Title
Prediction in ungauged basins: context, challenges, opportunities

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Author
Dunne, T

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Foreword

Prediction in ungauged basins: context, challenges, opportunities

Society increasingly looks to science for predictions, or at least explanations, of events, resources and hazards. Examples appear continually in government committee hearings, serious newspapers and television channels, and international re-insurance industries, to choose one commercial example. This expectation is particularly obvious in the case of water. People are nervous about (for example) water shortages, crop-threatening droughts, floods, water chemistry and pricing. Hydrologists would be wise to improve the capacity and reliability of their predictions to respond to this societal need.

Prediction is commonly thought of as a fundamental capability of science. Observations and understanding, conceptualised as explanatory theories, allow predictions, which then can be tested to refute or increase confidence in the original theory. In hydrology, the quality of these tests does not typically match up with tests in some other sciences that apply laboratory-tested principles and models to the environment. We have much to learn from disciplines, such as atmospheric science, physical oceanography and astrophysics, that have been successful at applying laboratory-tested principles at large scales in complex environments. Although it is true that hydrology has to contend with the interactions of more media (rock, soil, vegetation, engineered structures) than do the disciplines mentioned, there are still intellectual traditions, organisational approaches, analytical methods, and technologies to be learned from them in order to test the generality of landscape-scale hydrological theories.

Empirical investigation, including experimentation, is another fundamental tool of science. Hydrological investigations are conducted in a wide variety of environments – with diverse climates, topography, soils, land cover and manipulation by humans. They also occur at a wide range of temporal and spatial scales, and involve single or multiple processes. It is difficult to organise the vast amount of information from these studies into coherent theories. Diverse results are then seen as contradictory or at least leading to so much confusion that prediction is impossible. Yet, it should not be surprising that results from different locations differ in magnitude, even in the absence or presence of certain processes. Theories predict such a result, and allow organised interpretation and resolution of differences in measured magnitudes. Yet the bulk of the hydrological literature comprises a conceptually disordered resource of 'unique' descriptions, single-process studies and methods, but few attempts at organisation through the medium of broadly applicable, quantitative theory, or even conceptually organised descriptive summaries, that would facilitate both understanding and prediction. This is the 'fragmentation' problem, which the Predictions in Ungauged Basins (PUB) initiative has reduced to an encouraging degree, as this book illustrates.

There is a resilient meta-hypothesis in hydrological science that quantitative theories of linked hydrological processes at landscape scale, implemented and tested in a transparent and rigorous manner, could leverage the extensive body of environmental measurements into more reliable predictions. This is an interesting and challenging, if still unproven, idea. Such a development would require improvements in the conduct of both modelling and empirical investigations – a trajectory assessed in this book for the specific case of runoff predictions in ungauged basins (and by extension, unrecorded conditions in monitored locations).

The first attempt at promulgating general hydrological theory, based on fluid mechanics and thermodynamics, was Eagleson's 1970 book *Dynamic Hydrology*, followed by his suite of papers in *Water Resources Research* (1978) laying out a statistical dynamic formulation of various linked components of a land-surface water budget. Earlier attempts to develop theories of single processes, such as the work of Darcy, Richards, Horton, Theis, Toth, Penman and Monteith, had pointed the way, but Eagleson provided a guide for integration. More recent contributions by many people have illuminated ways of dealing with the representation of processes at a wide range of scales, and with the unwelcome fact that many material properties important in hydrology exhibit large, but crudely measured and poorly understood spatial variations.

The current book is an assessment of progress in combining models with new data-collection and processing tools to make predictions of streamflow, and therefore of associated hydrological fluxes such as evaporation and groundwater storage changes. It embraces the scientific approach of making a model-based prediction and then testing it, and recording the errors in an objective manner. Such a strategy measures progress in skill development and facilitates judicious assessment of the reliability of predictions. This is not common in hydrology, where calibration routinely hides uncertainties in process representation, landscape and material properties, and spatial

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variability of atmospheric events. However, the global survey of prediction methods indicates that tested, integrative modelling of biophysically controlled hydrological mechanisms is still a minority activity in catchment-scale streamflow predictions. Most predictions still consist of summaries, calibrations and extrapolations of strictly empirical information.

The local, empirically focused approach has obvious utility for making certain kinds of predictions within the interpolated range of measurements, although many hydrologists have emphasised the degree to which uncertainties debilitate the use of such predictions, even in that range. The approach is even more unreliable when it is applied to the important domains that society cares about, which lie outside of monitored localities (the ungauged basin), outside of the recorded range of 'possible' events, and in conditions of climate and land cover that may not yet exist but are anticipated. For these (true) prediction challenges, according to the meta-hypothesis, there would be value if we had methods based on a sound scientific platform of mechanistic understanding and rigorous testing. We would then know *how well* we could predict, and we would be able to agree on critical uncertainties, and to focus scientific research and technological innovation on them. But we are unlikely to select either of these foci if most hydrological predictions continue to be pragmatically ad hoc, not rigorously tested and compared, and aimed at generating locally acceptable solutions, rather than transferable hydrological understanding. The PUB initiative has made progress in overcoming these parochial vices.

It is often said that the urgent applicability of hydrological knowledge to human affairs encourages short cuts and discourages exploitation of the best practices of science. Although this may be understandable in specific applications under limitations of time and resources, there is no fundamental reason why the subsidised research community needs to limit its investigations in the same way. The research community is free to address the meta-hypothesis that rigorously formulated biophysical process models could assimilate new and better landscape measurements to yield predictions tested in the same way that some other environmental sciences achieve. This would not require that a prediction be correct at the first attempt, and it would allow an incorrect prediction to be explained by investigating whether the form of a mechanistic representation or the value of a critical parameter were accurate, rather than calibrating the prediction against measured output and announcing success. The book assesses progress in this direction.

Making this suggestion is not to argue against current hydrological practice. Much of it is required for urgent policy and management (remember that José Ortega y Gasset said, 'Life cannot wait until the sciences have explained the universe scientifically.'). Nevertheless, given the widespread dissatisfaction with hydrologists' ability to predict flood discharges or water yields in ungauged basins or those expected to result from climate change and other anthropogenic disturbances, surely there is an argument to be made for some investment in a different, more distinctively scientific strategy on the part of some hydrologists. The results could generate a higher-yielding strategy for the discipline.

The global organisation of the PUB initiative has also fostered an intermediate approach to organising the diversity of knowledge and approaches to runoff prediction, even for conditions and scales for which rigorous mechanistic models are not yet formulated, or at least parameterised, adequately for reliable predictions. This approach involves comparative hydrology – comparing results and the success of prediction methods at representing hydrological outcomes for different regions and scales. The strategy, referred to in the book as hydrological synthesis, is a formal way of comparing hydrological experience in diverse circumstances (I would say through the interpretation of available theory wherever possible), and is a welcome approach to ordering hydrological knowledge. Hydrological synthesis converts the disordered body of case study results into a gradually expanding sample of geographical range (or 'parameter space') that can be compared and interpolated. It raises questions about how regional differences and the general behaviour of hydrological response result from the nature of landscape–atmosphere interactions over time scales ranging from seconds to landform evolution time. The compilation of responses and predictions produces insights about which factors are critical controls on hydrological response at various scales. It also indicates the progress made in prediction at each scale, and the hydrological uncertainties requiring resolution. Synthesis through comparison of results and localities also encourages the use of information on patterns of hydrological landscape features, such as topography, soil and plant communities, to choose prediction methods, to group useful information and to apply results. These patterns are strongly correlated because they have evolved interactively, and the associations between them tend to limit the variability of hydrological response into clusters and trends, albeit with a still-unwelcome (for prediction) degree of variability. However, the PUB strategy has successfully organised knowledge, yielded transferable generalisations, and highlighted hypotheses for further investigation, as the book documents.

The fluid mechanical and thermodynamic theories of biophysical mechanisms at various scales needed for improving predictions are more securely developed and tested, at least at laboratory scale, than is the other part of the hydrological prediction problem – which is to attach

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these theories to the very complex boundaries and material properties of landscape features. The need to choose temporal and spatial resolutions for making these connections leads to challenging uncertainties about the operations of the mechanistic theories themselves. Although the problem is often characterised as a need for better *parameterisation* (which in hydrological modelling usually means some form of averaging of response to a stimulus), or for higher-*resolution* modelling with the same equations, there is often a need for better *formulation* in the sense of representing better *how* a process works, or even *which* process is working. For example, the volume and timing of runoff into a channel could be calculated as (a) the result of overland flow from a long contributing area with variable abstraction of water from the flow and a high surface resistance or (b) of unsaturated and then saturated subsurface flow from a shorter contributing area with different forms of flow resistance and water storage along the flow path. One could calibrate either representation against measurements of rainfall and runoff from a catchment. However, extrapolations of resulting predictions based on the inaccurate formulation to much larger rainstorms, snowmelt, drier initial conditions, timber harvest or other reasonably likely conditions would not be reliable. The unreliability could lead directly to misinformation if the prediction were required to predict not simply runoff but also soil-moisture patterns and evaporation, erosion, water quality, land management or effective pollution regulation (for example). This problem of improving process formulation, as it relates to hydrological prediction at landscape scale, needs to be tackled systematically through field measurement campaigns, modelling 'experiments' and syntheses of the kind documented here that search for environmental patterns and extend knowledge beyond individual case studies. The attractiveness of the challenge is that it invites new discoveries, based on new forms of measurement at a still-unsampled range of scales, as well as improvements in technology and physical and mathematical technique.

The landscape-features side of the problem is also an essential and attractive research target, but it also is challenging. Critical quantities vary in complicated, irregular and wide-ranging ways, and for some of them there is no agreed-upon measurement method. An extra impediment arises because the disciplines that have studied these features have attracted fewer scientists with an appetite for quantitative, theory-based generalisation. Thus, we have relatively few high-quality measurements of hydrological landscape properties and few quantitative theories of how coherent patterns and random variations develop in the first place, or how they differ from place to place. Technological developments have occurred in the measurement of surface hydrological properties, such as topography and albedo, and new data-processing methods for analysing and representing patterns are being employed. But the measurement and useful representation of subsurface material properties and geometry remains a serious impediment to prediction. Modelling the co-evolution of landscape patterns is beginning to develop, which should constrain the number and types of patterns that need to be considered for hydrological prediction.

In addition, field scientists need to engage with the task of theory-building in order to make useful measurements of critical properties that would encourage coherent progress in hydrological prediction. Field studies need to be designed and reported in a manner consistent with theoretical generalisation and hypothesis testing. The task of field studies is not only to report on exceptional circumstances (although these extend the sampling of geographical conditions), but to gradually extend understanding in a coherent and replicable manner. Often, reports that are portrayed as defying conventional wisdom turn out, at least qualitatively, to be physically reasonable and even predictable when extant theory is applied to the local circumstance. The strategy of hydrological synthesis – a formal way of comparing hydrological experience in diverse circumstances (I would say through the interpretation of available theory, wherever possible) – emphasised in this book is a welcome approach to ordering hydrological knowledge and setting an agenda for new discoveries and generalisations.

The book expresses an enduring aspiration of the community that established the International Association of Scientific Hydrology (since renamed as International Association of Hydrological Sciences). It re-focuses the goal of one branch of that community on a distinctively scientific approach to understanding and utilising hydrology at a time when technological advances in measurement and computation are becoming available for creative exploitation in the service of humankind. This is an exciting prospect.

Thomas Dunne