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INVITED COMMENTARY

A review of the Prediction in Ungauged Basins (PUB) decade in Canada

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Initiation of PUB

At the beginning of the twenty-first century, the focus of hydrological prediction had been on the development of empirical tools and simulation models that relied heavily on calibration. These predictive tools were disconnected from many hydrological science advances made since the International Hydrological Decade (IHD) of 1964–1974. The IHD period is now perceived as a time when both hydrological science and water resources prediction improved rapidly and in a coordinated manner. Unfortunately, several factors conspired against the success of the empirical prediction paradigm since the IHD – all due to the inability of empirical techniques to predict reliably outside of the situations used to develop them. The foremost of these was non-stationarity in climate, land use and water use, which caused hydrological systems to shift over time and sometimes changed the predominant water flow and energy processes governing the hydrological cycle (Burn and Hag Elnur 2002; Milly et al. 2008). Inadequate hydroclimatological observation networks (Shiklomanov et al. 2002; St-Hilaire et al. 2003) and notable gaps in hydrological process understanding (Sivapalan et al. 2003) also increased uncertainty in hydrological prediction. It was becoming clear that uncertainty in predictive ability was decreasing the resilience of society to water-related needs, development and hazards. In Canada, for example, we were not particularly prepared to predict the 1996 Saguenay flood (Nagarajan and Yau 2006) nor drought conditions in the southern Prairies in the early 2000s (D.W. Phillips 2002; Stewart et al. 2011).

The widespread occurrence of such situations and growing requirements for improved predictability prompted the International Association for Hydrological Sciences (IAHS) to launch the decade-long Prediction in Ungauged Basins (PUB) Initiative. PUB focused on tackling uncertainty associated with hydrological prediction and was organized under two science targets with the goal of reducing predictive uncertainty. The first target was to critically examine and improve existing technologies, and the second was to develop new and innovative tools and techniques. Six science themes stressed comparative and diagnostic analysis and interactive learning; the themes sought to balance existing knowledge (first target) with new science and technologies (second target) (Sivapalan et al. 2003). A key methodology was to be the replacement of model calibration with improved understanding to reduce predictive uncertainty.

As a large, diverse country with relatively sparse hydrometric and meteorological networks, and hydrological processes complicated by intense seasonality and cold conditions, hydrological prediction has been a challenge in Canada. The Canadian PUB effort was launched in March 2004 with a workshop in Yellowknife that focused on prediction in ungauged basins in cold regions (Spence et al. 2005). The objectives were to: (1) provide outreach to practitioners of the results of recent cold regions hydrology research in the context of predicting streamflow, (2) assess "state of the art" techniques to predict streamflow in ungauged basins in northern landscapes, and (3) define technical needs and recommend a Canadian research and development agenda that could deliver on these needs during the PUB decade. Workshop participants identified precipitation, evapotranspiration, storage and runoff as key water cycle processes needing improved understanding to support water resource management decisions and infrastructure design in Canada's cold regions. Addressing small basins and short time scales was identified as a priority because these were most under-observed and problematic in terms of prediction and engineering design. There was consensus that there was little knowledge about how streamflow response is influenced by poorly understood processes and rare events (e.g., draining of thawed permafrost lakes, extreme weather) and how to design and prepare for them.

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Until recently, most frequency analysis techniques used to assess rare events generally made the assumption of stationarity: that past catchment behaviour and response will be representative of the future. Our community is learning that stationarity does not exist and may never have existed (Milly et al. 2008). Canada's relatively short observation periods may have contributed to a false sense of security as basin responses became exposed to atmospheric drivers that only appear over multidecadal time scales. There may also be real change in climate forcing and land/water use that are altering streamflow regimes. Workshop attendees deemed that reducing risk would come from the development and adaptation of tools that incorporate hydrological processes. However, the level of understanding of runoff generation processes, flow pathways and residence times of water embedded in most predictive tools was basic and black-box approaches were often necessary. The consensus among the workshop participants was that the research basin approach, as advocated by Pomeroy et al. (2005), was the appropriate framework to address the call to improve the understanding of hydrological processes and support the incorporation of this knowledge into tools that would reduce predictive uncertainty.

The foundation for hydrological predictive tools is a well-designed, sustainable hydrometric and climatic network that can respond to current and anticipate future demands. New theories, algorithms and modelled data uncertainty cannot be tested if suitable observed data sets are not available. The network must be designed strategically and must support the development of new predictive tools. Participants recommended the formation of a network of research basins that was integrated within the Water Survey of Canada (WSC) hydrometric gauge network with the goal of collecting data and information towards improving prediction tools in ungauged basins (Spence et al. 2005).

Importantly, there was a call from participants to organize a national committee with linkages to the IAHS PUB initiative, the Canadian Geophysical Union (CGU), and the Canadian Water Resources Association (CWRA) to find ways to enact the workshop recommendations. It was proposed that this Canadian National Committee for Prediction in Ungauged Basins (CNC-PUB) organize workshops in the varied geographic areas of Canada to address specific prediction issues in Canada. A strong federal government role was encouraged, but regional, provincial or local working groups could lead efforts to organize workshops and enact subsequent recommendations. As grassroots working groups, they were seen as better facilitators of consultation on local water issues between scientists, water managers, industry and stakeholders. Working groups would define their own objectives, aligned with the PUB science themes focused on reducing predictive uncertainty.

PUB for the Orographically Challenged

Hydrologists from British Columbia led a workshop at Manning Park in November 2005 on the subject of PUB in mountainous regions. As in northern Canada, inadequate meteorological and hydrometric monitoring networks relative to the heterogeneity of landscape types, uncertainty in precipitation estimates, and a lack of understanding of hydrological processes make PUB distinctly problematic in mountain watersheds. Participants agreed that improved estimates of precipitation at higher elevations are crucial to reducing uncertainty in predicting streamflow in ungauged basins, whether for hydroelectric facility design and operation, water storage, forest management or transportation infrastructure design. While not formally associated with the PUB effort, but certainly of benefit to its progress, there have been improvements in numerical prediction tools and land surface assimilation systems over mountainous regions (Mailhot et al. 2012) and the availability of high-resolution precipitation products (e.g., Wang et al. 2012). Participants at Manning Park discussed why a research agenda for the mountains needed to be aligned with operational needs, and discussed how new advances in knowledge could be transferred to and adopted by practicing hydrologists. While there will always be a lag between the state of the art and the state of the practice, the issue for the workshop was how to minimize that lag. A significant recommendation that subsequently guided the PUB effort in Canada was that CNC-PUB address technology and knowledge transfer issues by pursuing avenues and opportunities for ongoing professional development (Whitfield et al. 2006).

IP3 – Improved Processes, Parameterization and Prediction in Cold Regions

The Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) funded a collaborative research network entitled "IP3 – Improved Processes and Parameterization for Prediction in Cold Regions" as a Canadian contribution to PUB and to the International Polar Year of 2007. IP3 was designed upon the recommendations emanating from the Yellowknife and Manning Park PUB workshops. In the spirit of the CNC-PUB initiative and following the research basin model of Pomeroy et al. (2005), a group of academics, government scientists and water resource managers built an integrated research network to improve understanding of cold-region hydrological processes and incorporate them into numerical models to reduce uncertainty in predictions.

IP3 worked towards improving the understanding of cold-region hydrological processes relating to snow accumulation and melt, permafrost, glaciers, and cold soils and lakes, taking this understanding to improve parameterisations of the representation of these processes in hydrological and land surface models, and then changing the models themselves to take advantage of improved parameterisations by using more appropriate modelling structures and data assimilation techniques. The resulting hydrological and land surface models are sensitive to land use and are capable of being linked directly to atmospheric models and to water resource system models and so provide the interface between changing atmosphere, land cover and water management and provide a way forward for hydrometeorological prediction where stationarity can no longer be assumed. The IP3 network focused on six research watersheds in northern Canada and the western Cordillera, all of which remain operational today, forming legacy platforms for ongoing research into hydrological processes and regimes important for generating useful data and information for responsible resource development and infrastructure design.

Research at the IP3 basins contributed widely to improved understanding of evaporation (Granger and Hedstrom 2010), snow accumulation, interception, redistribution and loss (MacDonald et al. 2009; Fang et al. 2010, 2013), snowmelt runoff (Bewley et al. 2010; Ellis et al. 2010; Pomeroy et al. 2012), infiltration and moisture dynamics in frozen soils (Wright et al. 2009; Guan et al. 2010; Zhang et al. 2010), groundwater flow (McClymont et al. 2010), runoff generation (Boucher and Carey 2010) and dynamic contributing areas to streamflow (DeBeer and Pomeroy 2010; Spence et al. 2010; Phillips et al. 2011). Many of these processes were incorporated in numerical models, primarily the Cold Regions Hydrological Model (CRHM; Pomeroy et al. 2007; Dornes et al. 2008a) and Modélisation Environmentale Communautaire Surface and Hydrology (MESH; Pietroniro et al. 2007; Dornes et al. 2008b, 2008c). These models have proven capable in simulating small basin hydrology across Canada and throughout the world (e.g., Dornes et al. 2008a; DeBeer and Pomeroy 2009). Importantly, the technology has been transferred to user groups across Canada and to larger Canadian watersheds. A series of nine open IP3 modelling classes were given to the water resource and hydrology community in Alberta, Northwest Territories, Saskatchewan, Manitoba and Ontario on how to operate the MESH and CRHM models. For instance, MESH was coupled to the Canadian Meteorological Centre's (CMC's) Global Environmental Multiscale (GEM) Numerical Weather Prediction (NWP) model and forced with the Canadian Precipitation Analysis (CaPA) assimilated precipitation product to develop soil moisture indices for the South Saskatchewan River Basin. CRHM was forced with the GEM-local area model runs at high resolution to provide the first high-resolution coupled atmospheric-hydrological model runs over the Canadian Rockies. The IP3 CRHM model has been applied for physically-based prediction of ungauged flows over 26,000 km^2 of mountain, boreal forest and prairie in the Smoky River Basin, Alberta, in an operational setting with forecasts of ungauged flows driven by GEM model output (Pomeroy et al. 2013). The foundational work during IP3 also translated into the successful application of MESH to the Laurentian Great Lakes watershed during a period of extreme low water levels (Fortin and Gronewold 2011). Improved streamflow and lake evaporation parameterization reduced uncertainty in explanations of the low lake levels (Deacu et al. 2012), enabling water managers to confidently develop water level management regulations for Lake Superior that can account for non-stationarity in climate (Yuzyk et al. 2012).

Low flows and temporary streams

The recent low water levels in the Great Lakes and the 2001–2003 Prairie drought demonstrated that low or zero streamflow can be as environmentally and socio-economically significant as floods (Smakhtin 2001), but the impact of low flows by their nature can be much more insidious and persistent. Two PUB workshops addressed the subjects of how to better understand and predict low and temporary flow hydrology in Canada: the PUB Low Flow workshop hosted in at the Institut National de la Recherche Scientifique – Centre Eau, Terre & Environnement in Québec City, Québec, and the PUB Zero Flow workshop held in 2011 in Drumheller, Alberta. Both workshops were documented in special issues of the *Canadian Water Resources Journal* (Spence et al. 2008; Boon et al. 2012).

The recurring theme of data availability was present at both these PUB workshops. The problem was seen as particularly acute when it came to predicting low-flow and zero-flow periods. The current configuration of the Water Survey of Canada (WSC) network is focused on perennial streams. The predominant streamflow measurement methodologies used are not conducive to resolving small flows, which are inherently hard to measure, and the data may not have the same quality in small drainage basins as in larger ones (Hamilton 2008). In addition to monitoring challenges, current model performance indicators are generally ill designed to account for the multivariate aspects related to low flows. Low-flow predictions have the additional caveat that they cannot be based solely on accurate estimation of amplitude, which tends to be the focus of flood predictions. There are many other characteristics of low flows that need to be accurately modelled and predicted, such as frequency of occurrence, duration and timing of the events (Daigle et al. 2011). Zero flow is easier to identify, but the time and place at which it occurs is very difficult to gauge and predict (MacCulloch and Whitfield 2012). This must be considered when assessing the uncertainty and declaring success when applying hydrological models in small headwater basins where contributing areas can be very small and streams intermittent.

The physical processes by which surface water interacts with groundwater are often neglected when predicting low or zero flows, even though groundwater is the most common store from which low flows are generated. Expanding low- and zero-flow characterization and prediction beyond magnitude, to include duration, persistence, seasonality and spatial extent, was recommended. This would require more explicit recognition of groundwater and other stores where appropriate, in models used to predict low flows. Much can be gained from improving predictions of low flow, stream intermittency and contributing area dynamics, because knowledge of these types of flow characteristics provides very useful information when estimating in-stream flow needs required to sustain ecological function (Bradford and Heinonen 2008), water availability for allocation purposes, and water chemistry characterization to determine withdrawal and effluent limits.

There are several Canadian physically-based deterministic models that incorporate hydrological processes that could lead to predicted intermittency; however, few examples of applications attempting to simulate intermittency exist. Some of these models, in their present form, are not capable of simulating the multivariate nature of low and intermittent flows. For instance, MESH, in its current form, still requires a perennial stream in each simulation grid (Davison and van der Kamp 2008). With statistical approaches, however, Sadri and Burn (2011) proposed multivariate pooled procedures for the joint estimation of several low-flow characteristics based on the use of copulas, which can efficiently estimate the bivariate (or multivariate) distribution for dependent variables. Software exists to implement pooled frequency analysis, for either high or low flows. An example is the REGIONS software (Ouarda et al. 2008), which includes modules for pooled frequency analysis in both stationary and non-stationary frameworks.

There has been subsequent success in simulating intermittent mountainous headwater streams (DeBeer and Pomeroy 2010). The sensitivity of runoff-forming processes in ungauged prairie streams and wetlands to drought was examined by Fang and Pomeroy (2007, 2008). Fang et al. (2010) and Shook et al. (2013) have made progress in understanding variable contributing areas to streamflow in the Prairie landscape. Pomeroy et al. (2013) developed CRHM to simulate ungauged prairie stream behaviour over long time periods to develop hydrological drought indices. Topographic analysis procedures that simulate saturated areas (Richardson et al. 2009; White et al. 2012) have now been developed that can be used to produce measures of dynamic contributing areas against which deterministic models could be tested.

Besides topography, there is a diversity of catchment characteristics that influence how storage is depleted from a watershed and the propensity of low flows (e.g., a dry climate, surficial geology, cryospheric processes). Workshop participants agreed that the conceptualization of low flows as a linear function of storage depletion needs to be rethought. Knowing relationships between low flows and landscape and geological characteristics would improve the traits that control low flow and stream intermittency better than current approaches that focus upon only dissecting hydrograph recessions or flow duration curves. Knowledge of these relationships, with a catchment or temporary stream classification system, would improve our ability to extrapolate across regions (Peters et al. 2012). Burn et al. (2008), Daigle et al. (2011) and Buttle et al. (2012) made initial progress in identifying the catchment traits important for low and temporary streamflow regimes in different regions of Canada.

Peatlands

With 1.1 million km^2 of peatlands covering 12% of Canada (National Wetlands Working Group 1988), their influence on Canadian hydrology is ubiquitous. One of the most common assumptions in Canada about landscape control on streamflow is the capability of peatlands to maintain baseflows during dry periods. A special session at the 2008 Canadian Water Resources Association Conference focused on assessing the state of knowledge of peatland hydrology in Canada and our community's ability to predict peatland hydrology and streamflow from the catchments that contain them. Using the outcomes from this session, Whitfield et al. (2009) outlined the challenges of predicting peatland hydrological response. One of the largest of these is the representation of relationships between hydraulic conductivity, storage and release capacity with depth. Surprisingly, discharge-water table relationships have only been made for a handful of peatlands so it is difficult to parameterize models, even if they include algorithms capable of handling continuous changes with depth. The inclusion of organic soils in CRHM (Pomeroy et al. 2007; Wright et al. 2009) during IP3 was a significant contribution to incorporating knowledge of hydrological processes into models. Jutras et al. (2009) demonstrated that models with such algorithms, such as the Peatland Hydrologic Impact Model (PHIM), can work in Canadian landscapes. However, the majority of Canadian peatlands are subject to freezing, which disrupts these relationships. This is one reason that Quinton and Carey (2008) recommend the development of coupled energy-water budgets in numerical models applied in northern Canada.

Topology (i.e., the landscape context in which peatlands reside) influences peatland evolution and behaviour and thus needs to be included in hydrological models applied to peatlands or catchments with peatlands. Devito et al. (1996) demonstrated the importance of location to peatland streamflow response. This requires models with the ability to incorporate topology. It also requires data and information about characteristic hydrological properties of different types of peatlands in different locations and in different regions. These are data and information that are not easily obtained in Canada. For instance, there are very few direct measurements of actual evapotranspiration from Canadian peatlands. Acquiring such measurements remains a major challenge (Proulx-McInnis et al. 2012). This is only one example of the common problem of parameterizing numerical models. While we have improved knowledge and have incorporated this knowledge into tools, finding the data to drive these robust models remains a significant impediment to reducing uncertainty in practical situations.

Framework for Integrated Research and Monitoring (FIRM)

In response to the recommendation at the Yellowknife workshop to define a sub-network within the WSC hydrometric gauge network that was integrated with a network of research basins, a working group developed what eventually became the Framework for Integrated Research and Monitoring or FIRM (Spence et al. 2009). FIRM was meant to identify the necessary components of integrated research and monitoring programs that could improve understanding and prediction of Canadian water resources. Seven characteristics of a successful integrated program were identified: programs must be (1) collaborative, (2) of high quality, (3) strategic, (4) relevant, (5) worthy of investment, (6) scale appropriate and (7) representative. Application of the FIRM concept to a specific research or policy question is via a cluster of activities including short- and long-term operational monitoring sites (e.g., WSC gauges) and process research. These clusters are designed to provide data and information, improve knowledge and develop predictive tools for practitioner and policy development, and/or to respond to worthy and relevant issues.

Collaborative efforts were defined as cross-disciplinary: those that include clients and outreach, apply multiple environmental datasets and promote scientific exchange among clusters through cross-validation efforts. Spence et al. (2009) stress that clusters require very specific research strategies that can develop enough understanding over a short time period to assemble and evaluate predictive models. It is crucial that research strategies have explicit and quantifiable uncertainty reduction and/or engineering design goals so as to gauge success. This gives strategies a defined life span, which is important for justifying return on investment. FIRM was recommended to WSC as a framework for planning of water research and monitoring because it (1) permits the rationalization of individual monitoring sites and research projects and the identification of gaps between demands and funding levels, (2) ensures the generation of the proper data and information needed for policy development and resource management, and (3) provides a means for improved linkages among the scientific, policy and resource management communities.

An evaluation of the PUB decade in Canada

The major goal of the international PUB initiative was to reduce the uncertainty associated with prediction by migrating away from tools that require calibration and curve-fitting towards more physically-based tools that do not require calibration. Ten years after the Yellowknife workshop, Canada has made substantial contributions to this goal. Hydrological process knowledge of cold regions, mountains, prairies and peatlands has improved immensely and many of these processes have been incorporated into deterministic models. This was largely through the CFCAS-funded IP3, Drought Research Initiative (DRI) and Western Canada Cryospheric networks, the International Polar Year program and the International Upper Great Lakes Study, along with several other efforts by individuals and smaller research and development networks.

Many other Canadian contributions that occurred independent of CNC-PUB deserve reporting as they reflect the initiatives of many colleagues. Cunderlik and Ouarda (2006) introduced a very significant contribution to flood frequency analysis that takes into account the non-stationary character of hydrologic records and can deal with time-dependent parameters of flood frequency distributions. Several improvements were made to scaling approaches to prediction in ungauged basins (Yue and Wang 2004; Schertzer et al. 2007; Buttle and Eimers 2009). Others have made contributions to physical hydrology (Dumedah and Coulibaly 2012; Samuel et al. 2012a, 2012b; Razavi and Coulibaly 2013). Moore et al. (2012) and Trubilowicz et al. (2013) developed novel approaches for prediction in ungauged basins using water balance models and ecological classifications. Not all of these contributions to PUB were in the realm of physical hydrology. Erosion prediction in ungauged basins was addressed in de Boer et al. (2003), while Bradford and Heinonen (2008) and Peters et al. (in press) addressed the ecological issues of low flows. Several authors reported on the development and implementation of practical tools for prediction (Metcalfe et al. 2005; Cheng et al. 2006; Yuan and Cheng 2008). Canadians also contributed directly at the international level (e.g., Blöschl et al. 2013; Hrachowitz et al. 2013; Pomeroy et al. 2013).

It should be noted that only one of the large networks, IP3, was formally associated with the international PUB programme. PUB in Canada had no budget, and no large institutional support, unlike similar past international programs (i.e., the International Hydrological Decade, the Global Energy and Water Cycling Experiment). CNC-PUB succeeded when it engaged grassroots groups to pursue research and development with a consideration for the PUB goals and encouraged them to incorporate those goals within their programs. Some of the Canadian successes during the PUB decade were not directly due to PUB efforts, but were fortuitous because of progress associated with other activities, for example, the 2010 Olympics and the International Upper Great Lakes Study.

Throughout the PUB decade, the clients of WSC repeatedly made recommendations to improve the effectiveness of the hydrometric network so that the data and information it produces would lead to quantifiable reductions in predictive uncertainty. This was particularly apparent at the low- and zero-flow workshops. FIRM is one framework or network design tool that could have been applied to address the data and information gaps that prevent reductions in predictive uncertainty in Canada's mountainous regions, or low-flow conditions. However, WSC and Environment Canada did not have the human resource capacity to accomplish the necessary network planning nor the managerial systems in place to promote the necessary horizontal synergies to adopt FIRM. Provincial and federal governments are currently making investments that address predictive uncertainty in water resource management to increase Canadian societal resilience to water-related threats and decrease risk to Canadians, but these are not necessarily explicitly applying FIRM. The Geological Survey of Canada (GSC) adopted FIRM in its approach to studying the state and evolution of Canada's glaciers. By applying the FIRM principles, the GSC has been able to engage its partners and clients in reaching the goals for its glacier network, including better prediction of the state and fate Canadian glaciers.

Research and development networks did not form around some issues the same way they did for cold regions and drought. During the PUB decade, there were recommendations to improve low-flow regionalization tools, prediction of stream intermittency and contributing areas to streamflow. The development of classification systems for intermittent streams and definition of homogeneous regions of low-flow regimes were other needs identified by practitioners. This may have been a human resources capacity issue, as there are only an estimated 50 research hydrologists in Canada. It may have also been a funding issue. Regardless, these knowledge and prediction deficiencies remain, and should be addressed in the future. The upper Great Lakes notwithstanding, many regions of Canada are currently dealing with extraordinary flooding and water excess issues, yet there will be another drought on the Canadian Prairies. It will be interesting to see how water management systems will react given that water demands associated with population and industrial growth have increased since the drought of the early 2000s. The resilience of these systems could be increased by having tools that can correctly predict how streams will behave during low-flow conditions or which streams will dry up and when.

All the advances in understanding hydrological processes will be for nought if the new knowledge is not applied by practicing hydrologists. It is for this reason that CNC-PUB made knowledge and technology transfer opportunities a priority. The IP3 network had a significant communication and education program that included small focused face-to-face meetings, model training courses and larger workshops. Workshops included presentations meant to inform participants of new findings, but also included significant information exchange meant to inform researchers of practical gaps and issues that need to be addressed. This opportunity for open feedback and communication has meant ongoing improvements to the applicability of hydrological research in Canada. A significant effort on the education front was the introduction of the joint Canadian Society for Hydrological Sciences and University of Saskatchewan Course on the Principles of Hydrology held annually since 2010 in Kananaskis, Alberta. This course, attended by a mix of graduate students and young to mid-career professionals, has grown in popularity since its inception and has trained over 140 students. As many practicing hydrologists have only been able to take one or two undergraduate courses in hydrology, this course remains an excellent means by which to inform practicing, or soon-to-be-practicing, hydrologists of the current state of the science.

In May 2011, Canada hosted an international workshop investigating the issues and opportunities for putting the results of PUB into practice. This was meant to address goals of the fourth biennium of the PUB decade of enhancing dialogue between the scientific and applications communities and promoting development of improved models that reflect the improved hydrological understanding generated during the first eight years of the PUB decade. It was an informative meeting, and the participants had clear opinions on how to implement technology transfer. Even after 10 years of effort, some still have the feeling that uptake from practitioners remains a notable gap. Many of the practitioners in attendance expressed ongoing concerns about having the time to learn new tools, and the ability to apply them in the time frames demanded by clients. This somehow needs to be considered by research hydrologists when in the model-development phase. A further impediment to the adoption of new tools, whether numerical models or new statistical approaches, is that they may be considered by the consulting community to be non-standard approaches, and therefore avoided. The practitioner community needs to consider how post-secondary institutions and professional engineering associations can better adopt and implement methods with improved performance or stronger foundations within upgraded or new tools, either through undergraduate courses or ongoing professional development.

The current improved numerical prediction tools do have greater data demands than previous ones, which also can discourage use. The effectiveness of operational hydrometeorological networks in Canada has been addressed elsewhere (e.g. Spence et al. 2007) and the data to drive enhanced predictive tools are not always easily available. The production of parameter and forcing data is one reason why a research basin network integrated with the WSC hydrometric network following the FIRM tenets would be valuable. What is also lacking is a communication strategy to advertise the availability of new datasets to the practicing water resource community. For example, there are a multitude of new precipitation databases, such as the North American Regional Reanalysis (NARR; http://www.emc.ncep.noaa.gov/mmb/rreanl/; NOAA 2013; Mesinger et al. 2006), Agriculture and Agri-food Canada's gridded products (http://www.agr.gc.ca/DW-GS/historical-historiques.jspx?lang=eng&jsEnabled=true; AAFC 2013), Environment Canada's CANGRID (PCIC 2013; http://www.cics.uvic.ca/climate/CanadaGriddedClimateData/CanadaGriddedClimateData1961to1990.htm) or Environment Canada's Canadian Precipitation Analysis (CaPA) (Environment Canada 2013; http://loki.qc.ec.gc.ca/DAI/capa-e.html; Mahfouf et al. 2007). At some PUB meetings, the practicing community seemed poorly informed about these products. Communication that provides a high-profile conduit for research and development notes would be very valuable, but a resourced institution would need to host and advertise it. Active and up-to-date online resources need to be used as tools for the mass dissemination of valuable information to the hydrological community and complement the traditional peer-reviewed literature medium for research results. Furthermore, online sources would support better linkages among academia, government, practitioners and the public, each of whom have a stake in the development and understanding of water resources in Canada.

What of the future? IAHS has already proposed a new initiative – Panta Rhei (Montanari et al. 2013). The purpose of Panta Rhei is to reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems. The practical aim is to improve our capability to make predictions of water resource systems dynamics to support sustainable societal development in a changing environment. There has been little Canadian interest in Panta Rhei, because in Canada natural drivers of hydrological non-stationarity (i.e., landscape and climate) remain a higher priority and a larger challenge than how human systems interact together with the water cycle. The Canadian North is changing rapidly (Déry et al. 2009) and there is evidence of landscape and climate change impacts on streamflow and water chemistry regimes across the country (Yue et al. 2003; Jeong et al. 2012), so the challenge has real implications for the Canadian economy. Canadian hydrology interest in the World Climate Research Programme's renamed Global Energy and Water Exchanges Project (GEWEX) has therefore been rekindled with the launch of the new Changing Cold Regions Network (CCRN). CCRN proposes to improve the understanding of past and ongoing changes in climate, land, vegetation and water, along with predicting their future integrated responses from the local to the regional scale in the western and northern interior of Canada. It is a direct successor to IP3 and DRI, and so will provide some base for Canadian hydrological prediction research as it moves to address non-stationary systems at multiple scales.

The PUB Decade in Canada strove to encourage enhanced knowledge and technology transfer to improve hydrological prediction, yet there still remains a divide between the hydrological research and water resource applications communities in Canada. Some divide is inevitable due to the translation time of research results and techniques into accepted practical methods. Whilst it appears to the authors of this review that the divide has narrowed over the last decade, there must be diligence and efforts to continue to narrow the divide. Research, innovation and development must continue, and hydrological researchers must also ensure that advances are readily and rapidly available to those who work to improve the resilience, sustainability and security of Canadian water resource systems. The PUB decade should be considered a success in Canada because of the advances in 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. Successful examples from northern Canada, the Great Lakes, Prairies and the Western Cordillera all demonstrate recent applications of these tools in addressing some of Canada's most pressing current water policy and management issues. But one important lesson from PUB is that one singular effort is not enough. 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 Canadian hydrology and water resource science and application. The recent set of two consecutive joint Canadian Geophysical Union-Canadian Water Resources Association meetings is an encouraging move in this direction.

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