

CHAPTER 1

SETTING THE STAGE

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1.1. Background and Motivation

Hydrology (as the ‘study of water’) is as old as the human civilization, and yet (as a ‘science’) is also very young. Some people may opine that ‘hydrology’ (as we are accustomed to refer to these days) is still at a crossroads as a scientific field; some others may argue that it is a full-fledged one; and still others may point out that even discussions and debates on whether it belongs to ‘science’ or ‘engineering’ are continuing. Amid all this confusion, one thing is clear: it is growing, and growing fast. If nothing else, the rapidly increasing number of text books, scientific journals, research articles, and conferences related to hydrology presents testimony to this.

The growth in hydrology may be seen from two broad angles. One, in terms of the growing number of sub-fields: surface hydrology, subsurface hydrology (or groundwater hydrology or hydrogeology),

hydrometeorology, hydroclimatology, paleohydrology, snow hydrology, urban hydrology, physical hydrology, chemical hydrology, isotope hydrology, ecohydrology (or hydroecology), vadose zone hydrology, and hydroinformatics, among others. The other, in terms of the growing number of scientific theories and mathematical techniques for measurements, modeling, and forecasting: for example, stochastic methods, scaling and fractal theories, remote sensing, geographic information systems, artificial neural networks, evolutionary computing techniques, wavelets, nonlinear dynamics and chaos, fuzzy logic and fuzzy set theory, support vector machines, and principal component analysis.

Either type of this growth is certainly good for hydrology. On one hand, the creation of sub-fields of hydrology facilitates 'compartmentalization' of the large hydrologic space (e.g. hydrologic cycle) into many smaller sub-spaces (e.g. hydrologic components) to better identify specific mechanisms of interest to be understood and issues that need to be resolved. On the other hand, the import of various scientific theories and mathematical techniques helps to better measure and understand such mechanisms and resolve the associated issues.

If, and when, these two types of growth go side by side, progress in hydrology can be remarkable. However, even this is only a partial job done, since the focus likely is still on a specific sub-field and a theory/technique (i.e. 'specialization'). Consequently, the central issues in the larger hydrologic space are either completely unaddressed or at least temporarily pushed to the background. Another increasingly recognizable danger in this kind of 'specialization' is the potential lack of communication among the different sub-groups and, consequently, the lack of knowledge about the broader hydrologic issues.

These dangers make it clear that, in order to achieve true progress in hydrology, there needs to be a good balance between the way we tend to pursue 'specialization' and the way 'generalization' must be pursued in hydrology. This balancing act, however, is a great challenge, especially since it also often requires knowledge of *all* the sub-fields for their salient characteristics and of *all* the theories/techniques for their advantages and limitations. In other words, for example, in order to choose the most appropriate technique to solve a given hydrologic

problem, knowledge of *all* the available techniques is essential in the first place (Although this makes the purpose of ‘specialization’ meaningless on an individual basis, when considered collectively it does not).

As for the mathematical techniques in hydrology, the current hydrologic literature is not only too vast but also increasingly specialized. For example, there are many books purely on stochastic methods or artificial neural networks. Although, this situation is a reflection of how far we have advanced in our scientific theories and understanding, it also creates a major problem: that is, there is not even a single book that can help one to gain knowledge of at least a few, let alone *all*, of the major techniques in hydrology. An obviously related problem is that the ‘search process’ for finding details about the different techniques is oftentimes strenuous. What is urgently needed, therefore, is a unique book that presents details of all the major techniques in hydrology, or at least a few of them. This is the motivation for this book.

It is relevant to note that, one of the main reasons for the proliferation of mathematical techniques in hydrology (and in other fields) is our advancements in measurement and computer technologies. The availability of more and better quality data (both in space and in time) and the increase in computational power and speed have certainly facilitated (and, sometimes, even ‘forced’ or ‘coerced’) the development of numerous ‘data-based’ approaches. Although data is central to almost all scientific endeavors (pattern recognition, modeling, forecasting, verification), our interpretation of ‘data-based’ approaches herein refers to ‘data-driven’ approaches (and, sometimes, also termed as ‘data-mining’ approaches; in a broader sense, ‘time series’ approaches). With this interpretation, the primary question we try to address in this book is: What is the best possible way for both experienced researchers and students of hydrology to learn the different data-based theories and techniques?

With numerous data-based approaches in existence and applied in hydrology, and more and more emerging day by day, it is near-impossible to present details of *all* the approaches in a single book. Therefore, the best possible way to achieve the above goal is to select a few ‘major’ data-based approaches and present comprehensive accounts of those approaches. Obviously, such a selection is subjective (upon us).

Nevertheless, our selection is based on the ‘popularity’ of an approach, the extent of its applications in hydrology thus far, and the potential for its future.

As per this, we select eight major data-based approaches for presentation in this book. These approaches are: stochastic methods, parameter estimation techniques, scaling and fractal methods, remote sensing techniques, artificial neural networks, evolutionary computing techniques, wavelets, and nonlinear dynamics and chaos methods. These approaches are chosen, as they have found key applications in the study of hydrologic system characteristics (e.g. determinism, stochasticity, linearity, nonlinearity, complexity, scale, self-organized criticality, thresholds, sensitivity to initial conditions), processes (e.g. rainfall, river flow, rainfall-runoff, evaporation and evapotranspiration, sediment transport, water quality, groundwater contamination), and the associated problems (e.g. system identification and prediction, synthetic data generation, data disaggregation, data measurement, model parameter estimation and uncertainty, regionalization).

1.2. Organization

The above eight approaches are presented in the following eight chapters, with a chapter for each approach. The approaches are also arranged (in the above order), so as to reflect roughly the chronological order in which they started to become an attraction in hydrology. For each approach, the presentation includes a comprehensive review of the fundamental concepts, their applications in hydrology thus far, and a discussion on potential future directions. Therefore, the book provides a much more efficient and effective way for the reader to get familiarized with the role of these major data-based approaches in hydrology. The final chapter summarizes the highlights of these eight chapters and also offers some future directions for further advancement of hydrology. Before we move on to details of the individual approaches, it would be helpful to present herein a brief account of these approaches.

In Chapter 2 (by Rajagopalan, Salas, and Lall), a detailed account of stochastic methods is presented, with particular emphasis placed on precipitation and streamflow modeling. The term ‘stochastic’ was

derived from the Greek word ‘Στόχος,’ which means ‘random.’ Stochastic methods in hydrology emerged during 1960s–early 1970s,¹⁻⁶ and have been dominating hydrologic studies ever since.⁷⁻¹⁸ They started off with parametric techniques and then advanced to nonparametric techniques; methods that combine parametric and nonparametric techniques have also been proposed. There exist numerous stochastic models in hydrology, and software programs as well. Popular among these models include ARMA (autoregressive moving average) models, alternating renewal models, Markov chain models, kernel density estimators, and *K*-nearest neighbor bootstrap models. Since their inception, stochastic methods have been applied to numerous hydrologic processes and problems, including for rainfall and streamflow data generation and disaggregation and for groundwater flow and contaminant transport studies. A particularly notable application of stochastic methods these days is for the downscaling of coarse-scale outputs from Global Climate Models or General Circulation Models (GCMs) to regional- and catchment-scale hydrologic variables.¹⁹⁻²⁴ Since global climate change is anticipated to increase the number and magnitude of extreme hydrologic events (e.g. floods, droughts), assessment of climate change impacts on hydrology and water resources would critically depend on our ability to accurately downscale the coarse-scale GCM outputs to catchment-scale hydrologic data. This suggests an even far greater role of stochastic methods in hydrologic studies in the future.

Parameter estimation is an important problem in our modeling endeavor, regardless of the type of model (e.g. physical-based, conceptual-based, black-box). Research on parameter estimation in hydrologic models and on the associated uncertainties gained importance in the 1980s,²⁵⁻²⁹ and has advanced tremendously during the last two decades,³⁰⁻⁴⁴ largely contributed by the development of more and more complex hydrologic models. Among the popular parameter estimation and uncertainty methods are the shuffled complex evolution (SCE) algorithm, genetic algorithm (GA), Monte Carlo Markov chain (MCMC) method, Bayesian recursive estimation, and the generalized likelihood uncertainty estimation (GLUE). Although the necessity of more complex models for a more adequate and accurate representation of our hydrologic systems has been clearly recognized in certain situations, our

increasing tendency to develop more and more complex models than perhaps that may actually be needed has also come to light and been questioned in terms of data and other limitations.⁴⁵⁻⁵⁴ Nevertheless, for both right and wrong reasons, we will be witnessing, at least in the near future, even more and more complex models and, hence, the model parameter estimation and uncertainty issues will continue to be important topics of research in hydrology. Chapter 3 (by Yilmaz, Vrugt, Gupta, and Sorooshian) presents details of the model parameter estimation and uncertainty issues, with special focus on model calibration in watershed hydrology.

Chapter 4 (by Veneziano and Langousis) presents a comprehensive account of scaling and fractal concepts in hydrology. Generally speaking, ‘scaling’ refers to a situation where the system/process properties are independent of the scale of observation, and the term ‘fractals’ is used to refer to ‘scaling with non-integer’ dimensions. The scaling and fractal ideas in hydrology go back to as early as the 1930s–1940s,^{55,56} but their importance was brought forth to better light in the 1960s.⁵⁷⁻⁵⁹ Further significant advancements have been made only since the 1980s.⁶⁰⁻⁸⁰ During this period, these concepts have found their applications in studying rainfall and river flow distributions, rainfall disaggregation, river networks, width functions, and groundwater flow and contaminant transport, among others. In addition to these, of particular current applications of the scaling and fractal ideas in hydrology include closely-related problems of catchment regionalization, catchment classification, and predictions in ungaged basins (PUBs).⁸¹⁻⁸³ With increasing calls in recent times for a generalized modeling framework in hydrology⁸⁴⁻⁸⁷ together with the need to make predictions in ungaged basins to deal with extreme hydrologic events, especially floods of far greater magnitudes potentially resulting from climate change, the scaling and fractal concepts will likely play a far more crucial role in future hydrologic and water resources studies.

Apart from computer power and speed, one of the main reasons that led to the development of sophisticated data-based approaches and their applications in hydrology is the availability of more and better quality hydrologic data made through remote sensing technology. Remote sensing (e.g. using geostationary satellites) facilitates measurements of

precipitation and other hydrometeorologic variables (e.g. land surface temperature, near-surface soil moisture, landscape roughness and vegetation cover, snow cover and water equivalent) at high resolutions both in space and in time. Although the origin of the remote sensing technology may be tracked down to more than 150 years ago with the invention of the camera (that too only from the perspective of an ‘equipment’), the revolution in ‘remote sensing’ technology (as we refer to these days) first began in the 1960s with the deployment of space satellites, advanced further in the 1970s with the deployment of the Landsat satellites, and has been continuing since then. Remotely sensed data have been studied and used for many different purposes in hydrology, including forecasting of precipitation and floods and estimation of soil moisture.⁸⁸⁻¹⁰⁶ With space missions and satellite technology growing at a very fast pace, remotely-sensed hydrologic and related data will be used to study numerous hydrologic problems at different spatial and temporal scales. One of the areas where remote sensing can play a vital role in the near future is the transboundary waters, where ground measurements are oftentimes extremely difficult, both for physical and for other reasons. Chapter 5 (by Anagnostou) presents a detailed account of remote sensing in hydrology, particularly focusing on precipitation nowcasting/forecasting and hydrologic applications.

Artificial neural networks (ANNs), developed based on our knowledge of the human nervous system, are probably the most widely used tool in hydrologic studies these days, perhaps next only to stochastic methods. The ability of ANNs to represent the nonlinear relationship between the input variable(s) and the output variable(s) only through a learning procedure with a transfer (activation) function, without the necessary knowledge of the underlying system, is arguably their strongest suit, which makes them often more attractive than the other methods. Applications of ANNs in hydrology started only as recently as the early 1990s,¹⁰⁷⁻¹¹¹ but have skyrocketed since then.¹¹²⁻¹²⁶ Thus far, artificial neural networks have been applied for numerous purposes in hydrology, including forecasting (rainfall, river flow, river stage, groundwater table depth, suspended sediment, evapotranspiration), data infilling or missing data estimation, and downscaling of GCM

outputs. There have and continue to be strong criticisms on the use of ANNs in hydrology on the basis of them being weak extrapolators, their lack of physical explanation, their inability to provide information on input/parameter selection, and the possibility of over-parameterization.^{113,127,128} Many studies have indeed addressed these (and many other) issues and also brought to light their utility and appropriateness for hydrologic modeling and forecasting.^{121,123,129-131} Nevertheless, there is also a clear recognition on the need to do much more in this respect. If and when this can be successfully done, the important role of ANNs in hydrologic modeling and forecasting will be beyond questionable. A comprehensive account of the state-of-the-art of ANNs in hydrology is presented in Chapter 6 (by Abrahart, See, Dawson, Shamseldin, and Wilby).

Chapter 7 (by Babovic and Rao) presents details of applications of evolutionary computation methods in hydrology, in particular on the role of genetic programming in hydrologic studies. Evolutionary computation generally refers to computation based on principles of natural evolution. There are many different methods under the umbrella of 'evolutionary computation,' depending upon the purpose of their use and the way the evolution principles are interpreted/used. These methods include genetic algorithms, genetic programming, ant colony algorithm, and particle swarm method, among others. Evolutionary computation studies in hydrology emerged in the early 1990s, and there has been a significant growth since then.¹³²⁻¹⁴⁶ Evolutionary computation methods have already found their applications in several areas and problems of hydrology, including precipitation, rainfall-runoff, water quality, evapotranspiration, soil moisture, groundwater, and sediment transport. However, these methods are still in the state of infancy and, thus, our knowledge of these methods remains very limited. As a result, we have thus far not been able to explore them enough for hydrologic modeling and forecasting, but this situation will change soon as we vigorously and rigorously continue our research in this direction. At the current time, use of these methods for calibration of rainfall-runoff models is gaining particular importance. Since the increasing availability of hydrologic data and, thus, the growing complexity of hydrologic models facilitate/necessitate data processing, parameter estimation, and many other tasks, evolutionary

computation methods will play a crucial role in dictating how we will go about hydrologic modeling in the future.

Wavelets are mathematical functions that cut up data into different frequency components and then study each component with a resolution matched to its scale. They have advantages over traditional Fourier methods in analyzing physical situations where the signal contains discontinuities and sharp spikes, which are commonplace in hydrology. Applications of wavelets in hydrology started in the 1990s and have been continuing at a very fast pace.¹⁴⁷⁻¹⁶¹ Among the areas and problems of hydrology where wavelets have been employed are precipitation fields and variability, river flow forecasting, streamflow simulation, rainfall-runoff relations, drought forecasting, suspended sediment discharge, and water quality. The outcomes of these studies are certainly encouraging, as they indicate the utility of wavelets for studying hydrologic signals as well as their superiority over some traditional signal processing methods (e.g. Fourier transforms). Nevertheless, there remain serious concerns on the lack of physical interpretation of the results from wavelet analysis. Development of wavelet-based models that take into account the intrinsic multiscale nature of physical relationships of hydrologic processes would help address these concerns. Another possible means may be by coupling wavelets with other methods that can represent, at least to a certain degree, the physical relationships. The literature on wavelets in hydrology provides good indications as to the positive direction in which we are moving. Chapter 8 (by Labat) presents an excellent account of wavelets and their applications in hydrology (and in earth sciences).

Hydrologic phenomena are inherently nonlinear and interdependent, and also possess hidden determinism and order. Their ‘complex’ and ‘random-looking’ behaviors need not always be the outcome of ‘random’ systems but can also arise from simple deterministic systems with sensitive dependence on initial conditions, called ‘chaos.’ Although the discovery of ‘chaos theory’ in the 1960s brought about a noticeable change in our perception of ‘complex’ systems,¹⁶² not much happened in ‘chaos’ research in hydrology until the 1980s due to the absence of powerful computers and nonlinear mathematical tools. Early studies on applications of nonlinear dynamics and chaos concepts in hydrology were conducted during the late 1980s–early 1990s.¹⁶³⁻¹⁶⁸ Since then, there

has been an enormous growth in chaos studies in hydrology.^{73,82,169-186} The application areas and problems include rainfall, river flow, rainfall-runoff, sediment transport, groundwater contaminant transport, modeling, prediction, noise reduction, scaling, disaggregation, missing data estimation, reconstruction of system equations, parameter estimation, and catchment classification. These studies and their outcomes certainly provide different perspectives and new avenues to study hydrologic systems and processes; simplification in hydrologic modeling is just one of them. In fact, arguments as to the potential of chaos theory to serve as a bridge between our traditional and dominant deterministic and stochastic theories have also been put forward.¹⁸⁶ A comprehensive account of nonlinear dynamics and chaos studies in hydrology is presented in Chapter 9 (by Sivakumar and Berndtsson).

There is no question that the above eight data-based approaches have significantly advanced hydrologic theory, research, and practice. A similar conclusion may also be arrived in regards to the other data-based approaches that are not part of this book, including fuzzy logic and fuzzy set theory, support vector machines, principal component analysis, and singular spectrum analysis. Despite these advances, however, there are also growing concerns on at least two important points: (i) our tendency to ‘specialize’ in these individual scientific theories and mathematical techniques, rather than to find ways to integrate them to better address the larger hydrologic issues; and (ii) the lack of ‘physical’ explanation of these concepts and the parameters involved in the methods to real catchments and their salient properties.⁵² Although there have certainly been some efforts in advancing research in this direction,^{2,7,9,87,121,123,130,187-189} they are few and far between. To achieve true progress in hydrology, this situation needs to change, and change quickly. These issues and the associated challenges are highlighted in the final chapter (by Sivakumar and Berndtsson).

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