CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

1 Introduction

Contributors: *G. Blöschl,* M. Sivapalan, T. Wagener, A. Viglione and H. H. G. Savenije*

1.1 Why we need runoff predictions

During the February 2007 Zambezi River flood, Paulo Zucula, the director of Mozambique's National Institute for Disaster Management, was trying to contain the disaster along the river: 'The evacuated people have been in camps for over a week without proper feeding … they are isolated and we can't go there by road, so we have to airlift some of them and drop food,' he said. Some 90 000 people were made homeless by the flood. According to an Oxfam worker, about 1000 people a day were arriving at the camps even without any shelter being provided. The government had learned the lessons of the previous 2001 flood, however, during which about 700 people died. This time it promptly launched missions by boat and helicopter to evacuate people from affected areas. But they were rapidly running short of food for the people in the 33 temporary camps, which also lacked tents, medicine and clean water.

In January 2008 a major flood again struck the Zambezi. This time some 50 000 people in Mozambique were displaced by the flood. 'Property and infrastructure is again being wrecked but we are more worried about the people,' said Paulo Zucula. The flood in the Zambezi valley was in fact worse than the floods of February 2007, and the authorities were forced to evacuate areas where the victims of earlier floods had been resettled.

What has this disaster got to do with runoff Predictions in Ungauged Basins (PUB)? A lot! The hydrology of the Zambezi valley in Mozambique is strongly affected by the presence of the Cahora Bassa Dam (see Figure 1.1). This dam, designed to release about 1900 m^3/s through its turbines for hydropower generation, has a limited flood release capacity. In order to deal with major flooding, it has to lower its reservoir level substantially before the onset of the flood season each year. It is a perpetual trade-off between the economic value of hydropower generation, the risk of flood damage and the risk of dam failure. What makes the operation of the dam even more complicated is that large parts of the upstream catchment of the Zambezi are literally ungauged. Runoff in the main stream of the Zambezi River may be governed by the upstream Kariba Dam, from where warnings are issued whenever they open the flood gates, but the operators have no knowledge of the inflow from the intermediate catchment, of which the Luangwa with its 50 000 km^2 is the largest. The Luangwa is completely ungauged. As a result, operators sometimes have to open the floodgates and discharge more water than would be necessary, with the benefit of hindsight. Better runoff predictions in the Luangwa could reduce flood releases, increase hydropower production, improve flood warning, and reduce downstream damage and suffering.

In Chapter 11, a case study by Hessel Winsemius shows that, even in an ungauged basin such as the Luangwa, much can be done in terms of improved flood predictions. Figure 1.2 is a screen dump of the online model that Winsemius developed for the Luangwa River basin, completely based on remotely sensed data (mostly precipitation and meteorological information). The model has been

Figure 1.1. The Cahora Bassa Dam, Mozambique, spilling through one of the eight flood gates.

* Coordinating contributor

Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales, ed. Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Savenije. Published by Cambridge University Press. © Cambridge University Press 2013.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

Table 1.1. *Need for runoff predictions in ungauged basins*

Hydrological problem	Water management purpose
How much water do we have?	Water allocation, long-term planning, groundwater recharge
When do we have water?	Water supply and hydropower production, planning of restoration measures
For how long do we have water?	Ecological purposes, hydropower potential, industrial and domestic water supply, irrigation
How dry will it be?	Environmental flows for ecological stream health, drought management, river restoration, assessing dilution of effluents
How high will the flood be?	Design of spillways, culverts, dams, dam removal, levees, reservoir management, river restoration, risk management
What are the dynamics of runoff?	All of the above plus water quality (sediments, nutrients) predictions

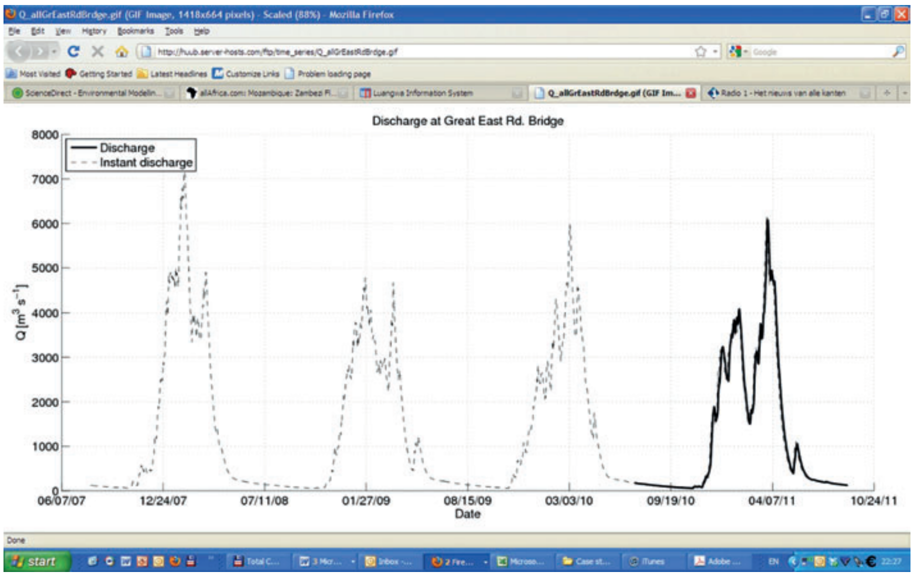

Figure 1.2. The online model that predicts runoff from the Luangwa River basin into the Zambezi, just upstream from Cahora Bassa Reservoir.

operational since 2009 and gives hourly updates of runoff estimates. The runoff is very substantial compared to the average outflow of the Cahora Bassa Dam, and so these predictions can indeed make a difference between life and death, early warning and forced displacement. It shows the direct relevance of PUB for society.

The challenges in the routine management of the Cahora Bassa Reservoir demonstrate the importance of runoff predictions for reservoir management, but there are many other purposes for which runoff predictions are needed. Flood predictions are needed for the design of spillways, culverts, dams, levees, reservoir management, river restoration and risk management. Low flow predictions are needed for determining environmental flows for ecological stream health, drought management, river restoration and assessing the dilution of discharges into a stream. Table 1.1 illustrates the range of problems for which runoff predictions in the context of integrated water resources and risk management are needed. All of them have direct societal relevance (Carr *et al*., 2012). Clearly, runoff predictions are important to a large part of humanity.

Unfortunately, in most catchments around the world, runoff is not measured. In any given region, in any part of the world, only a fraction of the catchments possess a stream gauge where water levels are gauged, which are then transformed into runoff, i.e., the volume of water per unit time that flows through a cross-section of a stream. All the other catchments have no stream gauge, and so are ungauged, and yet runoff information is needed almost everywhere people live for the multitude of purposes outlined above.

The only recourse is therefore to predict runoff in these catchments or locations using alternative data, or information or knowledge. How one can predict runoff for these ungauged catchments and how well one can do this are the subject matter of this book.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

1.2 Runoff predictions in ungauged basins are difficult

So, how can one predict runoff at the catchment scale? Unfortunately, there are currently no universal theories or equations applicable for predicting runoff at the catchment scale. Most of the knowledge we have of processes that occur within the catchment has been derived at the 'point' or laboratory scale (Dooge, 1986; Blöschl, 2005b). The equations of flow of water are essentially valid at the laboratory scale. Similarly, theories of infiltration we currently use are point-scale equations, and overland flow is clearly defined at the hydrodynamic scale, developed in hydraulic laboratories where turbulent processes are very well researched. The challenge for predictions is to move from the well-researched point-scale equations to the catchment scale, something termed the upscaling problem. One way of addressing the upscaling problem is to divide the catchment into smaller elements, which are small enough to apply these point-scale equations, and then assemble these pieces together to form a model of the entire catchment to make the required runoff predictions. This approach could work, in principle – geometrically the catchment can be easily decomposed into sufficiently uniform elements. This so-called reductionist approach is then the most logical way of building predictive models. For estimating runoff in ungauged catchments the approach will then lead to a form of distributed process-based hydrological models that solve the governing equations for mass, momentum and energy in a spatially explicit way, drawing on as much laboratory-scale process understanding as possible. In this book we will call this the Newtonian approach, as the essence of such models is based on Newtonian physics or mechanics.

The Newtonian approach has numerous strengths. First and foremost, it is based on cause-and-effect relationships. If you change an input or a parameter of the model at some location, there is a clearly defined response of the runoff to this change. This is very important for many applications, in particular for those related to change prediction. Land use change effects can be directly simulated by these types of models and, similarly, the approach lends itself naturally for climate impact analyses. Second, these models are spatially explicit and have the potential to represent processes within the catchment in much detail, such as spatial patterns in the infiltration characteristics, the exact channel shape or the presence of any hydraulic structures. Again, there is considerable benefit in the spatial representation, as any detailed knowledge one may have about the catchment can be fully exploited. Third, the underlying equations, such as Darcy's law or Manning's equation are known to work at the laboratory scale for a wide range of flow conditions, so it should be possible to extrapolate them to a wide range of hydrological situations, such as under much higher precipitation. The underlying equations are universal, so should be applicable everywhere at all times. This is appealing since it will generate generalisable knowledge. Also, there are many examples from sister disciplines, such as the atmospheric sciences and river hydraulics, where distributed models are the universal currency.

However, there are three problems with the Newtonian approach for predicting catchment runoff. When subdividing the catchment into computational units, it is necessary to characterise the system through which the water flows for every single element. In principle, this may appear to be a trivial task, but in practice it turns out to be very difficult. In essence, the medium through which the water flows is unknown. It is difficult to identify the spatial (and depth) distribution of the flow parameters, such as the hydraulic conductivity that describes how easily water moves through a medium such as soil or rock. The runoff estimated by the models is usually very sensitive to these parameters, and even a small change will produce a big change in runoff. It is not feasible to measure these parameters everywhere in a catchment, even in a research catchment, let alone in routine applications needed in water resources management, where almost always there are strict resource and time limitations. Second, even if we were able to characterise parameters such as hydraulic conductivity and roughness for every pixel within a catchment, computational resources currently do not allow us to actually use laboratory-scale computational elements – at least a trillion elements would be needed for a catchment of practical interest. Because of this, the elements or building blocks of distributed processes-based hydrological models are usually much larger, at least tens of metres. This leads to the problem of quantifying the flow processes within such elements, i.e., how to parameterise the effects of subgrid variability. This parameterisation is not very well understood either. Preferential flow phenomena may lead to flow dynamics that are very different from those at the laboratory scale. Third, many of the processes controlling catchment runoff are in fact not physical processes but chemical and biological processes. For example, soil chemical processes may strongly affect the infiltration characteristics. Biological activity of earth worms and plants may alter the hydraulic conductivity considerably. Stream–aquifer interactions are often controlled by biological activity at their interface and transpiration is, of course, a biologically driven process. So, while the flow processes *per se* are physical phenomena, they are controlled by many other processes that cannot be quantified by means of Newtonian physics.

Because of these issues, distributed process-based hydrological models often tend to produce biased results when applied to real catchments. To reduce bias in the

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

runoff predictions, at least some of the model parameters need to be calibrated to runoff data. However, this is of course not possible in ungauged basins.

A number of alternative methods have therefore been developed and have been the methods of choice in practical applications for a long time. These alternatives involve the use of runoff data from gauged catchments in a region, and models for ungauged catchments that strongly build on these runoff data. These can be statistical models or simple process models of a conceptual kind, without recourse to Newtonian physics. However, these models are centred on the notion of similarity between the gauged and the ungauged catchments. These types of models acknowledge that, even though there are no runoff data in the catchment of interest, runoff data do exist in other, similar catchments, and these can be transferred in some way in space to help make runoff predictions in the ungauged basins.

1.3 Fragmentation in hydrology

Because distributed process-based hydrological models are not the only method of making runoff predictions in ungauged basins, a plethora of other methods have been developed that are based on the notion of similarity. There is no one standard method of runoff predictions in ungauged basins, rather there are literally hundreds of different methods. They differ by their model structure, their parameters, and by the inputs they use. They also differ in what processes they represent. Depending on the environments, the relative role of snow processes, runoff generation processes and transpiration processes may differ, as may the factors that control them. Some of the differences between the models are directly related to the differences in climate and catchment characteristics. Also, historically, hydrologists have had less incentive than researchers in other disciplines in the earth sciences to collaborate with colleagues around the world, as the land surface is organised into separate river basins, and there is little water exchange across them. Unlike meteorology, for example, a single catchment can be studied with much success in isolation. As hydrologists we do not have a single object of study as, say, a physicist who studies the structure of a particular atom. All physicists around the world may study the hydrogen atom and the models they come up with relate to the same common object – one hydrogen atom. In contrast, every hydrological research group around the world is studying a different object, i.e., a different catchment with different response characteristics. This is a fundamental difference that hydrology must face up to.

All of these factors, collectively, have contributed to the fragmentation of hydrology at various levels.

Processes: Different processes in hydrology have often been dealt with separately, and therefore hydrologists have often looked at flow characteristics at different time scales in an independent way. The annual water yield is usually studied independently of knowledge of low flows of the catchment of interest; floods are often studied independently of knowledge of the seasonal flow patterns within catchments; and flow duration curves are studied separately. Is there a deeper connection between these processes? What is needed is a simultaneous treatment of these processes at different time scales.

Places: As each research group has tended to analyse their own catchments, over the years tremendous understanding of runoff processes has been developed for individual places, but transferring this to other places has been hard. Models are often tailor-made to a particular catchment and it is hard to reason why a particular model structure or model parameters should be preferred over others. Different schools of thought have developed their own favourite methods for different environments and purposes, e.g., statistical versus causal methods or physically based versus conceptual models. Generalising the findings of how well the models work and why has been notoriously difficult.

Scales: Research has been performed over a huge range of scales, and connecting them has caused tremendous difficulties. This is known as the scale problem in hydrology (Blöschl and Sivapalan, 1995). When upscaling laboratory-scale infiltration equations to the catchment scale, assumptions need to be made about the natural hydrological variability and how it is organised (Blöschl, 2001). Similarly, routing equations at a plot scale may differ from those at the hillslope scale. This situation has been exacerbated by the spectrum of disciplines involved, including engineers, geologists, soil scientists and meteorologists, each of them with different worldviews of at what scales processes should be conceptualised.

Current textbooks on hydrology propagate the same fragmented vision of hydrology, organised by process, and written in the form of recipes, e.g., ten different formulas for estimating infiltration, potential evaporation, and so on. The situation is literally analogous to 'a cacophony of noises … not a harmonious melody' (Sivapalan, 1997; Sivapalan *et al.*, 2003b). This fragmentation can be best illustrated by the famous Indian legend of the 'six blind men and the elephant'. By touching different parts of the body of an elephant, these blind men are trying to figure out for themselves what an elephant may look like, but have no other way of 'seeing' it. Each of them tries to make inferences about the elephant by touching one body part of the elephant: it seems like a wall to the blind man that touches the side of the elephant, a spear to the one who feels the tusk, a snake to the one who handles the trunk, a tree to the one who feels the leg, a fan to the one who

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

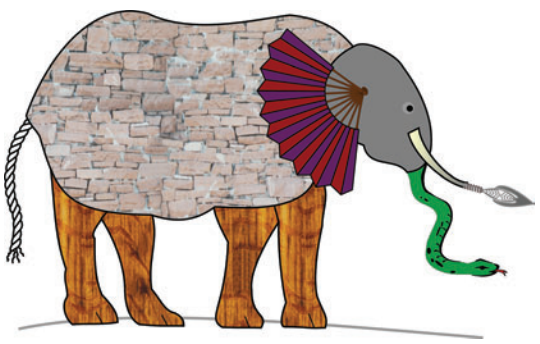

Figure 1.3. Fragmentation in hydrology: similar to the six blind men, a fragmented approach to hydrology makes it difficult to see the full pattern of catchment processes. From Sivapalan *et al.* (2003b), © Jason Hunt.

touches the ear, and a rope to the one who touches the tail (Figure 1.3). The experiences and interpretations of the six blind men are different, which makes it difficult for them to come up with a collective understanding and agree on the true nature of the beast they are trying to 'visualise'. A verse of John Godfrey Saxe's (1816–87) version of this famous Indian legend clearly brings out this confusion:

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!

Perhaps catchment hydrology is in a similar state. Like the six blind men, hydrologists too are often partly in the right but they continue to fail to grasp the holistic picture of the catchment, the object of their study. There is a clear and urgent need to develop a unified vision of hydrology at the catchment scale that overcomes the limitations that arise from their narrow perspectives. What is needed is a synthesis that helps to broaden their perspectives, and to go beyond what is perceived by an individual researcher or group.

1.4 The Prediction in Ungauged Basins initiative: a response to the challenge of fragmentation

About a decade ago, a new global initiative was launched by the hydrological community, under the aegis of the International Association of Hydrological Sciences (IAHS). Called Prediction in Ungauged Basins (PUB), one of the motivations of this grassroots initiative was to overcome the fragmentation in catchment hydrology (Sivapalan *et al.*, 2003b; SSG, 2003). The idea was to bring the scientific community together to use PUB to advance the collective understanding in hydrology, just as the six blind men in the Indian legend might have joined forces to enlighten themselves about the elephant to seek wisdom from other sources. The PUB initiative has been guided by a number of overarching principles to help reach its goals (Figure 1.4). First and foremost, the initiative was about real hydrological processes in real catchments, embracing a multitude of processes, places and scales. If real progress was to be made in overcoming the fragmentation, a diverse population of real catchments in different regions and at different scales had to be examined. A diverse range of processes and a diverse range of data and approaches had to be brought together, all focusing on the common science problem of predictions in ungauged basins. By making different catchments and methods comparable, the aim was to synthesise existing knowledge and create new knowledge, and in this way help improve the predictive abilities and reduce uncertainty. Comparability of diverse places, methods and applications was considered the key to the unification or synthesis needed to transcend the fragmentation and make fundamental progress in hydrology.

It was thus clear that to overcome the fragmentation the community had to be brought together. The PUB initiative was therefore designed as a global community effort, indeed a grassroots movement, consisting of a network of scientists from around the world, and inclusive of all interests. A balance of researchers interested in fundamental research as well as in what is immediately useful was considered valuable, as for any other relevant facets of the prediction problem. The benefits to be gained were clear: greater coherence of the science agenda, coordination of the research activities and a stimulus for the excitement of hydrological research. The PUB initiative has been a truly international effort, with contributors from every continent focusing on the issue of predictions in ungauged basins, leading to a network of concerned scientists.

Over the past decade, the IAHS PUB initiative has been the catalyst for a range of research activities organised around six cross-cutting themes, and executed through a large number of national, regional and global PUB working groups. These PUB themes are: (i) catchment similarity and classification, (ii) conceptualisation of process heterogeneity, (iii) uncertainty analysis and model diagnostics, (iv) new data collection approaches, (v) new hydrological theory and (vi) new modelling approaches. These themes are reflected in the frontispiece to this book, and figure prominently in the guide to PUB best practice that appears in Chapter 13 (Recommendations). The PUB research activities have contributed substantially to the literature, leading to significant advances in the various programs of PUB.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

Guiding Principles Behind PUB Science and Implementation Plan

A number of key principles naturally arise from the broad community objectives presented before, and have guided the development of the science and implementation plan of PUB. Special gratitude to Dunne (1998) for the inspiration it provided.

- In view of its societal obligations, PUB will focus on real hydrologic phenomena, such as floods, droughts, eutrophication of receiving waters, degradation of natural ecosystems, effects of climatic variability and change and/or land use changes etc. (after Dunne, 1998*);
- In being essentially a science initiative, PUB will mainly seek to advance fundamental knowledge of hydrological processes, even to the extent of going beyond the immediate problem solving needs or the community interest of the present time (after Dunne, 1998*);
- PUB will constantly focus attention on what is not known, indeed it will gain energy from its own uncertainties, emphasizing the need for empirical exploration and explicit attempts to validate or falsify new ideas (after Dunne, 1998*);
- PUB emphasizes learning from data from selected basins in different biomes or hydro-climatic regions, demonstrating the value of data and the need for future data requirements, and should not be seen as an alternative to data collection;
- PUB will be obligatorily be self-critical, and will include within it a strong element focused on continual assessment of its own progress, with the predictive uncertainty being used as the measure of progress (after Dunne, 1998*);
- PUB is necessarily integrative, will avoid and indeed overcome the fragmentation of approaches that has bedeviled hydrology in the past, and rather will seek convergence of a variety of approaches towards common objectives, also profiting from lateral perspectives into ancillary sciences (after Dunne, 1998*);
- Develop a hydrological prediction system that is capable of assessing the errors or uncertainty in model predictions, quantifying the different sources of the uncertainty – parameter estimates, climatic inputs and model structure – and constraining these uncertainties by making the best use of the information available from other sites and of measurement programs implemented at the site of interest.

*Dunne, T. (1998). Wolman Lecture: Hydrologic science .... in landscapes ....on a planet ... in the future. In: *Hydrologic Science: Taking Stock and Looking Ahead*, National Academy Press, Washington, D.C., 138p.

Figure 1.4. Guiding principles of the PUB Science Plan, SSG (2003), p. 47.

Work on this book also developed as a community effort and reflects all of the principles that have underpinned the PUB initiative (Figure 1.4). The book itself is an outcome of a strongly felt need to synthesise the state of the art of prediction in ungauged basins, and to carry out a comparative performance assessment of a range of prediction methods being used for the various runoff signatures. Since the book is focused on a synthesis of current prediction methods, it cannot possibly do justice to the enormous contributions of the range of activities that have been carried out under each of the six PUB themes. However, while the book is a contribution to PUB in its own right, its overall organisation has been inspired by the concepts and clarity of thinking engendered by the PUB initiative. In particular, the six PUB themes are reflected in the book in a cross-cutting way, and the outcomes reflect the progress that has been achieved over the past 10 years towards improved predictions in ungauged basins.

1.5 What this book aims to achieve: synthesis across processes, places and scales

This book is specifically devoted to predicting runoff in ungauged basins, i.e., at those locations where no runoff data are available. It will assess, on a comprehensive, objective, open and transparent basis, the state of hydrological predictions in the absence of data, and identify what are the prediction challenges of the future.

It will accomplish this assessment through a synthesis across processes, places and scales, as a response to the challenge of fragmentation in catchment hydrology. In this way it will strive to bring together research on predictions of runoff in ungauged basins that has so far been disparate. One of the goals of the proposed synthesis is to bring order to what otherwise looks like disorder, to identify connections where none existed, and in this way generate new ideas and novel approaches to advance the science of hydrology, and improve the practice of hydrological

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

predictions. There are three levels of synthesis pursued in this book (Blöschl, 2006), as described below.

1.5.1 Synthesis across processes

It appears that hydrologists have, so far, too often looked at individual runoff processes in isolation. It seems likely that there is a connection between floods and low flows, between the long-term behaviour of catchments and their short-term behaviour. The philosophy adopted in this book is that catchments are similar to whole organisms or ecosystems. The different parts are connected because they are themselves a result of process interactions and feedbacks over a wide range of time scales, from seconds of rainsplash processes on the land surface to millennia of landscape evolution processes. While individual parts of the system can be studied in isolation with considerable success, even more progress can be made holistically if the interactions of the parts are also studied. If catchments are viewed as being similar to organisms, then there is perhaps also an analogy with how to study them to understand how the organisms function.

A medical doctor has many different options for studying the state and functioning of a patient: taking the pulse, checking the breathing, ordering blood tests and so on. Ultimately, however, a doctor is not interested in one particular reading, say, the blood pressure alone, but in what the combination of all these diverse pieces of information reveals about the health of the patient. Just as with the doctor example, the idea of this book is to diagnose catchments in several different ways to understand their state and functioning (Figure 1.5).

In the case of catchments, taking the pulse, checking the breathing and making blood tests will be analogous to exploring the different characteristics of runoff variability, which in this book we define as runoff signatures. We call them ‘signatures’ to reflect the fact that they are the result of the functioning of the same catchment ‘organism’ and will therefore reveal some aspect of their state and internal dynamics. In this sense, signatures are response patterns. They emerge as complex catchment systems develop through co-evolution of climate, soils, vegetation and topography in natural landscapes. This is a major point of departure from their previous treatment in the literature. This point is exploited in a major way in Chapter 2, as the framework for the synthesis adopted in this book. The signatures are of course complementary, just as the medical tests on a human being are complementary. They represent different views of the internal dynamics and external manifestations of the same catchment organism, and so they can be used to construct a composite picture of the system functioning. The signatures are therefore a key vehicle for the synthesis we want to achieve.

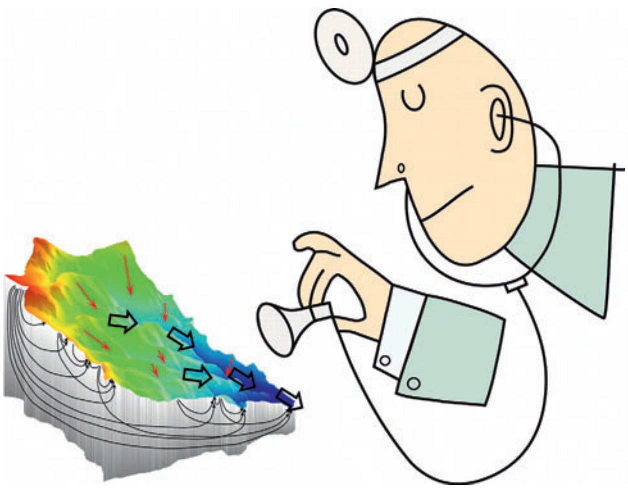

Figure 1.5. Synthesis across processes by diagnosing catchment functioning through runoff signatures. Partly based on Frisbee *et al.* (2011).

In this book the runoff signatures are viewed in such a way that runoff variability can be broken up into several components, each of them a manifestation of catchment functioning, albeit at different time scales, and each of them meaningful and representative of a certain class of applications of societal relevance.

- Annual runoff is a reflection of the competition of water and energy at the catchment scale in the interplay of climate, vegetation and soils.
- Seasonal runoff also reflects interaction between water and energy availability, but in addition catchment storage becomes very important and changes the character of runoff.
- Flow duration curve is the distribution function of runoff that forms a more complex signature linking short-term and long-term processes.
- Low flows result from the interplay between the dynamics of climate with geology, where persistence and long-term processes are of key importance.
- Floods are a reflection of catchment processes at the upper extreme and result from the interplay of weather, soils, topography and geology in a highly dynamic way.
- Hydrographs are the complex result of all these processes and are the most detailed signature of how a catchment behaves.

It is recognised in this book that these different runoff signatures need to be looked at simultaneously and in a consistent way, similarly to how a doctor examines a patient from different perspectives at the same time and in a consistent way. A consistent and coherent treatment of these signatures is therefore one of the cornerstones of this book.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

1.5.2 Synthesis across places

Overcoming the fragmentation across places is particularly difficult as catchments are indeed tremendously different. The approach adopted in this book to synthesise across places is built on the notion of 'similarity'. As a central theme throughout the book, this notion of hydrological similarity is used to compare different catchments and landscape units, to learn from their similarities and differences. We look at different places at the same time. Again, the analogy with the medical doctor is appropriate here. The medical profession has two options to understand a patient's medical condition, how the condition can be inferred from particular symptoms, to predict the future evolution of that person's health and to decide on any treatment. The first option is to look at this particular patient in much detail, including biopsy or surgery, to identify exactly the root cause of the symptoms. The second option is to pool the findings from many patients and to learn from their case histories. The crucial step is then to transfer the knowledge obtained from the large group of people to the particular person being treated. Each human being is different, but there are many common characteristics. Doctors pool together the information from many people and analyse the differences and the similarities. How will cancer evolve for a given state of the body? Clearly, doctors will resort to the case histories of thousands of patients around the world to make a prediction for that particular patient. The two options are complementary, and the medical profession has adopted a combination of these two approaches ever since the profession organised itself, if not before.

Hydrology could operate in a similar fashion. We could pool the information on many catchments together, and analyse their differences and similarities. How will runoff evolve for a given state of the catchment? Clearly, a viable path towards synthesis is to resort to the case histories of thousands of catchments around the world to make a prediction for a particular catchment. Similarity is the foundation of this synthesis, and is therefore a key theme of the book.

Hydrological similarity will help bring order to the current cacophony of catchment processes, models and data setups that bedevil the science today. Similarity is therefore the natural vehicle to organise the synthesis so as to assist towards holistic understanding of hydrological processes everywhere. Hydrological similarity will also help runoff prediction in ungauged basins, since it can help exploit the knowledge of hydrological processes at various levels of detail. To assist with predictions we therefore need to learn from what everybody has learned around the world, and pool together the wisdom and experience from many countries and the diversity of approaches. The concept of similarity makes different places comparable, and in this way assists in the generalisation of the understanding gained from one catchment to the collective understanding of how different catchments function under different conditions.

It is recognised in this book that a critically important part of synthesis across places is therefore a comparative assessment of how well different methods for runoff predictions work in ungauged basins. A consistent and coherent assessment of the performance of methods is therefore another of the cornerstones of this book.

1.5.3 Synthesis across scales

Hydrological processes occur at all scales, from microscopic water flow in soil pores to global-scale interactions of soil moisture and climate. Consequently, hydrological analysis has been performed at many scales, from the

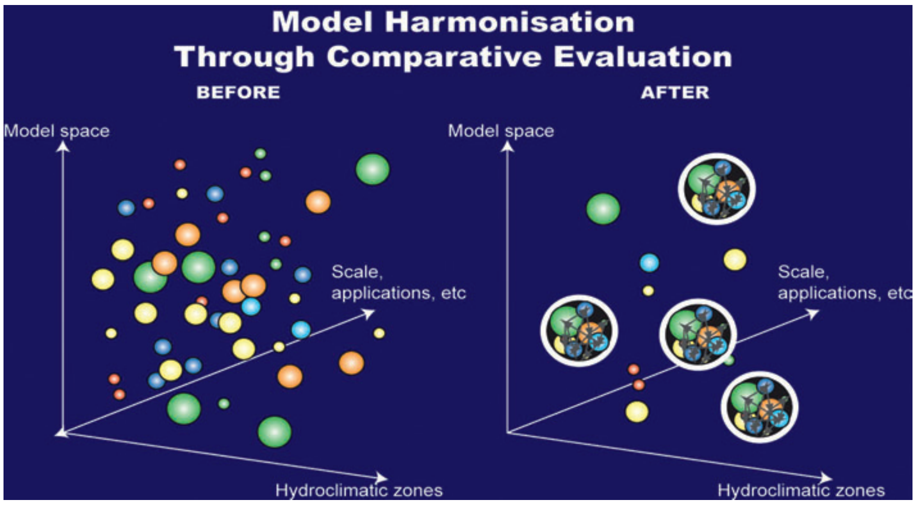

Figure 1.6. Harmonisation of process understanding and models through comparative evaluation across places (taken from PUB Science Plan, see SSG, 2003). The figure depicts the synthesis (harmonisation) that can be achieved through organising the activities and outcomes along the axes of climate, scale and methods, which has been the motivation behind this book.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

laboratory to the global scale. The goal in this book is to predict runoff at the catchment scale. This necessarily involves integration across spatial scales in some way. There are two strategies for approaching this scale problem to assist with making runoff predictions. The first is the upward or mechanistic approach. It is strongly based on laboratory experiments and involves an upscaling to the catchment scale, often by spatially explicit, distributed modelling approaches. While causal controls can be analysed very well by this approach, it is difficult to represent all catchment-scale process interactions. The second is the downward or holistic approach. It is strongly based on behaviour observed at the catchment scale, often based on lumped statistical methods or conceptual rainfall–runoff models. While these types of approaches do have the ability to capture process interactions at the catchment scale – if this information is represented in the data – identifying causality may be very difficult. The two approaches typically deal with scale issues in different ways. For example, in the upward mechanistic approach of rainfall–runoff modelling, measured point rainfall is distributed across the catchments and then routed explicitly across hillslopes and along the stream network to obtain flood peaks of catchments of different sizes. In contrast, in the downward statistical approach of regional flood frequency analysis a scaling relationship is usually established between flood peak and catchment area that embodies all processes in a holistic way. In both approaches, in practice, model parameters are usually calibrated in some way in order to reduce bias. Biases tend to change significantly with location but tend not to change much over the time scales we are interested in because much of the bias is related to unknown subsurface characteristics. Calibration therefore has the potential to increase the accuracy of runoff predictions. However, it is clear that if one calibrates parameters to compensate for the real uncertainty, this is likely to be a 'quick fix', which may jeopardise the physical realism of the model and therefore its predictive capability in ungauged basins.

This book takes a view that transcends any particular approach. We do not assume the primacy of either of the two prediction approaches. Of course, if hydrological information were to be available everywhere, and all the time, the upward approach would be preferred. But it never is. In fact this is the *raison d'être* proffered for the downward approach. We view runoff processes as space-time patterns of hydrological variability. Any approach is an *approximate* representation of this variability. The organisation of catchments into a stream network leaves an imprint on runoff response, turning them into organised entities, and the aim of runoff predictions is to connect the process to the pattern. Each of the two approaches connects process and pattern in different ways. In the book we are therefore inclusive of all these approaches. In our considered view these approaches need to be compared both in terms of their characteristics and in terms of their performance when applied to real catchments around the world. As the methods have different strengths and weaknesses, the choice of method is an interesting and important issue, and there will be many cases where it may be wise to use methods that combine the strengths of both approaches and minimise their weaknesses.

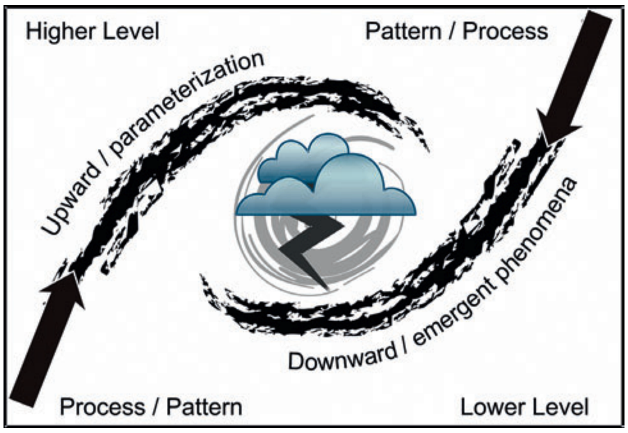

Figure 1.7. Reconciliation of downward and upward approaches – break or transition from a reliance on averaging and parameterisation of lower-level features to a culture of discovery and explanation of emergent phenomena at the higher level. From Sivapalan (2005).

1.6 How to read the book and what to get out of it

How is the synthesis across processes, places and scales reflected in the organisation of the book? Synthesis along these three axes has in fact been the guiding principle in the structuring of the book.

Synthesis across processes is reflected in the way that the book is organised around runoff signatures. Each of the Chapters 5 to 10 deals with one runoff signature – from annual runoff to runoff hydrographs. The commonality of structure of each chapter acknowledges that signatures have common causes in the way catchments function hydrologically. The signatures are simply different manifestations of the same spectrum of catchment processes, so a coherent and consistent treatment contributes to a synthesis across processes.

Synthesis across places is reflected in the way that hydrological similarity is one of the recurring themes of the book, also reflecting one of the key PUB themes (i.e., *catchment similarity and classification*). Hydrological similarity appears explicitly in Chapters 5 to 10 as a vehicle to advance understanding and predictions, through

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-02818-0 - Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales
Edited by Günter Blöschl, Murugesu Sivapalan, Thorsten Wagener, Alberto Viglione and Hubert Sa Venije
Excerpt
More information

its role in regionalisation of models and parameters. Hydrological similarity also appears explicitly in the comparative assessment of the performance of runoff predictions in ungauged basins around the world in each of these six chapters.

Synthesis across scales is reflected in the fact that statistical methods and process-based methods are treated in a consistent way throughout Chapters 5 to 10. Statistical methods and process-based methods represent different approaches to deal with scale issues that arise in predicting runoff in ungauged basins. Statistical methods usually are lumped or holistic representations of the entire catchment system, or many catchments, based on the behaviour observed at the catchment scale. They are therefore typically representative of the downward approach. Process-based methods, in contrast, are mechanistic methods based on a causal understanding of water flow at the process scale, and are therefore more representative of the upward approach. A common structure in these chapters has been adopted for comparability of the statistical and process-based methods, which may help in understanding the similarities and differences in how they bridge the scales.

Chapter 2 presents and articulates the synthesis framework used in the book. As data are the doorway to enhanced understanding and improved predictions, Chapter 3 is devoted to the specific data needed for making predictions in ungauged basins (and reflecting the PUB theme of *new data collection approaches*). Chapter 4 deals with the key issues of flow paths and storage in catchments, and lays the foundations of the general process insights used in the remaining chapters (and reflecting the PUB theme of *conceptualisation of process heterogeneity*). Much of what controls runoff is in the subsurface, so understanding these flow paths and storage-related processes is particularly important for predictions in ungauged basins. Chapters 5 to 10 are the main chapters of the book, each of them dealing with one runoff signature. The structure of each chapter is almost identical, where first the practical needs of the particular signature and its societal relevance are highlighted; in the next section, the process interactions that underpin the signature are reviewed, including how these can be used to define hydrological similarity. The following two sections review statistical and process-based methods for predictions in ungauged basins (reflecting the PUB theme of *new modelling approaches*). Again, wherever possible and reasonable, the types of methods are organised in a similar way across all chapters. Chapters 5 to 10 all close with a comparative assessment of the performance of methods of runoff predictions in ungauged basins around the world, based both on a literature review and on dedicated comparative analysis of numerous data sets that underpinned many of these historical studies. The performance assessment is carried out through a cross-validation of model predictions in over 20 000 catchments, which represents one measure of predictive uncertainty: it reflects the PUB theme focused on *uncertainty analysis and model diagnostics*. Chapter 11 contains several case studies from around the world. The purpose here is to highlight the societal relevance of predictions in ungauged basins in different contexts, and to demonstrate that many of the methods presented in the book actually work for purposes that are important to society. Finally, Chapter 12 synthesises the findings of the previous chapters, and undertakes a yet higher level synthesis to generate profound conclusions and implications for hydrological science, and recommendations for hydrological practice, as summarised in Chapter 13.

© in this web service Cambridge University Press www.cambridge.org