Invited Commentary: Themes and Issues from the Workshop ‘‘Operational River Flow and Water Supply Forecasting’’

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Abstract: River flow and water supply forecasting are important applications of hydrologic sciences. Water management decisions and the issuance of flood warnings depend greatly upon real-time predictions of hydrologic events to come. A group of over 70 hydrologic practitioners and researchers gathered for a workshop devoted to operational hydrologic forecasting, which was held in Vancouver, British Columbia, on 6–7 October 2011. The goal of the workshop was to share ideas about the applicability of new operational forecasting techniques. Presentations were given on topics such as ensemble forecasting, verification of deterministic and probabilistic forecasts, and quality control of environmental data. This commentary summarizes these presentations and provides highlights from the group and open forum discussions.

Résumé: La prévision des débits et des apports en eau est un important champ d’activité des sciences hydrologiques. Les décisions relatives à la gestion des ressources en eau ainsi que l’émission d’alertes d’inondation s’appuient largement sur l’anticipation des événements hydrologiques à venir. Un groupe d’environ 70 praticiens et chercheurs en hydrologie se sont regroupés lors d’un atelier entièrement consacré à la prévision hydrologique opérationnelle qui s’est tenu à Vancouver, Colombie-Britannique, les 6 et 7 octobre 2011. Cet atelier visait notamment à échanger des idées sur l’applicabilité de nouvelles techniques de prévision dans un contexte opérationnel. Les nouvelles tendances en prévisions hydrologiques comme la prévision d’ensemble, la vérification des prévisions hydrologiques déterministes et probabilistes, le contrôle de qualité des données environnementales sont des exemples de sujets qui ont fait l’objet de conférences lors de cet événement. Cet article résume les différentes présentations ainsi que les échanges entre les participants lors d’un forum de discussion qui a eu lieu à l’issu de cet atelier.

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Introduction

Forecasting river flow and water supply are important operational applications of hydrologic sciences. Depending on the objective, the forecast horizon can be short-range, i.e., a few hours or several days into the future, or it can be long-range, i.e., several months into the future. River flow forecasting refers to producing short-range forecasts in a daily or sub-daily temporal resolution. Water supply forecasting refers to generating long-range forecasts, often with a coarse temporal resolution such as months or seasons. Much depends on these forecasts, such as preventing loss of life and property or helping make optimal water resource management decisions.

Only a few conferences or workshops have a specific focus on operational hydrologic forecasting. To fill a need for more communication on this topic, a workshop entitled "Operational River Flow and Water Supply Forecasting" was held in Vancouver, British Columbia, on 6–7 October 2011, under the auspices of the Canadian Society for Hydrologic Sciences. A group of over 70 hydrologic practitioners and researchers from Canada, the northwestern US, and Sweden attended the workshop. The motivation of this workshop was to bring together hydrologic forecasters and those doing research relevant to forecasting, to share ideas about the applicability of new forecasting techniques in an operational context, and possibly to influence the direction of future forecasting-related research and development (R&D). Although most of the participants were practitioners from hydropower, consulting, or government entities, academicians were also represented. Eighteen presentations were given on topics including ensemble forecasting, data assimilation, forecast post-processing, verification of deterministic and probabilistic forecasts, and quality control of environmental data. Titles and authors of the presentations are listed in Table 1. Presentations are available at the Canadian Water Resources Association-Canadian Society for Hydrological Sciences website (Canadian Society for Hydrological Sciences, 2011). Breakout group discussions focused on three specific topics: (i) hydrologic modelling, forecast systems, and information technology (IT) requirements, (ii) ensemble forecasting, and (iii) environmental monitoring and hydrologic modelling. The group discussions were designed to assess the methods available to the practitioner, the hydrologists' vision, and the ensuing need for data, information, techniques, and tools.

This commentary is a summary of the presentations and discussions. It describes the techniques currently in use, innovative forecast systems under development, and the key knowledge gaps highlighted during the workshop. The sections below represent the major themes of the workshop.

The Forecasting Process

While sharing many of the same issues and considerations with other types of hydrologic prediction (such as simulations for model testing, or evaluating impacts of land use or climate change), hydrologic forecasting has additional requirements and constraints. In operational (real-time) forecasting, agencies force strict time constraints upon the forecasters. Accomplishing the necessary tasks in a short amount of time requires the development of complex IT infrastructure, including databases, data visualization tools, and data dissemination systems. Other forecasting-specific steps in the modelling process may include the following: the selection of numerical weather predictions or other sources of climate data for use as hydrologic model forcings; data assimilation, i.e., the insertion of observations into a dynamical model to correct simulated basin states and thereby improve the quality and accuracy of the forecast; forecast post-processing, i.e., the correction of modelling biases and/or modelling errors; the quantification of the level of confidence in the forecast; and the communication of forecasts to decision makers on a regular basis and in a timely manner. A hydrologic forecasting system additionally requires real-time availability of environmental data, environmental data quality control, regular forecast verification, and the R&D necessary to generate information that is essential to build sophisticated modelling systems. All this combines to make operational hydrologic forecasting a demanding task for both models and forecasters.

Hydrologic Forecast Models

Operational and Research Models

Central to a hydrologic forecast system is the hydrologic model used. Most of the models and forecast

Table 1. Titles and authors of workshop presentations (Canadian Society for Hydrological Sciences, 2011). Names of presenters are in bold and are cited in the text.

Title of Presentation	Author
Assessing hydrological forecasts at Hydro-Québec	**Luc Perreault** (Hydro-Québec Research Institute) Jocelyn Gaudet (Hydro-Québec Research Institute) James Merleau (Hydro-Québec Research Institute) Mylène Teasdale (Hydro-Québec Research Institute)
Evaluation of deterministic and probabilistic meteorological forecasts for BC watersheds	**Greg West** (University of British Columbia and BC Hydro) Dominique Bourdin (University of British Columbia) Katelyn Wells (University of British Columbia) Doug McCollor (University of British Columbia and BC Hydro) Roland Stull (University of British Columbia)
Verification of BC Hydro's short- and long-range reservoir inflow forecasts	**Adam Gobena** (BC Hydro) Frank Weber (BC Hydro)
Inflow forecast at Hydro-Québec Production	**Marie-Claude Simard** (Hydro-Québec)
The Ensemble River Forecast System: Towards gaining certainty in uncertainty	**Frank Weber** (BC Hydro) Dimeji Omikunle (Accenture Business Services) Scott Weston (BC Hydro) Adam Gobena (BC Hydro)
Short-term hydrological ensemble prediction-design and preliminary results	**Bruce Davison** (Environment Canada and McGill University) Vincent Fortin (Environment Canada) Al Pietroniro (Environment Canada) Peter Yau (McGill University) Robert Leconte (University of Sherbrooke) Muluneh Mekonnen (University of Saskatchewan)
Member-to-member ensemble hydrometeorological modelling	**Dominique Bourdin** (University of British Columbia) Roland Stull (University of British Columbia)
An experience on the selection of members for simplifying a multimodel hydrological ensemble prediction system	**Darwin Brochero** (Université Laval) François Anctil (Université Laval) Christian Gagné (Université Laval)
Similarities and difference in hydrologic forecasting approaches between Europe and America	**Peter Gijsbers** (Deltares USA) Edwin Welles (Deltares USA) Albrecht Weerts (Deltares NL) Micha Werner (Deltares NL and UNESCO-IHE)
Accurate forecasts begin with accurate observations: How improved data production systems can lead the way	**Stuart Hamilton** (Aquatic Informatics) Dave Hutchinson (Environment Canada) Touraj Farahmand (Aquatic Informatics) Derek Forsbloom (Aquatic Informatics)
How much do we trust our models? Memes in streamflow forecast adjustment	**Rashawn Tama** (USDA Natural Resources Conservation Service) **David Garen** (USDA Natural Resources Conservation Service) Gus Goodbody (USDA Natural Resources Conservation Service)
Implication of data assimilation in ensemble streamflow prediction	**Hamid Moradkhani** (Portland State University) Caleb DeChant (Portland State University) Reza Najafi (Portland State University)
High resolution modelling of climate processes in diverse landscapes	**James Byrne** (University of Lethbridge)

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Table 1. (*Continued*).

Title of Presentation	Author
Flow-regime estimation in UK ungauged basins	**Michael Allchin** (Mapmatics) Andy Young (Wallingford HydroSolutions UK) Matt Holmes (Wallingford HydroSolutions Australia)
Toward improving the multi-modelling hydrologic forecasting: Integration of data assimilation and bayesian model averaging	**Hamid Moradkhani** (Portland State University) Mark Parrish (Portland State University) Caleb DeChant (Portland State University)
Probability spring flood forecasts in northern Sweden	**Susanne Nyström** (Vattenfall Hydropower AB Sweden) **Barbro Johansson** (Swedish Meteorological and Hydrological Institute) Jonas Olsson (Swedish Meteorological and Hydrological Institute)
Development of an inflow forecasting model for the Pointe du Bois spillway replacement project	**Phil Slota** (Manitoba Hydro) John Crawford (Manitoba Hydro) Noël Evora (Manitoba Hydro)
Near real time forecasting of water levels along lower Fraser River during freshet 2011	**Khalid Khan** (BC Ministry of Forest, Lands and Natural Resource Operations) Lotte Flint-Petersen (BC Ministry of Forest, Lands and Natural Resource Operations) Hannah Chiew (BC Ministry of Forest, Lands and Natural Resource Operations)

systems presented during the workshop were operational implementations at hydroelectric utilities. All operational applications of hydrologic models presented employed conceptual, i.e., grey-box, process-oriented (as opposed to empirical, black-box or physically-based, white-box) watershed models, which are spatially lumped or semi-distributed, i.e., having a single or only a few spatial computational units. These included HSAMI (Fortin, 2000), used by Hydro-Québec (Simard), the UBC Watershed Model (Quick and Pipes, 1977), used by BC Hydro (Weber), the Sacramento model within the US National Weather Service River Forecast System (Burnash *et al.*, 1973; Burnash, 1995) used by River Forecast Centers in the US (Gijsbers), the HBV model (Bergström, 1976, 1992), used by Vattenfall in Sweden (Nyström, Johansson), the HEC-HMS modelling system (United States Army Corps of Engineers, 2000), applied by Manitoba Hydro for streamflow forecasting during project construction (Slota), and the WARNS model, an adaptation of the UBC Watershed Model by the BC River Forecast Centre, used to generate input to the MIKE-11 hydraulic routing modelling system (DHI, 2000) for flood inundation forecasting on the lower Fraser River (Khan). Assuming that the models presented at this workshop are representative of operational forecasting, it is noteworthy that most watershed models currently being used are implementations of science from three decades or more ago.

In contrast, model development in academia during the past two decades has, in many cases, moved toward spatially distributed conceptual models, in which parameters and processes vary in space at a high resolution, and towards models with a much greater physical basis than most of the aforementioned operational forecast models. Fully distributed models better capture the spatial variability of hydrological processes and, in theory, can make better use of spatial fields, such as remote sensing and GIS data. Several examples of these models were presented. The GENESYS model (MacDonald *et al.*, 2009) was originally developed to simulate detailed landscape dependent micrometeorology needed for modelling daily snow and rainfall processes in mountainous terrain, but it can also be used for forecasting (Byrne). The MESH model (Pietroniro *et al.*, 2007) has been used in a short-range ensemble forecast system (Davison). The WATFLOOD (Kouwen, 2010) and WaSIM-ETH (Schulla, 1997, 2012) models are being incorporated into a multi-model forecast system (Bourdin).

A different type of prediction – that of estimating changes to flow duration curves due to anthropogenic watershed impacts – was also discussed (Allchin). Spatial techniques for estimating statistical streamflow characteristics were developed and demonstrated for a basin in the UK. While not producing predictions in the sense of real-time forecasts, such products are useful in long-range planning with particular application to ungauged basins.

Model Selection and Issues in the Adoption of New Technology

Models selected for operational implementation depend on various criteria – some scientific, some based on convenience or familiarity – but two criteria specifically mentioned during workshop discussions were ease of use and good documentation. Model use and model code need to be well enough documented and usable to be able to pass what was dubbed the "bus test": if the developer were to be hit and killed by a bus, would others still be able to operate and further develop the model? Since scientific progress is constant, and modelling platforms should incorporate new knowledge as it becomes available, this criterion is valid for both established and research models.

Some important questions related to model choice and keeping up with advancing technology received considerable discussion during the workshop. Forecasters are well aware of the fact that their forecasts are uncertain and can be judged wrong, if the error is sufficiently large. With acknowledged room for improvement, it may be tempting to blame the model as a major source of error, and it is understandable to hope that newer models are also more accurate models. However, as mentioned previously, most operational agencies have not adopted the latest hydrologic models coming out of the research community, instead relying on models from some decades ago. One could assert that, given the advances in hydrologic and computer sciences over the past three or more decades, forecast agencies are not taking full advantage of their modelling possibilities. There are, however, some very valid reasons for agencies not adopting new modelling technologies, and much of the breakout group and open forum discussions revolved around this topic. A number of reasons why forecast agencies continue to use older watershed models were cited by the participants:

(i) Forcing data at a spatial resolution required by complex models may not be available in real-time, particularly in remote and mountainous regions.
(ii) Institutional momentum in the use of the existing, older models due to expensive IT infrastructure and resident expertise has been built up over the years.
(iii) Current models have a proven track record, which is especially important when major decisions are based on their predictions. While it is very attractive to use cutting-edge technology, agencies typically err on the cautious side to avoid unpleasant surprises.
(iv) Proof that another watershed model would indeed lead to better results and is worth the investment is lacking. Forecast agencies may be justified in using 30-year-old technology if they can clearly demonstrate the forecast worthiness of their old models in well-designed model and/or forecast benchmarking experiments.
(v) Investments in environmental monitoring, model calibration, data pre-processing, and forecast post-processing could perhaps improve forecasts as much as or more than a change in the hydrologic model.

While all of these reasons are valid and understandable, the fact that decades-old models have remained in current use may also indicate an inconvenient truth about missing or ineffective R&D investments by forecasting agencies over the past decades. Or, it could mean that academic R&D is far outstripping the ability of operational agencies to keep up with the rapid pace of development and the continually increasing resources needed to implement these more complex and expensive modelling technologies. In any event, the development of objective, region-specific model performance rankings would be a critical first step towards opening the agencies' doors for new watershed models.

Environmental Monitoring

Hydrologic forecasting, like all hydrologic modelling, depends on accurate environmental observations. Part of the breakout group and open forum discussions during the workshop therefore centred on the topics of "environmental monitoring and hydrologic modelling". Sampling of hydroclimatic variables poses an immense challenge to all agencies. Common issues include difficulties in designing optimal and cost-effective monitoring networks, maintaining long-term data sites during cost-cutting periods, developing successful business cases for data collection expenses, and ensuring the quality of environmental data. While these issues are universal, there are no simple, obvious solutions. Two novel suggestions brought up during the workshop for low-cost ad hoc monitoring data expansion, however, were the collection of temperature data on transmission towers and the engagement of the outdoor sports community to collect snow and climate information.

With the trend towards modelling at higher spatial resolutions and with the quality of interpolated fields being tied to the availability of representative station coverage, existing monitoring networks will require careful re-evaluation. Precipitation radar can be useful for estimating precipitation fields for flood forecasting applications, but difficulties in establishing the relationship between radar reflectivity and precipitation rate at the surface, and the problem of mountains blocking the beam, have so far limited its use in hydrologic forecasting. Other emerging alternatives that have found their way into some forecast systems (Davison, Bourdin) are output from numerical weather prediction (NWP) models and blended products, like the Canadian Precipitation Analysis (CaPA; Mahfouf *et al.*, 2007). CaPA combines several sources of information – NWP model output, surface observations, and eventually also satellite products and precipitation radar – into a single dataset. Comparing hydrologic model simulations forced with NWP output or CaPA data with the status-quo will require continued R&D by the individual forecast agencies.

It was noted (Gijsbers) that in North America, quality-control of hydroclimatic data for river flow and water supply forecasting is typically done by the forecasting agencies, whereas in Europe, it is done outside those agencies. The latter might have advantages if it means that information from multiple monitoring networks is available for improved spatial quality control. However, to obtain reliable environmental data in North America, quality control of raw environmental data is typically a necessary step in the forecast production chain. Pertinent perspectives on many of these hydrometric data quality issues and some correction techniques (as implemented in Aquatic Informatics software) were discussed at the workshop (Hamilton). At the core of the *Aquatic Informatics Real-Time Quality-Enhanced Discharge* system is a piecewise linear dynamical machine learning model that has been developed to, for example, detect sensor faults and anomalies and to estimate data. A nonlinear dynamical machine-learning model is presently under development, and it promises to be more accurate than linear techniques for modelling highly chaotic signals. The application relies on automated quality control processes, which allows the hydrologist to evaluate the data point-by-point; conveniently and effectively.

Ensemble Forecasting

The workshop clearly showed that the R&D focus among forecast agencies is on further developing their prediction systems particularly in the area of generating reliable forecast uncertainty distributions. The technique used for generating probabilistic forecasts with process-oriented models is ensemble forecasting. Ensemble forecasting is similar to standard Monte-Carlo simulations, i.e., the model is run several times with different variables and/or parameters to generate a set (ensemble) of possible outcomes. Ensemble forecasting has been in use in hydrologic applications for many years (Day, 1985) but primarily only to characterize streamflow forecast uncertainty due to future weather uncertainty. Emerging ensemble forecast systems intend to capture as many sources of uncertainty as are known and feasible to incorporate into the system.

Despite some differences in ensemble prediction systems (EPS) described during the workshop, some commonalities emerged. Many agencies are in the process of incorporating short-range weather forecast uncertainty into their EPSs, either from the North American Ensemble Forecast System (NAEFS) or an ensemble of mesoscale NWPs. While it is generally assumed that a weighted sum of the ensemble NWPs outperforms any one deterministic NWP, spatial resolution does matter (West): spatially more highly resolved operational deterministic NWP model forecasts are on average more skillful than the ensemble mean of the spatially coarser NAEFS forecasts up to a forecast horizon of about 4 days (depending on the performance measure used and the forecast point location). A changeover from operational deterministic NWPs to NAEFS forecasts on about day 5 was suggested. It is unclear, however, whether the NAEFS forecast up to day 4 is still useful because there might be value in having uncertainty information from the forecast ensemble available. Since the majority of the workshop participants are forecasters or academics – not forecast users – the use and value of probabilistic information was neither demonstrated nor discussed.

Beyond the forecast horizon of deterministic or ensemble NWPs, agencies typically revert to forcing hydrologic models with historically observed weather sequences for generating long-range forecasts. A variant of that technique is the use of stochastically generated weather sequences as model forcings to get around the limitations of using relatively short historical records and as a way to capture long-range weather forecasting uncertainty (Weber). Another approach is the use of climatologically analogous years as hydrologic model forcing, as in the example presented for long-range spring flood forecasts in northern Sweden (Nyström, Johansson). In this case, climatological similarity was determined with climate indices or the persistence of large-scale atmospheric weather patterns; these authors also demonstrated the use of seasonal ensemble forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF).

Increasingly, hydrologic ensemble prediction systems are designed to run ensembles of initial model states, hydrologic models, and/or model parameter sets. Such "super ensembles" were the topic of several workshop presentations. One project combines hydrologic model, model parameterization, initial condition, and boundary condition ensembles into one super ensemble (Bourdin). Current efforts with BC Hydro's Ensemble River Forecast System (Weber) focus on integrating NAEFS ensemble short-range weather forecasts with ensembles of historically observed and stochastically generated climate forcings and an ensemble of hydrologic model parameter sets. Environment Canada's MESH-based hydrologic EPS, envisioned to be run over the Great Lakes watershed, is being designed to combine ensembles of model forcings, initial conditions, land surface schemes, model physics, and model parameters (Davison).

With ensemble systems that capture multiple sources of uncertainty, many hundreds or even thousands of ensemble members can result. Processing all of these can become burdensome computationally, both on the forecast production and the forecast user side. It was suggested that, on the forecast production side, parallel computing could offer a solution to reduce the significant computational run-time. On the forecast user side, sampling from the full ensemble could reduce the number of ensemble members to a manageable size without significantly altering the statistical characteristics of the distribution (Brochero).

Multi-modelling, a technique of objectively and quantitatively combining forecasts from several models into a single forecast, can be considered to be another form of ensemble forecasting and has recently gained attention in the hydrologic community (Moradkhani). The multi-model combination is essentially a weighted sum of the individual model results, the magnitude of the weights depending on the relative skills of the candidate models. The calculation of multi-model weights requires time series of observations and corresponding historical forecasts or hindcasts (produced after-the-fact) from each model. The goal of multi-modelling is to create forecasts that have a greater skill than those from any individual model. Since this is a relatively new endeavour in hydrology, there are no existing operational examples of this technique. Multi-model ensembles will require either a forecasting agency to run multiple models or multiple agencies to run different models in a way that permits the combination of the forecasts. For example, forecast dates, forecast lead times, modelling time steps, and the model calibration period would have to be coordinated for the forecast to be useful in a multi-modelling system.

Since most of the hydrologic super ensemble or multi-modelling systems are either still under development or have only recently been launched, none of the presenters demonstrated that the goal of producing reliable forecast distributions has been met. Forecast verification will retain a critical role in developing mature systems, particularly in determining whether and for which forecast dates and forecast horizons uncertainties are being correctly calculated. The process may require several iterations of fine-tuning the ensemble systems, i.e., verifying ensemble forecasts (or hindcasts), adjusting the distributions of variables and parameters, and/or adding or removing stochastic components.

Data Assimilation / Model State Updating

Only one presentation dealt explicitly with the assimilation of hydroclimatic data into river flow and water supply forecast systems for the purposes of updating model state variables (Moradkhani). In this example, snow water equivalent (SWE) observations were used to update simulated SWE model states using a Bayesian approach, demonstrating the potential to improve probabilistic water supply forecasts. While there have been a few other examples of snow data assimilation appearing in the literature, this technique has not yet found widespread usage in operational settings (Slater and Clark, 2006; Day, 1990). Snow data assimilation has, however, been incorporated into the snowpack modelling system underlying the SNODAS product produced by the US National Weather Service and distributed by the US National Snow and Ice Data Center (Barrett, 2003). Data assimilation, then, has been shown to have potential for improving streamflow forecasts, but further testing and development remains necessary before it can become a standard operational technique.

Forecast Post-Processing

Post-processing of forecasts can mean any adjustment or change to the output of forecast models before issuing the forecasts to the users. Such adjustments can be based on subjective professional judgment by forecasters, or they can be the result of objective mathematical debiasing and variance adjustment algorithms. This topic was discussed by several presenters at the workshop.

Differences between North American and European forecasting paradigms, and specifically how hydrologists interact with models during the forecasting process, were discussed (Gijsbers). The European style is mostly objective, lends itself to a high level of automation, and removes the human impact from the interpretation of forecast verification statistics. In comparison, the North American systems tend to be hands-on and have significant hydrologist intervention in the modelling process. These two paradigms have their respective advantages and disadvantages. On the one hand, the North American style helps the hydrologist have a deeper understanding of the data and model than the European style, and it thereby makes it possible to intervene if necessary. On the other hand, it has the disadvantage of being subjective, and it can potentially lead to forecast degradation (as discussed below). To further substantiate Gijsbers's theory, there was general agreement amongst the (mostly North American) workshop participants that critical human review of model output is an essential element of forecast production. A key driver for such human-based forecast post-processing is the hydrologist's need for a credible "story line" to deliver the forecasts. This entails having a good understanding of the current physical processes and being able to explain the forecast issued and its evolution from one forecast date to the next. Assuming that no suitable automated process can be found, it was therefore felt that human intervention with the modelling process could be justified despite the introduction of unknown uncertainty into forecasts.

The role of scrutinizing, and, if necessary, subjectively adjusting, model output before final forecasts are issued in the specific realm of water supply forecasting was discussed (Tama, Garen). Such adjustments are based on professional judgment whose foundations lie in hydrologic concepts, professional experience, and memes. Memes are ways of thinking that are generally accepted, passed from individual to individual, and persist over time possibly without any robust supporting scientific evidence. In this context, a meme may be one of several heuristic shortcut ideas that seem to exist as common understandings in a hydrologic culture. However, these concepts, heuristics, and memes often go unexamined and untested to see if they actually provide helpful guidance. To attempt to shed some light on this issue, the performance of water supply forecasts for some case study basins was examined by comparing raw statistical model forecasts with adjusted, published forecasts (Tama, Garen). Overall, the number of cases where the adjustments improved accuracy was about the same as the number where they degraded the accuracy. Examples were given when the memes of "the water supply forecast should be about the same percent of average as the snowpack" and "all forecasts in a region ought to have about the same percent of average" were not valid and, in fact, led to forecast degradation. The message was that hydrologists should be more careful in the thought processes used when judging whether raw model output needs to be changed for final forecast issuance.

Additional discussions revolved around the necessity to post-process forecasts using objective mathematical algorithms to remove bias and to ensure that the variance correctly represents forecast uncertainty. Some argued that models should be designed and calibrated so that forecasts do not have to be bias-corrected. Others thought that, due to limitations of watershed models, e.g., in their ability to simulate the seasonal behaviour of river flows accurately, forecasts will likely continue to require the correction of seasonal modelling biases from long-range forecasts for the foreseeable future. R&D activities need to consider the improvement of models and model calibration techniques to minimize seasonal modelling biases as well as the development of bias correction techniques that fit the various watershed models and forecast systems.

Forecast Verification

Evaluating past published or reconstructed forecasts for accuracy, bias, and proper error variance is an integral part of the hydrologic forecasting process. Forecast verification helps to determine whether forecasts are accurate and skillful and whether they meet user requirements. Forecast verification is also used to better understand the strengths and weaknesses of forecasting systems, to establish a skill and accuracy reference against which subsequent changes in forecast procedures or the introduction of new technologies can be measured, and to justify funding for targeted R&D.

Several examples of statistical measures are available for forecast verification, and the advantages and disadvantages of the probability integral transform and the continuous ranked probability score were discussed in detail (Perreault). Several verification measures used in BC Hydro's Hydrologic Forecast Verification System, which was designed to evaluate both short- and long-range forecasts, forecasts produced with continuous simulation and statistical models, and deterministic and probabilistic techniques were also discussed (Gobena). A similar effort applied to meteorological forecasts was described as well (West).

Conclusion

Judging from the liveliness of the discussions, the workshop themes broadly captured the main concerns faced by the operational forecasting community. Despite the variety of groups represented at the workshop, there was considerable consensus on the issues and knowledge gaps in operational forecasting. The following main R&D opportunities crystallized:

(i) Develop objective, hydrologic region-specific performance rankings for watershed models.
(ii) Re-design existing environmental monitoring networks for use with spatially distributed hydrologic models.
(iii) Compare hydrologic model simulations forced with NWP output or CaPA data with the status-quo.
(iv) Regularly verify ensemble forecasts to determine in which situations EPSs do and do not accurately capture forecast uncertainty.
(v) Improve watershed models and model calibration techniques with the objective of minimizing the necessity for correcting seasonal biases.
(vi) Develop bias correction techniques that fit the various watershed models and forecast systems.

On a cautionary note, however, several participants aired their concerns with the resources required to maintain complex forecast systems and to keep up with the state of the art in the research community. These systems, which may run super ensembles using fully distributed hydrologic models on computer clusters, require ever-greater resources to develop and maintain. The concern, then, is whether the best available science and technology might become too expensive for small forecasting agencies. It is possible that some hydrologic forecast groups might not even try to keep up with the state of the art, or they might need to contract some of the modelling work to specialized agencies rather than try to allocate increasing in-house resources to do this work themselves.

It was clear by the end of the workshop that many advances in forecasting techniques have been made in recent years. It was also clear that most operational agencies are dealing with similar issues, and it was instructive to see this and have the chance to share concerns and experiences with each other. It is hoped that with greater collaboration between the forecasting groups and with targeted R&D, river flow and water supply forecasting services will continue to become more reliable and effective.

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