1 International Perspectives on PUB and Pathways Forward: Outcomes of the Perth PUB Workshop

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Hydrological prediction, where data are available, is relatively easily achieved, albeit subject to significant uncertainties. These uncertainties become crucial when attempting to predict the effects of change in a given catchment. However, the problem of ungauged catchments (by far, the majority) presents marked difficulties for hydrological prediction. Over recent decades there has been a continual decline in hydrological gauging networks, reducing the accuracy of hydrological prediction whilst increasing the uncertainty associated with the prediction and management of both water quantity and quality. Additional threats to water sustainability include encroaching anthropogenic impacts (such as land use change) and climate variability and change.

The International Association of Hydrological Sciences (IAHS) has recently launched a new, exciting initiative, the IAHS Decade on Predictions in Ungauged Basins (PUB) (2003–2012), aimed at "*formulating and implementing appropriate science programmes to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make predictions in ungauged basins*" (Sivapalan *et al.*, 2003).

Recognizing the great diversity of interests and expertise of hydrologists, and practical prediction needs, PUB has adopted a philosophy of plurality in terms of applications, hydro-climatic regions and prediction methods, yet it converges with a single-minded focus on the assessment, and eventual reduction, of predictive uncertainty. In line with the philosophy of plurality, and with a desire to energize hydrologists worldwide from the grass-roots level, PUB has resolved that the main engines of the research activities and progress will be PUB Working Groups, centred on applications, hydro-climatic regions, and/or modelling approaches, formed in a self-organizing manner, and cutting across traditional boundaries of specialization.

OBJECTIVES OF THE PERTH PUB WORKSHOP

To support the PUB mission, a workshop was convened at St Catherine's College, University of Western Australia, Perth, 2–5 February 2004, with major support from the Australian Academy Technological Sciences and Engineering (ATSE) and the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), arranged through the University of Yamanashi (Japan). This workshop aimed to bring together a number of Australian and Japanese researchers and practitioners, supported by a small number of international scientists, to have in-depth discussions of the current state of hydrological prediction in Australia, Japan, and the Asia-Pacific region, and potential new problems that are likely to arise in the future in the context of declining hydrological gauging networks, natural variability and human-induced long-term climate changes and land-use changes. The workshop also aimed to assess the potential of exciting new opportunities for predictions that arise from improved hydrological theories, novel data collection techniques including remote sensing, and a new generation of models that are founded on these new theories and data sources.

The main objective of the workshop was to provide an informal setting for identifying the problems with the current state of the art and to identify potential pathways forward. It was also envisaged that the workshop would act as a catalyst for the formation of a number of PUB Working Groups formed around research opportunities (e.g. theories, data, models) that show the greatest promise to advance our predictive capability for management of water quantity, water quality and natural hazards.

This book presents the main ideas and challenges considered at the Perth workshop as well as a summary of the break-out group discussions organized during the workshop. The 23 invited chapters, and the chapter summarizing the break-out group discussions, deal with diverse areas of hydrological prediction and are organized by theme as follows:

– National, regional and global perspectives on PUB
– Nature of hydrological predictions: floods, droughts, sediments and water quality
– New data sources and new approaches for hydrological modelling
– Approaches towards greater process understanding and integration
– Uncertainty estimation and model identification
– Strategies towards integration: breakout group summaries

The following sections summarize the essential ideas presented in each of the 24 chapters that follow this introductory chapter, and are organized according to the headings above.

NATIONAL, REGIONAL AND GLOBAL PERSPECTIVES ON PUB

The first four chapters deal with setting the hydrological context both in terms of the differences in the prediction challenges faced by Australia, Japan and the Asia-Pacific region, as well as reviewing previous approaches to hydrological prediction and regionalization. Two experienced scientists from Japan and Australia were invited to share their perspectives on PUB, and in this way help highlight the sharp differences in perspectives between Japan and Australia on PUB, arising from contrasts in the nature of hydrological variability experienced in the two countries. Indeed, these substantial differences in hydrology cause Japan and Australia to be seen as two end members of the broad spectrum of perspectives as far as PUB is concerned.

Takeuchi (2005; Ch. 2) explains that in Japan, and a large part of the Asia-Pacific region, the climate is warm and humid, the land is orogenically active and human activity is mostly rice paddy agriculture. The co-existence of these factors is unique to the region; the warm humid climate provides ideal conditions for rice paddy agriculture, making rice the staple diet across the Asia-Pacific region. The dependence on rice also means that it is necessary for people to live on flood plains, and consequently, to live with floods. Management of water, particularly for irrigation and flood control, is therefore paramount in this region, and structural and non-structural approaches to management have formed the backbone of the unique man–nature co-existence and hydraulic civilization for thousands of years. Rapid urbanization and industrialization in recent decades have become major challenges to the established modes of the man–nature co-existence. Given the rapid pace of regional development, PUB will have to deal with the struggle to seek a new equilibrium with the natural environment, and will need to develop new methods that utilize new data sources and improved process knowledge, combined with historical experience.

Yang *et al.* (2005; Ch. 3) present the Chinese perspective on PUB, and coming from the same region as Japan, essentially echo the sentiments of Takeuchi. The major differences to Japan are the substantial heterogeneity of China's climate and hydrology, and the enormous expansion of its population over a short period of time. Under pressure of a burgeoning population, scarcity of water resources is a major constraint on social and economic development in northern China, and exploitation of precious water resources has led to widespread degradation of the natural ecosystems and the environment. On the other hand, floods remain a major threat to most areas in southern China. It is clear that the need for accurate predictions of both droughts and floods is driving PUB efforts in China; nevertheless, there is also increasing concern about the effects of increased economic and development activity, and the use of water, on the degradation of the natural environment.

The hydrological setting for the Australian interest in, and contributions to, the problem of PUB, is provided by McMahon (2005; Ch. 4). The over-riding issue that stands out in Australian hydrology is the extent of hydrological variability, which is very large by world standards, and yet McMahon claims it is predictable. He demonstrates that the lengths of periods of low rainfall are similar worldwide but the deficits below median rainfall are larger in Australian than in most other places. He profiles the significant impacts made to stream hydrology from large inter-basin transfer and river regulation in Australia, and also reviews the considerable work that has been done in the areas of modelling and regionalization.

In contrast to the preceding three chapters, Lettenmaier (2005; Ch. 5) provides a global perspective on PUB, supporting the idea that PUB has the potential to mobilize the global hydrological research community to address problems of both scientific and practical relevance. As in Takeuchi (2005) and Yang *et al.* (2005), he argues that the hydrological consequences of climate change and land-use and land-cover change will figure prominently as major future challenges for PUB. On the basis of his review Lettenmaier concludes that: (1) we lack common, widely accepted methods for estimating the uncertainty of hydrological predictions, which tend to be dominated by the sensitivity of water balance processes to vegetation cover change; and (2) the research community must endeavour to provide practitioners with established and reproducible protocols for representing climate change in water resources and water quality management decisions. Lettenmaier's review also addresses the issue of predictability of seasonal streamflow forecasting, arguing for improved understanding and quantification of the relative contributions to forecast errors of uncertainty in hydrological initial conditions *vs* skill in forecasting climate (the hydrological drivers). Lettenmaier concludes that these are the issues of great interest to the programme managers who will be in a position to support the research that the PUB community will undertake.

NATURE OF HYDROLOGICAL PREDICTIONS: FLOODS, DROUGHTS, SEDIMENTS AND WATER QUALITY

The nature of hydrological predictions, i.e. the quantity or variable that we should predict, differs from hydrologist to hydrologist, from application to application, and from place to place. Indeed, for this reason, the PUB science plan (Sivapalan *et al.*, 2003) has adopted the philosophy of plurality of predictions and predictive approaches. The quantities of interest, and the methods used to make these predictions, differ according to the underlying natural variability exhibited by the hydrological cycle in any given location, and the extent of human impacts. The six chapters in this section deal specifically with the key issues of climate variability, flood and drought risk estimation, erosion and sediment transport, and their impacts on water resources and water quality management. They focus particularly on the Australian and Japanese impacts of floods and droughts, sediment transport and water quality, and current approaches to managing their impact.

Kawamura & Kuzuha (2005; Ch. 6) survey the PUB issues related to drought and water resource management in Japan. The water resources situation is reviewed first, along with a brief outline of methods of water resources management, including the past and present situation and challenges for the future. The authors then present a depth–area–duration analysis of the temporal and spatial distribution of scarce precipitation over the whole of Japan, to provide a backdrop to the national water resources assessment. Finally, integrated water resources management strategies for the Fukuoka Metropolitan Area are detailed as a specific example of water resource management, in order to provide the background and motivation for PUB prediction objectives in Japan.

Tachikawa *et al.* (2005; Ch. 7) pick up on the theme of flood prediction in Japan. About 50% of the people and 75% of the properties in Japan are located within flood prone areas, even though these areas constitute just 10% of the total land area of the country. About 70% of the total land area is mountainous and prone to severe erosion, landslides and debris flows, and impact on people and property in a significant way. Floods and sedimentation disasters occur every year in many different parts of Japan. Motivated by these factors, there is considerable emphasis in Japan on the development of flood runoff models to assist in the prevention and/or amelioration of flood and sediment disasters through the formulation of flood protection plans and improvement of the existing flood warning systems. This chapter, by Tachikawa *et al.*, provides an historical survey of hydrological models that have been developed and applied in Japan. Both conceptual models, and increasingly distributed physically-based models, are now being used, frequently in combination with geographic information systems (GIS) and radar rainfall observation technologies. Tachikawa *et al.* conclude with a call for a method for evaluating existing rainfall–runoff models to be developed under PUB, along with new guidelines for flood runoff modelling.

The chapter by Ichikawa (2005, Ch. 8) focuses on the prediction of sediment movement, arguing that it is one of the most challenging tasks in water-related research, and an urgent problem in practical terms, especially in Japan. The chapter introduces the meteorological and geographical characteristics of Japan which impact on sediment movement, and describes the situations relevant to sediment movement in river basins and the current status of studies dealing with sediment movement in Japan. It concludes by summarizing the remaining academic challenges regarding sediment movement.

The next two chapters deal with issues related to floods and droughts in Australia in the context of long-term climate variability. Franks (2005; Ch. 9) provides context to climate variability in eastern Australia, demonstrating the marked roles of the El Nino/ Southern Oscillation (ENSO) and Inter-decadal Pacific Oscillation (IPO) in dictating flood and drought risk over seasonal, inter-annual and multi-decadal time scales. He identifies a number of key PUB issues that need to be addressed before robust flood and drought risk estimation and assessment can be achieved: (1) IPO modulation of ENSO event magnitude and frequency controls multi-decadal flood and drought risk, invalidating traditional flood and drought risk estimation techniques; (2) the spatial variability of ENSO and IPO impacts dictates that there is a need to develop a regionalized model of climate impacts to provide robust estimation of their effects in ungauged basins; (3) given short instrumental records relative to the persistence of IPO, the instrumental record requires augmentation with proxy measures of pre-instrumental climate variability; and (4) regionalized conceptual hydrological models that recognize ENSO/IPO effects must be developed in order to provide a consistent framework for estimation of robust long-term flood and drought risk at the catchment scale.

Power *et al.* (2005, Ch. 10) pick up on the theme of decadal and longer-term variability and changes in climate addressed by Franks (2005). Interest in this problem has grown in Australia due to recent experience of, and concern regarding, droughts that have lasted many years, with no clear links to ENSO or rising temperatures over the land areas and the oceans. Power *et al.* examine decadal variability predicted by the BMRC (Bureau of Meteorology Research Centre, Australia) climate model, which simulates the complete, coupled atmosphere/ocean/land/sea-ice system. A century-long simulation of the climate, along with a series of sensitivity experiments, is used to quantify the predictability of naturally occurring decadal changes in the Southern Ocean and the South Atlantic. The results show that a large fraction of the modelled decadal variability in surface temperature over southern Australia, southern Africa and New Zealand, associated with oceanic temperature changes, appears to be predictable.

The final chapter in this section by Bradd (2005, Ch. 11) discusses issues related to water quality prediction in Australia, where land and water resources are being adversely affected by the degradation of river basins by a range of land-use practices. One such example is the impact of dryland and stream salinity arising from the large-scale clearing of native vegetation. Whilst there is now good understanding of the inter-relationships between the human impact and water quality, sustainable management of land and water resources requires the development of predictive models for water quality, so that more reliable information can be provided to stakeholders for making responsible decisions. Water quality prediction requires a good understanding of the hydrological processes; on the other hand, water quality parameters can provide a means for better understanding hydrological flow paths. Bradd concludes that this is an area of significant importance to the PUB community.

NEW DATA SOURCES AND NEW APPROACHES TO HYDROLOGICAL MODELLING

This section contains four chapters presenting potential advances in hydrological prediction capability through advances in modelling capability and the use of new data sources. First, Lakshmi (2005; Ch. 12) surveys the potential of remote sensing data bases to assist in the predictions of ungauged basins. Then Post *et al.* (2005; Ch. 13) advocate a data-based, top-down approach to hydrological modelling. The final two chapters by Zehe *et al.* (2005; Ch. 14) and Lee *et al.* (2005; Ch. 15), following a bottom-up argument, present the development and application of the Representative Elementary Watershed (REW) approach as a potentially new blueprint for the development of physically-based, distributed models.

As traditional methods for monitoring of river basins through ground observations become expensive to maintain, non-traditional methods, through the use of satellite observations combined with modelling and data assimilation, become a natural way forward. Lakshmi (2005) presents a useful methodology for the integration of hydrological models with satellite data to achieve improved estimates of soil moisture under uncertain precipitation inputs. He suggests that this method of satellite data integration overcomes inaccuracies in model physics, as well as parameter errors, to achieve a solution for the hydrological states that is consistent with observations.

Post *et al.* (2005) review top-down approaches to hydrological modelling and introduce the PUB Top-Down Modelling Working Group (TDWG) that has been formed under the PUB umbrella. The top-down approach is a data-based approach, and involves learning about the catchment's functioning and deriving a model structure directly from the available data. Model refinement is carried out through incorporating new processes into the model structure only where the observed data supports it. In comparison, Post *et al.* argue that the alternative, bottom-up approach has in the past focused on developing complex models based on small-scale processes operating in a catchment without explicit consideration of processes operating at the (larger) catchment scale. In reality, processes that may be dominant at one scale may be less important or even irrelevant at another scale. Indeed, the hypothesis that much of the process complexity that occurs at finer scales is unnecessary to model hydrological response at the whole-catchment scale, is a fundamental motivation of the top-down approach to modelling, and the TDWG.

Zehe *et al.* (2005) present the Representative Elementary Watershed (REW) approach as a novel framework for the development of distributed hydrological models for meso-scale catchments. They pick up on previous work by Reggiani *et al.* (1998, 1999) who derived a set of balance equations for mass, energy and momentum at the scale of the REW (i.e. sub-watersheds which are representative of the watershed in question and are organized around the river network); they also developed a constitutive theory to support and to complete the set of balance equations. Here, Zehe *et al.* (2005) extend this earlier work and present an approach to develop and assess closure relations capable of parameterizing the effects of typical subscale variabilities and structures that exist inside the REW, on the exchanges of water mass between different sub-regions within the REW. By adopting the pattern–process paradigm and the idea of potential natural states from theoretical ecology, they argue that it is possible to assess typical closure relations for specific landscapes and that these closure relations are transferable to different but similar catchments within the same landscape or region. The essence of the pattern-process paradigm is that similarity of patterns (e.g. in soils, vegetation and subsurface structures) in, for example, two different catchments of a specific landscape, is an indicator of process similarity and can be used to at least partially tackle the vexed equifinality problem in hydrological modelling.

The next chapter by Lee *et al.* (2005) documents the progress that has been made towards the adoption of the REW-scale balance equations and constitutive theory derived by Reggiani *et al.* (1998, 1999), towards the development of a new distributed model based on the REW framework. In particular, it surveys the progress made towards: (1) the development of reasonable closure relations for the mass exchange fluxes within and between various REW sub-regions that effectively parameterize the effects of sub-REW heterogeneity of climatic and landscape properties; (2) numerical solution of the resulting governing equations, consisting of a set of coupled ordinary differential equations and algebraic equations for a number of REWs and the sub-regions within them; (3) approaches for the estimation of model parameters that are physically meaningful at the REW scale; (4) methodologies for the verification of the model predictions generated by the REW-scale model in an actual catchment; and (5) approaches to assess the reliability of the new model through estimation of model predictive uncertainty. Finally, this chapter also presents, for illustrative purposes, a preliminary application and validation of the new REW-scale model in a catchment in the southwest of Western Australia.

APPROACHES TOWARDS GREATER PROCESS UNDERSTANDING AND INTEGRATION

The PUB science plan emphasizes a paradigm shift away from methods based on calibration and towards methods based on increased understanding. There are many avenues towards gaining the required understanding: experimental process studies at many scales, diagnostic studies with existing models, exchanges with adjoining fields such as geomorphology, ecology, etc., and the use of new types of observations and data that give deeper insights into hydrological processes. This section contains six chapters which deal with approaches towards gaining improved process understanding and integration through the use of these different perspectives.

Wood *et al.* (2005; Ch. 16) propose the central hypothesis that PUB science questions cannot be fully addressed through field observations alone. They argue for the development and use of a virtual hydrologic laboratory, which consists of hydrological models of various levels of complexity that can serve the role of virtual hydrologic laboratories for investigative purposes. Through the use of a number of examples, they show how using such virtual hydrologic laboratories one can explore a range of PUB science questions. For example, the exploration of catchment evolution in gauged catchments with the use of a detailed model could result in improved understanding of catchment form and function in general, and could lead to improved hydrological predictions in ungauged basins. Similarly, a virtual laboratory model could help guide more targeted observational programmes, and could help distinguish between competing hydrological theories, and elucidate the usefulness of new observations. Through these examples, Wood *et al.* argue strongly that the creation of virtual laboratories for various catchments, as a compliment to possible observational programmes, is not only feasible, but necessary.

The next chapter, by McDonnell *et al.* (2005; Ch. 17), is focused on the understanding and insights towards improved models that can be gained through field experiments. In particular, they present new ideas that will accelerate advancements within PUB from a process perspective. Some of their key ideas and findings include: (1) Catchments appear to operate like a series of cryptic reservoirs that connect and disconnect and this concept may be a way forward to collapsing hillslope complexity into simple measures of emergent behaviour at the catchment scale. (2) Time source components estimated for broad classes of catchment behaviour may be used to identify and distinguish those parameter sets in our models that produce "efficient" results for the right reasons and for the wrong reasons. Use of such "soft data" may be a way to bring our collective field intelligence to ungauged catchments and transfer valuable process knowledge from gauged catchments to ungauged ones; they can also be used as key model calibration criteria. (3) Simple landscape metrics that we can assemble through a synthesis of many different field studies may provide a way forward for ungauged catchment assessment and classification. Some of the results presented by McDonnell *et al.* point to the role of topography, topology and landscape organization as being templates for hydrological processes. For example, the relationships between mean residence time and terrain/landscape organization could inform PUB by elucidating fundamental properties of catchments that provide a first-order control on water age and runoff response. McDonnell *et al.* also argue that these new data sources and process concepts may form new measures of model acceptability, as the community moves away from traditional calibration-reliant model schemes to more process-based descriptions. Measures of water flow path, source and age may help to constrain conceptualizations of runoff generation and thus help reduce predictive uncertainty.

Thoms (2005; Ch. 18) picks up of the theme on interdisciplinary research and learning and how it can help advance hydrological predictions. River basins comprise interacting subsystems, e.g. geomorphological, hydrological and ecological, whose structure and function have traditionally been studied by separate disciplines, each within their own paradigms and perspectives. Inter-disciplinary science and problem solving, to be successful, requires the joining of two or more of these disciplinary areas into a single integrative conceptual-empirical structure. Thoms presents a new framework for the inter-disciplinary study of river basin ecosystems, which is hierarchical, integrative, holistic and process-based, and allows the incorporation of paradigms from different disciplines for the prediction of process-pattern relationships at appropriate scales. Thoms then presents an illustrative application that helps to determine environmental water allocations for a large Australian lowland river system.

Continuing on the same theme, Raupach (2005, Ch. 19) discusses the idea of ecological optimality and its usefulness in hydrological prediction in data-sparse environments. The Ecological Optimality Hypothesis (EOH) holds that "*evolutionary selection pressures drive ecosystems towards a state of maximum utilization of available light, water and nutrient resources for the production of biomass, so that long-term net primary production (NPP) over many reproductive cycles takes the largest possible value under the constraints of available resources*". The attractiveness of an EOH for hydrological prediction is that it provides a powerful constraint on the NPP and the associated use of resources by the ecosystem, one of which is water. Since NPP and transpiration are closely coupled, a constraint is therefore available on transpiration, often the largest loss flux in the water balance, especially in arid regions. The aims of this chapter are to survey ecological optimality both as a principle and as a tool for hydrological prediction, and to identify some major future challenges in this rich and exciting frontier.

The general theme that hydrological predictions—including predictions in ungauged basins—are aided by incorporating information about energy, carbon and nutrient exchanges is picked up again in the next chapter, by Raupach *et al.* (2005; Ch.

20). From a modelling standpoint, major terms in the water balance, especially transpiration, are biologically controlled and hence linked with carbon and nutrient cycles. A model which acknowledges these biological controls is a better hydrological model than one which does not. From an observational and calibration standpoint, a fully coupled terrestrial biosphere model (that includes coupled water, energy, carbon and nutrient cycles) is able to make a broader range of predictions than a purely water balance model, so that many more kinds of observation (e.g. vegetation cover, carbon uptake, energy fluxes, etc.) are available to constrain the model. This chapter reviews the state of development of terrestrial biosphere models, focusing on the coupling of water exchanges with those of other entities—energy, carbon, and nutrients. In addressing these issues, the chapter also highlights tensions between simplicity and complexity, and approaches to dealing with these. The chapter then explores the "aggregation problem", i.e. the problem of applying small-scale process information at large scales. Both of these issues are highly relevant not just to terrestrial biosphere models, but also to hydrological models at the whole-catchment scale.

Fiorentino & Iacobellis (2005; Ch. 21), as part of a presentation of their MEDCLUB PUB Working Group, present a philosophical perspective on the PUB science question: "*How can we maximize the scientific value of available data in generating improved prediction?*" They argue, as in the PUB Science Plan (Sivapalan *et al*., 2003), that PUB's strongest efforts should be devoted to *understanding*, and acknowledge that we can only gain new understanding by connecting new information (based on observations or extracted from models) to patterns that we already understand. They discuss a new definition of complexity (Csikszentmihalyi, 1993) based on the degree to which something is simultaneously *differentiated* and *integrated*. According to this view, complexity evolves along the corridor that leads to knowledge and theory, and what is more highly differentiated and integrated is more complex. This leads to the conclusion that while high levels of differentiation without integration promote the complicated status, high integration without differentiation produces a coarse condition. It then follows that in order to improve modelling and reduce predictive uncertainty, we tend to avoid the complicated and are not interested in the coarse.

UNCERTAINTY ESTIMATION AND MODEL IDENTIFICATION

The ultimate goal of the PUB initiative is to quantify predictive uncertainty, identify its sources (parameter, climatic inputs, human impacts and model structure and conceptualization), and find systematic ways of reducing this uncertainty. This section aims to provide new insights into possible approaches to uncertainty estimation, model selection, and uncertainty reduction. The first two chapters approach this from a Bayesian perspective whilst the final chapter attempts this from a time series modelling approach. Both approaches, however, view data as the ultimate arbiter of model identification.

Uncertainty is ever present in hydrological modelling, and hydrologists have always been keen to make use of new tools that will advance model development and reduce predictive uncertainty. Bayesian methods are seen as providing a framework to incorporate expert knowledge explicitly in handling uncertainty, and have found widespread use in hydrological applications. Recent advances in the statistical and geophysics literature point to a new way of modelling that is neither statistical nor physical, but a fusion of both. The chapter by Campbell (2005, Ch. 22) presents a candidate framework for building physical-statistical models to apply to prediction problems in ungauged basins. This methodology seeks to provide optimal predictions by integrating multiple data sources, physically-based models and expert knowledge. The theoretical details of this broad framework are presented by Campbell (2005) through an illustrative example. Whilst this is not a comprehensive example of the application of the new methodology, it should be sufficient to inspire others to apply this sort of thinking to the PUB problem and help develop more optimal solutions.

The traditional approach to PUB is built on the fundamental assumptions: (1) of the existence of one correct model (even if such a model yet to be identified); (2) that this model is applicable at all times and flow conditions, and to all catchments within a certain neighbourhood; and (3) that the there is a unique 1:1 relationship between the model parameters and catchment physiographic attributes. Violations of these assumptions can lead to a multitude of errors resulting in incorrect designs and poor management decisions. Sharma *et al.* (2005; Ch. 23) present a Bayesian view of rainfall–runoff model development and comparison to address this problem. They present a new class of rainfall–runoff models (called a Hierarchical Mixture of Experts or HME) where the model itself is dynamic and switches between alternate states in a probabilistic fashion depending on the catchment's antecedent wetness condition. Bayesian inference is then used to address the issue of predictive uncertainty by formulating a probability distribution (i.e. the posterior distribution) of the model unknowns (parameters and model outputs) that contribute to the uncertainty, after taking into account the observed data.

The final chapter in this section, by Norton (2005; Ch. 24), looks at PUB from the perspective of state estimation. The connection between PUB and state estimation is that they both concern the internal variables of a basin. Flow is predicted from rainfall and other climatic inputs by use of some sort of hydrological model of the basin dynamics. The model describes, implicitly or explicitly, how the inputs affect internal variables within the basin (e.g. storages) and fluxes, including the flows to be predicted. The state-estimation problem is designed precisely to estimate the current values of the key or essential internal variables of a system, and thereafter the outputs. The test of whether the internal variables comprising the state are essential is that the future state, and hence outputs, can be predicted solely from knowledge of the present state and the future forcing inputs. In other words, at any point in time the state variables are the means by which the history of the system affects its future behaviour. Starting from the current state, prediction is no more than substitution of the future inputs into the state-space model. Norton argues that the PUB problem is one of *robust* state estimation, taking into account the error in the model and in the uncertainty specification. It aims to provide state estimates which remain usable over a given range of model uncertainty. The various approaches to robust state estimation, especially their underlying assumptions and limitations, are reviewed, and are distinguished in terms of how their overall aim is formalized and how the uncertainty is prescribed. The PUB problem is then fitted into this robust-state-estimation framework and some state-estimation strategies for PUB are suggested.

STRATEGIES TOWARDS INTEGRATION: BREAKOUT GROUP SUMMARIES

The final chapter of this volume, by Franks *et al.* (2005; Ch. 25), attempts to summarize the outcomes of the breakout discussion sessions held during the workshop. Delegates were divided into small groups, each associated with different areas of hydrological prediction, and were posed a number of questions related to the current state of the art; in particular, the diversity of approaches currently utilized. The breakout groups were then asked to identify any opportunities or synergies to be achieved through comparison and then integration of the diverse techniques available.

The results of the breakout group discussions demonstrate that data are the very cornerstone of the application of hydrological science. Key to many existing methods for predictions in ungauged basins is the availability of data in nearby or similar catchments for regionalization-type approaches. Importantly, all breakout groups recognized the fundamental issue of identifying and adequately representing key hydrological processes if predictions are to be improved. To achieve this, there was the recognition that ultimately we need to move from a reliance on data elsewhere and develop a more process-based approach for prediction.

The results also indicate that there are many areas of hydrological prediction where benefits would result from greater integration of current techniques. In the first instance, the simple inter-comparison of the available techniques would provide valuable guidance as to the performance of different approaches in different environments with different availability of data. It may also be that numerous diverse technologies, when viewed in isolation for a particular hydrological objective, can only achieve so much. Through the inter-comparison and integration of these diverse techniques it is quite possible that biases induced by a particular technique can be checked through alternative and independent techniques. The comparison and integration of techniques may therefore serve as a tool for progressing techniques for hydrological estimation in ungauged basins.

Another key theme underlying all the groups' deliberations was the issue of the quantification of uncertainty. The robust estimation of the reliability of predictions is a necessary prerequisite for the inter-comparison, evaluation and improvement of current methods and models. Ultimately, the quantification of uncertainty provides a framework for assessing the worth of hydrological techniques in application. The breakout groups identified key issues that could be addressed with the IAHS Predictions in Ungauged Basins (PUB) framework. It is hoped that the issues raised through this process may be addressed by collaborative working groups so that demonstrable progress in the practical application of hydrological science can be shown.

CONCLUDING REMARKS

Attending the Perth PUB workshop, participating in the spirited discussions there, and editing this book, have given us a very good sense of the current status of hydrological predictions in Australia, Japan and the Asia-Pacific region and to a certain extent globally, and also a sense of the broad perspectives and collective wisdom held by the broader hydrological community.

Above all, the many presentations and the detailed discussions around the PUB theme provided a ringing endorsement of the wisdom that is encapsulated in the PUB Science Plan. The contributions that appear in this book have reconfirmed that PUB is seen by the hydrological community, both practitioners and researchers, as a very challenging, exciting and multi-faceted problem that will occupy the minds of hydrologists for a long time to come.

The perspectives on PUB and the methods used will clearly differ from place to place, and will depend on the nature of hydrological variability that is experienced in these places, and the role of human impacts. Methods appropriate in one place may not be sufficient or needed in other places. Nevertheless, there are emerging issues that are universal and PUB will have to grapple with these in the future. In particular, it is increasingly felt that *hydrological change*, due to changes in land use and land cover, climate change, and human interference with the hydrological cycle, are threatening to overwhelm natural variability in many parts of the world, and must be faced squarely if we are to have any confidence in our predictions in real places where real people live. Predicting and managing such changes are becoming, if they have not already become, major challenges in almost all countries.

The nature of hydrological predictions (the quantities of interest, the expectations of society) is also changing rapidly. Whilst natural water-related hazards such as floods and droughts continue to be major concerns that need to be prevented or managed, degradation of land areas and deterioration of water quality in riverine, riparian, estuarine and coastal ecosystems are becoming major problems everywhere due to the scale of human impacts and the increased emphasis by society and governments on sustainable development. PUB must evolve quickly to deliver the increased levels of predictive capability and sophistication needed to address these concerns.

We conclude with a summary of the collective wisdom and recommendations arising out of the Perth workshop, especially from the breakout group discussions:

– Individual hydrological studies tend to be somewhat *ad hoc*, especially in the selection of specific models toward a specific problem. Inter-comparison of alternative approaches is recommended to gain deeper understanding of what models and methods work best, where, and why.
– In the case of the hydrological aspects of modelling water quality and ecosystem health, greater effort must be placed in developing models that are capable of more universal applicability. This can only be achieved through greater efforts into developing a more fundamental understanding of the complex interactions between water quantity, quality and ecosystem dynamics.
– New measurement technologies are increasingly available. However, these should not be seen as replacing traditional gauging of catchments. Greater emphasis needs to be placed on evaluating how these technologies can be integrated into existing methodologies and modelling strategies to increase the power of hydrological techniques in predicting in ungauged basins.
– The inter-comparison of alternative approaches, as well as the evaluation of the worth of integrating new technologies, requires a formal framework for fair comparison. This needs to be done within a robust and formal uncertainty estimation framework. Therefore, greater emphasis needs to be placed on the development of robust frameworks for routine quantification of uncertainty.

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