationship with understanding (the "evil"). Probability theory and statistics, which traditionally provided the tools for dealing with randomness and uncertainty, have been regarded by some as the "necessary evil" but not as an essential part of hydrology and geophysics. Some took a step further to banish them from hydrology, replacing them with deterministic sensitivity analysis and fuzzy-logic representations. Others attempted to demonstrate that irregular fluctuations observed in natural processes are au fond manifestations of underlying chaotic deterministic dynamics with low dimensionality, thus attempting to render probabilistic descriptions unnecessary.

Some of the above recent developments are simply flawed because they make erroneous use of probability and statistics (which, remarkably, provide the tools for such analyses), whereas the entire underlying logic is just a false dichotomy. To see this, it suffices to recall that Pierre Simon Laplace, perhaps the most famous proponent of determinism in the history of philosophy of science (cf. Laplace's demon), is, at the same time, one of the founders of probability theory, which he regarded as "nothing but common sense reduced to calculation". This harmonizes with James Clerk Maxwell's view that "the true logic for this world is the calculus of Probabilities" and was more recently and epigrammatically formulated in the title of Edwin Thompson Jaynes's book "Probability Theory: The Logic of Science" (2003).

Abandoning dichotomous logic, either on ontological or epistemic grounds, we can identify randomness or stochasticity with unpredictability. Admitting that (a) uncertainty is an intrinsic property of nature; (b) causality implies dependence of natural processes in time and thus suggests predictability; but, (c) even the tiniest uncertainty (e.g., in initial conditions) may result in unpredictability after a certain time horizon, we may shape a stochastic representation of natural processes that is consistent with Karl Popper's indeterministic world view. In this representation, probability quantifies uncertainty according to the Kolmogorov system, in which probability is a normalized measure, i.e., a function that maps sets (areas where the initial conditions or the parameter values lie) to real numbers (in the interval [0, 1]). In such a representation, predictability (suggested by deterministic laws) and unpredictability (randomness) coexist, are not separable or additive components, and it is a matter of specifying the time horizon of prediction to decide which of the two dominates.

An elementary numerical example has been devised to illustrate the above ideas and demonstrate that they offer a pragmatic and useful guide for practice, rather than just pertaining to philosophical discussions. A chaotic model, with fully and a priori known deterministic dynamics and deterministic inputs (without any random agent), is assumed to represent the hydrological balance in an area partly covered by vegetation. Experimentation with this toy model demonstrates, inter alia, that: (1) for short time horizons the deterministic dynamics is able to give

good predictions; but (2) these predictions become extremely inaccurate and useless for long time horizons; (3) for such horizons a naïve statistical prediction (average of past data) which fully neglects the deterministic dynamics is more skilful; and (4) if this statistical prediction, in addition to past data, is combined with the probability theory (the principle of maximum entropy, in particular), it can provide a more informative prediction. Also, the toy model shows that the trajectories of the system state (and derivative properties thereof) do not resemble a regular (e.g., periodic) deterministic process nor a purely random process, but exhibit patterns indicating anti-persistence and persistence (where the latter statistically complies with a Hurst-Kolmogorov behaviour). If the process is averaged over long time scales, the anti-persistent behaviour improves predictability, whereas the persistent behaviour substantially deteriorates it. A stochastic representation of this deterministic system, which incorporates dynamics, is not only possible, but also powerful as it provides good predictions for both short and long horizons and helps to decide on when the deterministic dynamics should be considered or neglected.

Obviously, a natural system is extremely more complex than this simple toy model and hence unpredictability is naturally even more prominent in the former. In addition, in a complex natural system, we can never know the exact dynamics and we must infer it from past data, which implies additional uncertainty and an additional role of stochastics in the process of formulating the system equations and estimating the involved parameters. Data also offer the only solid grounds to test any hypothesis about the dynamics, and failure of performing such testing against evidence from data renders the hypothesised dynamics worthless.

If this perception of natural phenomena is adequately plausible, then it may help in studying interesting fundamental questions regarding the current state and the trends of hydrological and water resources research and their promising future paths. For instance: (i) Will it ever be possible to achieve a fully “physically based” modelling of hydrological systems that will not depend on data or stochastic representations? (ii) To what extent can hydrological uncertainty be reduced and what are the effective means for such reduction? (iii) Are current stochastic methods in hydrology consistent with observed natural behaviours? What paths should we explore for their advancement? (iv) Can deterministic methods provide solid scientific grounds for water resources engineering and management? In particular, can there be risk-free hydraulic engineering and water management? (v) Is the current (particularly important) interface between hydrology and climate satisfactory?. In particular, should hydrology rely on climate models that are not properly validated (i.e., for periods and scales not used in calibration)? In effect, is the evolution of climate and its impacts on water resources deterministically predictable?