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Making Sense of Uncertainty in Hydrologic Modelling

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"There is thus plenty of scope for a younger generation of hydrologists to continue the approach based on careful simplification. It is to be hoped that some of them would find it more satisfying to derive simpler conceptual models through approximate analysis rather than seek closer approximations to uncertain data by using ever more complex models involving a further extension of the number of parameters to be calibrated."

So concludes Jim Dooge's last paper "Bringing it all together". This presentation offers a personal perspective on some of the nuances in Dooge's parting remark. It argues that it is imperative for hydrological science to make sense of the uncertainty that pervades hydrologic modelling at the catchment scale. This is by no means a new imperative. Yet, with apologies to Dooge, we have yet "to bring it all together". While the presentation will focus on conceptual rainfall-runoff (CRR) models, its message has relevance to a wider range of environmental models.

Hydrologic modelling at the catchment scale using CRR models has been actively researched for more than half a century. We have a plethora of models in the literature, yet, somewhat embarrassingly, the gains in predictive ability have been quite limited. The Sacramento model, one of the early CRR models, remains the benchmark. Regionalization, the process of transferring information from gauged to ungauged catchments, remains an unsolved problem – the fact that catchments with apparently similar attributes produce apparently inconsistent CRR parameters when calibrated to data, is symptomatic of deep unresolved issues confronting catchment-scale hydrology.

One of the most neglected areas in CRR modelling has been the proper accounting of the major sources of error affecting prediction. A CRR model represents a highly simplified hypothesis of the transformation of rainfall into runoff. Sub-scale temporal and spatial variability and mis-specification of processes introduce an irreducible model error about which little is currently known. If this were the only major source of uncertainty, one would have thought that careful experiments should have guided the science of catchment hydrology towards identifying models with reduced model error and thus improved prediction. One of the reasons this outcome has not materialized is because hydrological observation systems at the catchment scale are far from perfect. Indeed the principal catchment forcing (rainfall) is often subject to uncomfortably large sampling errors – for example, the sampling of catchment rainfall over a 1000 km2 catchment using four raingauges can introduce a 15% standard error, which means one can only estimate the true catchment rainfall to ±30% with 95% confidence. When ignored or treated simplistically, such errors confound analyses of CRR parameters, model adequacy and predictive skill.

Dooge recognised that "most hydrological systems of interest represent a zone between purely deterministic approach in which equations can be analysed and a stochastic approach in which statistical distributions can be handled." Taking this insight one step further, CRR models need to be formally seen as part of a larger hydro-observation system in which models of the hydrological observation systems are accorded as much scientific respect and zeal as the CRR models themselves. It is should be self-evident that ultimately it is our hydrological observation systems that define the "reality" against which CRR model hypotheses are scrutinized and predictive performance is assessed. We need to understand that "reality" if we are to practice good science, let alone advance it.

The hydro-observation system needs to be underpinned by a framework that 1) accounts for all major sources of uncertainty, including sampling and measurement errors in the observed catchment data (both in forcing and response), as well as the irreducible model error in not only the CRR model but also in the observation system models that transform actual observations into hydrologically meaningful quantities; 2) that makes use of all relevant information; and 3) that is "objective" in the sense that all hypotheses are open to scrutiny. We will call this the "total error" framework.

One way to implement this total error framework is to describe the hydro-observation system as a hierarchical probability model and use a Bayesian approach to make inferences and scrutinize hypotheses. The mathematical formulation is seductively simple but, in truth, hides dark and troubling secrets. A number of our findings are described to give a sense of the opportunities and challenges that a total error approach brings to hydrologic modelling.

The consequences of ignoring rainfall errors when calibrating CRR models are illustrated. Parameters can exhibit a bias that depends on the choice of raingauges and period of record – in essence parameters are being "fitted to

rainfall errors". Estimates of parameter uncertainty can be exceedingly optimistic. Such behaviour can confound the search for relationships between CRR parameters and catchment attributes and thus undermine the intent of regionalization.

Most CRR studies do not adequately evaluate predictive uncertainty and thus hide potentially serious shortcomings in the CRR model and its calibration. A total error approach forces one to "raise the bar" in model validation. Both the precision and accuracy of predictions needs scrutiny requiring the use of new diagnostic tests.

The main goal of a total error approach is to make sense of uncertainty by decomposing predictive error into its major constituents, namely input, response and model error. From a science perspective, our primary interest is in characterizing model error as this offers the promise of being able to discriminate between competing models in a more rigorous manner than is currently practiced. Unfortunately, there is "no free lunch" in hydrology. Without strong prior information on the probability models describing two of the three major sources of error, the calibration of CRR models to rainfall-runoff data is generally ill-posed and meaningful decomposition of errors is not possible.

As hydrologists we are virtually clueless about model error. It therefore makes sense to focus first on characterizing the probability models describing errors in rainfall and runoff and then treating model error as the "remnant" error when calibrating to rainfall-runoff data. Several studies deriving rainfall error models using data from dense raingauge networks, radar and conditional simulation are presented. A review of runoff error highlights the need to recognize the key role of systematic error persisting through the runoff time series. Some insight is offered about the nature of model error.

The total error framework formally fuses the hydrologic observation system with the hydrologic model and thus offers the prospect of making sense of uncertainty that is all too evident in catchment-scale modelling. Its strengths are that it is model independent and that it relies on scrutiny of evidence to justify a particular selection of hydrologic and error models. However, experience is limited. There is much to do.