



Runoff Prediction in Ungauged Basins

Synthesis across Processes,
Places and Scales

EDITED BY

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Runoff Prediction in Ungauged Basins

Synthesis across Processes, Places and Scales

Predicting water runoff in the mostly ungauged water catchment areas of the world is vital to practical applications such as the design of drainage infrastructure and flooding defences, for runoff forecasting and for catchment management tasks such as water allocation and climate impact analysis.

This important new book synthesises decades of rigorous analytical research from around the world, forming a holistic approach to catchment hydrology, and providing a one-stop resource for hydrologists in both developed and developing countries. It brings together results from individual location-based studies with comparative analysis along gradients of climate and landscape features. Topics include data for runoff regionalisation and the prediction of runoff hydrographs, flow duration curves, flow paths and residence times, annual and seasonal runoff, and floods.

Illustrated with many case studies, and including a final chapter on recommendations for researchers and practitioners, this book is written by expert international authors involved in the prestigious International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) initiative. It is a key resource for academic researchers in the fields of hydrology, hydrogeology, ecology, geography, soil science, and environmental and civil engineering, and professionals working with water runoff in ungauged water basins.

GÜNTER BLÖSCHL is Professor of Hydrology, Director of the Centre for Water Resource Systems, and Head of the Institute of Hydraulic Engineering and Water Resources Management at the Vienna University of Technology. He has published extensively on subjects related to hydrology and water resources and served as an editor and associate editor for ten of the best scientific journals in the field. Professor Blöschl has been elected Fellow of the American Geophysical Union and the German Academy of Science and Engineering, has chaired the International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) initiative, and has been elected President of the European Geosciences Union. Recently he has been awarded the prestigious Advanced Grant of the European Research Council (ERC).

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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

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

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

Preface

Sustainable management of river basins requires a variety of tools that can generate runoff predictions over a range of time and space scales. The most widely used predictive tools for runoff are essentially data-driven, i.e., they are estimated from gauged data. Unfortunately, in most catchments around the world runoff is not gauged. In any given region, in any part of the world, only a small fraction of the catchments possess a stream gauge where runoff is gauged. All other catchments have no stream gauge, and are therefore ungauged, and yet runoff information is needed almost everywhere people live for a multitude of management purposes.

Lack of universal theories or equations applicable directly at the catchment scale has led to a plethora of models being developed and used for predicting runoff. These models differ markedly in their model concepts and structure, their parameters, and the inputs they use. They also differ in terms of what dominant processes they represent, and the scales at which they make predictions. Most models are developed by people with different disciplinary backgrounds, while benefiting from local observations, experiences and practices, which are influenced by local climate conditions and catchment characteristics. Consequently, they tend to have unique features not applicable in other places: every hydrological research group around the world seemingly studies a different object: their local catchment. The net result has been considerable fragmentation, a ‘cacophony’, and a dissipation of effort that is not conducive to further advances.

The Decade on Predictions in Ungauged Basins (PUB) launched by the International Association of Hydrological Sciences (IAHS) in 2003 was aimed at achieving major advances in the capacity to make predictions in ungauged basins, through harnessing improved understanding of climatic and landscape controls on hydrological processes. The future vision of PUB was indeed to help make a transformation ‘from cacophony to a harmonious melody’. One of the clear tasks that the PUB initiative set out to achieve was to address the fragmentation of modelling approaches through *comparative evaluation*: ‘Classify model performances in terms of time and space scales, climate, data requirements and type of application, and explore reasons for the model performances in terms of hydrological insights and climate–soil–vegetation–topography controls.’ This book has completed such a comparative evaluation, which is one of its major highlights.

However, PUB also had a higher ambition. It was felt that focusing on a grand problem such as PUB, which needed to draw heavily on new fundamental and theoretical advances in hydrology and associated earth system sciences to address the immediate problem-solving needs of society, had the potential benefit of enabling hydrology to meet both its scientific and its societal obligations. In other words, PUB was also seen as the vehicle to advance and revitalise the science of hydrology. Indeed, over the past decade, the PUB community has made huge strides in advancing both predictive capability and fundamental understanding of hydrological processes, working together in a concerted and coordinated manner. The PUB effort has helped to challenge long-held assumptions and question common paradigms, and has increased the constructive dialogue between different sub-disciplines and schools of thought.

So, as PUB comes to an official close, this book represents one contribution to PUB, which can be seen as another important step both in the development of PUB and in the growth of hydrology as a holistic earth science. This book does not even pretend to document all of the advances and contributions that the PUB community has achieved. These are substantial and should not go unnoticed, and will be documented in some other form. This book is mainly and explicitly focused on a synthesis of runoff predictions in ungauged basins, organised across processes, places and scales. This synthesis attempts to place current practice, experience and prediction uncertainty of a range of prediction methods in an ordered way, so that new insights can be gained not only about the methods themselves but also about how runoff variability changes across processes, places and scales. We believe we have succeeded in bringing some order to the disorder, to the extent of at least partially helping to transition ‘from cacophony to a harmonious melody’, even if it meant asking new questions that only future research can answer. We believe that this is a positive development both for predictions and for the science. This is also reflected in the organisation of the book, as one whole, internally self-consistent tome, with one coherent theme, rather than a collection of chapters that focus on several different PUB themes that one could equally well produce under the circumstances. We had to make a choice about the organisation of the book in our quest for the ‘harmony’; we hope that it made a

difference, since there was a clear price we had to pay for achieving this harmony.

The book started as a PUB benchmark report, but over time metamorphosed into a synthesis, mainly building on a comparative assessment of thousands of studies from all around the world, with predictive uncertainty assessed along the axes of processes, places and scales, and interpreted hydrologically. The literature on the current state of the art of runoff predictions, in terms of the various signatures, was reviewed by over 130 contributing authors, and organised into several chapters. The painstaking effort of comparative assessment was carried out by several able assistants in Vienna, who toiled hard to do the analyses and generate new insights from them, with the support of several of the book contributors as well as the cooperation of scores of the original study authors, who provided the data sources needed for the assessment. All of the chapters went through numerous (countless) revisions by the contributors themselves, and then by the editors, as part of the overall synthesis effort.

The evolution of both the outlines and the contents of the book over the past three years or more was a process unto itself, confusing and confounding editors and contributors alike as it moved along, crystallising into its present shape only in the final few months. In other words, the editorial process was a co-evolutionary process, no less a complex system than the catchment that is the subject of our study. In that sense, the ‘blind men and the elephant’ metaphor applies to the book just as it does to the PUB initiative. Some messages that appear in the synthesis chapter were not there at the beginning, or were only vaguely there, and emerged through the process of writing the book. In that sense, the synthesis did serve its purpose. However, we are humble enough to admit that the book is not the end, but only the end of a beginning, and we remain blind men, still blind to the true reality that is catchment hydrology. Hopefully, there is a broader vision that challenges the narrow vision that has helped us to shape this book.

Readers will not fail to notice scores of photographs of real catchments in colour throughout the book. Our decision to include them is a tribute to the late Vit Klemeš, former President of the IAHS, and comes from our determination that catchments henceforth be seen as inimitable objects that are alive, and not just defined by the techniques and abstractions we may use, from time to time, to analyse them. In a series of papers, Klemeš emphasised the primacy of process understanding over techniques in hydrological research. Techniques are certainly needed for predictions in ungauged basins, but the focus in this book – as in much of the PUB initiative – has been on the hydrology, with the techniques playing an essential but supporting role. It is the hydrological interpretation of the

patterns that various analysis techniques and models produced that takes centre stage in this book.

The contents of the book, in a sense, reflect the lessons learned from the diversity offered by nature’s own experiments, as expressed through the thousands of studies surveyed in this book. Through its comparative performance assessment of methods across processes, places and scales, the book takes an approach to generalisation through learning from the differences and similarities between catchments around the world. It throws light on the status of PUB at the present moment and can serve as a benchmark against which future progress can be judged. Along the way, the book has also come out with a new scientific framework that can potentially guide future efforts aimed at improving runoff predictions in ungauged basins and at advancing the science of hydrology. This proposed new framework has centred on a higher-level synthesis of what we can learn from individual places with generalised understanding gained from comparing the differences between places, thus benefiting from legacies of co-evolution. Maybe this is too esoteric to include in a book on predictions, or maybe it will trigger new ways of doing things; only time will tell.

This book is aimed at hydrologists, earth and environmental scientists with an interest in water, especially early career scientists, aspiring graduate students and practitioners, as well as hydrology teachers. Yet it is not a textbook, manual, handbook nor even a monograph. It puts predictions in a new light, it makes catchment hydrology more coherent and exciting, and runoff variability and water balance more holistic. Perhaps the book can serve as a ready reference for students and new entrants to hydrology wanting to get a sense of the holistic nature of catchment water balance, and to imagine new and innovative ways to make runoff predictions. We hope that, in the long run, it will change the way hydrology is taught, researched and practised.

The book owes its genesis to the IAHS Predictions in Ungauged Basin initiative. We are truly grateful to the IAHS for having the wisdom and courage to start such a 10-year global effort, and for bringing the hydrological community together globally on such a daunting task. We could not have completed this book without the underlying community support that IAHS managed to pull together. Indeed, the synthesis presented in the book is built on the collective experience, inputs and insights of a large number of researchers around the world, and is therefore truly a grassroots effort, even if the grass roots are no longer visible. We as editors hope that, in spite of the challenges and frustrations faced along the way, it has been a worthwhile effort and that the final product reflects well on the best intentions and profound wisdom of the hydrology community, and the high ambitions of the PUB