Chapter 8

LAND-USE PRACTICES AND CHANGES – FORESTRY

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Current Status

Canada has about 10% of the world's forests (418 million ha) and about 20% of the planet's freshwater resources (but only about 7% of the planet's renewable freshwater resources; CFS, 2002; EC, 2003). Forests recycle water to the atmosphere, thereby decreasing water transport into ground and surface water. They also filter air and water, moderate climate, provide habitat for wildlife, stabilize soil, and form a dominant feature of Canada's economy, culture, traditions, and history. Because of these attributes, forested watersheds provide a range of important services to humans and society, including provision of clean stream water and support of healthy aquatic ecosystems. For example, a number of major urban centres derive some or all of their water supplies from forested watersheds. Natural disturbances (e.g., insect defoliation and wildfires) and anthropogenic influences (e.g., fire suppression and timber harvesting) can temporarily alter the equilibrium of the hydrologic cycle by altering groundwater recharge-discharge dynamics, the position of the water table, and streamflow regimes.

Except for harvesting activities, fire and insect infestations are the dominant stand-renewing agents in most Canadian forests. For example, infestations of spruce budworm sweep through eastern boreal and maritime forests at approximately 35-year intervals, causing major stand renewal events and shifts in stand age structure. Wildfire has a greater immediate impact than insect infestations on forest hydrologic cycles because of its sudden nature and its profound alteration of organic matter. Fires occur regularly in the boreal forest, the mean fire cycle being 126 years (CCFM, 2002), with a range of 63 to 185 years (Bergeron, 1991; Larsen, 1997; Larsen and MacDonald, 1998). Fire is more frequent in the coniferous forests of west-central Canada (northwestern Ontario, Manitoba, Saskatchewan, and Alberta), and less frequent in the wetter forests of central and eastern Canada (Ontario, Quebec, and the Atlantic Provinces) and the Pacific maritime ecozone (mean fire cycle of 770 years) (Stocks et al., 2002). Fire frequency is a function of fuel quantity, quality, and dryness as well as fire weather; the conditions affecting the formation and spread of wildfires, including wind speed, thunderstorms, and stability of air systems. In Canada, the driest and windiest region is west-central Canada, and this is also where fire is most frequent.

Forest hydrology research in Canada was strongly supported by government in the late 1960s and early 1970s, a period known as the International Hydrological Decade. Gauges were set up and monitored in many watersheds, and a variety of studies examined the most immediate impacts of clear-cut harvesting practices on streamflow and erosion. The results of these studies were used in developing current forest management practices, which protect Canada's soils and freshwater resources. Although most harvesting operations still involve a one-pass removal system ("clear-cutting"), gradual removal approaches, including selection cutting, shelterwood cutting, and seed tree cutting, are increasingly used in Canada. The overall size of clear-cuts generally has been reduced, and the number of unharvested strips ("leave" strips) within cutblocks has increased, which has increased cutblock heterogeneity.

Across Canada, there are few comparable data on the effects of forest fires on watershed hydrology (Schindler et al., 1980; Bayley et al., 1992), but the immediate impact of a burn on streamflow volume and timing appears to be similar to that of a clear-cut. This similarity might be expected because in both types of disturbances the transpiring vegetation is removed, which results in decreases in evapotranspiration (ET) (Amiro et al., 1999; Amiro, 2001). However, differences in harvesting and fire in particular, with respect to interception of precipitation by logging debris and post-disturbance recovery, make any similarities less certain.

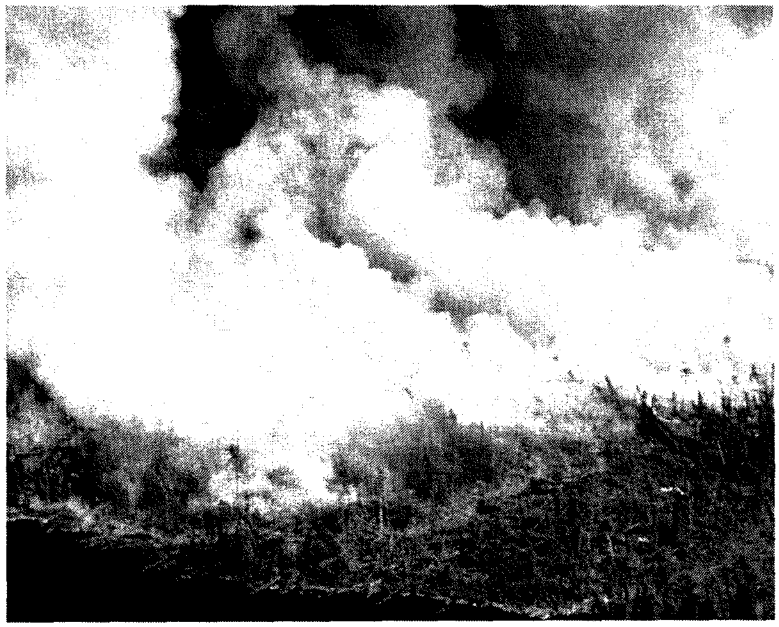
This chapter outlines the major impacts of timber harvesting and fire on forest hydrology and the subsequent impacts on freshwater availability, with emphasis on the boreal forest, the largest forest region in Canada.

Trends

Timber Harvesting

Canada's land area is about 922 million ha, of which about 418 million ha are forested. Commercial forests (capable of producing commercial tree species as well as other non-timber benefits) represent about 235 million ha, of which about 119 million ha are managed and about 1 million ha are harvested annually. The largest areas are harvested in Quebec and British Columbia (349,113 ha and 204,472 ha in 2000, respectively; CCFM, 2002). Seventy-one percent of Canada's forests are controlled by provincial governments, 23% by the federal government, and 6% by private landowners. Softwood species are harvested most often (86% of the total commercial timber harvest in 1995), primarily for the production of pulp and paper and for export. However, the harvest of hardwood species, used primarily to produce oriented strand board, laminated veneer lumber, furniture, flooring, plywood, and moldings, was 6% greater in the period 1990 to 1995 than the average pre-1990s hardwood harvest. This trend reflects the evolution of the forest products industry over the past 25 years and is predicted to continue. Harvesting rates were below Annual Allowable Cut rates for the period for which records are available, from 1970 to 1999 (CCFM, 2002).

Canada has evolved from a colonial supplier of wood products to European countries in its early years to a major international player in forestry. Because Canada is still growing, land-use changes, including those arising from urbanization, oil and gas exploration, mining, and agriculture, infringe on forests across Canada, most prominently in the southern boreal forest, the Carolinian forest, and the aspen parkland forest (CCFM, 2002). However, although some forest is being lost near urban centres, there are also gains in forested areas on marginal agricultural lands and in urban areas, the so-called urban forests (CCFM, 2002).



Forest fire south of Lake 240 in the Experimental Lakes Area in northwestern Ontario.

Current timber harvesting regulations in the provinces and territories generally strive to maintain a productive forest land base. Following the removal of timber, most harvested areas are allowed to regenerate naturally, the remainder being actively seeded or planted (CFS, 2002). The extent of seeding and planting varies considerably in accordance with the diversity of forest conditions and provincial and territorial policies. Since 1975, silvicultural practices adopted by the provinces and territories have ensured that 90% of harvested sites are regenerated within 10 years after the timber harvest, ensuring the long-term viability of forests in Canada.

Fire

Fire frequency in Canada's boreal forests decreased from the end of the Little Ice Age, around 1850, until the mid 20th century, in spite of a general warming trend (Flannigan et al., 1998). From 1960 to 1995, the trend was reversed, and fire frequency was 60% greater than during the previous 40 years (1920–1960; Amiro et al., 2001a). On average, 9000 wildfires have burned about 2 million ha of forest annually (data for 1958–2000), with approximately half of this area representing productive forests. However, the total area burned can vary from year to year by a factor of more than 10; this variability was particularly apparent in the 1990s (Amiro et al., 2002). Most fires are less than 10 ha in size, and only 1.5% of all fires are greater than 1000 ha in size. These large fires account for 93% of the total area burned. Approximately 80% of burned forest is considered commercially non-productive. Salvage logging of fire-killed trees in accessible areas is a common forestry operation. Similar to harvested forests, burned forests are usually allowed to regenerate naturally.

Climate Change

Global climate change has the potential to increase fire frequency in Canada's west-central boreal forest since warmer and drier conditions are predicted to occur in that region (Flannigan et al., 1998; Amiro et al., 2001a). There is also a potential for feedback to the atmosphere through this pathway. Already, forest fires in Canada emit on average the equivalent of 18% of current carbon dioxide (CO_2) emissions from the Canadian energy sector, a proportion that reaches 75% in peak fire years (Amiro et al., 2001b).

Impacts of Disturbance on Water Quantity and Regime

Research has demonstrated that the most significant changes in forested watersheds following timber harvest are changes in water table levels, streamflow quantity and regime, water quality, erosion, and sedimentation, and possibly alterations to local groundwater recharge and discharge dynamics. It is likely that similar changes occur after fire. Notably, watershed impacts differ between forestry practices and other land uses, including agriculture and mining.

The hydrologic cycle consists of three major components: precipitation; surface and subsurface water flow and storage; and evaporation from soil, vegetation, lakes, streams, and oceans. The movement of precipitation to ground and surface waters is affected by the amount of forest cover and by forest health and maturity. ET is the process by which water moves through the soil and plants into the atmosphere. In the boreal forest of west-central Canada, a significant portion (66–82%) of the total annual precipitation is returned to the atmosphere as ET (Lieffers and Rothwell, 1986), whereas in wetter areas, including central Quebec, only about one-third of the total annual precipitation is returned to the atmosphere in this form (Guillemette et al., 1999).

The removal of vegetation through timber harvest or destruction by high-intensity wildfire produces short-lived, significant decreases in water losses through ET and decreases in precipitation interception, which together lead to increases in soil water content in disturbed areas. However, local geophysical and climatological characteristics vary throughout Canada's ecozones. Consequently, the effects of timber harvest and fires on streamflow regimes also differ across the country.

Forest cover maintains stability of the infiltration capacity of the soil, decreases runoff, lowers wind speed, and increases precipitation interception, thereby significantly affecting the local microclimate and hydrologic cycle. Conversely, afforestation (the direct conversion by humans of land that has not been forested for a period of at least 50 years to forested land through planting, seeding, or human-induced promotion of natural seeding) affects the local hydrologic cycle by, most prominently, increasing ET, lowering water tables, stabilizing soil infiltration capacities, and decreasing runoff. Although water use by trees is significant, afforestation may reduce local drought conditions under certain circumstances; however, relevant data from Canada are limited (Buttle, 1996). In addition, certain tree species can be used as bioremediators, ameliorating the effects of pollution through a process called phytoremediation. These trees can capture pollutants, thereby removing them from contaminated terrestrial ecosystems and preventing them from reaching aquatic ecosystems (Dietz and Schnoor, 2001).

Canada has a long history of watershed research and monitoring, which has demonstrated how forests can be managed to increase water yield for many needs. Extensive regional and experimental watershed manipulations have been used since the 1960s to investigate the effects of forest management activities on streamflow (Berry, 1991). Such approaches have led to significant increases in our knowledge of the biological and physical processes that regulate watershed hydrology and have contributed to the design and implementation of safer land-use practices. In some areas, scientific findings have been used to guide planning and decision making in the conservation and restoration of riparian forests, wetlands, wildlife habitat, stream habitat, and stream banks, and to minimize the impacts of roads on water quantity and quality. However, in other areas, particularly in the southern boreal forest, construction of roads and railroads has impounded and negatively affected significant areas of riparian forests and wetlands (Poff et al., 1997).

One of the most important results of forestry studies was the realization that production of sediment was linked most strongly to the building and use of forestry roads and to direct perturbations of the stream bank by machinery (Mattice, 1977). Changes in forestry practices have been implemented across Canada to minimize these impacts, including the maintenance of streamside buffer strips and modifications to road-building methods with respect to surface water discharge, culvert placement and sizing, and stream-crossing structures (Ottens and Rudd, 1977). Studies have shown that, when regulations are respected, inputs of sediments into streams because of forest operations are short-lived and often small (Plamondon, 1982). Protection of soils and recovery from logging may be more problematic on steep slopes in areas of high precipitation and low soil stability. However, even in the extreme conditions of the forests on Vancouver Island and the Queen Charlotte Islands, erosion from bare soil was a minor and highly variable contributor to stream sedimentation compared with mass wastage (landslides) from either harvested or unharvested areas (Roberts and Church, 1986; Hetherington, 1992). In both locations, climatic and physical variables had a significant influence on the degree of sediment production and transport into streams.

Effects on Groundwater Recharge-Discharge

Timber harvesting may have both positive and negative impacts on groundwater. An example of the former is the increase in water recharge into groundwater that results from temporary reduction in ET. This effect is likely more significant in dry areas with minimal groundwater recharge under full forest cover. In contrast, the effect is minimal where groundwater recharge is significant. Logging may have a negative effect on local flow of groundwater in steep terrain, where road cuts may intercept lateral drainage and shunt that water into the surface drainage system. This results in loss of water from the drainage system via surface flow and can lead to significant soil erosion. These negative impacts are likely both local and minor (Hetherington, 1992); of more importance in such cases are the potential effects on slope stability.

Changes in Water Table Levels

The boreal zone supports large expanses of forested wetlands because of its relatively flat topography, an abundance of poorly drained surficial deposits and shallow bedrock impervious to water, and a cool and humid climate (Vitt et al., 2000). In these areas, the amount of precipitation and the preharvest position of the water table influence the effect of timber harvesting on the hydrology of the cut-block (an area in which timber is to be or has already been harvested) (Dubé et al., 1995). Depth to the water table is an important, but nonlinear, ecological feature. Frequent rises of the water table to shallow depths may dramatically influence tree growth as well as the trajectory of vegetation dynamics following disturbance.

Water levels are usually high following snowmelt and decrease through the summer when ET is highest. During periods of high rainfall, as well as after snowmelt, the water table is near the soil surface in forested wetlands. The removal of trees decreases ET losses, which results in a less pronounced drop in the water table during periods of low rainfall. Consequently, the difference between seasonal maximum and minimum water levels is less in harvested than in unharvested areas (Dubé et al., 1995). The effects of timber harvest on hydrology are generally restricted to the cut-block itself and do not extend into adjacent uncut tree stands, independent of cut-block position and size. Water tables generally return to natural levels within the first 10 m from the forest edge into the adjacent tree stand (Dubé et al., 1995). The effects of rises in the water table are most severe near the centre of cut-blocks. This suggests lateral water flow from the centre of the cut-blocks toward natural areas bordering the cut-block, creating uneven water table fluctuations throughout the cut-block. Although the effects of water table rises may be ameliorated within short distances into bordering natural tree stands, runoff from cut-blocks may have significant impacts on watershed hydrology.

In conjunction with changes in the water table in cut-blocks, rates of greenhouse gas dynamics in forests may also be affected. For example, well-drained heterogeneous soils have the ability to serve as carbon sinks (Whalen and Reeburgh, 1996). However, timber harvesting has the potential to cause saturation of poorly drained mineral and organic soils, which can then become significant sources of carbon in the form of methane (Roulet and Moore, 1995).

Effects on Streamflow Quantity

By reducing interception of precipitation and ET losses, timber harvesting increases the flow of water out of the watershed. The importance of this effect depends on the ET loss per unit land area, which is a function of water availability, evaporative demand, and, to a lesser extent, vegetation type. Absolute increases in streamflow quantity are larger in warm, wet areas and lower in cool, dry areas. Relative increases in streamflow are larger in dry than in wet areas. Through studies in the eastern, temperate hardwood forest, Hornbeck et al. (1997) found that most of the increases in water yield resulted from increased summer low flows. However, reducing snow interception by harvesting the coniferous cover in the wetter areas of the boreal forest may have a greater effect on annual yield than any reduction in summer flows (Guillemette et al., 1999).

Examples of increases in annual water yield resulting from clear-cutting operations range from 160 mm in Kenora, Ontario (Nicolson et al., 1982), to 349 mm at Carnation Creek on Vancouver Island, British Columbia (Hartman and Scrivener, 1990). Forest perturbations by windthrow and fires at Rawson Lake, Ontario, also increased streamflow by about 170 mm (Schindler et al., 1980). Large fires affect a significant proportion of entire higher-order basins within days. Therefore, the short-term absolute impact of large fires on water yield can be greater than that of gradual harvesting of a basin over many years.

Within a basin, water yield increases are in rough proportion to the area harvested. Buttle and Metcalfe (2000) showed that the effects of various harvesting techniques on stream hydrology were minimal if less than 25% of the area within a watershed was harvested. They attributed this in part to the ability of larger basins to buffer the hydrologic impacts of the relatively small degree of recent forest disturbances. The duration of the effects of tree removal or death on water yield depends on the rate of vegetation regrowth and can range from 7 to 30 years (Swanson and Hillman, 1977).

Effects on Streamflow Regime

Forest removal increases streamflow rates, a beneficial effect for small streams, in which low flow constrains the aquatic ecosystem. Peak flows from snowmelt are the dominant hydrologic feature of most boreal and montane watersheds. Forest harvesting has a direct impact on snowmelt and thus on spring peak flows (Whitaker et al., 2002), but the effect is highly variable (Fig. 1). Peak flows above bankful discharge (the momentary maximum peak flow before a stream overflows its banks onto the floodplain) (1.5-year return period) have been shown to shape stream morphology (Dunne and Leopold, 1978). Results from paired basin studies indicate that snowmelt peak flows above bankful discharge can be increased by up to 50% by removing more than 25% of forest area or volume (Fig. 1). The effect of forest cover removal on peak flow may be amplified if aspect (the angular orientation of the basin with respect to the sun) is uniform throughout the basin. However, the proposed model of peak flow changes for Minnesota (Verry, 1986),

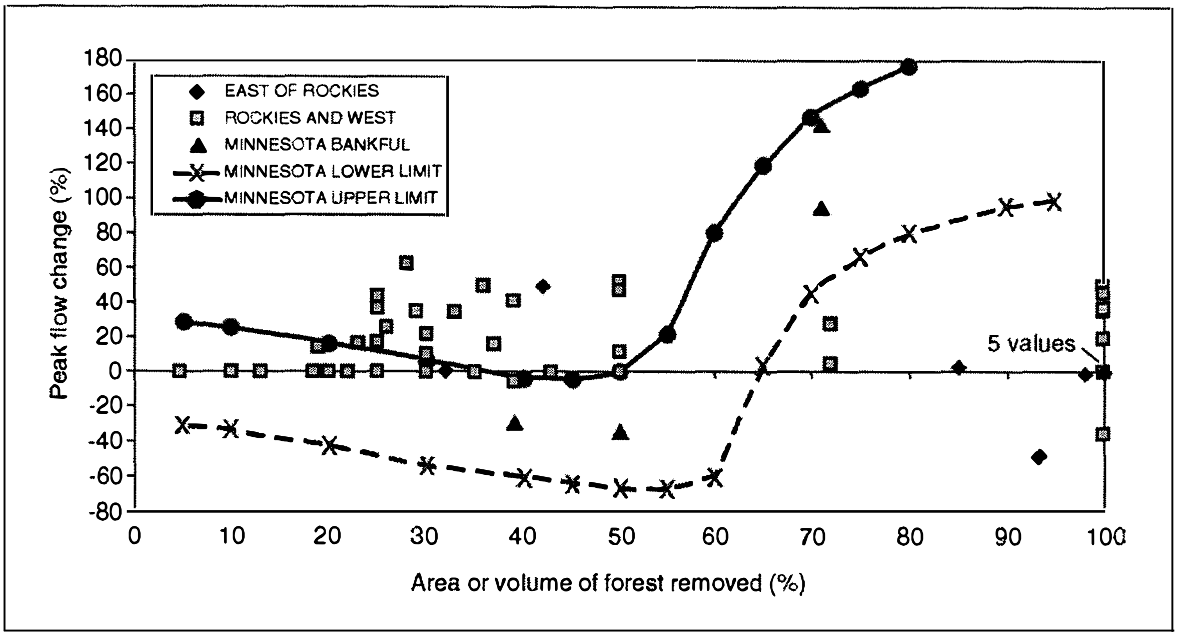


Fig. 1. Changes in snowmelt peak flow above bankful discharge in relation to forest removal by harvesting, fire, or insects in North America. Adapted from Verry (1986) and Plamondon (1993, 2002). The upper and lower limits represent a generalized hypothesis of the impact of snowmelt on peak flow for Minnesota (Verry, 1986).

an area similar to northwestern Ontario, indicates that increases in snowmelt peak flow are likely to occur above 50 to 60% forest removal. Harvesting less than 50% of the basin desynchronizes snowmelt between open and forested areas and tends to decrease peak flows.

Increases in rainfall-induced bankful peak flows are better related to the proportion of forest removal (Fig. 2) than those for snowmelt peak flow. Rainfall peak flow augmentation is caused primarily by an increase in soil water content, which should be well correlated with the percentage of forest removal. Soil disturbances, including roads and skid trails, may increase or decrease peak flow, depending on the time between water pulses generated by the watershed source areas and the disturbed areas. The impact recedes with canopy closure. Also, the impact of harvesting is smaller in hardwood than in coniferous forests because of the smaller interception losses by leafless hardwoods outside of the growing season.

Low flows in summer are generally increased by timber harvest because of rising water tables in response to decreased precipitation interception and decreased ET (Dubé et al., 1995). Summer rainfall may produce small to moderate increases in storm and peak flows in harvested areas relative to forested basins (Pomeroy et al., 1997) because of the generally wetter soils in harvested areas (as a result of decreased ET); therefore, the potential for streamside soil saturation and streamflow generation may be increased.

Although the impact of increased streamflow may be significant on primary streams, the cumulative effect on secondary and tertiary streams may be negligible. In addition, because of the overall small impact at the watershed scale, the potential impact of forestry on downstream flooding may be small (Martin et al., 2000). This situation is quite different from land-use changes that cause a permanent change in the ecosystem. For example, permanent conversion of forest cover over 27% of the 95,000 km^2 drainage basin above St. Paul, Minnesota, increased annual flood peaks by 43% (Miller and Frink, 1982).

The removal of riparian trees and road-building can have potential impacts on stream biota. Depending on the situation, logging can have positive or negative effects on stream morphology and fish habitat (Ralph et al., 1994). Even partial removal of riparian vegetation can cause elevation of water temperatures and can increase the exposure of the stream to ultraviolet (UV) radiation. Elevated temperatures and increased UV radiation cause changes in stream invertebrate communities (Kelly et al., 2003) and, in conjunction with increased nutrients from timber harvesting, undesirable algal growth. Inadequately installed culverts on logging roads often block the passage of fish, either by creating jumps that are too high or water velocities that are too great to overcome.

The effects of harvesting or fires on lake and stream properties are often difficult to separate from those of climate, even in well-designed studies with control basins (Schindler et al., 1996; Steedman and Kushneriuk, 2000). Removal of the riparian trees around small lakes by either natural disturbances or harvesting increases

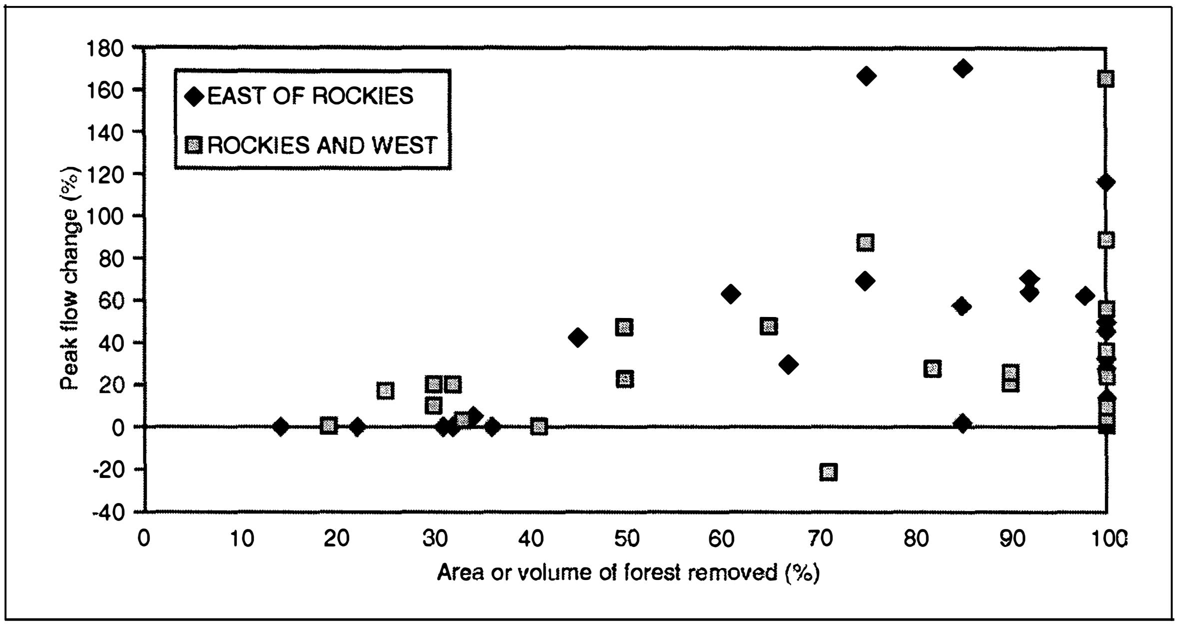


Fig. 2. Changes in rainfall peak flow above bankful discharge in relation to forest removal by harvesting, fire, or insects in North America. Adapted from Plamondon (1993, 2002).

over-water wind speeds and either increases (France, 1997) or decreases (Steedman and Kushneriuk, 2000) the depth of the thermocline. Maintenance of buffer strips prevents the increase in over-water wind speed (Steedman and Kushneriuk, 2000). Schindler et al. (1996) reported an increase in lake water clarity following fires during a dry period with reduced precipitation and streamflow to lakes. Steedman and Kushneriuk (2000) reported the contrary, a decrease in water clarity following harvesting, but stated that the effects could have been related to climate.

Increased sediment yields to lakes as a result of fires or harvesting have the potential to silt spawning beds and disturb the habitats of fish and other freshwater organisms (Beaty, 1994). These problems point to the need for the maintenance and reinforcement of measures to prevent erosion and sedimentation during harvesting. However, there are as yet no hard and fast rules to determine threshold levels of erosion and siltation with respect to fish populations. For example, Gunn and Sein (2000) found that lake trout populations were insensitive to a major reduction in spawning habitat through simulated siltation, but they were severely affected by road access and ensuing fishing pressure. Murphy et al. (1986) showed that adequate buffer strips maintained or enhanced fish habitat and productivity, while removal of buffer strips had a negative impact on these variables. Changes in water flow patterns in harvested areas above a buffer strip can also affect trout spawning beds (Curry and Devito, 1996), although it seems that no direct experimental evidence exists on the magnitude of the effects on trout spawning success.

Changes in Land Use

Human settlement in Canada has resulted in large-scale conversions of forests to urban and agricultural land uses. The changes in the natural components of the hydrologic cycle brought about by these land-use changes have had large impacts on water quantity, water quality, and the timing of flow events. As a result of these changes, there is lingering confusion between the impacts of forest harvesting and those of land-use changes on water resources. Hydrologic research across Canada and around the world has shown the importance of forest and other wildlands in the regulation of streamflow and the maintenance of water quality. As a general rule, harvesting impacts on streamflow regime and water quality are usually short-lived and less severe than those brought about by land-use changes, provided that forest soils are protected and vegetation recovery is rapid.

Knowledge and Program Needs

There is an increasing demand for forests to provide clean water for a multiplicity of purposes, including fisheries, agriculture, and recreation. It is imperative to continue research to address existing and emerging issues as they pertain to the quantity as well as the quality of freshwater resources in Canada. Improved knowledge and understanding of forest-water relationships are needed to integrate water issues into forestry and related decision-making systems and to support water quantity and quality criteria in support of sustainable forest management practices.

In 2001, the Canadian Forest Service carried out a scoping exercise to identify research opportunities in forest hydrology (Beall et al., 2001). A number of broad research elements were identified and grouped into three research themes pertaining to freshwater availability. Priorities have not been established, nor has the linkage with respect to currently available information been fully carried out. However, the themes and results from that exercise are pertinent to the current exercise and are presented here:

- Effects of forest condition, natural disturbance, and forest management activities:
  - effects of harvesting on water quantity
  - effects of wildfire, insect outbreaks, and forest condition (e.g., regenerating versus old growth) on water quantity
  - effects of intensive forest management on surface and ground water supplies
  - development of forest management practices to preserve or enhance water supply, and
  - effects of forest management and disturbances on forest aquatic ecosystem habitat, productivity, and diversity.
- Climate variability and climate change effects:
  - effects of climate variability and climate change on forest hydrologic cycles
  - impacts on water supply from forested areas (timing and quantity), and
  - impacts on ecological integrity of aquatic ecosystems.
- Synthesis and integration:
  - development and adaptation of large-basin and national process and empirical models, which integrate hydrologic and biogeochemical cycles to improve prediction capabilities and provide decision support
  - retrieval, assessment, and archiving of long-term data sets for development and validation of models and development of a national database
  - scaling up of plot-based and patch-based results to landscape and regional scales
  - scaling down regional climate models to provide realistic scenarios for input to process models, and
  - determination of socioeconomic costs and benefits resulting from altered forest hydrologic regimes due to anthropogenic and natural disturbances.

The significant variability in harvesting and site preparation perturbations and in wildfire intensity in watersheds, as well as the variability in Canada's ecozones has resulted in a large variance in the responses of individual nutrients and elements to natural and anthropogenic disturbances. Most watershed studies have been conducted near the southern extent of the boreal forest, and most of those were performed in central and eastern Canada (Ontario and Quebec). The relevance of results from eastern Canada to other areas of Canada, where different physiographic and soil conditions prevail, remains unclear and warrants further investigation (Buttle et al., 2000). Although hydrologic research has increased over the past 3 to 5 years in Canada, the results of these studies have not been widely disseminated or are still being worked up. Hence, many forest managers must fall back on studies from smaller scales and from forest environments that are not necessarily directly relevant to the Canadian context (J.M. Buttle, pers. comm.).

References

Amiro, B.D. 2001. Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest. Glob. Change Biol. 7: 253-268.

Amiro, B.D., M.D. Flannigan, B.J. Stocks and B.M. Wotton. 2002. Perspectives on carbon emissions from Canadian forest fires. For. Chron. 78: 388-390.

Amiro, B.D., J.I. MacPherson and R.L. Desjardins. 1999. BOREAS flight measurements of forest-fire effects on carbon dioxide and energy fluxes. Agric. For. Meteorol. 96: 199-208.

Amiro, B.D., B.J. Stocks, M.E. Alexander, M.D. Flannigan and B.M. Wotton. 2001a. Fire, climate change, carbon and fuel management in the Canadian boreal forest. Int. J. Wildland Fire 10: 405-413.

Amiro, B.D., J.B. Todd, B.M. Wotton, K.A. Logan, M.D. Flannigan, B.J. Stocks, J.A. Mason, D.L. Martell and K.G. Hirsch. 2001b. Direct carbon emissions from Canadian forest fires, 1959-1999. Can. J. For. Res. 31: 512-525.

Bayley, S.E., D.W. Schindler, K.G. Beaty, B.R. Parker and M.P. Stainton. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. Can. J. Fish. Aquat. Sci. 49: 584-596.

Beall, F., R. Stewart, I. Campbell, C. Campbell, H. Hirvonen and P. Bemier. 2001. Forest water resources – CFS scoping paper. Nat. Res. Can., Can. For. Serv., Ottawa, Ont., Canada.

Beaty, K.G. 1994. Sediment transport in a small stream following two successive forest fires. Can. J. Fish. Aquat. Sci. 51: 2723-2733.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992.

Berry, G.J. 1991. Hydrology of drained and undrained black spruce peatlands: streamflow and hydrologic balance. Forest Information Systems Ltd., Victoria, B.C., Canada. COFRDA Rep. 3317.

Buttle, J.M. 1996. Identifying hydrological responses to basin restoration: an example from southern Ontario. *In* McDonnell, J.J., J.B. Stribling, L.R. Neville and D.J. Leopold (ed.), Watershed restoration management: physical, chemical, and biological considerations. Amer. Water Res. Assoc., Hemdon, Va., U.S.A. TPS-96-1.

Buttle, J.M., I.F. Creed and J.W. Pomeroy. 2000. Advances in Canadian forest hydrology, 1995-1998. Hydrolog. Process. 14: 1551-1578.

Buttle, J.M. and R.A. Metcalfe. 2000. Boreal forest disturbance and streamflow response, northeastern Ontario. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 5-18.

CCFM (Canadian Council of Forest Ministers). 2002. Compendium of Canadian forestry statistics. Natural Resources Canada, Ottawa, Ont., Canada.

CFS (Canadian Forest Service). 2002. 2000-2001 The state of Canada's forests. Sustainable forestry – a reality in Canada. Nat. Res. Can., Can. For. Serv., Ottawa, Ont., Canada.

Curry, R.A. and K. Devito. 1996. Hydrogeology of brook trout (*Salvelinus fontinalis*) spawning and incubation habitats: implications for forestry and land use development. Can. J. For. Res. 26: 767-772.

Dietz, A.C. and J.L. Schnoor. 2001. Advances in phytoremediation. Environ. Health Perspect. 109(Suppl. 1): 163-168.

Dubé, S., A.P. Plamondon and R.L. Rothwell. 1995. Watering up after clear-cutting on forested wetlands of the St. Lawrence lowland. Water Resour. Res. 31: 1741-1750.

Dunne, Y. and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman & Co., San Francisco, Ca., U.S.A.

EC (Environment Canada). 2003. Freshwater Website. Environment Canada, Ottawa, Ont., Canada. Available from: http://www.ec.gc.ca/water/e_main.html; Internet. Cited 15 September 2003.

Flannigan, M.D., Y. Bergeron, O. Engelmark and B.M. Wotton. 1998. Future wildfire in circumboreal forests in relation to global warming. J. Veg. Sci. 9: 469-476.

France, R. 1997. Land-water linkages: influence of riparian deforestation on lake thermocline depth and possible consequences for cold stenotherms. Can. J. Fish. Aquat. Sci. 54: 1299-1305.

Guillemette, F., A.P. Plamondon and D. Levesque. 1999. Effets de la coupe sur le bilan hydrologique. Bassin expérimental du ruisseau des Eaux-Volées (BEREV). Département des sciences du bois et de la forêt. Université Laval, Québec, Canada.

Gunn, J.M. and R. Sein. 2000. Effects of forestry roads on reproductive habitat and exploitation of lake trout *(Salvelinus namaycush)* in three experimental lakes. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 97-104.

Hartman, G.F. and J.C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Can. Bull. Fish. Aquat. Sci., No. 223.

Hetherington, E.D. 1992. Watershed hydrology, p. 33-47. *In* Hogan, D.L., P.J. Tschaplinski and S. Chatwin (ed.), Carnation Creek and the Queen Charlotte Islands fish/forestry workshop: applying 20 years of coast research to management solutions. B.C. Min. For. Res. Program, Victoria, B.C., Canada.

Hornbeck, J.W., C.W. Martin and C. Eagar. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. Can. J. For. Res. 27: 2043-2052.

Kelly, D.J., M.L. Bothwell and D.W. Schindler. 2003. Effects of solar radiation on stream benthic communities: an intersite comparison. Ecology 84: 2724-2740.

Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. J. Biogeogr. 24: 663-674.

Larsen, C.P.S. and G.M. MacDonald. 1998. An 840-year record of fire and vegetation in a boreal white spruce forest. Ecology 79: 106-118.

Lieffers, V.J. and R.L. Rothwell. 1986. Effects of depth of water table and substrate temperature on root and top growth of *Picea mariana* and *Larix laricina* seedlings. Can. J. For. Res. 16: 1201-1206.

Martin, C.W., J.W. Hornbeck, G.E. Likens and D.C. Buso. 2000. Impact of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 19-29.

Mattice, C.R. 1977. Forest road erosion in northern Ontario: a preliminary analysis. Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont., Canada. Inf. Rep. O-X-254.

Miller, J. and D.L. Frink. 1982. Changes in flood response in the Red River of the North Basin, North Dakota-Minnesota. U.S. Geol. Surv., Bismarck, N.D., U.S.A. Open File Rep. 82-774.

Murphy, M.L., J. Heifetz, S.W. Johnson, K.V. Koski and J.F. Thedinga. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Can. J. Fish. Aquat. Sci. 43: 1521-1533.

Nicolson, J.A., N.W. Foster and I.K. Morrison. 1982. Forest harvesting effects on water quality and nutrient status in the boreal forest, p. 71-89. *In* Steed, G.L. and H.R. Hudson (ed.), Proc. Can. Hydrol. Symp. '82 – Hydrologic processes of forested areas. Nat. Res. Counc. Can., Ottawa, Ont., Canada.

Ottens, J. and J. Rudd. 1977. Environmental protection costs in logging road design and construction to prevent increased sedimentation in the Carnation Creek watershed (Vancouver Island). Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C., Canada. Inf. Rep. BC-X-155.

Plamondon, A.P. 1982. Augmentation de la concentration des sédiments en suspension suite a l'exploitation forestière et durée de l'effet. Can. J. For. Res. 13: 883-892.

Plamondon, A.P. 1993. Influence des coupes forestières sur le régime d'écoulement de l'eau et sa qualité. Centre de recherche en biologie forestière, Université Laval et Ministère des forêts, Québec, Canada. 179 p.

Plamondon, A.P. 2002. La récolte forestière et les débits de pointe : État des connaissances sur la prévision des augmentations des pointes, le concept de l'aire équivalente de coupe acceptable et les taux régressifs des effets de la coupe sur les débits de pointe. Direction de l'environnement forestier, Ministère des ressources naturelles, Québec, Canada.

Poff, L.N., J.D. Allen, M.B. Bain, J.R. Kerr, K.L. Prestegaard, B.D. Richter, R.E. Sparka and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47: 769-784.

Pomeroy, J.W., R.J. Granger, A. Pietroniro, J.E. Elliot, B. Toth and N. Hedstrom. 1997. Hydrologic pathways in the Prince Albert Model Forest. Final report to the Prince Albert Model Forest Association, Nat. Hydrol. Res. Inst., Environ. Can., Saskatoon, Sask., Canada.

Ralph, S.C., G.C. Poole, L.L. Conquest and R.J. Naiman. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. 51: 37-51.

Roberts, R.G. and M. Church. 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Can. J. For. Res. 16: 1092-1106.

Roulet, N.T. and T.R. Moore. 1995. The effect of forestry drainage practices on the emission of methane from northern peatlands. Can. J. For. Res. 25: 491-499.

Schindler, D.W., S.E. Bayley, B.R. Parker, K.G. Beaty, D.R. Cruikshank, E.J. Fee, E.U. Schindler and M.P. Stainton. 1996. The effects of climate warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnol. Oceanogr. 41: 1004-1017.

Schindler, D.W., R.W. Newbury, K.G. Beaty, J. Prokopowich, T. Ruszczynski and J.A. Dalton. 1980. Effects of windstorms and forest fire on chemical losses from forested watersheds and on the quality of receiving stream. Can. J. Fish. Aquat. Sci. 37: 328-334.

Steedman, R.J. and R.S. Kushneriuk. 2000. Effects of experimental clearcut logging on thermal stratification, dissolved oxygen, and lake trout *(Salvelinus namaycush)* habitat volume in three small boreal forest lakes. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 82-91.

Stocks, B.J., J.A. Mason, J.B. Todd, E.M. Bosch, B.M. Wotton, B.D. Amiro, M.D. Flannigan, K.G. Hirsch, K.A. Logan, D.L. Martell and W.R. Skinner. 2002. Large forest fires in Canada, 1959-1997. J. Geophys. Res. 108: FFR5-1-FFR5-12.

Swanson, R.H. and G.R. Hillman. 1977. Predicted increased water yield after clear-cutting verified in west-central Alberta. Can. For. Serv., North. For. Res. Cent., Edmonton, Alta., Canada. Inf. Rep. NOR-X-198.

Verry, E.S. 1986. Forest harvesting and water: the lake states experience. Water Resour. Bull. 22: 1039-1047.

Vitt, D.H., L.A. Halsey, I.E. Bauer and C. Campbell. 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Can. J. Earth Sci. 37: 683-693.

Whalen, S.C. and W.S. Reeburgh. 1996. Moisture and temperature sensitivity of CH_4 oxidation in boreal soils. Soil Biol. Biochem. 28: 1271-1281.

Whitaker, A., Y. Alila, J. Beckers and D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. Water Resour. Res. 38: 1172.

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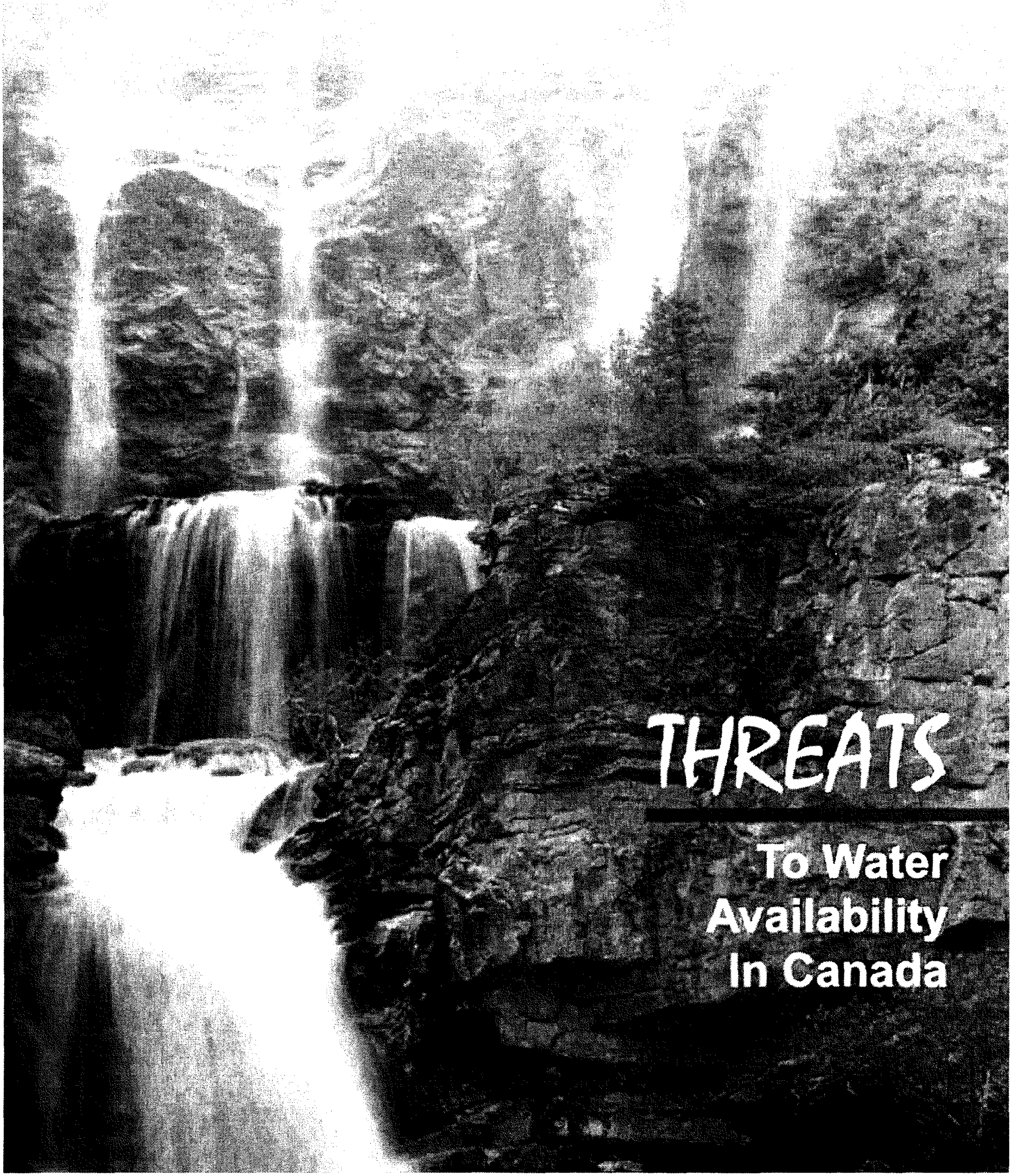

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