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# Research developments in the hydrological sciences in Canada (1995–1998): surface water — quantity, quality and ecology

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## Abstract:

Canadian research contributions to quantity, quality and ecology of surface waters during 1995–1998 (182 items) are summarized under six headings: understanding the pristine hydrological system (49); climate variability and hydrological systems (23); streamflow data, modelling and simulation (23); regional, international and flood hydrology (31); land use effects on the hydrological system (35); and sustainability of hydrological systems (21). The most encouraging developments have occurred in increased understanding of the interconnectedness of components of the hydrological cycle and, especially, of the links between biosphere and hydrosphere. Canadian hydrologists also have played a significant role in global environmental change research and in applied development research. The most discouraging development has been the collapse of the national water monitoring programme and the decay of integrated experimental research areas. The overall impression is that hydrology in Canada is a maturing discipline; the physical, chemical and biological components are becoming less isolated; and anthropogenic impacts on surface water are more frequently considered to fall within the purview of hydrological science. The role of hydrology in relation to sustainability is increasingly actively debated. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS surface water; quantity; quality; ecology; land use; sustainability

## INTRODUCTION

According to the National Research Council (1991) of the USA, the scope of hydrological science includes '(1) the physical and chemical processes in the cycling of continental water at all scales as well as those biological processes that significantly interact with the hydrologic cycle and (2) the spatial and temporal characteristics of the global water balance in all compartments of the earth system'. Although civil and agricultural engineers have pioneered and developed water supply and water-related hazard reduction programmes, a comprehensive understanding of the water cycle by hydrological scientists has emerged more slowly. Problems such as the geographical redistribution of water resources due to climate change, the ecological consequences of large-scale water transfers, the effect of land use changes on the regional hydrological cycle, the effect of non-point sources of pollution on the quality of surface water at the regional scale and the possibility of changing regimes of regional floods and droughts have been neglected.

If this was true for the USA in the late 1980s, the same theme can be developed for Canada in the 1990s, but with notable success and evidence of progress. The very fact that this invited paper was to include the traditionally diverse fields of water quantity, quality and ecology is evidence of our increasing recognition of the interconnectedness of components of the hydrological cycle. I have chosen to organize this review along the following lines.

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1. Understanding the pristine hydrological system.
2. Climate variability and hydrological systems.
3. Streamflow data, modelling and simulation.
4. Regional, international and flood hydrology.
5. Land use effects on the hydrological system.
6. Sustainability of hydrological systems.

## UNDERSTANDING THE PRISTINE HYDROLOGICAL SYSTEM

### *Remote sensing and geographical information systems*

It was probably during the International Hydrological Decade (1965–1974) that Canadian hydrologists became aware of the problems associated with paired watershed studies and the need for improved characterization of the morphometry of drainage basins. Progress in this direction has been achieved with respect to automated recognition of valley lines and drainage networks (Martz and Garbrecht, 1995; Garbrecht and Martz, 1996a,b, 1997), non-point source identification (Cluis *et al*., 1996), representation of nested catchment areas (Mackay and Band, 1998), and the relationship between terrain representation, resolution and watershed processes (Band *et al*., 1995) and the central problem of scale (Band and Moore, 1995). Emaruchi *et al*. (1997) combined Landsat data and an artificial neural network system to estimate runoff indices and Kite and Pietroniro (1996) summarized remote sensing applications in hydrological modelling. Mayfield *et al*. (1996) underlined the importance of data sharing and information technology in the Ecoresearch Programme. The routine use of Terrain Resources Information Management (TRIM) data by hydrologists in British Columbia has improved the accuracy of the depiction of topography in this mountainous province (Cheong, 1994).

Without the use of remote sensing and geographical information systems the analysis of the hydrology of Canada's ten million square kilometres of terrain would remain stubbornly qualitative.

### *Runoff generation mechanisms*

A lively debate, initiated in the UK in the 1960s, taken up in Japan in the 1970s, clarified in New Zealand in the 1980s and firmly centred in North America during the 1990s, is being actively pursued in Canada by Buttle and others (D. L. Peters *et al*., 1995; Buttle and House, 1997) and Moore (Moore and Thompson, 1996; Thompson and Moore, 1996). The essence of the problem is the relationship between time delays experienced by water moving over and through soils of highly heterogeneous and spatially variable properties. The discussion has been developed by Hill and Roulet and others in the context of surface water ecology (e.g. Devito *et al*., 1996; Hill, 1996; Hill and Brooks, 1996; Hill and Devito, 1996). In this latter literature, Hill has pioneered the closer integration of hydrological–chemical interactions in biogeochemical cycles. A third version of this debate involves runoff generation in semi-arid agricultural catchments (Motha and Wigham, 1995; Zhu *et al*., 1997), where overland flow is more dominant.

Canada can be regarded without exaggeration as a leader in the unravelling of variable runoff sources, pathways and sinks in watershed hydrology, both under this direct experimental approach, and in the more indirect or inferential approach discussed below.

### *Hydrograph separation*

This technique, developed in the 1970s, was critically re-evaluated by Buttle and Peters (1997). Although there are serious problems with its use with only one kind of tracer, a number of studies have successfully identified hydrological pathways (Caissie *et al*., 1996; Laudon and Slaymaker, 1997) by using two or more tracers. In both of these cases, in Catamaran Brook in New Brunswick and in Miller Creek in British Columbia, conductivity was useful in performing the hydrograph separation. Significant sources of disturbance from mine tailings (Al and Blowes, 1996) and suburban development (Buttle *et al*., 1995) also have been analysed by hydrograph separation. Although hydrograph separation can be considered as just one application of hydrological analysis, it is treated separately here because of the powerful inferences provided with respect to the functioning of the watershed system.

### *Surface water ecology*

The overview papers on biospheric aspects of the hydrological cycle provide a sense of the growing awareness among hydrologists of the importance of surface water ecology (Bass *et al*., 1997; Hutjes *et al*., 1998). In particular, the 34 authors comprising Hutjes *et al*. (1998) described the Core Project of the IGBP entitled *Biospheric Aspects of the Hydrologic Cycle*.

It is most encouraging to see the extent to which Canadian hydrologists have recognized the importance of the role of biomass in watershed systems. From the role of large organic debris in steep river channels (Hogan and Bird, 1994) to the investigation of fish habitat as a function of hydrological behaviour (Hartman *et al*., 1996), the biotic factor is crucial.

The importance of geology and soils as fundamental controls of stream water chemistry has been confirmed (MacLean *et al*., 1995; Bouchard *et al*., 1996; Branfireun *et al*., 1996; Cameron, 1996; Hudson and Quick, 1997; Grasby *et al*., 1999). The issue of nitrate release from temperate forests (Creed *et al*., 1996; Creed and Band, 1998a,b), oxygen requirements of fish (Barton and Taylor, 1996), the export of dissolved organic carbon (Hinton *et al*., 1997; Waddington and Roulet, 1997), the role of phytoplankton (Robarts *et al*., 1995; Faye and Diamond, 1996), and the development of a species tolerance index for maximum water temperature (Wichert and Lin, 1996) are problems that have been explored extensively in the literature. A more holistic approach is taken by Freitas *et al*. (1997), Hayashi *et al*. (1998) and Papineau (1996) in their use of mass balance models to assess water and solute fluxes.

## CLIMATE VARIABILITY AND HYDROLOGICAL SYSTEMS

Because of our increased sensitivity to the implications of possible global warming, focused effort on evaluating climatic variability is occurring. Excellent collaboration between climatologists and hydrologists has developed on this topic. Two broad categories of research can be identified: (i) analysis of available data to determine causal links, and (ii) potential impacts.

### *Relationship between climatic and hydrological variability*

Moore and McKendry (1996) and Moore (1996) investigated relationships between synoptic climate changes, snowpack and runoff response in British Columbia's Coast Mountains. Leith and Whitfield (1998) examined effects in south central British Columbia and determined that spring runoff starts earlier, late summer to early autumn flows are lower and early winter flows are higher during recent warming.

Westmacott and Burn (1997) have examined climate effects on the Churchill–Nelson River regime and found that temperature increases over the past 100 years have affected the magnitude and timing of hydrological events. Yulianti and Burn (1998) and Gan (1998) examined links between climate warming and low streamflows in the Prairies, and Rannie (1999) completed a comprehensive analysis of hydroclimate in the Red River basin before 1870. Hamilton and Moore (1996) and Rouse *et al*. (1997) examined effects of climate variability on the Arctic and sub-Arctic freshwater regime. Clair and Ehrman (1998) used neural networks to assess the influence of changing climates on discharge, dissolved organic carbon and nitrogen export in eastern Canada. Hendershot *et al*. (1996) examined influences of acid precipitation on aluminium geochemistry in watersheds. Lawford *et al*. (1995) discussed hydrometeorological aspects of flood hazards across Canada. Although much of this work is concerned directly with climate change, it is important to note that hydrological variability continues to be the theme against which claims to have established climate change must be judged.

 

*Potential impacts*

Verseghy (1996) discussed runoff modelling in general circulation models and directed attention to the importance of improved land surface models. Cohen (1995, 1996, 1997) has completed a comprehensive series of studies on the Mackenzie Basin within which a variety of scenarios of possible climate change are discussed. Cohen *et al*. (1996) discusses impacts on each of the water balance components. Magnuson *et al*. (1997) have a similar objective in their study of the Laurentian Great Lakes and Precambrian Shield. Band *et al*. (1996) examine the sensitivity of ecosystem processes to potential climate change. Watson *et al*. (1996) contains a comprehensive collection of scenarios to which many Canadians have contributed: Stewart on forest impacts (Chapter 1), Roulet on non-tidal wetlands (Chapter 6), Prowse, Woo, Brown and Taylor on the cryosphere (Chapter 7) and Arnott and Hecky on hydrology and freshwater ecology (Chapter 10). This is another area of hydrological research in which Canadian contributions continue to be substantial.

## STREAMFLOW DATA, MODELLING AND SIMULATION

Identification of errors in streamflow data (Druce, 1996), estimating missing hydrological data (Simonovic, 1995; Bennis *et al*., 1997), automated handling of stage and discharge rating curves (DeGagne *et al*., 1996), determining biases of correlation dimension estimates of streamflow data (Wang and Gan, 1998), multifractal analysis of daily river flows (Pandey *et al*., 1998) and analysis of geomorphological response to river flow regulation for a variety of time and space scales (Church, 1995) comprise interesting ways of handling primary hydrological data.

Astatkie and Watt (1998) modelled daily streamflow series, whereas Astatkie *et al*. (1996) examined sources of non-linearity in streamflow data by using a nested threshold autoregressive model. Short-term streamflow forecasting with the aid of artificial neural networks (Zealand *et al*., 1999) in a 20 000 $km^2$ basin in north-western Ontario has consistently outperformed a conventional model in terms of root-mean-square error (RMSE). Distributed hydrological models continue to be improved (Donald *et al*., 1995) and deterministic empirical models also continue to be useful in dealing with components of the hydrograph (Jayatilaka and Gilham, 1996; Jayatilaka *et al*., 1996; Moore, 1997); but note the follow up discussion by McDonnell and Buttle (1998). Automated procedures for calibration of conceptual rainfall–runoff models are being developed (Gan and Biftu, 1996). Perhaps the most interesting Canadian contributions to hydrological modelling have come from Kite (1995) and Kite *et al*. (1998). He discusses scaling of input data for macroscale modelling and applications of an atmospheric model to simulation of streamflow series. Kite (1997) is an instructive example for the Columbia River.

Whitfield and Covic (1998) discussed statistical independence of rainfall and runoff events, whereas Gan *et al*. (1997) examined the effects of model complexity and structure on hydrological modelling. Of the five models tested on three basins in Africa and the USA, the Xinanjiang performed consistently well because of its incorporation of a non-uniform distribution of runoff-producing areas. Rasmussen (1996) compared contemporaneous Autoregressive Moving Average (ARMA) models for streamflow simulation. In a characteristically iconoclastic way, Klemes (1995) rewrote the history of the theory of stochastic reservoirs on the basis of two early Russian hydrologists who were previously unknown in the English literature. This group of contributions belongs to the core of analytical hydrology and the themes are well established in the literature. In the most central of issues, that of scaling and scale effects, the contributions of Band and Moore (1995), Church (1995), Pandey *et al*. (1998) and Kite (1995, 1997) should be noted.

## REGIONAL, INTERNATIONAL AND FLOOD HYDROLOGY

Major contributions to the analysis of flood hydrology have been made by Canadian hydrologists. Watt's (1995) summary of the national Flood Damage Reduction programme (1976–1995) provides a definitive contribution to Canadian flood hydrology. Twenty-one authors associated with the Industrial Chair in

 

Statistical Hydrology at Institut National de Recherche Scientifique (INRS)-eau (1996) produced a definitive summary of methods for regional flood-frequency analysis. They compared four methods for delineating homogeneous regions and seven regional estimation methods, and concluded that a regional bootstrap and an empirical Bayes approach were the best methodologies for comparison of regional models. Lapointe *et al*. (1998) and Brooks and Lawrence (1999) made a comprehensive analysis of the Ha! Ha! River flood in Quebec in 1996 and Sellars (1999) carried out an award winning hydraulic study of the 1997 Red River flood.

The subsequent discussion of additional work on this topic is divided into three sections: (i) regional hydrology; (ii) flood hydrology; and (iii) international applications of Canadian hydrological expertise.

### *Regional hydrology*

Eastern Canada, especially Quebec and New Brunswick, has seen intensive focus on developing new techniques of regional hydrological analysis (Gingras *et al*., 1995; Ribeiro-Correa *et al*., 1995; Ashkar and Ouarda, 1996; Birikundavyi *et al*., 1997; Burn, 1997a; Anctil *et al*., 1998; Pandey and Nguyen, 1998; El-Jabi *et al*., 1998; Perrone and Mudramootoo, 1998). Almost all of this work has been inspired by strong schools of engineering hydrology, with both theoretical rigour and practical application to water resource management.

### *Flood hydrology*

The closely related techniques of flood frequency analysis have also been emphasized in research in eastern Canada (Birikundavyi and Rousselle, 1997; Dupuis, 1997). By contrast, in western Canada interest has focused on flood estimation techniques for ungauged watersheds (Loukas and Quick, 1995, 1996). Tolland *et al*. (1998) emphasize the need for standardization of peak flow estimates independently for rain, snowmelt and rain on snow floods. Two of the reasons for this contrast between the emphasis on flood-frequency analysis and flood estimation techniques are the longer hydrological records in Quebec and the needs of the forest industry in British Columbia for information on small, steep watersheds.

Other aspects of flood hydrology to which there have been significant Canadian contributions include flood mapping using satellite technology (Barber *et al*., 1997), Great Lakes flood thresholds and impacts (Gabriel *et al*., 1997), simulated interior floods (Nkemdirim and Kendrick, 1995) and flood hazard evaluation (Slaymaker, 1996). For example, Bouillon *et al*. (1999) calculated flood hazard in the Chateauguay basin in Quebec.

### *International applications*

The International Development Research Centre has played a formative role in funding applications of Canadian hydrological expertise to international development. Flood hydrology in Amazonia (Lesack and Melack, 1995), runoff estimation in India (Jain *et al*., 1998), nitrate problems (Watson *et al*., 1997), trace-element water and sediment geochemistry in India (Konhauser *et al*., 1997), comprehensive water resource development in Africa (Shady and Groves, 1996), and water resources and security in the Middle East (Lonergan, 1996) are some of the applications of Canadian hydrology to development research. Garfias *et al*. (1996) demonstrated the value of comparing rainfall–runoff models for application in the Bolivian Andes. This undoubtedly is an incomplete listing of Canada's international hydrological work during 1995–98, but it gives a flavour of the range of activity.

## LAND USE EFFECTS ON THE HYDROLOGICAL SYSTEM

### *Agriculture*

Nitrate output from agricultural watersheds (Borkchina *et al*., 1995), water quality trends (Gemza, 1995), atrazine and metachlor loadings from pesticides (Fischer *et al*., 1995; Gaynor *et al*., 1995; Caux and Kent, 1995), chlorinated organic contaminants (Richardson and Levings, 1996), trace metal pollution from the application of pesticides (Renaud *et al*., 1998; Mayer and Reyes, 1996) and general agricultural water quality (Johnson and Watelet, 1996) are continuing problems. A particularly interesting example of the interdisciplinary nature of such research is Stone *et al*.'s (1995) study of phosphate sorption by fluvial sediment.

*Forestry*

The hydrological effects of reforestation (Buttle, 1995, 1996) and of clear-cutting (Dube *et al*., 1995; Chatwin, 1996; Hartman *et al*., 1996; Hudson and Golding, 1997a,b; Miller *et al*., 1997; Price, 1997; Paterson *et al*., 1998) are well documented. For example, in spite of over 90% removal of forest from four watersheds in north-western Ontario, lake sediment chrysophytes showed only minor changes (Paterson *et al*., 1998). General conclusions on the critical control of logging road density and age on sediment production and water quality deterioration under forest management have been confirmed. However, the impacts of forest management under helicopter logging or where road densities are low remain contradictory.

*Urban*

Chambers *et al*. (1997) wrote a major review of municipal wastewater effluent impact on surface waters across Canada and concluded that there is a need to review sewage treatment requirements in Canada. Further research is needed on cumulative impacts and on long-term exposure to persistent pollutants and a more integrated approach to wastewater management is needed. Larkin and Hall (1998) documented hydrocarbon pollution in the Brunette River; Winter and Duthie (1998) showed urbanization effects on water quality in the British Columbia interior; and Charlton and LeSage (1996) and Diamond and Ling-Lamprecht (1996) showed water quality trends in Hamilton Harbour. Morin and Leclerc (1998) gave a comprehensive review of the impact of civil works on a shallow lake in the St Lawrence River; Cox et al (1996) discuss the need to plan for urbanisation; Nicholls (1995), Guo and Adams (1998) and Gaume et al (1998) discuss urban water quality trends.

*Mining*

Pentz and Kostaschuk (1999) identified the impact of placer mining on suspended sediment in reaches of sensitive fish habitat in central Yukon Territory. Whereas direct discharge for active placer mines was not significant, erosion of previously mined disturbed areas had a pronounced effect.

*General*

Barica (1995) placed water quality problems in the broader context of environmental issues. Crowder *et al*. (1996) provided comparative natural and anthropogenic rates of change in habitat quality for a portion of the Lake Ontario shoreline. Boyle *et al*. (1997) documented 164 years of land cover changes in the lower Fraser basin and their hydrological effects. McDaniels *et al*. (1998) documented public perception of water quality in the same region. Peters *et al*. (1995) modelled the benefits from improved water quality, Zandbergen and Hall (1998) analysed the British Columbia water quality index, and Yu and MacLaren (1995) compared two methodologies for waste stream characterization.

## SUSTAINABILITY OF HYDROLOGICAL SYSTEMS

There is an increasing number of papers that address the issue of sustainability directly (Caux, 1995; Francis, 1996; Burn, 1997b; De Loe, 1997a,b,c). From the perspective of hydrological science, questions of the need for monitoring, habitat restoration and water policy are surely also sustainability issues. Booth and Quinn (1995) and Pearse and Quinn (1996) engage in discussions of Federal water policy, and a number of studies examine the question of the effectiveness of habitat restoration programmes (Kilgour *et al*., 1996; Allan, 1997; Helfield and Diamond, 1997; Ellsworth, 1997; Slaney and Martin, 1997; Ward, 1997; Koning *et al*., 1998; Gaboury *et al*., 1999). Simonovic and Bender (1996) address the interesting question of modelling and analysis in a user-friendly environment and demonstrate the value of their approach with reference to fish habitat and power development in northern Manitoba.

In my opinion, however, the most serious concern of all is that of the collapse of the national monitoring programme. Barnes and Day (1995), Pilon *et al*. (1996) and Perrone *et al*. (1998) spell out the problem with clarify. The decay of programmes such as the Experimental Lakes Area in north-western Ontario is catastrophic. In the case of the Turkey Lakes Watershed in central Ontario, we risk the loss of one of the most important inland waters monitoring exercises, both in a continental and a global context. But is anyone listening?

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