Invited Commentary: A Framework for Integrated Research and Monitoring (FIRM)

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Water managers in Canada are tasked with maintaining clean, adequate, safe water supplies for human uses while at the same time conserving the ecological integrity of the freshwater ecosystems that sustain the economy. This task requires strategic efforts to ensure Canadians are able to understand and predict the cleanliness, availability and renewability of their water resource. The vast majority of the time, water professionals are able to make wise and informed decisions with regard to engineering design, environmental assessment and water allocation. However, numerous popular publications highlight the uncertainty faced by Canadian institutions with respect to managing Canada's water (Bakker, 2007; Hoover *et al.*, 2007; Morris *et al.*, 2007). For example, why could we not reliably predict and prevent the travel of contaminants through pathways to source waters in Walkerton in 2000 or North Battleford in 2001? Why can we not characterize the mean annual flood across much of the Arctic Archipelago, an area of increasing importance for the country? Why can we not expeditiously explain the recent record low water levels in the upper Great Lakes with confidence? Recognition of change in the climate and landscape presents challenges as we now need to address some of the long held assumptions in our methodologies — notably that of stationarity.

In a recent commentary in this journal, Hamilton and Whitfield (2008) call for a new approach to how Canada generates understanding of its water resources. For much of the 20th century, the focus was on description of the spatial distribution and temporal availability of the quantity and quality of water rather than understanding the processes that created the observed patterns. However, as resources have become scarcer due to availability or quality limitations, water managers' demands are no longer satisfied with reports of mere abundance or state. In the dynamic operating environment of the 21st century, where we all recognize that complex landscape changes and climatic variability have an impact on water, an understanding of biogeophysical processes is needed. Without an understanding of hydrological and aquatic ecological processes we cannot possibly make informed decisions about how water resources will change under different conditions.

Developing the environmental science and monitoring capacity to be able to respond to this fundamental change in water resource management will require a fresh approach. It will require new

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partnership frameworks able to maximize the quality of the science, the efficiency of the monitoring, and the transfer of knowledge for decision-making. This commentary describes the necessary traits of a Framework for Integrated Research and Monitoring (FIRM) that can be used to couple science and monitoring for improved understanding and prediction of Canadian water resources. FIRM includes three hierarchical levels of activity. The first level includes individual experimental or monitoring sites and projects. The second level is composed of clusters of these sites or projects. Each cluster contains research and monitoring activities all dedicated to addressing a specific research question or management issue. For the purposes of this commentary, we define the activities within these clusters as "integrated" because they incorporate investigations of biogeophysical processes and measurements of environmental components where planning, management, justification and product delivery are explicitly tied to one another. Using this definition allows us to apply FIRM to any such program, regardless of the biogeophysical system of interest. At the third level, a dynamic network of clusters produces high quality data and advanced research results. These are directed to answering the spectrum of strategic questions and developing predictive tools used to respond to current priorities and ready proactive actions in anticipation of future demands.

There have been several Canadian programs that emulate clusters. These are often regional in scope, sometimes reactionary, but are always multidisciplinary in participation and include high quality environmental research closely coordinated with operational monitoring agencies (e.g., Northern Rivers Ecosystem Initiative (Gummer *et al.,* 2006)). Collaboration with the broader user or practicing community has been essential for the success of these programs (Hall *et al.,* 2006). When all stakeholders are involved, the development and implementation of new tools and technologies is much easier.

Most attempts to establish a sustainable national network of clusters to monitor and assess the environment in a collaborative holistic integrated manner have been plagued by generally inadequate or unpredictable government funding; a possible exception is the Canadian Model Forest Network in its early years. Furthermore, there is no national standard or uniform framework for developing or managing clusters. This leads to ad hoc arrangements and, inevitably, funding fluctuations that lead to unsustainable or diminished operations at experimental sites. Similarly, the lack of recognition that a proactive collaborative approach is needed for the development of clusters has, in part, led to the decay of network planning mechanisms for individual operational monitoring networks. This makes it difficult for these monitoring programs to respond to new policy initiatives and leaves many operational monitoring network sites (e.g., Water Survey of Canada gauges) without clear objectives and easy targets for budget reduction. A collaborative framework embedded into both operational monitoring agency network planning and science agency project planning is needed. Furthermore, encouraging collaborative efforts with stakeholders will lead to a more stable and cohesive approach to integration. That said, experience has shown that while good will and cooperation are crucial, they are not enough.

Most clusters in Canada have been developed to answer specific questions for specific places. Creating a sustainable network of clusters under one umbrella across the country has proven difficult partly because over time answers are found for the original questions and thus the rationale for the original suite of experimental and monitoring sites within a cluster is no longer relevant. This should be perceived as a positive, rather than a negative; it demonstrates that clusters work! It is clear that management of a network of clusters must be strategic in its investment of resources to permit reallocation to new clusters as older clusters provide solutions and new water management issues arise or are foreseen.

Cluster strategies need explicit allocation, environmental and/or engineering design prediction goals that include uncertainty quantification. They also require a defined life span that is a function of time or an objective. For example, the life span of the experimental and observational sites needed to achieve a cluster goal of defining how and why water supply from Prairie streams changes over time is different than those used to discern the impact of a specific pollutant on a specific aquatic habitat. Knowing the life span of each cluster and its component parts makes strategic decision-making of everything from individual sites to the entire network much easier to operate within a finite funding envelope.

Fundamental to ensuring the success of the entire network is strong underlying relevance of the information needed from each cluster. Variables monitored and processes investigated need to be matched to information needed for policy development and technical demands. Good design never guarantees long-term support or funding, but continued relevance does. From a traditional monitoring network perspective, the variable life span of clusters will result in a dynamic array of observation and experimental sites that are, if funded adequately, flexible enough to be reactive to changes in priorities and emerging issues. This characteristic should, over time, permit a broad base of support to remain as the entire network of clusters as a whole continues to deliver outputs of value to many users. If this is the case, contributors will likely remain committed.

One possible approach to reducing the uncertainty associated with decision-making is to simply increase the density of long-term monitoring sites. This approach takes a prolonged dedicated investment, one that in Canada has been lacking and difficult to maintain for the required length of time. Furthermore, not all questions require long-term monitoring for answers. The correct observational strategies to answer specific questions depend on the time and space scales of the phenomena of interest. This requires focused observational and experimental sites sampling the environment at the proper scale to discern the proper signals. Depending on the cluster, this may involve a comparable investment but over a shorter time period. The benefit of an integrated approach is a clear timeline between investment and return.

If new investments are to be made, in particular with research, clusters and the activities within must be worthy and provide societal benefit. Azar *et al.* (2003) demonstrated the significant return on society's investment in traditional observational networks. The benefit-to-cost ratio is expected to be even higher with the FIRM approach as it includes additional benefits, such as scientific training, that a traditional monitoring framework does not. Furthermore, investment in traditional monitoring alone only increases the data volume and does not permit the development of new predictive tools. The Mackenzie GEWEX Study (MAGS) (Rouse *et al.,* 2003), which defined the Mackenzie River Basin's water and energy budget and how and why it fluctuates, demonstrated how a focused program can coordinate scientific expertise, data collection, modelling and research to improve prediction, and acts as a good model for a cluster.

The lack of datasets at multiple space and time scales is a key gap in the water management community's information base that increases uncertainty in prediction and decision-making. The current lack of understanding of the nutrient flux to Lake Winnipeg from its watershed is a prime example of this kind of knowledge gap. We do not understand how the hydrological and aquatic ecosystems function at a multiplicity of scales within this watershed. Nor do we understand how the nonlinear coupling and feedbacks between aquatic chemistry, ecosystem components, landforms, water and energy operate to produce the measured nutrient flux at the mouths of Lake Winnipeg's tributary rivers. As a result, we do not know the best way to reduce the nutrient flux. This one problem alone demonstrates that research and monitoring within clusters need to be enacted at appropriate scales to ensure research and monitoring gaps are filled and predictive goals of each specific cluster are reached. Furthermore, the scales of importance in a given cluster will dictate the appropriate investigative methodologies and the collaborative partners best able to make the observations.

The diverse nature of Canada's geography likely necessitates a wide representative network of clusters to permit the diverse issues across the array of ecosystems and/or hydrological regimes to be addressed. This also may be necessary at the cluster scale. If the methodology adopted within a cluster requires representativeness, then the coverage of operational monitoring or experimental research sites within the design of a single cluster must be extensive enough and designed to ensure precision, accuracy and a minimum of uncertainty in the results. The network should be designed to encourage the transfer and testing of predictive tools among clusters.

The first application of FIRM in Canada has been in the development of Natural Resources Canada's Glacier-Climate Observing System (http://pathways.geosemantica.net/WSHome.aspx?ws-NGP_SECC&locale-en-CA). Canada's geography and climate support a glacier-climate diversity that spans that observed globally (Demuth and Keller, 2006). The Geological Survey of Canada, the Canada Centre for Remote Sensing, Environment Canada and several academic partners are carrying out a collaborative effort to take high quality measurements of Canada's glacier-climate-hydrological variables. Principal in such an effort are nested scales of observation and analysis that are commensurate with "upstream" scales of forcing, in-situ, local scale processes and downstream impacts on the freshwater system. Such an effort clearly needs to be multi-disciplinary and thereby able to generate both baseline information on the normal state and trends of Canada's land ice resources and new knowledge on hydro-climatic processes. This will permit observation schemes that, in part, flow back to permit better observations, and reduce the uncertainty in the task of recognizing trends of concern as they may apply to risk management strategies (utilizing either baseline data or the results of applying predictive tools) or gauging the long-term effectiveness of environmental protocols (e.g., air quality, climate change). Each observing cluster (Cordillera, Queen Elizabeth Islands and Baffin Island) has within it several representative benchmark monitoring sites within a research watershed, where ground truth and process studies are conducted. Regional perspectives are developed through the commensurate application of both airborne and satellite remote sensing technology, hydrological modelling and the necessary data assimilation.

Hamilton and Whitfield (2008) provided a compelling argument that Canada needs updated means by which to better generate understanding of its water resources. Notwithstanding the importance of historical observations and studies and the perspectives they generated during the halcyon days of Canadian glaciology and hydrology (Swanson *et al.,* 1988; Ommanney, 2002), this discussion and Canada's new approach to glacier-climate monitoring imply that there are seven key characteristics for an integrated research and monitoring program to be successful in the 21st century. These programs need to be: i) collaborative; ii) of high quality; iii) strategic; iv) relevant; v) worthy of investment; vi) scale appropriate; and vii) representative.

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