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Advances in Canadian forest hydrology, 1999–2003

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Abstract:

Understanding key hydrological processes and properties is critical to sustaining the ecological, economic, social and cultural roles of Canada's varied forest types. This review examines recent progress in studying the hydrology of Canada's forest landscapes. Work in some areas, such as snow interception, accumulation and melt under forest cover, has led to modelling tools that can be readily applied for operational purposes. Our understanding in other areas, such as the link between runoff-generating processes in different forest landscapes and hydrochemical fluxes to receiving waters, is much more tentative. The 1999–2003 period saw considerable research examining hydrological and biogeochemical responses to natural and anthropogenic disturbance of forest landscapes, spurred by major funding initiatives at the provincial and federal levels. This work has provided valuable insight; however, application of the findings beyond the experimental site is often restricted by such issues as a limited consideration of the background variability of hydrological systems, incomplete appreciation of hydrological aspects at the experiment planning stage, and experimental design problems that often bedevil studies of basin response to disturbance. Overcoming these constraints will require, among other things, continued support for long-term hydroecological monitoring programmes, the embedding of process measurement and modelling studies within these programmes, and greater responsiveness to the vagaries of policy directions related to Canada's forest resources. Progress in these and related areas will contribute greatly to the development of hydrological indicators of sustainable forest management in Canada. Copyright © 2005 John Wiley & Sons, Ltd.

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INTRODUCTION

Forest covers $417{\cdot}6 \times 10^6$ ha of Canada's land area (almost half the country), and plays critical ecological, economic, social and cultural roles at the local, regional, national and global scales. Sustaining these roles depends, in part, on knowledge of the dominant hydrological processes and properties of the forest landscapes in Canada's various ecoregions (Figure 1). This knowledge is critical to understanding such diverse issues as: forest productivity; the quantity and quality of water moving to receiving wetlands, streams and lakes; the role of forests in surface–atmosphere exchanges of energy, water and carbon; and the physical and biogeochemical implications of disturbance to forest landscapes. This last theme is of particular relevance given the scale and intensity of forest disturbance in Canada. Thus, $\sim 0{\cdot}4\%$ ($1{\cdot}7 \times 10^6$ ha) of Canada's forests is harvested annually, with $\sim 0{\cdot}5\%$ ($2{\cdot}1 \times 10^6$ ha) disturbed by fire or insect outbreaks (Natural Resources Canada, 1998), although the balance between these disturbances may be changing. Thus, the area burned within the managed forest area of Ontario remained relatively constant at $0{\cdot}5 \times 10^6$ ha decade^{-1} between 1951 and 1990, whereas the total clearcut area in Ontario increased from $0{\cdot}5 \times 10^6$ ha (1951–60) to $>2 \times 10^6$ ha (1981–90) (Schroeder and Perera 2002). Our ability to understand, predict and manage the varied consequences of these and other natural and anthropogenic disturbances to forest ecosystems, as well

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Figure 1. Terrestrial ecoregions of Canada (after Canadian Council of Forest Ministers (1997))

as our efforts to sustain the ecological, economic, social and cultural roles of Canada's forests, needs to be based on sound hydrological principles.

This review builds on an earlier examination of the state of forest hydrology in Canada (Buttle *et al*., 2000), and identifies progress on many of the major themes discussed in that review. Much of this advance has been driven by important funding programmes initiated shortly before or during the period covered by the present review, with a significant influence on the location, intensity and objectives of research related to hydrological properties and processes in Canada's forest landscapes. Examples at the provincial level include the Forest Renewal British Columbia (FRBC) programme, which began in the early 1990s and provided a major impetus to forest hydrology research in that province, and the Ontario Living Legacy programme, which started in the late 1990s and has supported several projects related to the hydrological consequences of forest disturbance. The Sustainable Forest Management Network (SFMN) was initiated at the federal level, with a mission of developing research networks among universities, industry, government and First Nations to promote sustainable resource management strategies for Canada's forests. This network has supported considerable research into the hydroecological implications of forest disturbance in Canada (e.g. Carignan and Steedman 2000).

PRECIPITATION AND SNOW PROCESSES

Rainfall interception, throughfall and stemflow

The limited Canadian research between 1999 and 2003 on interception, throughfall and stemflow during rainfall in forest stands was mainly concerned with the role of these processes in forest nutrient cycling and the effects of acid deposition on nutrient fluxes from the canopy to the forest floor. Specific hydrological processes received relatively little attention; nevertheless, the work is still relevant to forest hydrology. Thus, Houle *et al.* (1999a) assessed the number of collectors required to measure throughfall depth associated with a predetermined error and confidence level as a function of the measurement time interval for a mixed hardwood stand 50 km northwest of Quebec City. The results assist in designing sampling strategies for estimating throughfall inputs in forest landscapes. Houle *et al.* (1999b) examined ion deposition in precipitation, throughfall and stemflow in deciduous and coniferous stands in the same drainage basin. Average annual interception in the deciduous and coniferous stands was 11% and 18% of total precipitation respectively, and stemflow contributed 3% and 1% of the annual net precipitation reaching the forest floor in the deciduous and coniferous stands respectively. All values agree with those reported in the literature. Gordon *et al.* (2000) examined throughfall and stemflow fluxes in equal-age plantations of red, black and white spruce in central Ontario. Absolute water fluxes were not reported; however, the relative ranking of throughfall fluxes was black spruce > red spruce > white spruce, and the relative ranking of stemflow fluxes was white spruce > red spruce >> black spruce. These differences were attributed to the unique morphologies (e.g. bark roughness, branch angle, crown structure) associated with each species, and reinforce a recent call (Levia and Frost, 2003) to consider morphological properties when assessing interception, throughfall and stemflow studies conducted in differing forest types.

Yanni *et al.*'s (2000) simulation of throughfall and streamflow in four Nova Scotia basins using the ForHyM2 model is an exception to the research focus of the previous studies. The ForHyM2 model (Arp and Yin, 1992) is an operational hydrology model designed to simulate water fluxes in forest ecosystems using limited input data. Three basins were dominated by spruce and pine with variable amounts of hemlock and fir, and the fourth basin was dominated by maple, oak, birch and beech. Modelled throughfall agreed well with nearby measurements (Percy, 1989), and modelled average annual interception was 9·4% of mean annual gross precipitation. Water inputs had to be augmented by fog drip contributions of ~150 to ~180 mm year^{-1} to obtain good agreement between observed and simulated streamflows, and more work is needed to develop and validate models of this important but often-overlooked process in maritime forests on Canada's east and west coasts.

Snowfall, snow interception, and snowmelt

Recent progress on snow accumulation and melt in forest landscapes falls into three somewhat overlapping categories.

Process-based research. Winkler (2001a) studied snow accumulation and melt in pine and spruce–fir mature stands, juvenile stands and clearcuts at Mayson Lake and Upper Penticton Creek, south-central British Columbia. Smaller peak snow water equivalent (SWE) occurred under forest cover than in clearcuts, with the exception of a juvenile spruce–fir stand. Average snowmelt rates in forest stands were 0·4–0·9 times those in the clearcut at Mayson Lake and 0·6–0·7 times those in the clearcut at Upper Penticton Creek, with no difference in melt rate between juvenile spruce–fir stands and the clearcut. Daily melt rates from continuous lysimeter measurements were earlier and larger in the juvenile-thinned pine stand relative to the juvenile-unthinned pine stand and clearcut, whereas clearcut melt rates exceeded those in all other stands later in the season. Stand structural properties provided significant explanations of standardized ratios of forest-to-clearcut peak SWE and melt. A radiation budget model that incorporated the standardized ratio of forest-to-clearcut melt successfully predicted measured snowmelt at Mayson Lake.

Murray and Buttle (2003) noted that most research into forest harvesting impacts on snow accumulation and melt has been for coniferous stands. They compared snow accumulation and melt in adjacent hardwood maple and clearcut stands in central Ontario, focusing on the role of slope aspect and canopy density in controlling interstand differences in melt. As expected, accumulation and melt in the clearcut exceeded that in the forest; however, the control of aspect on between-stand differences in melt was far greater than that of canopy density.

Faria *et al.* (2000) built on previous work suggesting that melt rates within forests decrease with increasing SWE (e.g. Buttle and McDonnell, 1987) and that SWE varies at both the stand and intrastand scales. They measured changes in spatial distributions of SWE before and during melt in five stands of differing canopy density in central Saskatchewan. A log-normal distribution fit the pre-melt SWE frequency distribution within stands. Greater variability in SWE resulted in earlier exposure of ground under spatially uniform melt simulations; however, the spatial distribution of daily melt was inversely correlated with SWE, which further accelerated snow cover depletion. Inclusion of within-stand covariance of SWE and melt improved estimates of measured changes in snow-covered area relative to simulations that only considered the effect of SWE distribution on snow-cover depletion.

Integrated process- and modelling-based research. The distinction between this category and the next is that here the modelling work is largely intended to complement our understanding of the hydrological process. Energy balance estimates of snowmelt in a subarctic spruce woodland incorporating differential melt rates due to canopy shading were used to examine the relationship between variability in mean daily snow depth and the spatial scale at which snow depth was determined, and to assess the information loss occurring with increasing spatial scale of aggregation (Woo and Giesbrecht, 2000a). Information loss increased with snow depth variability as melt progressed, and this scale-induced information loss should be considered when modelling snowmelt in regions exhibiting large spatial variations in melt. Woo and Giesbrecht (2000b) modelled snowmelt under a subarctic spruce tree, based on physical melt processes, canopy geometry, and field-derived empirical functions and coefficients. Simulations compared well with measured daily snow depths, and the tree canopy enhanced the snow surface's longwave radiation balance. Changing melt intensities produced by the tree's presence induced a strong asymmetry in melt rates among different azimuths within and beyond the tree canopy. A companion paper (Giesbrecht and Woo, 2000) used a simplified version of the model to simulate melt in a subarctic spruce woodland using a geographical information system. The model included topographic and tree shadow effects on the radiative component of melt energy. Melt for zone types in the forest was estimated from meteorological data at an open site. Skewness of the snow depth distribution decreased as melt progressed, while variability in snow depth increased. The authors cautioned that the error associated with using point values of snowmelt to estimate spatially averaged melt exceeded 200%.

Parviainen and Pomeroy (2000) extended the research of Pomeroy and colleagues (e.g. Hedstrom and Pomeroy, 1998) into snow interception and sublimation in forest landscapes summarized in Buttle *et al.*'s (2000) previous report. They coupled physically based equations describing snow interception and sublimation processes with a one-dimensional land surface scheme (the Canadian Land Surface Scheme (CLASS); Verseghy, 1991; Verseghy *et al.*, 1993). The coupled model was tested against measured sublimation in mature and regenerating jack pine stands in central Saskatchewan. It provided good simulations for the mature stand, but did not estimate latent heat fluxes well during events with greater snow loads and incoming solar radiation. This was attributed to errors introduced by solving for within-canopy humidity and to the role of subcanopy snow energetics not considered in the coupled model.

Modelling- and monitoring-based research for operational purposes. Bhatti *et al.* (2000) obtained good predictions of measured peak SWE using the ForHyM2 model in a jack pine site in northeastern Ontario, with greater SWE in open areas relative to beneath the canopy as observed elsewhere (see Murray and Buttle (2003) for a review). Similar agreement between measured and modelled SWE occurred when ForHyM2 was applied to forested basins in Nova Scotia (Yanni *et al*., 2000). Pomeroy *et al*. (2002) predicted forest SWE based on stand properties (canopy density, leaf area index) and seasonal snow accumulation or snowfall in nearby small clearings S_c. The model was derived from physically based snow interception equations obtained by Pomeroy and colleagues (e.g. Pomeroy *et al*., 1998) in the Wolf Creek basin in the Yukon and in central Saskatchewan, and was consistent with Kuz'min's (1960) relationship between snow accumulation in a forest S_f and canopy density C_c:

$$S_f = S_c(1 - 0{\cdot}37C_c) \tag{1}$$

The authors suggested that relationships of this form are spatially transferable between cold-climate forests.

The issue of hydrological recovery (restoration of the hydrological characteristics of harvested sites to a near-preharvest condition; Hudson, 2000) during stand regeneration is an important theme in forest hydrology that is closely linked to the issue of sustainable forest management. Hudson (2000) compared snow accumulation and melt in regenerating stands in coastal British Columbia across a range of canopy heights, based on the assumed relationship between canopy height and degree of stand regeneration. Recovery factors were calculated using linear interpolations between extremes defined by the peak accumulation or melt rate of old growth and clearcut equivalent plots. An asymptotic exponential model provided a reasonable description of rapid initial recovery as a function of either canopy height or canopy density. The results suggested a hydrological recovery threshold where the height of the tallest trees in the stand is roughly equal to the mean peak snowpack depth for open sites. Relationships of this type can be used to estimate the degree to which regenerating stands have reached complete hydrological recovery. However, tree height provided relatively poor predictions of hydrological recovery in juvenile forest stands in south-central British Columbia (Winkler, 2001b). The largest proportion of variability in forest peak SWE relative to that in the open was explained by crown volume, length and closure, whereas melt was best predicted by the square root of basal area. Winkler (2001b) suggests that incorporation of stand-structure variables representing snow interception and shading under varying forest cover conditions provides a sounder means of estimating hydrological recovery than tree height alone.

The H_{60} concept is used in western Canada and the USA to relate snow-covered area in mountain basins to peak flows during spring melt. The H_{60} line is the elevation above which 60% of the basin lies, and the snow-covered area above the H_{60} line can be considered to be the major source area of water contributing to peak flows (Gluns, 2001). The H_{60} approach to estimated peak flows to snow-covered area comes largely from Gartska *et al*. (1958), who found that peak streamflow occurrence from a Colorado basin corresponded to a snow-covered area of 45% (i.e. elevations higher than the H_{45} line). The H_{60} concept has been used to guide harvesting operations in the southern British Columbia interior, based on the untested assumption that forest removal above the H_{60} line will increase SWE, melt, and runoff contributions to peak flows. Gluns (2001) evaluated the applicability of the concept using snowline elevation and streamflow data for five snowmelts in two small basins near Nelson, British Columbia. About 65% of each basin was snow covered at the time of peak flow, suggesting that the H_{60} concept is a valid planning tool for evaluating forest-harvesting plans in south-central British Columbia.

RUNOFF PROCESSES AND BASIN WATER BALANCE

There was not as much research on this topic as was summarized in the previous progress report; nevertheless, many of the same issues related to runoff production and streamflow generation highlighted by Buttle *et al*. (2000), such as the role of various runoff processes in forest landscapes, the degree of hydrological coupling between hillslopes and receiving waters, and the influence of this coupling on basin streamflow characteristics, have also been examined in several studies since 1998. Much of this work has formed part of larger multidisciplinary studies, such as the Boreal Ecosystem–Atmosphere Study (BOREAS) and the Canadian GEWEX programme.

Forested Precambrian Shield

A major impetus for research into runoff processes in forested basins continues to be interest in the response of terrestrial and aquatic ecosystems on the Canadian Shield to acid deposition. This work recognizes the important role that runoff processes and water flowpaths exert on the chemistry of water moving through terrestrial ecosystems to receiving waters. Many studies during the past 5 years were conducted at two long-term research sites: the Turkey Lakes Watershed (TLW) in central Ontario, and the Muskoka–Haliburton area of south-central Ontario.

Hazlett *et al.* (2001) related stream and soil water chemistry from two first-order basins in the TLW during snowmelt to assess water flowpaths. Snowmelt inputs bypassed the deeper soil zone in the high-elevation basin, reducing buffering of snowmelt acidity. Relatively greater input of deeper soil water in the low-elevation basin (indicated by patterns of dissolved silica in streamwater and shallow and deep soil waters) led to higher pH and base cation concentrations and smaller aluminium levels in streamflow. Surficial geology plays a critical role in the hydrology and hydrochemistry of forested basins, as shown by Semkin *et al.*'s (2002) use of silica as a conservative tracer in a mixing model approach to estimate contributions to streamflow from pre-melt streamflow, water routed through the forest floor, and water routed through the upper mineral soil during five snowmelts in Hazlett *et al.*'s (2001) high-elevation basin. On average, pre-melt streamflow, and water routed through the forest floor and upper mineral soil contributed 9%, 28%, and 63% of basin discharge, respectively. A greater proportion of forest-floor water was delivered at maximum discharge. Semkin *et al.* (2002) argued for the development of a perched water table above the surficial ablation till–underlying basal till contact in the basin. This shallow groundwater initially delivered water to the stream through the upper mineral soil, shifting to return flow as the water table intersected the ground surface at maximum discharge. Deeper till contributions were insignificant, consistent with Hazlett *et al.*'s (2001) soil water and streamflow chemistry relationships for this basin. Buttle *et al.* (2001b) examined groundwater characteristics during spring snowmelt for the Hazlett *et al.* (2001) basins. Stable isotopic signatures were used to estimate groundwater residence times. Interbasin differences in changes in piezometric surface elevation and groundwater residence time with depth agreed with differences in the depth of the dominant flow pathway suggested by Hazlett *et al.* (2001) and Semkin *et al.* (2002). No consistent relationships were found between groundwater flow characteristics and the Beven and Kirkby (1979) $\ln(a/\tan\beta)$ topographic index for either basin (where a is the upslope area draining to a given location and β is the slope gradient at that point).

Studies of runoff processes in the Muskoka–Haliburton area of south-central Ontario have focused on water transport through forest slopes via preferential pathways. Input and pre-event soil water controls on throughfall partitioning between overland and subsurface flow and between bypassing flow and translatory flow were examined at the slope scale (Buttle and Turcotte, 1999). Overland flow under intense throughfall onto dry soils suggests this pathway was most effective during drought conditions, which promoted hydrophobicity of the organic layer. Limited infiltration induced by soil hydrophobicity was also hypothesized by Biron *et al.* (1999) to account for rapid surface runoff over unsaturated near-stream soils in a forested basin near Montreal, Quebec. Artificial tracer irrigations (Buttle and McDonald, 2000, 2002; Buttle *et al.*, 2001a) highlighted a number of key aspects of preferential flow on forest slopes, including:

1. Control of runoff generation for small to medium-sized events by coupled vertical and lateral macropore flow.
2. Greater pre-event soil water displacement with larger events and greater antecedent wetness.
3. Increased bypass flow to depth at sites with greater surface-derived macroporosities.
4. Complex mixing of event and pre-event water in slope runoff in a thin layer above the soil–bedrock interface.

5. Combined control of antecedent soil wetness, soil depth and bedrock topography on the thickness, connectivity and upslope extent of the pre-event saturated layer above the bedrock surface, which in turn dictated whether vertical preferential and matrix flow reaching the bedrock surface participated in slope runoff.

Hypermaritime forest landscapes

The benefits of combined hydrometric and tracing approaches were highlighted in Gibson *et al.*'s (2000) study of runoff generation on bog–forest uplands in the Prince Rupert area of coastal northern British Columbia. Shallow hillslope groundwater accounted for 85% of peak streamflow during a mid-summer rainfall. Analysis of baseflow discharge and isotopic response also allowed estimation of groundwater residence time and soil storage capacity. Systematic shifts in deuterium excess of rainfall were used for labelling shallow and deep groundwaters based on their residence time signatures, and the work also reinforced the value of using reactive tracers (e.g. dissolved organic carbon (DOC)) to study water cycling processes.

Forested landscapes underlain by discontinuous permafrost

Research has focused on the role of permafrost in controlling temporal and spatial patterns of slope runoff contributions to streamflow generation. South-facing subarctic forested slopes in the Wolf Creek basin in the southern Yukon were not underlain by permafrost (Carey and Woo, 1999). These slopes had earlier snowmelt but no lateral surface or subsurface flow, since meltwater infiltrated the seasonally frozen soil cover with low ice content. Summer moisture exchanges were dominated by infiltration and evaporation. Conversely, deep percolation during snowmelt was hindered on the north-facing slope, where an organic layer overlay clay sediments with permafrost. This led to surface runoff in rills and gullies produced by years of overland flow on the slope, as well as subsurface flow through pipes and the organic soil matrix. Soil pipes at the organic and mineral soil horizon interface transmitted water only when the water table was within or above this interface (Carey and Woo, 2000). Pipe flow was described by the Manning equation combined with estimates of contributing areas that changed in extent with slope wetness. Significant pipeflow contributions to slope runoff occurred during snowmelt; however, matrix flow within the organic layer dominated runoff when ground thaw lowered water tables. Carey and Woo (2000) concluded that models of hydrological processes in permafrost environments must consider the control the frost table exerts on the phreatic surface, and thus on the potential for pipeflow. Subsurface flows on the north-facing slope during the summer were confined to the conductive organic layer. Slope evaporation decreased as both frost and water tables descended during the summer. Slope water balances during snowmelt and summer periods on four contrasting aspects showed that snowmelt runoff was confined to slopes with organic soils with an ice-rich base that prevents meltwater infiltration (Carey and Woo, 2001). Flow was unimpeded through frozen but porous organic materials, and lateral runoff was initiated when the organic layer's storage capacity was exceeded. Summer runoff was confined to wet organic-covered slopes, with larger flow from slopes where the water table was close to the surface. For some slope segments, inflow from upslope relative to outflow at the slope base affected the slope water balance significantly. The slope remained wet and runoff was enhanced when inflow equalled or exceeded outflow; however, minor inflow from upslope led to lowering of the water table, reduced runoff in the organic layer and drying of near-surface soils. Carey and Woo (2001) noted that interslope differences in such factors as frost, vegetation, soils and microclimate can produce strong contrasts in slope water balances, with important implications for streamflow generation in subarctic basins.

Interactions among SWE, rainfall magnitude and timing, thaw depth and antecedent levels in surface water stores also controlled water balance dynamics and streamflow generation in a boreal forest basin in northern Manitoba (Metcalfe and Buttle, 1999, 2001). Interannual differences in the amount and timing of rainfall relative to active layer thickness largely dictated the degree to which surface stores on slopes and in wetlands are filled by initial meltwater inputs. These differences in storage capacity, in turn, controlled whether subsequent meltwater and rainfall were exported as streamflow. Isotopic and geochemical hydrograph separations showed that meltwater dominated streamflow during conditions of intense melt on slopes with limited soil thawing combined with large pre-melt storage in surface depressions (Metcalfe and Buttle, 2001). Conversely, smaller melt intensities combined with deeper active layers and smaller storage levels in basin wetlands led to subdued streamflows largely supplied by older water routed through less-permeable deeper peat layers and mineral soil.

Methodological issues related to runoff processes in forest landscapes

Hydrological research in forest landscapes increasingly requires data on soil water content (SWC). Time domain reflectometry (TDR) has become the method of choice for obtaining such data, due to its ease of operation and ability to be coupled with data loggers for continuous measurement of SWC at various depths and locations. Spittlehouse (2000) reviewed the methodological challenges facing the use of TDR to measure SWC in stony soil, and discussed various factors to be considered when calibrating the TDR. Greater SWCs were measured in a clearcut relative to a forest site in southern interior British Columbia, consistent with previous work suggesting that removal of forest canopy should increase SWCs due to reduced interception and evaporation losses (e.g. Elliott *et al.*, 1998). Instead, Spittlehouse (2000) attributed the clearcut SWC to the smaller average stone content of its soils, and highlighted the need to consider soil properties when interpreting the hydrological consequences of forest disturbance.

Estimation of runoff fluxes and water balance components in Canada's forest regions is severely limited by a shortage of hydrometric monitoring stations, which often have a short record length (Prowse, 1990). These stations are also located on large rivers (>1000 km^2), and hydrological data are generally unavailable for lakes and streams that may be impacted by harvesting operations at the scale of a forest management plan (10–100 km^2). In response to this data limitation, Gibson (2001) used the evaporative enrichment of stable environmental isotopes (^{18}O and deuterium) in surface waters as an indicator of water balance variations in forest and tundra landscapes of northern Canada. He reviewed the underlying assumptions, along with the applicability of an isotopic steady-state model to lakes of varying size. The method provided reasonable estimates of basin-wide evaporation rates, and permitted discrimination between evaporation and transpiration losses when combined with hydrometric estimates of total evapotranspiration. Gibson *et al.* (2002) extended the method to estimate throughflow, residence time and basin runoff to 70 headwater lakes in northern and north-central Alberta. Runoff to lakes in wetland-dominated basins exceeded that in upland-dominated lakes, with generally greater runoff from basins with low bog : fen ratios. However, there was no clear indication that forest disturbance (either by harvesting or fire) produced a significant change in runoff : precipitation ratios relative to reference lake basins. Nevertheless, Gibson *et al.* (2002) contended that the approach provides a useful tool for studying hydrological controls on lake chemistry and ecology, and for assessing the hydrological consequences of forest disturbance.

Hydroecological models are increasingly used to simulate runoff production and streamflow generation in forest landscapes, both in Canada (e.g. Alila and Beckers, 2001; Whitaker *et al.*, 2002, 2003) and in other countries (e.g. Tague and Band, 2001). Such models often use digital topographic data to simulate spatial variations in basin wetness and to route water from slopes to the stream channel. However, the degree to which surface topography reflects the hydraulic gradients driving shallow subsurface flow in forest basins is often unclear. Hutchinson and Moore (2000) examined this issue by measuring outflow from nine throughflow troughs at a road cut on a forested slope in the lower mainland of British Columbia. They also measured the spatial distribution of the water table draining to the troughs. The upslope contributing area derived from topography of the underlying basal till (surveyed by hand augering to refusal) provided a reasonable description of throughflow distribution across the slope at low flows; however, surface topography was a better approximation of water table form at high flows. Estimates of effective hydraulic conductivities K_H at slope widths <10 m varied over two orders of magnitude, with no consistent relationship with saturated layer thickness. Conversely, there was a linear increase in K_H with saturated layer thickness for greater flows at slope widths of ~ 10 m. All K_H versus saturated-layer thickness profiles contradicted the parabolic and power-law transmissivity profiles sometimes assumed by hydrological modellers. Hutchinson and Moore (2000) also noted that shunting of water by discrete macropores can overwhelm topographic controls on throughflow at slope widths <10 m.

FOREST HYDROCHEMISTRY

Our knowledge of the impacts of acid deposition and climate variability on biogeochemical cycling in forests is based on a limited number of basin studies. Significant variability in sulphur (S) and nitrogen (N) export among basins within a relatively small region has been reported for eastern Canada (e.g. Creed and Band, 1998a,b; Devito *et al*., 1999; Beall *et al*., 2001; Watmough and Dillon, 2002), and information obtained from a single basin may not accurately reflect a given region's sensitivity to acid deposition and/or climate change (Watmough and Dillon, 2002). Wetlands, a common feature in Canadian forests, represent critical interfaces between slopes and receiving streams and lakes. Significant relationships have been observed between the proportion of wetlands in basins and export of DOC (Prepas *et al*., 2001a; Creed *et al*., 2003), phosphorus (P; Devito *et al*., 2000; Evans *et al*., 2000; Prepas *et al*., 2001a), N (Prepas *et al*., 2001a), and S (Devito *et al*., 1999). The reader is directed to Price *et al*. (2005) for a more comprehensive discussion of biogeochemical cycling in and export from wetlands. Studies focused on the interactions of hydrological and biogeochemical cycles and their impacts on S and N export from forest basins are discussed below.

Sulphur

Forests in eastern Canada have received reduced S deposition since the early 1980s (Environment Canada, 1997), leading to the expectation of decreased sulphate (SO_4) export from basins; however, SO_4 export persists downstream of wetlands in some basins (Dillon and LaZerte, 1992). Mass balance studies showed net SO_4 export following summer droughts in a forested swamp in a basin with shallow tills (<1 m), but net SO_4 retention in a forested swamp in a basin with deeper tills (≥ 1 m; Devito, 1995). Devito and Hill (1999) examined the relationship between water table elevation, SO_4 mobilization versus immobilization in the wetlands' surface peat, and SO_4 export from basins in central Ontario. They also estimated the depth to which SO_4 mobilization occurs in the wetland in order to quantify SO_4 pools available for future export pulses. They found a critical threshold response of increased SO_4 mobilization when the water table declined such that the capillary fringe no longer extended to the surface (i.e. ≥ 25 cm), resulting in drainage and aeration of the peat. The total S pool in wetlands suggested that recovery periods resulting from recent reductions in atmospheric S deposition to streams draining wetland-dominated basins may be significantly longer than those observed for upland-dominated basins (Devito and Hill, 1999).

In order to predict which landscapes are most susceptible to prolonged acidification from atmospheric deposition, Devito *et al.* (1999) explored the spatial extent of the SO_4 pulse phenomenon and wetland susceptibility to water table drawdowns and, therefore, episodic SO_4 release following droughts. Classifying basins based on $<50\%$ or $\geq 50\%$ coverage of uplands with a till depth >1 m helped to identify which basins with wetlands produce large SO_4 export following dry conditions. Basins with largely shallow upland tills (<1 m) had transient upland–wetland hydrological connections that promoted large water table drawdowns, reoxidation of accumulated S in the wetlands, and large SO_4 export. In contrast, basins with predominantly deep tills (≥ 1 m) experienced continuous upland–wetland hydrological connections, leading to smaller water table drawdowns and smaller SO_4 export (Devito *et al*., 1999).

Eimers and Dillon (2002) expanded this conceptual model by examining a gradient of basins varying from no wetland coverage to significant wetland areas and till depths ranging from <1 m to ≥ 1 m. The high degree of synchrony in interannual patterns of SO_4 export between basins suggested that processes affecting the entire basin (i.e. both upland and wetlands) are involved in net SO_4 export. Reduced atmospheric S loading in basins with no wetlands may desorb SO_4 previously adsorbed under greater S loading as soils shift toward an altered 'equilibrium state' (*sensu* Reuss and Johnson, 1986), whereas warmer and drier conditions in basins with or without wetlands result in higher mineralization rates of organic S compounds in both upland and wetland soils and greater S export (Houle *et al.*, 2001; Eimers and Dillon, 2002).

Nitrogen

In contrast to S, N deposition rates have not changed since the 1980s, leading to concerns regarding N saturation of forest ecosystems (Aber *et al.*, 1989). Increased nitrate-N (NO_3-N) export from forest slopes to receiving surface waters is a diagnostic for N saturation (Stoddard, 1994), but the NO_3-N *source* and the *processes* by which NO_3-N is mobilized from the slope to the stream remain unclear.

Creed *et al.* (2002) characterized the spatial heterogeneity in total N and potentially mineralizable N (PMN) pools in soils in a deciduous forest in central Ontario. They hypothesized that topography regulates the spatial pattern of these pools through a combination of static factors (slope, aspect and elevation) that influence radiation, temperature and moisture conditions, and dynamic factors (catenary position, profile and planar curvature) that influence downslope transport of materials. This was tested using statistical models to explore the topographic basis for patterns of N and PMN pools. Multiple linear regression and tree regression models produced similar pool totals (i.e. within 5% of each other) but dissimilar patterns, with the latter producing a more realistic heterogeneous distribution of N. Static factors were the most important predictors of the pattern of N pools; however, a hydrologically based sampling strategy may find both static and dynamic factors to be significant predictors.

Spoelstra *et al.* (2001) used $^{15}N/^{14}N$ and $^{18}O/^{16}O$ isotopic ratios of NO_3-N to determine the source of exports from deciduous basins in central Ontario. Although external N (i.e. atmospheric deposition of NO_3-N and ammonium-N (NH_4-N)) was significant, internal N (i.e. NO_3-N produced by nitrification of NH_4-N) was the dominant source of NO_3-N exported from basins. Lamontagne *et al.* (2000b) used NO_3-N labelled with ^{15}N to evaluate storage locations of N inputs to a coniferous basin in western Ontario. Surface organic horizons were the main short-term (few years) sinks for N inputs; however, comparison of an N mass balance with ^{15}N recovery suggested that fine or coarse woody debris on the forest floor is a significant missing sink for ^{15}N. Lamontagne and Schiff (1999) demonstrated considerable spatial heterogeneity in N sinks within a forest landscape. Forest 'islands' were N sinks, and the lichen, moss and grass community on surrounding bedrock outcrops were N sources. Although forest islands covered a small proportion of the basin, they had a major impact on NO_3-N export because most of the water leaving the basin had to move through at least one forest island before leaving the system (Lamontagne and Schiff 1999). Future studies must consider the pattern of N pools, N sources versus N sinks, and the control of antecedent conditions on hydrological connectivity among these functional groups for more effective models of N export from basins.

Natural variability in N export from basins has been explained by the N flushing hypothesis (Creed *et al.*, 1996). N flushing may be regulated by matrix processes via water table fluctuations or by macropore processes via preferential flow pathways. Pathways of mobilization from N pools to streams were investigated by Hill *et al.* (1999) and Buttle *et al.* (2001a). Hill *et al.* (1999) hypothesized that NO_3-N flushing occurs by preferential flow pathways that mobilize NO_3-N rapidly from the surface soil both down the soil profile and down the slope, and that the N chemistry of subsurface stormflow was controlled by mixing of event water moving via macropore flow with pre-event soil matrix water. There was no evidence of NO_3-N flushing, and NO_3-N concentrations in subsurface storm flow were small despite input inorganic N concentrations several orders of magnitude larger than in the mineral soil water. Large rates of microbial immobilization of NO_3-N in infiltrating water, small rates of net N mineralization, and no net nitrification in the surface soil resulted in small inorganic N concentrations in pre-event soil water and little or no NO_3-N flushing. The N in subsurface stormflow at the soil–bedrock interface consisted of N in *event* water transported via macropores (Hill *et al.*, 1999; Buttle *et al.*, 2001a). These studies emphasize the need to consider how hydrology, surficial geology and topography (of both the surface and bedrock surface) on forest slopes interact with soil processes to control N export.

These complex interactions between acid deposition impacts in the face of climatic variability and extreme climatic events in the short term, and climate change in the long term, mean that generalization of observed short-term patterns to longer time scales must be approached with caution (e.g. Biron *et al.*, 1999; Courchesne *et al.*, 2001).

HYDROLOGICAL AND HYDROCHEMICAL ASPECTS OF FOREST DISTURBANCE

Recent studies have improved our understanding of surface water response to basin disturbance, including deforestation by clearcut harvesting and wildfire (Carignan and Steedman, 2000). Most of this work has focused on the boreal forest, which comprises 32% of Canada's forest cover (Natural Resources Canada, 1998). Current forest management strategies assume that harvesting activities emulate wildfire and, therefore, will sustain boreal forest dynamics. This assumption is based on wildfire effects on terrestrial ecosystems, and does not consider aquatic ecosystems (Pinel-Alloul *et al.*, 2002). Several major research programmes were initiated to investigate human impacts on hydrological and biogeochemical linkages between the land and waters in forest landscapes in Canada.

Natural variability of the hydrological system

We examined 30-year hydrological patterns in different forest regions to provide a template for comparing the conclusions of published studies. There is substantial heterogeneity in climatic conditions within each region, and our selected sites should not be considered representative of a given region. We chose sites closest to the geographic region within which previous studies of forest disturbance impacts on hydrology were conducted. Trends in annual precipitation P, potential evapotranspiration PET, and discharge Q (Figures 2 and 3) suggest significant differences in the magnitude of land–atmospheric versus land–aquatic hydrological exchanges among the forest regions. For example, selected sites in the boreal forest show $P < PET$ in the Boreal Cordillera, $P \cong PET$ in the Boreal Plain, and $P > PET$ in the Boreal Shield. Changes in the hydrological balance in moving from the western to the eastern edges of the boreal forest will have important implications for predicting the potential impacts of forest disturbance in this region.

We also examined cumulative departures from normal monthly precipitation (CDNP) and temperature (CDNT) (Figure 4). Positive slopes of CDNP and CDNT indicate wetting and warming conditions respectively, and negative slopes indicate drying and cooling conditions, respectively, compared with the long-term average (Winter *et al.*, 2001). Cumulative departures from monthly precipitation or temperature are useful in depicting naturally occurring oscillations in climatic conditions. For example, the stations selected have precipitation signals showing: (1) large variability with multiple major overlapping climatic oscillations ranging from a few years to decades (e.g. Boreal Shield); (2) moderate variability with a single minor climatic oscillation of ~10 years (e.g. Boreal Plain); and (3) small variability with no apparent climatic oscillations (e.g. Boreal Cordillera). The stations selected show similar variability in the temperature signals. Of interest is the fact that boreal forest sites with relatively small variability in CDNP show relatively large changes in CDNT (e.g. Boreal Cordillera) and those with relatively large variability in CDNP show relatively small variability in CDNT (e.g. Boreal Shield).

Our analysis highlights the importance of discriminating the disturbance 'signal' from the natural variability of background 'noise' when quantifying the impacts of forest disturbance on hydrology and the physical, chemical, and biological characteristics of aquatic ecosystems that hydrology regulates in Canadian forests.

Disturbance by harvesting and wildfires

There were few studies of the potential impacts of timber harvesting on surface waters to report in the previous review of forest hydrology in Canada (Buttle *et al.*, 2000). In contrast, there were many studies on this topic between 1999 and 2003, including those from several basin manipulation experiments. The introduction to a special issue of the *Canadian Journal of Fisheries and Aquatic Sciences* (2000; **50** (Suppl. 2)) on the impacts of forest disturbance on aquatic ecosystems identified the main science questions underlying

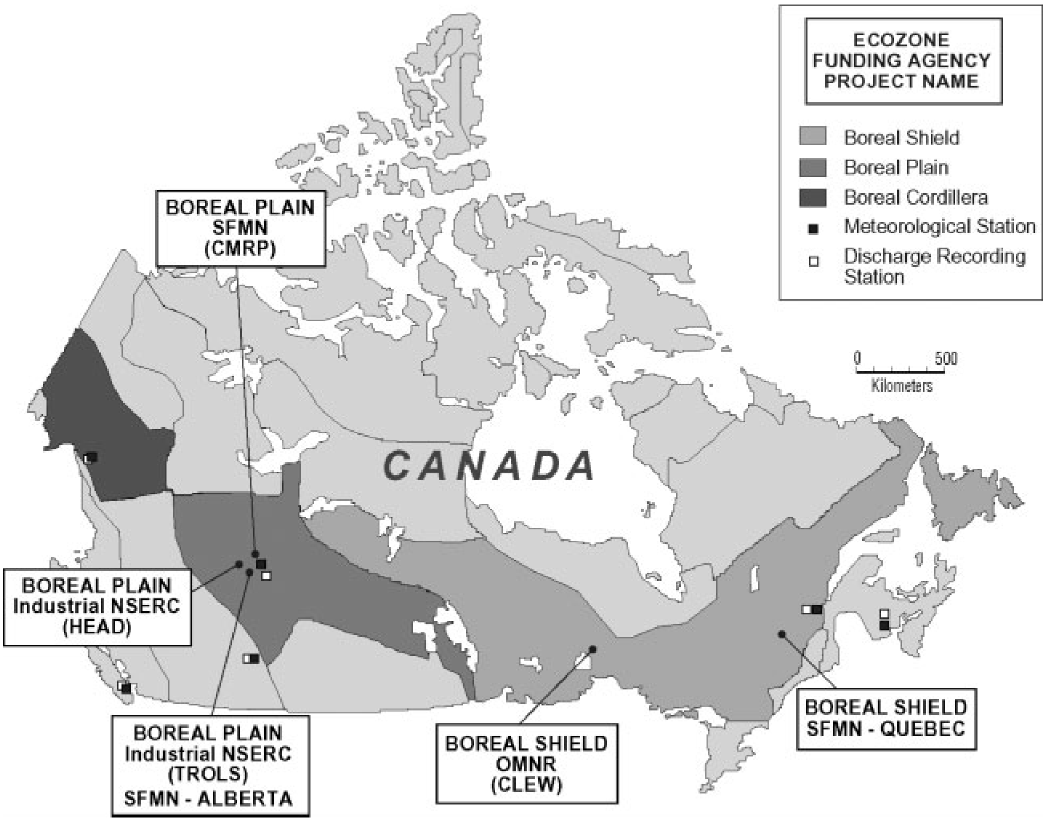

Figure 2. Distribution of major research programmes conducted to examine the effects of forest disturbance on terrestrial and/or aquatic ecosystems within the boreal ecozones (after Canadian Council of Forest Ministers (1997)). CLEW: Coldwater Lakes Experimental Watershed; CMRP: Caribou Mountains Research Project; HEAD: Hydrology, Ecology and Disturbance; NSERC: Natural Sciences and Engineering Research Council of Canada; OMNR: Ontario Ministry of Natural Resources; SFMN: Sustainable Forest Management Network. Locations of meteorological and discharge recording stations used to characterize natural variability in hydroclimatic conditions for different forest regions in Canada are also shown. Meteorological recording stations include: Nanaimo in the Pacific Maritime (49°03′N, 123°52′W), Whitehorse in the Boreal Cordillera (60°43′N, 135°05′W), Glacier National Park in the Montane Cordillera (51°18′N, 117°31′W), Athabasca in the Boreal Plain (54°49′N, 113°32′W), Rivere Verte Ouest in the Boreal Shield (46°59′N, 71°50′W), and Fredericton in the Atlantic Maritime (45°52′N, 66°32′W). Discharge recording stations include: Bings Creek in the Pacific Maritime (48°47′N, 123°43′W), Takhini River in the Boreal Cordillera, 60°51′N, 134°44′W), Beaver River in the Montane Cordillera (51°29′N, 117°29′W), Willow River in the Boreal Plain (55°55′N, 113°55′W), Jacques-Cartier in the Boreal Shield (46°53′N, 71°31′W), and Lepreau River in the Atlantic Maritime (45°10′N, 66°28′W)

contemporary concerns about the sustainability of aquatic ecosystems as: (1) Has human activity compromised the ability of forests to produce clean water and support productive and diverse aquatic biota? (2) Will new stresses have a synergistic or antagonistic effect on existing stresses? The following summarizes studies that address these two questions.

Response to disturbance: streams. Water quantity: Prevost *et al.* (1999) used a paired-basin approach to examine the effects of draining a forested peatland in Quebec (Table I). Baseflow increased by 25% following ditching in the treatment basin. Peak flows seemed unaffected by drainage; however, a definitive conclusion could not be drawn due to the lack of high flow events during the calibration period. McFarlane's (2001) analysis of two control and treatment basin pairs in southeastern British Columbia identified specific changes in peak flow; however, they could not be conclusively related to forest cover removal. Results did not support a threshold level of harvesting above which changes in peak flows could be detected. McFarlane

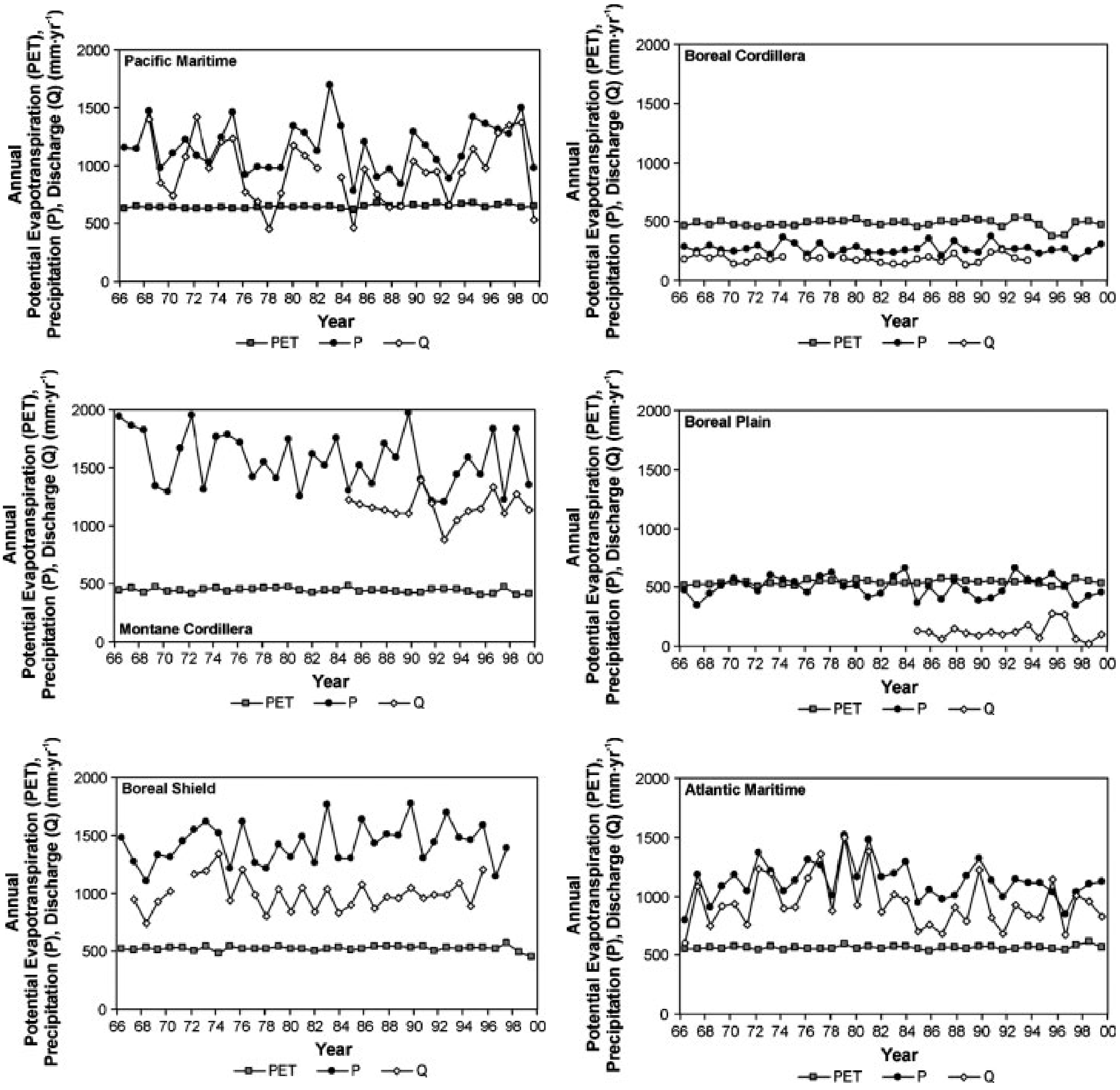

Figure 3. Trends in annual precipitation P, potential evapotranspiration PET (Thornthwaite, 1948), and discharge Q for different forest regions in Canada, 1966–2000

(2001) noted that high statistical power for detecting hydrological changes requires more years of data than are generally available in paired-basin studies, leading to acceptance of the null hypothesis of no change when in fact change may have occurred.

Caissie *et al*. (2002) examined streamflow changes at Catamaran Brook, New Brunswick, for two sub-basins subjected to clearcutting of 2·3% (Middle Reach) and 23·4% (Tributary 1) of the basin areas. Annual and seasonal water yield at Middle Reach did not change following harvesting, based on comparisons of post-harvest data with pre-logging regressions, which used water yield for the Little Southwest Miramichi River (basin area 1340 km^2) as the statistical control. Regressions between peak flow and stormflow volume for Middle Reach against storm rainfall did not differ significantly between pre- and post-logging periods.

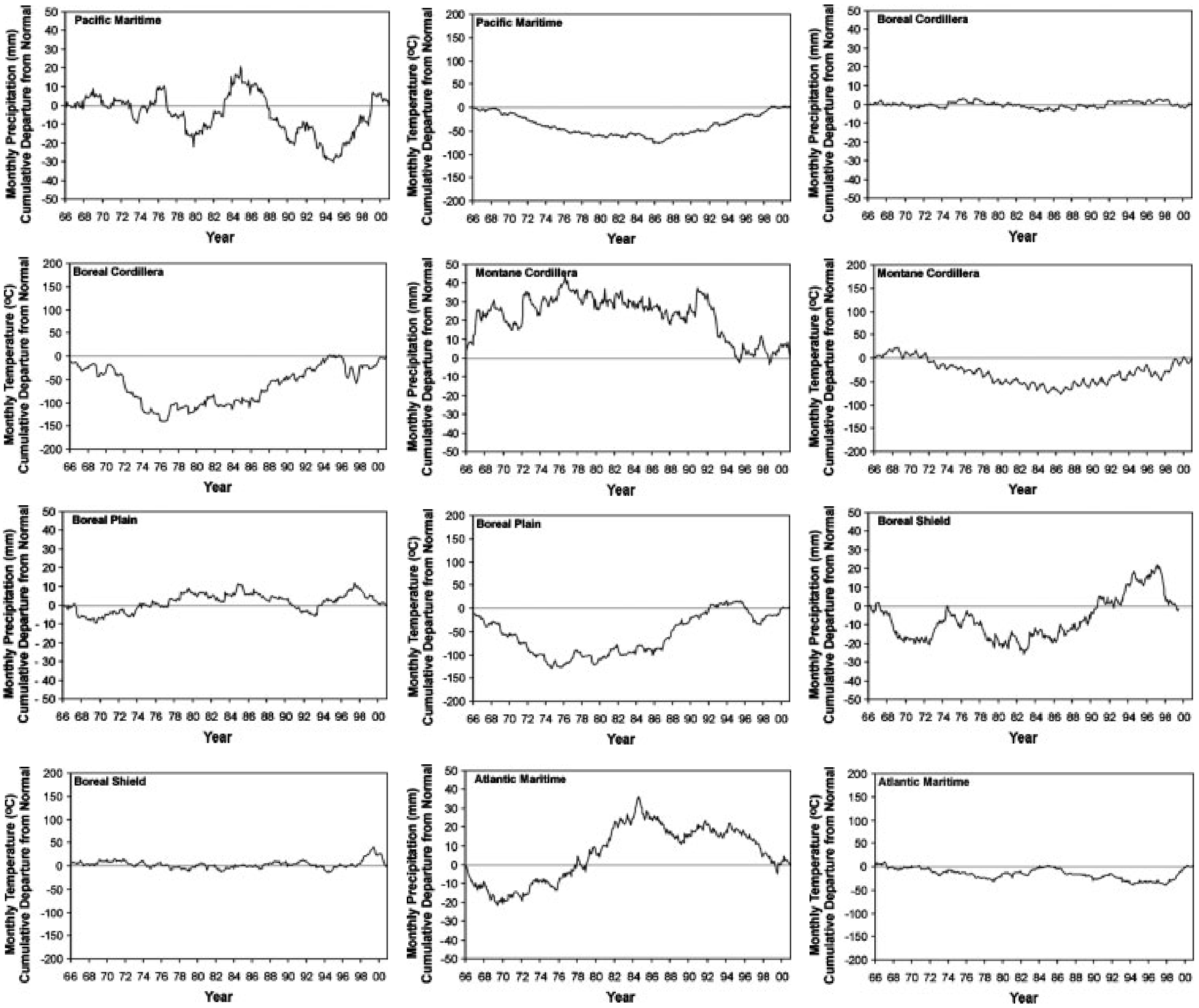

Figure 4. Cumulative departures from normal for monthly precipitation (CDNP) and mean monthly air temperature (CDNT), 1966–2000. The climatic analysis was based on the meteorological recording stations identified in Figure 2

Comparison of pre- and post-harvest regressions of Tributary 1 peak flow against both storm rainfall and Middle Reach peak flow indicated that harvesting increased peak flows. However, there was no statistically detectable effect on storm flow volumes at Tributary 1.

Buttle and Metcalfe (2000) examined streamflow response to boreal forest disturbance (fire and harvesting) in six sub-basins of the Moose River basin, northeastern Ontario; two had ‘medium’ drainage areas (400–1100 km^2) and four had ‘large’ (6800–12 000 km^2) areas. They determined the extent of forest disturbance using remote-sensing images from two dates, and analysed streamflow data using an after-the-fact pairing for the medium and large basins, with the least disturbed basin in each size group serving as a control. Disturbance effects on annual runoff and peak flows could not be detected by double-mass curves and trend analysis. However, changes in small and medium flows in two basins appeared to be related to forest disturbance in the medium and one large basin, respectively.

Whitaker *et al.* (2003) explored the effects of different forest harvesting scenarios on streamflow by applying the Distributed Hydrology–Soil–Vegetation Model (DHSVM) to Redfish Creek, a mountainous

Table I. Basin-scale experiments to document the effects of forest harvesting on water quantity and physical water quality

Location	Forest type	Treatment(s)	Number of treatment streams	Response variables[a]	Reference
Eastern Quebec	Black spruce peatland	Drainage to lower water table	1	Q, T, S	Prevost *et al.* (1999)
Hayward Brook Watershed Study, New Brunswick	Mixed forest (hardwood and softwood)	Clearcut and shelterwood harvesting (3 to 26% of basin area); 30 to 60 m riparian buffers	4	T	Bourque and Pomeroy (2002)
Copper Lake watershed, Newfoundland	Balsam fir, black spruce	Clearcut harvesting (18%) with no riparian buffer; clearcut harvesting (26%) with a 20 m riparian buffer	2	T	Curry *et al.* (2002)
Central interior, British Columbia	Sub-boreal spruce biogeoclimatic zone	Clearcut harvesting (13% and 9%); 30 m riparian management zone with retention of non-commercial trees	2	T	Mellina *et al.* (2002)
Catamaran Brook, New Brunswick	Boreal spruce (65% conifer–35% deciduous)	Clearcut harvesting: 2·3% for Middle Reach; 23·4% for Tributary 1	2[b]	Q	Caissie *et al.* (2002)

[a] Q: streamflow; T: water temperature; S: suspended sediment.
[b] Harvesting at Middle Reach had no detectable effect, so it was used as a control for Tributary 1.

snowmelt-dominated basin in the southern British Columbia interior. Modelled and observed SWE and snow-covered area agreed reasonably well. Simulations revealed significant year-to-year variations in harvesting effects on streamflow (particularly peak flow), in agreement with empirical results from 30 years of post-harvest data at Fool Creek, Colorado (Troendle and King, 1985). Harvesting below the H_{60} elevation did not influence simulated peak flows, since the snow had melted from that zone by the time of peak flow. This supports use of the H_{60} elevation as the basis for a weighting factor in the calculation of equivalent clearcut area within the Interior Watershed Assessment Procedure (British Columbia Ministry of Forests and Ministry of the Environment, 1999).

Despite this activity, there is still a relative shortage of empirical studies on disturbance impacts (both natural and anthropogenic) on water yields and peak and low flows in Canada's various forest landscapes. This contrasts with the lively and ongoing debate regarding the influence of forest management on peak flows in the Cascade Mountains of western Oregon (Jones and Grant, 1996; Thomas and Megahan, 1998; Beschta *et al.*, 2000), and the recent call in the USA to examine harvesting impacts on flooding during extreme events under a range of management practices, physiographic conditions, and event types (DeWalle, 2003). The absence of studies specific to the Canadian environment means that inferences about forest disturbance impacts on a basin's hydrological regime are often drawn from work conducted in other parts of the world. Thus, Scherer's (2001) review of research on the impacts of forest-cover removal on peak flow magnitude and timing, water yield and low flows relevant to conditions in the central and southern interior of British Columbia showed that only five of the 18 studies were conducted in Canada, with the remainder from Arizona, Colorado, Idaho, Montana, Oregon and Utah. The issue of importation of research results to the Canadian context is an important one. In some cases importation is hampered by the absence of analogues to the Canadian situation, such as the large-scale harvesting and fire disturbance occurring in the Boreal Shield and Boreal Plains landscapes. In cases where harvesting under similar forest cover and climatic conditions occurs elsewhere, direct importation of research results may not be appropriate. For example, some hydrologists in British Columbia are questioning the extent to which the non-glaciated Oregon Coast Range provides a good model for glaciated British Columbia environments. In addition, many US studies of harvesting impacts on basin streamflow conducted in the 1960s and 1970s employed practices, particularly in relation to road construction and maintenance and site preparation (e.g. slash burning), that are no longer in use.

Stream temperature: Four studies used basin-scale experiments to document the effects of forest management on stream temperatures (Table I). Prevost *et al.* (1999) found that draining a forested peatland decreased weekly minimum temperature by 2 °C and increased weekly maximum temperature by 7 °C. Water temperature in the drained basin often reached 25 °C or more. Bourque and Pomeroy (2002) detected slight warming in four streams after harvesting, despite retention of generous riparian buffers. They attributed warming to advection of heated subsurface water from the cutblocks. They also related variations in pre- and post-harvest temperatures among treatment streams to indices of solar irradiance on the streams and cutblocks and mean slope gradient in the cutblocks. Mellina *et al.* (2002) found downstream cooling for both of their study streams, even after harvesting reduced riparian canopy cover to about half its pretreatment value. This was attributed to the presence of small lakes upstream of the study reaches, where temperatures exceeded the equilibrium temperature for conditions in the stream reaches. A synoptic survey of lake-headed and non-lake-headed streams with a range of forest management histories confirmed that stream reaches exhibit downstream cooling for some distance below small lakes, even through cutblocks. Despite this trend, there was a net warming of up to ~2–4 °C (in terms of daily maximum temperature) during August at the downstream ends of the cutblocks relative to predicted temperatures based on a pre-logging regression with the control. Curry *et al.* (2002) found greater fall-season water temperatures in a stream with no buffer, but a treatment effect could not be detected in a stream with a 20 m buffer. To isolate treatment effects, Curry *et al.* (2002) used an analysis of covariance (ANCOVA) on daily mean water temperature, with daily mean air temperature as a covariate. Curry *et al.* (2002) also found temperatures in brook trout incubation habitats similar to surface water temperatures, reflecting the dominance of downwelling hyporheic flow over upwelling groundwater.

Several studies modelled stream temperature. Caissie *et al.* (1998) related maximum daily water temperatures at Catamaran Brook, New Brunswick, to air temperatures using both logistic regression and stochastic models, the latter including a sine component for the seasonal cycle and a second-order Markov process to account for short-term deviations. St-Hilaire *et al.* (2000), also focusing on Catamaran Brook, modified the CEQUEAU parametric-conceptual model to account for lateral heat advection of heat via subsurface flow, in order to simulate the effect of groundwater warming in clearcuts on stream temperatures. Inclusion of heat inputs by lateral inflow improved stream temperature simulations. Mitchell (1999) developed a regression model based on monthly data to predict the effect of clearcut harvesting with no buffers.

Suspended sediment: Kreutzweiser and Capell (2001) studied fine sediment infiltration into the streambed at six locations representing a gradient of harvesting impacts in the TLW, Ontario. Greatest sedimentation rates for the inorganic fraction were downstream of road-improvement activities and where skidder tracks in the riparian zone channelled flow into the stream. Lowest sedimentation rates occurred at a shelterwood treatment, where logging roads were not a factor. The organic fraction of the particle-size distribution appeared unaffected by harvesting activities. Prevost *et al.* (1999) found that ditching a forested peatland to improve drainage increased suspended sediment concentrations by 100–200 times for the following few weeks. Concentrations then returned to pre-drainage levels, except during one rainstorm 2 years after treatment.

A number of sediment-related studies have been conducted through funding from FRBC. Most have not been reported in peer-reviewed journals, although some results have been presented in Forest Service Technical Reports or conference proceedings (e.g. Hudson, 2001; Henderson and Toews, 2001; Jordan, 2001). Christie and Fletcher (1999) examined harvesting impacts on sediment geochemistry in five small streams in the Stuart–Takla Fish–Forestry Interaction Project in the sub-boreal spruce biogeoclimatic zone of British Columbia. Prior to logging, each stream had distinctive sediment chemistry associated with basin geology. Harvesting alone did not change sediment geochemistry, probably because the presence of riparian buffers reduced sediment inputs to the channels. Road crossings did, however, alter sediment geochemistry by introducing abraded zinc from galvanized culverts and sediment via erosion of the road bed and ditches. Patterns of sediment geochemistry, both along the streams and through time, allowed calculation of sediment transport and dispersion rates. Although focused on potential impacts of logging activity on geochemical exploration, this study identified the potential value of sediment geochemistry for tracing forestry-related sediment disturbances.

Methodological issues: Many of the experimental studies involved relatively short pretreatment periods (1–2 years). Three used regression analysis or ANCOVA using daily time series to control for interannual variations in weather and hydrological conditions, and Bourque and Pomeroy (2002) 'standardized' their data by dividing treatment stream temperatures by the corresponding control stream temperature. One potential problem is the likely autocorrelation in the daily time series and the error terms in the regression analyses or ANCOVAs. This reduces the effective degrees of freedom compared with those calculated from sample size, biasing the estimated significance levels for hypothesis tests. Future studies should consider time-series regression approaches (e.g. generalized least squares) for paired-basin calibration using short pretreatment periods. Another problem is that the pretreatment regressions may not be stable from year to year.

Buttle and Metcalfe (2000) attributed the lack of detectable effects to buffering of flow changes by the large basins and relatively low levels of disturbance (maximum of 25% of the basin area). Other issues are the confounding by interbasin differences in physiographic characteristics and climatic variability in both space and time, which could lead to differing streamflow trends amongst basins even in the absence of disturbance effects. These issues are unavoidable when studying medium-to-large basins, where rigorously controlled experiments are not feasible. Climatic variability also limits our capacity to extrapolate the results of studies of hydrological responses to forest disturbance conducted at small experimental basin scales to basins of similar size, geology and topography in other locations. However, an important point is that lack of a detectable effect is not the same as no effect. A potential strategy is to supplement statistical analyses with modelling studies. For example, an exercise along the lines of that of Whitaker *et al.* (2003), if done prior to an experiment or in conjunction with a statistical analysis of historical hydrometric data, may provide a first estimate of the likely magnitude and direction of a treatment effect as an aid to interpreting statistical results (e.g. by conducting a statistical power analysis along the lines of McFarlane (2001)).

One weakness of Whitaker *et al.*'s (2003) study is that the DHSVM could only be tested against current conditions at Redfish Creek. As Klemeš (1986) stressed, such a test does not guarantee that a model can accurately predict streamflow under changed conditions (i.e. after logging in this case). Future model applications should focus on paired-basin situations where the treatment effect can be estimated statistically through comparison with a control. Such work is currently being conducted by Alila and co-workers at the University of British Columbia, using data from the Carnation Creek and Penticton Creek experiments in British Columbia.

Response to disturbance: water quality. In addition to often-cited increases in water levels, water and sediment yields, and water temperatures, harvesting may also impact hydrological linkages between terrestrial and aquatic systems and, thus, influence ecosystem productivity and integrity. Alterations to such linkages may be indicated by changes in the chemical composition of receiving surface waters. Increased particulate nutrient loads often result from erosion by water flowing over soil surfaces compacted during harvesting and associated activities (e.g. roads; Jones and Grant, 1996). Increased dissolved loads are associated with enhanced microbial conversion of nutrients at the soil surface from non-mobile to mobile forms, and subsequent export when the rising water table flushes mobile nutrients over the saturated soil surface to the stream or lake (Hornberger *et al.*, 1994; Creed *et al.*, 1996). However, changes in the chemical composition of surface waters following harvesting vary substantially between localities, even within a physiographic region.

Comparison of Boreal Shield versus Boreal Plain: Studies of forest disturbance effects on the chemical composition of receiving surface waters have focused on the Boreal Shield and the Boreal Plain (Table II).

Basin characteristics of boreal lakes vary. Lakes on the Boreal Shield are smaller and deeper with shorter water residence times, and their basins are smaller and steeper with smaller wetland coverage than on the Boreal Plain (Table III). Similarly, indicators of water quality vary. Lakes on the Boreal Shield have smaller concentrations of DOC, total P, total N, and chlorophyll *a* than those on the Boreal Plain (Table IV). Despite these differences, significant trends in the responses of these lakes to forest disturbances have emerged.

The number of water quality indicators affected by forest disturbance was greater in the oligotrophic Boreal Shield lakes than in the eutrophic Boreal Plain lakes (Table V). For example, Boreal Shield lakes had increased DOC, P and N loadings following both harvest and wildfire disturbances (Steedman, 2000; Carignan *et al*., 2000a; Lamontagne *et al*., 2000a; Enache and Prairie, 2000). In contrast, Boreal Plain lakes had no change in DOC or N loading, but had increased P loading following harvest disturbances (Prepas *et al*., 2001a) and increased DOC, P and N loading following wildfire disturbances (McEachern *et al*., 2000). The degree to which the impacts of increased loadings cascaded up the trophic structure was limited, with generally greater phytoplankton biomass, variable zooplankton biomass, and no change in fish biomass (Planas *et al*., 2000; Patoine *et al*., 2000; St-Onge and Magnan, 2000; Prepas *et al*., 2001a). There was interlake variability within

Table II. Characteristics of the Boreal Shield and Boreal Plain sub-regions of the Canadian boreal forest

	Boreal Shield	Boreal Plain	Reference
Climate	Relatively wet, with total annual precipitation > annual potential evapotranspiration	Relatively dry, with annual precipitation < annual potential evapotranspiration	Prepas *et al*. (2001a), Carignan *et al*. (2000a)
Geology	Gneissic complex covered by glacial deposits; glacial deposits range from 0 to 2 m in thickness, but can exceed 10 m in some locations	Sedimentary bedrock that subsequent glaciation formed into rolling moraines and lacustrine deposits in the southern region, and permafrost-laden soils of deltaic and marine origin in the northern region; glacial drift ranges in thickness from 20 to 200 m and is interbedded with clays, sands, and gravels	Prepas *et al*. (2001a), Steedman (2000), Carignan *et al*. (2000a)
Soils	Range from well to poorly drained and from sandy to organic soils with abundant boulders and granite outcrops	Range from well to poorly drained and from sandy to organic layers.	Tokarsky and Epp (1987), Carignan *et al*. (2000a)
Forest	Mainly black spruce, balsam fir, jackpine, white birch, and trembling aspen	Mainly trembling aspen and white spruce, with black spruce, balsam poplar, paper birch and tamarack common in wet areas and jack pine and balsam fir common in dry areas.	Prepas *et al*. (2001a), Carignan *et al*. (2000a)
Trophic status	Oligotrophic to mesotrophic lakes that have smaller P and N concentrations and are less productive	Eutrophic lakes that have larger P and N concentrations and are more productive	Mitchell and Prepas (1990), Pinel-Alloul *et al*. (2002)
Phytoplankton community	Mainly flagellates (chrysophytes, dinoflagellates, cryptophytes) and diatoms	Mainly cyanobacteria	Prepas *et al*. (2001a), Planas *et al*. (2000)
Zooplankton community	Mainly rotifers based on density and cladocerans and copepods based on biomass	Mainly rotifers based on density and cladocerans and copepods based on biomass	Patoine *et al*. (2000)

Table III. A comparison of drainage basin characteristics for undisturbed Boreal Plain and Boreal Shield lakes (based on data presented in D'Arcy and Carignan (1997), Carignan *et al.* (2000a), and Prepas *et al.* (2001a,b) that were summarized in Pinel-Alloul *et al.* (2002))

Parameter	Boreal Shield		Boreal Plain	
	Mean	SD	Mean	SD
Lake area (km^2)	0·3	0·2	1·3	2·0
Lake volume (10^6 m^3)	1·9	2·1	6·3	15·8
Mean depth (m)	5·2	2·3	3·1	2·9
Maximum depth (m)	14·6	6·7	7·1	8·0
Basin area (km^2)	2·7	1·8	11·5	18·1
Drainage area (km^2)[a]	2·3	1·6	10·2	18·5
Drainage area slope (%)	11·7	5·0	3·3	2·4
Drainage ratio (drainage area/lake area)	8·2	5·2	8·0	4·7
Wetland cover (%)	1·6	1·8	17·0	1·1
Water residence time (years)	1·1	0·8	6·6	5·2

[a] Basin area minus lake area.

Table IV. Comparison of water quality parameters for undisturbed Boreal Plain and Boreal Shield lakes (based on data presented in D'Arcy and Carignan (1997), Carignan *et al.* (2000a), and Prepas *et al.* (2001b) that were summarized in Pinel-Alloul *et al.* (2002))

Parameter	Boreal Shield		Boreal Plain	
	Mean	SD	Mean	SD
pH	6·2	0·6	7·3	(–)
Alkalinity (mg l^{-1})	54·0	29·0	80·0	11·0
Dissolved organic carbon (mg l^{-1})	4·5	1·6	17·0	1·1
Total P (μg l^{-1})	8·3	4·4	54·0	5·5
Total dissolved P (μg l^{-1})	2·6	1·1	17·0	1·6
Ammonia (μg l^{-1})	7·7	4·8	72·0	34·0
Nitrate (μg l^{-1})	16·0	16·0	7·7	2·5
Total N (μg l^{-1})	233·0	41·1	1215	106·0
Sulphate (mg l^{-1})	1·1	0·3	6·0	2·1
Calcium (mg l^{-1})	1·4	0·4	19·0	2·0
Magnesium (mg l^{-1})	0·4	0·1	7·4	1·2
Chlorophyll *a* (μg l^{-1})	2·4	1·4	19·0	2·7
Light extinction coefficient (m^{-1})	0·9	0·3	2·9	0·3

each boreal subregion, with some water quality indicators in disturbed lakes responding strongly to increases in the lake's drainage ratio (i.e. ratio of drainage area to lake area; Table IV).

Current strategies for sustainable forest management assume that management practices will sustain boreal forest dynamics if they emulate natural disturbance regimes (e.g. wildfire; Hunter, 1993). Consequently, recent studies have focused on comparing harvesting and wildfire impacts on aquatic ecosystems (e.g. Carignan *et al.*, 2000a; McEachern *et al.*, 2000; Prepas *et al.*, 2001a). It is perhaps not surprising that the intensity of disturbance effect in terms of magnitude and/or duration was greater for wildfire than for harvesting, given that the former disturbed a greater proportion of the basin (Table V). However, the ability of very hot forest fires to consume understory vegetation and mineralize organic matter in surface soils (e.g. Bayley *et al.*, 1992) also contributes to the greater disturbance that fire may pose to aquatic ecosystems relative to harvesting.

Table V. Impacts of harvesting and wildfire on surface water quality in Canadian forests

	Harvesting	Wildfire	Intensity of effect (in terms of magnitude and/or duration)	Reference
Boreal Shield	OMNR-CLEW[a] study used a before and after controlled impact design where the impact was a partial clearcut that averaged 55% of the basin, ranging from 33 to 71%. SFM-Quebec study used a comparative design between reference and harvested lakes, where the harvest averaged 38% of the basin, ranging from 7 to 73%	SFM-Quebec[b] study used a comparative design between reference and burnt lakes where the burnt areas averaged 90% of the basin, ranging from 50 to 100%		
DOC concentration	Greater	No effect	Harvesting > wildfire	Steedman (2000), Carignan *et al*. (2000a), Lamontagne *et al*. (2000a), Enache and Prairie (2000)
P concentration	Greater	Greater	Harvesting < wildfire	Carignan *et al*. (2000a), Lamontagne *et al*. (2000a), Enache and Prairie (2000)
N concentration	Greater	Greater	Harvesting < wildfire	Carignan *et al*. (2000a), Lamontagne *et al*. (2000a)
Phytoplankton biomass	Greater	Greater	Harvesting < wildfire	Planas *et al*. (2000)
Zooplankton biomass	Smaller	Greater	Harvesting < wildfire	Patoine *et al*. (2000)
Fish biomass	No effect (except smaller proportion of small fish in disturbed lakes)	No effect (except smaller proportion of small fish in disturbed lakes)	Harvesting = wildfire	St-Onge and Magnan (2000)

Boreal Plain				
	Industrial NSERC-TROLS[c] study focused on upland lakes (<50% wetland cover) and used a before and after controlled impact design where the impact was a partial clearcut that averaged 14% of the basin, ranging from 0 to 35%	SFM-CMRP[d] study focused on lowland lakes (>50% wetland cover) with permafrost and used a comparative design between reference and burnt lakes where the burnt areas averaged 84% of the basin, ranging from 60 to 100%		
DOC	No effect	Greater	Harvesting < wildfire	Prepas *et al.* (2001a), McEachern *et al.* (2000)
P	Greater concentration in shallow (non-stratified) lakes; marginally greater in deep (stratified) lakes.	Greater	Harvesting < wildfire	Prepas *et al.* (2001a), McEachern *et al.* (2000)
N	No effect	Greater	Harvesting < wildfire	Prepas *et al.* (2001a), McEachern *et al.* (2000)
Phytoplankton biomass	Greater biomass in shallow lakes, marginally greater biomass in deep lakes	No effect	Harvesting > wildfire	Prepas *et al.* (2001a), McEachern *et al.* (2000)
Zooplankton biomass	Greater biomass in shallow lakes, smaller biomass in deep lakes	No data		Prepas *et al.* (2001a)
Fish biomass	No data	No data		

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[a] Coldwater Lakes Experimental Watersheds (CLEW) was a *before and after controlled impact study* conducted from 1991 to 2000, with 5 years of before-impact monitoring (1991–95) and 5 years after-impact monitoring (1996–2000).

[b] SFM-Quebec was a *comparative study* conducted following harvesting and wildfire disturbances in 1995 for 3 years (1996 to 1998).

[c] Terrestrial, Riparian, Organisms, Lakes and Streams study (TROLS) was a *before and after controlled impact study* conducted from 1995 to 1998, with 2 years before-impact monitoring (1995–96) and 2 years after-impact monitoring (1997–98).

[d] SFM-Caribou Mountains Research Project (CMRP) was a *comparative study* conducted in 1997, 2 years following a 1995 wildfire.

Results from empirically based studies such as those previously described cannot be extrapolated in time or space. Consequently, process-based monitoring and modelling approaches must be incorporated into the experimental design of studies so that: (1) the 'noise' in the chemical response of lakes resulting from climatic variability and/or climate change within each sub-region of the boreal forest can be effectively characterized (e.g. process-based models can be used to simulate hydrological processes across the complete range of climatic conditions); and (2) the 'signal' in the lakes' chemical response to forest disturbance can be effectively discriminated from the noise (e.g. models can simulate both the 'signal' and the 'noise' using different simulation scenarios).

Effectiveness of forest buffer strips: Riparian forests buffers (strips of forest left between harvested blocks and adjacent surface waters) have been considered important sinks for particulate and dissolved nutrients in hydrological flows. Therefore, they are used to mitigate changes resulting from increased water and nutrient loads to lakes and streams following harvest (Castelle *et al.*, 1994). Widespread acceptance that buffer strips protect aquatic resources is paralleled by recognition that guidelines regarding buffer strip design have not been established based on scientific merit. Consequently, buffer strips often satisfy neither those who want these areas protected nor those who want access to the timber held in these protected areas (Buttle, 2002).

Guidelines requiring forest industries to leave a standard width of buffer strip around surface water bodies are often based on a 'rule of thumb' that adjusts buffer width depending on slope angle. Although one study implied that standard-width buffer strips reduce nutrient loadings to lakes (Carignan *et al.*, 2000a), other studies indicated that these buffers do not reduce nutrient loading to lakes (e.g. Steedman, 2000; Steedman and Kushneriuk, 2000; Prepas *et al.*, 2001a; Pinel-Alloul *et al.*, 2002). Intersite variability is a major constraint when assessing the effectiveness of forest buffers, and the use of fixed-width buffer strips without a consideration of water flowpaths upslope of and within the buffer may result in underprotection of aquatic resources in some sites and overprotection in others. Fundamental knowledge on the impacts of harvesting on lakes and the effectiveness of buffer strips in mitigating these impacts in the boreal forest is lacking.

Buttle (2002) points out that the standard application of the forest buffer concept does not consider such basic hydrological concepts as: (1) lake area relative to the area of forest draining to the lake (i.e. the drainage ratio); (2) the degree to which harvested areas are hydrologically connected to the stream or lake; or (3) the relative input from local, intermediate and regional groundwater systems to the stream or lake. He contends that these hydrological considerations can assist in designing effective buffer strips. Recognizing that hydrological data are often not available for this task, Buttle (2002) offers simple proxies of hydrological conditions that can be generated using automated analysis of digital elevation data. For example, topographic indices (TIs), such as that of Beven and Kirkby (1979), can be used to identify groundwater discharge sites along the land–water interface (Buttle, 2002). Wolniewicz (2002) combined the TI with topographic depressions and flat slopes and used a simple inundation routine to map temporal changes in recharge versus discharge areas. These maps can be used as a basis for designing buffer strips that mitigate water, sediment and nutrient loadings to surface waters. Hydrologically based designs of buffer strips will likely move away from forested ribbons along streams and of rings around lakes to forest patches that protect critical recharge or discharge zones within the landscape. Furthermore, there is recognition that the design of buffer strips for mitigating water, sediment and nutrient loadings to surface waters may not be sufficient to alleviate other impacts (e.g. increases in wind speeds over the lake with implications for internal lake processes), and that more research on the role of buffer strips in allaying all ecological impacts that harvesting may pose to receiving waters is needed (Buttle, 2002).

Criteria and indicators for sustainable forest management (SFM). Despite the potential ambiguity of 'SFM', the term has been retained in national and international initiatives and defined as the maintenance of a series of criteria and indicators (Kneeshaw *et al.*, 2000). A criterion is a category or class of processes characterized by a set of related indicators that are monitored periodically to assess change. An indicator is a quantitative or qualitative variable that can be measured or described and which, when observed periodically, demonstrates trends (http://www.mpci.org/criteria_e.html). In Canada, the Canadian Council of Forest Ministers (CCFM, 1997) have identified criteria of SFM, including: (1) conservation of biological diversity; (2) ecosystem condition and productivity; (3) conservation of soil and water resources; (4) global ecological cycles; (5) multiple benefits of forests to society; and (6) accepting society's responsibility. Major research programmes, including the SFMN Centres of Excellence, have focused on defining indicators for each criterion.

Kneeshaw *et al.* (2000) note that scientific knowledge must be incorporated into indicator development. They define the essential attributes of indicators of SFM as being: (1) scientifically sound; (2) operationally feasible; (3) socially responsible and internationally credible; (4) measured following a standard method; (5) easily measurable and cost effective; (6) easily interpretable and directly linked to environmental changes generated by *local* management activities, but relatively insensitive to more *global* sources of variation; (7) integrated; and (8) linked to prescriptions. For the criterion related to the conservation of water resources, indicators must be identified that denote the functional and structural integrity of aquatic ecosystems and the natural resources associated with these ecosystems. To show threshold and achieved target levels of indicators, this preservation must incorporate the *natural range of variation* of the functional and structural properties as determined by their response following *natural disturbance regimes* (Kneeshaw *et al.*, 2000).

Table VI summarizes studies that have developed hydrologically based indicators to predict potential changes in surface water quality in response to natural and/or anthropogenic disturbance regimes. Many have focused on the drainage ratio, such that large drainage-ratio lakes (large basin area : small lake area) have enhanced potential for nutrient loading via surface drainage to the lakes and short water residence (or water renewal) times, and small-ratio lakes (small basin area : large lake area) have reduced potential for such nutrient loading and longer water residence times. This ratio was correlated to surface water quality parameters on both the Boreal Shield and Boreal Plain (cf. Pinel-Alloul *et al.*, 2002).

More indicators may be required to represent the hydrological controls acting on a lake when moving from relatively simple hydrological systems on the Boreal Shield to the more complex Boreal Plain (Buttle *et al.*, 2000). Devito *et al.*, (2000) developed a conceptual model of the hierarchy of these controls and identified indicators that represent each level of this hierarchy, including: (1) a lake's hydrogeologic setting, which defines the relative importance of subsurface flow contributions from local, intermediate and regional flow systems; (2) the hydrologic efficiency of surface water drainage from the basin's contributing source areas to the lake; and (3) the surface versus subsurface pathways of water moving from source areas to the lake. Recognition of this hierarchy of landscape controls was important in predicting the potential loading of nutrients to lakes on the Boreal Plain (Devito *et al.*, 2000). Subsequent studies recognized that nutrient source areas vary with the hydrological conditions required for mobilization of specific nutrients. For example, source areas for DOC, dissolved organic N and total P may be characterized by topographic depressions and flat zones (i.e. saturated areas with longer water residence times), and NO_3-N and NH_4-N source areas may be characterized by gentle slopes with large upslope contributing areas (i.e. saturated areas with shorter water residence times) (Creed and Beall, 2003). In addition to these 'static' indicators, research is under way to develop 'dynamic' indicators that relate the natural variability in hydrologic fluxes from forests to surface waters to the natural variability in the contributing source areas within the forest (e.g. Krezek, 2001; Wolniewicz, 2002).

CONCLUSIONS

We began this review by noting that our ability to understand and manage the response of forest ecosystems to natural and anthropogenic disturbance, and to manage forest resources in a sustainable fashion, will depend on a sound grasp of hydrological principles operating in Canada's varied forest landscapes. Progress has

Table VI. Hydrologically based indicators of potential changes in surface water quality in response to natural and anthropogenic disturbance regimes

Potential impacts of forest disturbance	Possible implications	Physiographic region	Hydrologically based indicator	Reference
Change in DOC	DOC influences physical (e.g. *increase in surface water temperature, decrease in thickness of the warm surface layer*), chemical (e.g. *formation of toxic trihalomethanes, related to Hg loading*) and biological (*loss of habitat for warm-water fish due to temperature changes and loss of habitat for cold-water fish due to increased oxygen deficits in deep waters*) characteristics of lakes	Boreal Shield (Quebec)	Drainage ratio *(drainage area vs lake area*)	Carignan *et al.* (1999, 2000a,b), Kneeshaw *et al.* (2000)
		Boreal Shield (Ontario)	Size and organization of wetlands (i.e. *flat slopes and topographic depressions*)	Creed *et al.* (2003)
		Boreal Plain (Alberta) <50% wetlands	No significant relationship between upland lakes (∼15% wetland) and drainage ratio	Prepas *et al.* (2001a), Pinel-Alloul *et al.* (2002)
		Boreal Plain (Alberta) >50% wetlands	Drainage ratio (*basin area vs lake area*)	McEachern *et al.* (2000)
		Boreal Shield (Quebec)	Drainage ratio (*basin area vs lake area*)	Carignan *et al.* (2000a)
Change in P	Changes in P and/or N may affect drinking water supply, trophic structure (including support of fisheries), and recreation. There is a relatively high proportion of cyanobacteria in lakes on the Boreal Plain. Cyanobacteria produce toxins that may impact aquatic food webs, and changes in concentrations, particularly P and/or N, may create conditions favourable for cyanobacteria	Boreal Plain (Alberta) <50% wetlands	Drainage ratio (*basin area vs lake volume*)	Kotak *et al.* (1995), Ghadouani *et al.* (1998), Prepas *et al.* (2001a,b), Pinel-Alloul *et al.* (2002)
		Boreal Plain (Alberta) <50% wetlands	Hydrogeologic position index (*a function of the order of the lake, the elevation of the lake relative to surrounding of landscape, and the position of the lake within the groundwater flow system*); hydrologic flushing index (*a function of the size and organization of wetlands*); hydrologic filtering index (*a function of the topographic concavity vs convexity of the riparian forest*)	Devito *et al.* (2000)

		Boreal Plain (Alberta) >50% wetlands	No significant relationship with drainage ratio	McEachern *et al*. (2000)
Change in N	Changes in P and/or N may affect drinking water supply, trophic structure (including support of fisheries), and recreation	Boreal Shield (Quebec)	No significant relationship with drainage ratio	Carignan *et al*. (2000a)
		Boreal Shield (Ontario)	Size and organization of wetlands (i.e. *flat slopes and topographic depressions*) was directly related to dissolved organic N, and size, shape and organization of variable source areas (i.e. *gentle slopes with large contributing areas*) was directly related to nitrate + ammonium N	Creed and Beall (2003)
		Boreal Plain (Alberta) <50% wetlands	No significant relationship between upland lakes (~15% wetland) and drainage ratio	Pinel-Alloul *et al*. (2002)
		Boreal Plain (Alberta) >50% wetlands	No significant relationship with drainage ratio	McEachern *et al*. (2000)

been made in obtaining a better understanding of hydrologic conditions in these landscapes; however, further advance will require us to come to terms with the following research issues:

1. *Improved understanding of subsurface hydrology*. Several studies cited here have highlighted our inability to anticipate the hydrologic response of a forested slope or basin without considering the nature of its subsurface flowpaths. We must develop tools or techniques for characterizing such flowpaths. A starting point would be determining what (if any) relationship exists between surface features and subsurface flowpaths. We also need to improve our predictive understanding of the nature of fractured bedrock, macropores, and hyporheic zones and their possible role in regulating a basin's hydrologic response. This is particularly important for attempts to evaluate the hydrologic consequences of various forest management practices, since we must be able to predict the within-basin variability in these subsurface flowpaths prior to conducting paired-basin studies.
2. *Improved understanding of the effects of climatic variability and climate change on forest hydrology*. Canada's ecoregions vary in their long-term climatic trends, as well as in the amplitude and frequency of oscillations about those trends. Furthermore, climatic conditions range from $P > PET$ (e.g. sites in the Pacific Maritime, Montane Cordillera, Boreal Shield and Atlantic Maritime) to $P < PET$ (e.g. sites in the Boreal Cordillera and Boreal Plain). We need to quantify climatic variability and climate change at the regional scale, and to continue to define climatic, hydrologic and biogeochemical interactions prior to making effective comparisons of hydrological processes in Canada's various forest regions.
3. *Continued basin-scale monitoring programmes in the forest regions of Canada*. Canada has several ongoing basin-scale monitoring programmes managed by provincial and/or federal government agencies for more than 20 years (e.g. TLW in Ontario) and which have formed the basis of internationally recognized research (e.g. see special issues on research at the TLW; Jeffries and Foster, 2001; Jeffries, 2002). Unfortunately, the future of these programmes is uncertain, as institutional priorities are continuously changing. There are several points to be considered when extending these programs into the 21st century:
   - Management and science must be connected so that adaptive ecosystem management strategies can be studied. A closer relationship between agencies that are monitoring basins with universities that are conducting process-based studies will have synergistic effects. Long-term databases provide a context for the short-term studies conducted by most university research programmes. In turn, process-based studies provide government agencies with greater insight into the hydrological behaviour of the basins, thus assisting in the interpretation of long-term trends.
   - Process-based monitoring and modelling should be embedded in basin monitoring programmes. The concept of equifinality suggests that 'given the limitations of both our model structures and observed data, there may be many representations of a basin that may be equally valid in terms of their ability to produce acceptable simulations of the available data' (Beven, 2000: 22). In other words, we risk obtaining the right answer for the wrong reason. This risk is amplified by focusing solely on external data (e.g. basin streamflow). To place constraints on equifinality, both internal (i.e. hydrological processes) and external data should be collected to calibrate and/or confirm a suite of models of basin hydrological response.
   - We must shift our focus from 'average' responses to 'spatially and/or temporally distributed' responses. We often focus on the average yield through time rather than the extremes, and on the average basin yield rather than the spatially and temporally variant nature of the contributing source areas of that yield. This limits our ability to assess basin responses to forest disturbance. The focus on average water yield does not allow us to assess, for example, the downstream impacts of increased peak discharges during extreme events, a research issue recently highlighted by DeWalle (2003) and made even more important by the projected increase in the frequency of extreme precipitation events (Watson and the Core Writing Team, 2001). Also, the spatially and temporally varying runoff source areas must be identified to develop forest management plans that avoid or minimize disturbance in these areas. This, in turn, can help mitigate the impacts of forestry operations, such as roads, skidder trails and landings, on slope stability and on water, nutrient, sediment, and thermal fluxes to receiving waters. Recent technological innovations, including

airborne laser altimetry and airborne and satellite remote sensing, should be used to improve our capacity to conduct spatially and temporally intensive monitoring.
- We need to *complete* a network of basin monitoring programs (*sensu* the US Long-Term Ecological Research (LTER) sites) that monitor both internal and external hydrologic data in significant forest regions in Canada. This will create a valuable resource for both pure and applied hydrological studies in Canada.
- We need to *coordinate* our network so that common approaches can be adopted to facilitate intra- and inter-basin comparisons.
- Finally, and probably most importantly, financial and logistical support for these basin monitoring programmes must become a priority for government agencies.

4. *Conducting basin experiments within the context of basin monitoring programmes*. Basin-scale or ecosystem experiments are powerful, in that they measure the basin-scale response to forest disturbances, thus allowing managers and scientists to test hypotheses about controls and management of basin processes (Carpenter, 1998). Such experiments are being conducted in Canada; however, recommended improvements in their experimental design include:
   - Incorporation of hydrology (both the science and the scientists) at the planning stage of basin experiments and not after the fact. Most basin experiments reviewed here investigated different forest disturbance scenarios by inferring a hydrological role in the observed basin responses without providing data to support these inferences.
   - Explicit consideration of how long the basin should be studied prior to experiment initiation. Experiments based on a 'paired-basin' design (where one basin serves as the reference and the other as the treatment) are limited, since basins are rarely equivalent in terms of their hydrological features. Experiments based on a 'before-and-after comparison' design are limited, since the 'pre-experiment' data are collected for a time interval that may not fully represent the hydrological conditions that occur during the experiment. Incorporation of process-based understanding (via conceptual or mechanistic models) into the interpretation of experimental data will help alleviate erroneous conclusions based on 'false' reference conditions.
   - Returning to the original spirit of 'adaptive management' (*sensu* Holling, 1978). Our experimental designs need to be able to respond quickly, both to the insights we obtain into the dominant processes identified in the monitoring/modelling phase and the reality of frequent and/or rapid changes in policies related to forest management (e.g. by the time a basin experiment is completed, the policy that was being investigated may no longer be relevant).
5. *Greater integration between forest hydrology and forest ecology*. This call recognizing the numerous interests and challenges faced by both fields of study was also made by Buttle *et al.* (2000) in their review of progress in Canadian forest hydrology during the 1995–98 period. Examples of research themes that would benefit from greater linkage between forest hydrology and forest ecology include:
   - relationships between regeneration and growth for different tree species and temporal changes in water interception and evapotranspiration;
   - the use of stable isotopes (e.g. δD, $\delta^{18}O$) to study water use by plants and the implications for use of these isotopes as tracers of water movement in forest ecosystems;
   - the use of stable isotopes (e.g. $\delta^{34}S$, $\delta^{13}C$, $\delta^{15}N$) to study element sources and cycling in forests;
   - incorporation of more-realistic concepts of soil water storage and movement in models of nutrient transport and transformation in forest soils, in order to extend beyond the relatively simplistic current algorithms (e.g. the compartment approach in ForHyM2) to incorporate the role of preferential flow.
6. *Addressing the following questions in experimental basin research*:
   - Does harvesting emulate wildfire? Forest management plans are shifting towards models based on natural wildfire regimes (Hunter, 1993). However, the underlying assumptions that fire and harvesting have similar impacts on ecosystems and that plans that emulate wildfire should preserve ecosystem integrity remain largely unverified (Carignan and Steedman, 2000).

- What is the form and rate of hydrologic recovery following forest disturbance in various forest landscapes in Canada? Such studies should recognize that different aspects of a basin's hydrology may recover at different rates.
- Are current measures to protect water resources from forest harvesting impacts (e.g. buffer strips along streams and around lake shores) effective in mitigating the hydroecological effects on receiving waters?
- How do we scale studies from the basin to the region? The scale of process studies (<1 km^2) is significantly smaller than the scale of forest management plans or natural disturbance regimes (>100 km^2). Scientists cannot conduct process studies at these coarser scales. We need to develop a scientific basis for scaling processes from the plot or basin to the region.
- What are the cumulative impacts of natural and/or anthropogenic disturbances at the regional scale? The nature of disturbances and their timing, magnitude, and frequency of occurrence at the regional scale may be highly variable. We need a scientific basis for predicting the cumulative impacts of these disturbances on forest hydrology.

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