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PUTTING PREDICTION IN UNGAUGED BASINS INTO PRACTICE

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1.1 ABSTRACT

The International Association for Hydrological Sciences (IAHS) Prediction in Ungauged Basins (PUB) initiative had the goal of decreasing the uncertainty in hydrological prediction. The 4th biennium of the PUB decade culminated in a 2011 workshop to summarize progress on sharing and consolidating efforts to maximize the use of new knowledge and techniques for prediction in ungauged basins in practice. The chapter summarizes the presentations and discussions that took place at the workshop. These followed four themes; maximizing the predictive value of available information, improving process realism in physically based predictive approaches, improving access to measurement and information technology for prediction, and reducing uncertainty in the face of environmental changes. It is hoped that this monograph provides a snapshot of the state of the art in prediction that can be used as a benchmark for further advances.

1.2 RÉSUMÉ

L’initiative Décennie de prévisions en bassins non jaugés (PBNJ) de l’AISH (Association internationale des sciences hydrologiques) avait pour but de diminuer l’incertitude entourant les prévisions hydrologiques. La 4^{e} période biennale de la décennie de PBNJ a été couronnée par un atelier tenu en 2011, lequel visait à résumer les progrès entourant le partage et la consolidation des efforts en vue de maximiser l’utilisation des nouvelles connaissances et

techniques pour la prévision en bassins non jaugés dans la pratique. Le chapitre résume les présentations et les discussions qui ont eu lieu à l'atelier. Celles-ci ont porté sur quatre thèmes; maximiser la valeur prédictive des données, améliorer le réalisme du processus en ce qui concerne les approches prédictives fondées sur des critères physiques, améliorer l'accès aux mesures et aux technologies de l'information pour la prévision et réduire l'incertitude face aux modifications ou à la dégradation de l'environnement. Les intéressés espèrent que cette monographie présente un instantané de l'état actuel des réalisations en matière de prévisions pouvant servir de point de référence pour d'autres avancées.

1.3 INTRODUCTION

The overarching goal of the International Association for Hydrological Sciences (IAHS) Prediction in Ungauged (PUB) Initiative was to reduce uncertainty associated with prediction in ungauged basins. Prediction in ungauged basins remains difficult in many parts of the world because of an inadequate global gauging network for model calibration and regionalization using many current methods. This problem is most acute in developing countries and cold regions, which are among the most vulnerable regions to watershed stressors, but it is an issue everywhere. Poor gauging adds uncertainty to input data, model structure, and model parameterization. Non-stationarity in climate, land cover, and anthropogenic influences means even well gauged regions face uncertainty in prediction. The goals of the 4th biennium (2009-2011) of the PUB Initiative were to share and consolidate between and across PUB themes and working groups the variety of regional efforts, perspectives, and approaches that maximize the predictive value of streamflow data and their use. From May 10-14, 2011 in Canmore, Alberta, Canada, a workshop was convened to summarize and report on the progress made during the 4th biennium. The workshop consisted of invited theme papers, contributed case study papers, and work group discussions that all focused on how we presently predict within ungauged basins in areas where data availability ranges from very rich to very poor.

The core perspective of the workshop was evaluating how the availability of data affects how we make predictions, and seeking opportunities to transfer knowledge or skill or concepts amongst regions where data availability differs greatly. The invited papers and case studies follow four themes:

1. How to maximize the predictive value of available information.
2. How to improve process realism in physically based predictive approaches.
3. How to access measurement and information technology for prediction.
4. How to reduce uncertainty in the face of other environmental changes.

Within the workshops the participants considered how these would apply within data-rich, data-sparse, and data-poor watersheds and regions. This monograph is a summary and expansion of the presentations and discussions at the workshop; the expansion includes a sampling of PUB research and methodologies that could be of use to practitioners.

1.4 HOW TO MAXIMIZE THE PREDICTIVE VALUE OF AVAILABLE INFORMATION

The first suite of chapters provides different perspectives on how we are presently using available information and tools to make predictions in ungauged basins based on discussions at the workshop. Liu *et al*. (Chapter 2) describes how the predictive value of available data in ungauged basins is maximized in China. Based on the Chinese saying, "Even a clever housewife cannot cook a meal without rice", borrowing, substituting and generating are the three basic methods of obtaining information to model a basin of interest. That is specifically, extrapolating and/or interpolating amongst the data from adjacent catchments, or obtaining the information by simulation or experiments. These three approaches also apply to how knowledge and tools derived from hydrological prediction research can be applied to prediction in ungauged basins. Another approach to maximizing the use of existing information is provided by Clarke and Buarque (Chapter 3) in their description of a case study in the Amazon basin. In the Amazon, the estimation of precipitation is crucial for sound hydrological predictions in both ungauged and gauged basins. They present a parametric geostatistical model to estimate the Gumbel distribution of annual maximum one-day rainfall at sites without rain gauges in the Amazon and Tocantins basins of Brazil. Applying a model that is based upon all the available rain gauges produces better precipitation estimates than other methods.

Pomeroy *et al*. (Chapter 4) discussed how process hydrology study results from research basins could be used to generate physically based algorithms and appropriate model structures that could be used to predict in ungauged basins far away from the research basins. The application of deductive, inductive, and abductive approaches to derive models using physical rules, observed behavior, and borrowed hydrological relationships from similar ecosystems was demonstrated in Canadian basins. The value of intensive research basins as the source of information to be transferred to ungauged basins was emphasized.

Danny Marks reported at the workshop on how information from data-rich sites in mountain basins could be used to improve prediction at data-sparse sites in similar environments. In the mountains of western North America, nearly all the watersheds are ungauged. The hydrology of mountain basins is complicated and sensitive to weather and climate, and sufficiently non-linear that statistical rainfall/runoff or precipitation/runoff relationships are unreliable. While there are 50 years of research developing the techniques of hydrologic forecasting, Marks suggested that it is now time for hydrology and hydrological prediction to be addressed as a science and that prediction should be based on the understanding of meteorological, land surface, and hydrological processes and their interactions. He suggested that we re-evaluate our measurement strategy to better capture landscape gradients and the end-members and our understanding of the distributions of hydro-climatic parameters across complex landscapes. Marks also suggested that we continue to invest in basic hydrologic and hydroclimatic process research since the few existing outdoor laboratories provide high quality, long time series data records, allow us to characterize processes and distributions, and allow detailed uncertainty analysis. Only in a very few locations in the world is this possible, making these sites incredibly valuable.

1.5 HOW TO IMPROVE PROCESS REALISM IN PHYSICALLY BASED PREDICTIVE APPROACHES

The next suite of chapters addresses the importance of better understanding and representing geophysical processes in predictive tools. A study describing the use of physical principles to make predictions of floods in a Russian ungauged basin is presented in Gelfan (Chapter 5). The approach uses a data-rich small proxy-basin which is hydrologically similar to the poorly gauged study basin. First, a physically based model of flood generation was developed in the proxy-basin, and then applied to the study basin. Using modelled daily meteorological forcing, the hydrological model generated a series of snowmelt flood hydrographs. The approach allows the derivation of frequency distribution of flood volume without utilizing any streamflow observations in the study basin. The proposed approach is targeted for hydrological engineering practice and considered as a suitable alternative to the traditional methods of flood risk assessment in ungauged or poorly gauged basins.

Jim McNamara reported to the workshop on the mutual reliance of improving process information and improving predictions in ungauged basins. For lumped models, statistical process representation is based upon coarse states, sparse data, and a small computational requirement. For fully distributed models, the physics based process representation relies on large data sets and fine resolution, requiring extensive computer resources. Semi-distributed and conceptual models fall in between lumped and distributed models. McNamara also addressed the issues of models which are right for the wrong reasons or wrong for the right reasons, reminding us that models need to get the right answers for the right reasons (Kirchner, 2006). McNamara discussed reductionism, an approach to understanding the nature of complex things by the interaction of their parts, and its contribution to PUB. He supported this reductionist approach in principle, suggesting that Newton was indeed correct; that model failures result from poor characterization of heterogeneous landscapes, and that hydrology is inherently a local science because of large regional variations in landscape variations; however, he also proposed that we could improve predictions by [1] retaining the computational efficiency and philosophy of lumped models, [2] observing how catchments create physically lumped properties, and replacing physical lumping in models with physically lumped properties. McNamara emphasized that storage is not commonly measured, is frequently estimated as the residual of the water balance, and is generally treated as a secondary model calibration target; yet improved characterization of storage will lead to improved predictions. He suggested that better understanding and description of the mechanisms responsible for storage and retention of water in the watershed are needed to improve predictions. Finally, he argued that true physically based models are a myth; that hydrological models can only address hydrologically relevant process and properties.

Jeff McDonnell reported to the workshop his belief that accurate prediction of headwater streamflow response implies adequate modelling of sources, flowpaths, and residence time of water and solutes (Hewlett and Troendle, 1975). McDonnell explained that quantifying the watershed residence time would improve model predictions. He demonstrated that for some basins there was no relationship between basin area and residence time, while in other basins there was a scaling of residence time and basin areas. McDonnell also argued that we need to be "getting the right answers for the right reasons" (Kirchner, 2006); developing models that are minimally parameterized and therefore stand some chance of failing the tests to which they are subjected. He demonstrated that defining residence time scaling could lead to significant improvements in process realism, and in some cases basin parameter transfer could be addressed within broad geological units.

1.6 HOW TO ACCESS MEASUREMENT AND INFORMATION TECHNOLOGY FOR PREDICTION

The third section discusses the essential first step in modelling and prediction of developing meteorological forcing data for input to hydrological models, whether for gauged or ungauged basins (Garen, Chapter 6). These forcing data may be from stations, and/or interpolations of real-time weather forecasting. Garen (Chapter 6) describes how preparation of forcing data can require significant database and software infrastructure, especially for real-time forecasting. In ungauged basins, without streamflow measurements to use as a check on simulation skill, it is especially critical to ensure that such model forcings are accurately prepared.

Hydrological ensemble forecasting is increasingly used in scientific and in operational modes (Renner and Werner, Chapter 7). Forecast ensembles are created either by forcing a hydrological model with meteorological ensemble forecast input or by running multiple hydrological models. While the resulting spaghetti plots provide some feeling of future variability, they are often difficult to interpret. Archived forecasts or hindcasts can be used as the basis for probabilistic forecasts that represent the predictive uncertainty of future flows and are thus useful for decision makers. The forecast horizon in combination with basin characteristics such as size and travel time, determine the contribution of different sources of uncertainty; knowledge that is crucial when aiming to improve forecast accuracy in either gauged or ungauged basins.

Vincent Fortin suggested to the workshop that there might soon be no such thing as a truly ungauged basin. Geostationary satellites today provide products such as rainfall estimates (PERSIANN), surface soil moisture (SMOS), water surface altimetry (SWOT), and water storage anomalies (GRACE). The availability of these types of data makes modelling the atmosphere over any basin easier and provides measurements of state variables (storage) and estimates of discharge of large rivers. Fortin described how re-analysis products and modern data-assimilation systems ingest massive amounts of data on the state of the atmosphere and provide physically based gridded datasets which can then be used for hydrological prediction. He also described products based upon the GEM atmospheric model that Environment Canada makes available; [1] CaPA: a near real-time precipitation analysis system, [2] MESH: a framework for surface and hydrology prediction. He demonstrated how these products have been applied to the prediction of water level changes in the Great Lakes basin. Today, the only (proven) method to forecast the weather for more than a few days is to forecast it everywhere by running a numerical weather prediction model (NWP) from initial conditions estimated from observations of the earth's atmosphere, oceans, and land. There are limits to what we can afford in terms of horizontal resolution, but GEM can zoom in on a region of interest using a limited-area model (LAM). Fortin also described ensemble forecasting where the aim is to represent uncertainty dynamically, based upon different initial conditions, different numerical models, or different weather forecasts. The differences between these model outputs should result in differences in forecasts that should reflect the uncertainty in estimates of initial conditions and in the limitations of our numerical models.

1.7 REDUCING UNCERTAINTY IN THE CONTEXT OF ENVIRONMENTAL CHANGES

Reducing uncertainty within prediction in ungauged basins is addressed in almost every PUB related publication and paper. In this workshop we asked some authors to consider other perspectives on uncertainty where the context of the prediction would contribute to the overall uncertainty. To start off this section of the monograph, Wheater *et al*. (Chapter 8) addressed how uncertainty could be reduced when land use change is creating non-stationarity. Prediction of the effects of changing land use and land management practices (i.e. catchment non-stationarity) for ungauged catchments is an issue of considerable practical importance for catchment planning and management. The issues of land use non-stationarity raise difficult methodological and management challenges. Wheater *et al*. describe the development and application of a detailed physics based model with and without local data, to represent field-scale effects of land management practices. They suggest that addressing impacts of land management practice can be done through mapping of land management effects on soil structure and runoff processes, using regionalized indices of catchment response to constrain conceptual model parameterizations for ungauged application and upscaling the results to catchment scale using meta-models.

Regionalizing hydrological responses to ungauged catchments is a difficult problem (Post, Chapter 9); however, typical practical application of the PUB problem involves not just predicting the historical hydrological response of a catchment, but also requires a prediction of the hydrological response of a catchment into the future. Changes in catchment hydrological functioning can be brought about through changes in land use and land management, or through changes due to a changing climate. Post suggests that to solve this latter issue, we must first understand the hydrological functioning of a catchment under historical conditions; then we must improve the models used to represent this hydrological functioning; and finally modify the model structure to incorporate hydrological processes which are assumed will change under a changing climate. Water managers, however, require estimates of current and future water availability *now* in order to more effectively manage water resources. Solutions to the problem of non-stationarity need to be found, but assessments of water availability will continue using whatever methods and models are available.

Dornes (Chapter 10) addressed how we might combine both inductive and deductive approaches in prediction. Dornes demonstrates using a data driven modelling approach to represent landscape heterogeneity coupled with a physics based approach for detailed snowmelt process descriptions. Using a physically based hydrological land surface simulation, he demonstrated that using distributed initial conditions of snowcover and incoming solar radiation showed an appropriate representation of both the basin hydrographs and the snowcover ablation; however, aggregated simulations were unable to describe the dynamics of the basin streamflow when the runoff response was largely governed by solar radiation, but when temperature was a key factor in the onset of melt the differences were less. The modelling methodology capitalized on the strength of both modelling approaches, and appears to be an effective method to reduce the size of the parameter sets and still retain physical reality. Therefore it can be a useful approach when applying physically based hydrological models in poorly or ungauged basins.

1.8 CASE STUDY PAPERS

The next section of the monograph includes short case study papers based upon some of the many posters that workshop participants presented on their personal experiences with prediction in ungauged basins. Several of these chapters address the issue of maximizing the predictive value of available information. Hughes (Chapter 11) reports on how predictions in ungauged basins are practiced at the national scale in South Africa. Minihane (Chapter 12) describes the procedures used for estimating the mean monthly discharges in the Lugenda River in northern Mozambique. Munro (Chapter 13) describes the methodology used to generate a runoff record for a recently ungauged glaciated watershed in the Canadian Rockies. Collectively these provide classic examples of the diversity of methodologies and scales of predicting in ungauged basins that exist.

Others addressed specific issues of process realism in making predictions. Keinzle (Chapter 14) reports on the procedure developed to estimate model parameters in a mountainous region in Canada. Littlewood (Chapter 15) describes how regionalization methods can be used to reduce the uncertainty of predicted flows in ungauged basins in the United Kingdom.

Several authors contributed case studies that deal with new technologies or newly available data types. Gutpta *et al*. (Chapter 16) consider the options available for near real time predictions of streamflow in the Canadian Prairies. Boyle *et al*. (Chapter 17) examined how SNODAS estimates of snow water equivalence can improve model predictions in snow dominated watersheds in the Rocky Mountains of the western United States. Kahl *et al*. (Chapter 18) describe how information from satellite imagery can be combined with an energy balance model to improve estimates of snow water equivalence in the Sierra Nevada in the western United States. Armstrong *et al*. (Chapter 19) show how prairie flooding, where runoff water fills glacial-legacy depressional storage to rapidly increase the basin contributing area, can be modelled using high resolution digital elevation models and a fill and spill runoff algorithm.

1.9 SUMMARIES

During the workshop, participants were tasked with synthesizing how the various approaches for prediction can be implemented in specific hydroclimatic regions given the typical availability of meteorological and catchment data and current understanding of hydrology. To ensure thorough evaluation of existing and new predictive methods, participants were tasked to examine a gradient of data-rich to data-poor contexts for that region. This permitted the sharing of ideas and consolidation of knowledge between and across the PUB Themes and Working Groups, and the variety of regional efforts and perspectives represented by research conducted during the PUB decade to date. Sessions summarized and synthesized the new approaches in hydrometeorological measurement, remote sensing, land surface modelling, process verification, catchment characterization and information management that have characterized development of innovative models during the PUB decade.

Whitfield *et al*. (Chapter 20) provide a summary and a synthesis of the discussion that occurred in the work groups. The work groups agreed that the lack of data with which to inform any type of predictive model, in combination with the wide diversity of hydrological landscapes, makes prediction in ungauged basins extraordinarily challenging. While the research of the past decade has great potential to advance the practice of hydrological prediction in ungauged basins, in particular thanks to the development of gridded hydrometeorological products and research activities in relatively data-rich research basins, the transfer to practice has been more limited. The work groups identified the need for continued detailed physical research, a watershed classification system and other tools designed to enhance the development of transferable data, indices, parameters, and indicators. A need was identified for standardized and generalized physiographic information to be collected using the same set of tools that are widely used by practicing hydrologists. Development and maintenance of these types of tools require ongoing communication and collaboration among all hydrologists. The work group summary includes recommendations that address the following needs:

1. to maintain continuity, and validate new methods during implementation.
2. to provide better interfaces to the complex datasets that are needed.

3. for openness and transparency in all predictive approaches.
4. for common operating platforms.
5. for better outreach to practitioners.

The legacy of the PUB decade includes significant advances in the understanding of hydrological processes and development and testing, in research settings, of revised or new methods for PUB. The challenge remains to address the need to adopt standards and globally generalized approaches for practitioners to make predictions in ungauged basins; the participants in the workshop portion of this meeting have suggested approaches that will address this situation. Three participants in the workshop, Denis Hughes, Ross Woods, and Chris Spence, were tasked with providing a synthesis and summary of the major findings of the workshop. They suggest that the key themes to emerge were [1] the need to decrease the gap between process understanding and model structure, [2] the need to constrain uncertain model inputs and outputs, and [3] the need to address the barriers that exist to adoption of new approaches by practitioners (Hughes *et al*., Chapter 21).

It was clear from the workshop discussions that a major divide exists between the hydrological research and water resource applications communities. Some divide is inevitable, due to the translation time of research results and techniques into accepted practical methods. It is hoped that the workshop helped to narrow the divide amongst participants and that this monograph will do the same for a wider audience. Still, there must be diligence and efforts to continue to narrow the divide. Whilst research, innovation and development must continue, hydrological researchers must also ensure that advances are readily and rapidly available to those who work to improve the resilience, sustainability, and security of water resource systems. The successes of the PUB decade in improving the understanding of hydrological processes, the increased availability of spatially distributed hydrometeorological data, the development of more robust physically based and statistical prediction tools, and the transfer of this information to the water resources practitioner community should be built upon. The process of researcher-practitioner engagement, information and technology transfer, and the development of new and relevant scientific tools for prediction must be an ongoing feature of hydrology and water resource science and application.

While the progress made during the PUB decade was critically evaluated, the outcome provides guidance for continued innovation now that the PUB decade has ended. The principal aim of the workshop was to make progress towards a crystallization of the ‘state of the art’ of predicting in ungauged basins. This “snapshot” could then support the further development of techniques that would contribute directly to the practical solution of real-world challenges in water resources management. It is hoped that this monograph forms part of that progress.

1.10 ACKNOWLEDGEMENTS

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