CHAPTER 7

The Importance of Forests in the Hydrological Regime

E.D. Hetherington

Pacific Forestry Centre, Canadian Forestry Service, Victoria, B.C. V8Z 1M5

Introduction

Canada is a nation of vast forests as well as extensive water resources. These forests, which occupy almost half of the total land area, are unique associations of trees and soils that have developed together through geologic time. They exist where precipitation is sufficient for the development of trees and, during most years, is surplus to their growth needs. The stems, branches, and foliage of the trees within a forest make up a three-dimensional matrix that interacts with rain, snow, sunlight, and wind. Furthermore, the layer of soil occupied by the tree roots is a porous matrix that absorbs rain and snowmelt to delay and temporarily store the water en route to a visible stream channel. Roots also extract water from this layer, reducing the amount available for streamflow. Through this intimate association, water movement and storage are affected by forests (Fig. 1) and by changes in the forest cover.

The importance and influence of forests and forest management operations in relation to water in Canada are the subjects of this chapter. The focus is on knowledge gained from Canadian research and experience, whereas previous reviews (Freedman 1982; Jeffrey 1970; Moore 1983; Plamondon 1981) relied heavily on literature from other countries, particularly the United States.

Forest Hydrology in Canada

Canadian activity in forest hydrology[1] and watershed management[2] is of fairly recent origin. Active forest hydrology research began in the late 1950's in the Wilson Creek watershed in Manitoba and in the early 1960's in southern Alberta (Jeffrey 1967). The late W. W. Jeffrey was instrumental in initiating the Alberta watershed research program and promoting the expansion of forest hydrology activity in Canada during the 1960's. By the early 1970's, several experimental watershed studies had developed in other provinces, and additional research has since been carried out in a number of other watersheds (Fig. 2). These studies have been concentrated in southern Canada where commercial forests and man's use of water coincide. Forest hydrology programs are also now offered at four universities in Canada: British Columbia (Vancouver), Alberta (Edmonton), Laval (Quebec), and New Brunswick (Fredericton). With this increase in information, awareness, and trained personnel, water-related concerns and knowledge have been increasingly incorporated into forest management regulations and practices in most provinces. At present, watershed management in Canada consists mainly of putting constraints on forestry operations to maintain the water resource in its existing state. The one exception is in Alberta, where purposeful manipulation of forests with the objective of enhancing the water resource has been done experimentally (Golding 1981).

---

[1] Forest hydrology is the science of water-related factors influenced by the forest and forms the technical basis for watershed management.

[2] Watershed management denotes operational management of forest land for water-related purposes.

Popular Beliefs

Although there is a growing body of scientific information on forest-water relationships in Canada and elsewhere, several incorrect popular beliefs about these relationships persist. Many believe that forests "conserve water and provide maximum runoff" and "regulate streamflow by controlling spring snowmelt and sustaining summer flows." Others believe that forests "protect against floods" and that "the forest floor acts as a sponge that holds back water and reduces peak flows." Forests are thus commonly viewed as having positive effects on streamflow. In contrast, popular beliefs concerning the effects of forest harvesting on water are usually expressed in negative terms such as "logging dries up streams," "logging causes flooding," "clearcutting produces greater snowmelt runoff," and "logging silts up streams." Forest hydrology research has shown that most of these beliefs are either overly simplistic or false.

Issues and Concerns

Concerns about forest-water interactions arise from direct observation or perceptions of what constitutes desirable or adverse situations. However, conflicting mandates resulting from the separation of management responsibilities for these two resources are an

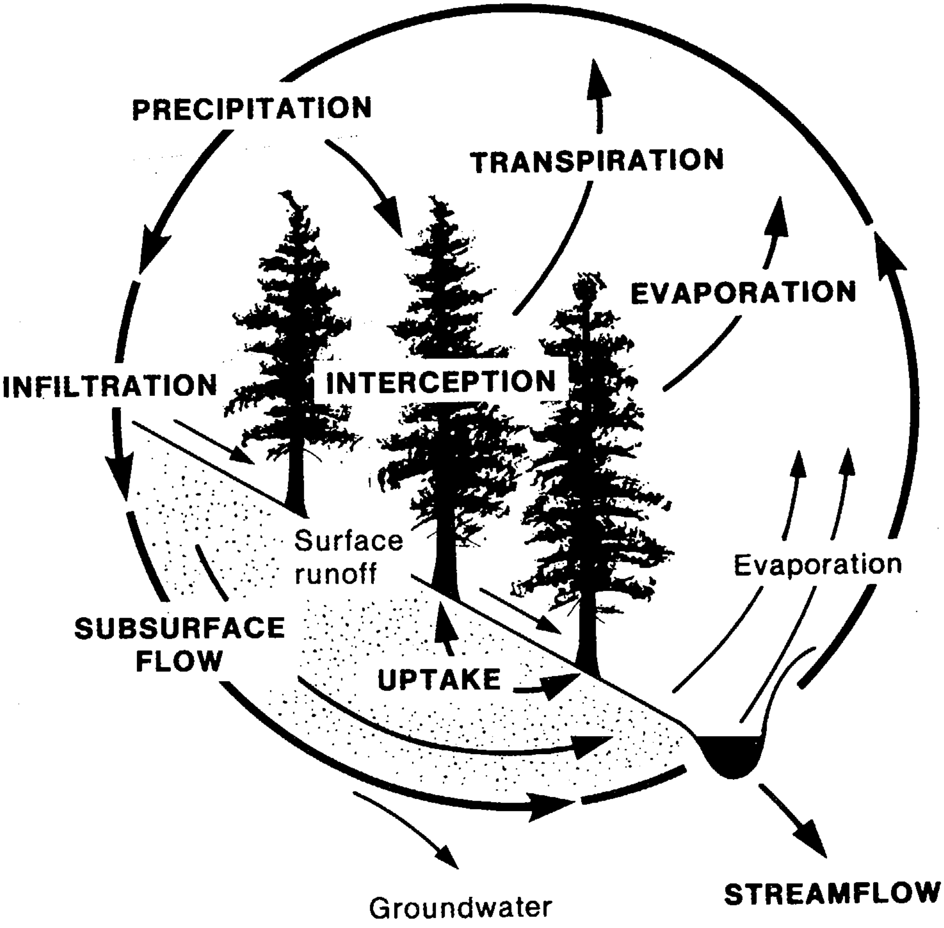


FIG. 1. Diagram illustrating the relative importance of components of the hydrologic cycle in forested areas.

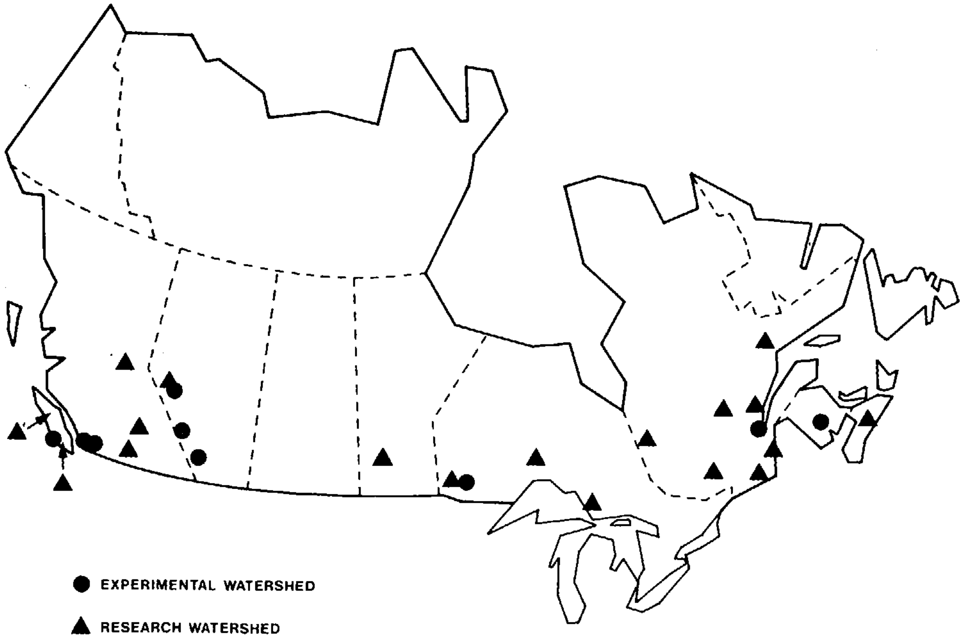


FIG. 2. Distribution of forest hydrology study watersheds in Canada. Experimental watershed studies involve the calibration of study streams against control streams prior to treatments such as logging. Research watershed studies are those that lack pretreatment calibrations. The research watersheds indicated on the map represent the principal locations of watershed-scale forest hydrology studies. There are also many individual study sites or watersheds where research related to forest hydrology has been conducted that are not shown.

underlying source of many problems. Forests and water in Canada are administered separately by both provincial and federal governments. Furthermore, forests are mostlly a provincial responsibility, while fish and their habitat in many streams and rivers, particularly those with anadromous fish such as salmon, fall under federal jurisdiction.

Most of the contentious issues stem from concerns about potential effects of forestry operations on the water resource. The degree of concern varies regionally and is greatest in provinces where forestry is important economically, and where people live close to current forest management activity. The one concern prevalent in all provinces involves the impacts of logging on fish and their habitat, which includes water quality and the physical attributes of the stream channel. However, fisheries impacts are a major issue only in British Columbia and the Atlantic provinces. An issue of growing importance in many areas of Canada is public concern over possible contamination of water and fish by herbicides used for forestry. Similar concerns over the impacts on water and fish of forest pesticide spraying to control spruce budworm outbreaks in eastern Canada have a lower profile than they once had.

Concerns over the effects of forest harvesting on water supplies are centered mainly on water used for domestic needs and irrigation in British Columbia and on managing forests to enhance water supplies in Alberta (Swanson 1978). Logging as an alleged cause of local flooding has occasionally been an issue in British Columbia, Alberta, and some of the Atlantic provinces. Forest management around waterways subject to recreational use is of some concern in parts of Ontario and Quebec. In addition to these identifiable regional issues, numerous local forestry-water problems and concerns exist in most parts of southern Canada, as illustrated by an earlier review of problems in British Columbia (Jeffrey 1968b).

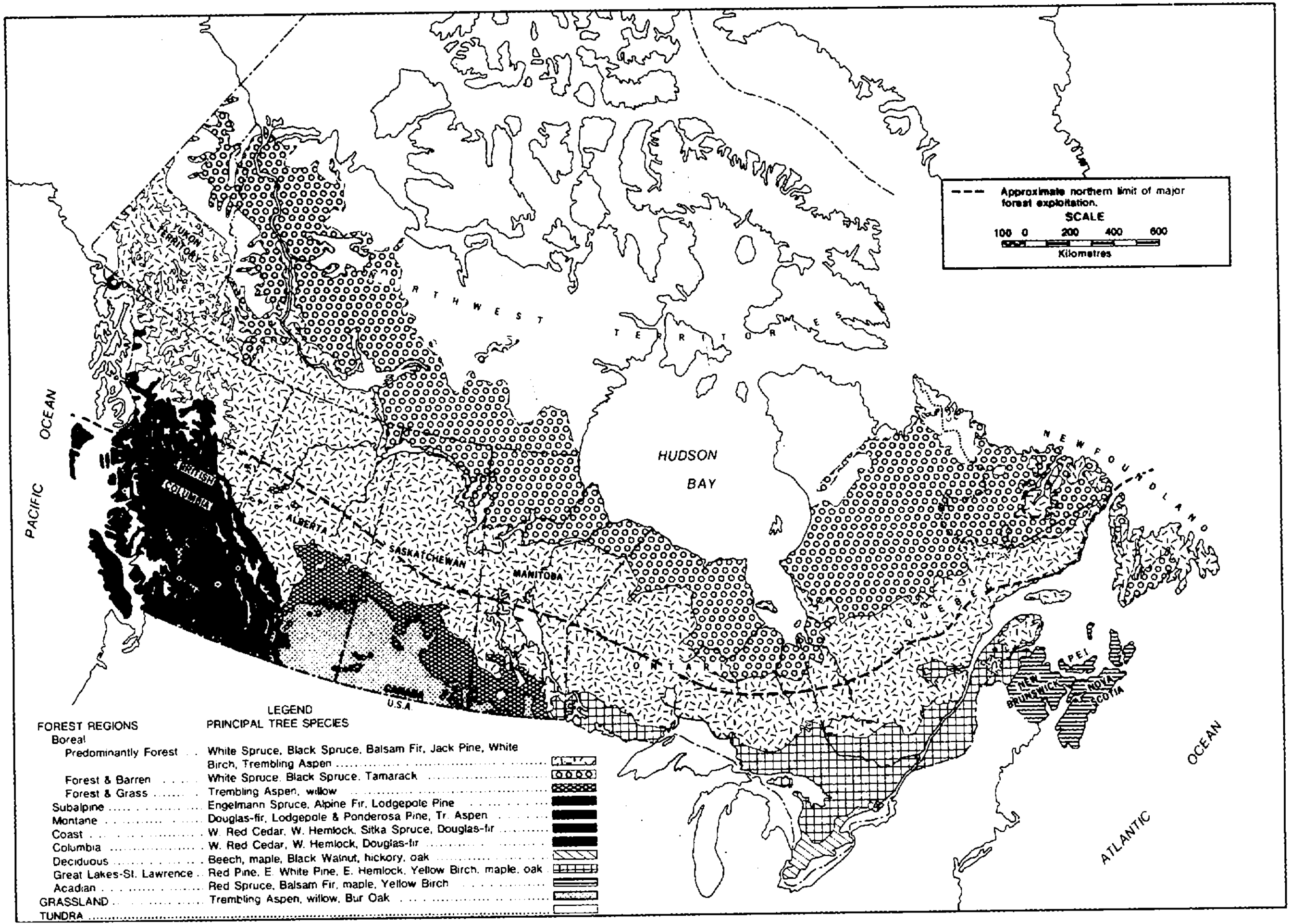


FIG. 3. Forest regions of Canada. (After Rowe (1972) with modifications by Weetman (1983). Reproduced by permission of the Minister of Supply and Services Canada.)

Regional Considerations

Canada is a country with great diversity of forests, soils, terrain, and climate (see chapter by A. H. Laycock in this volume). Although broad regional categorization of forests is possible (Fig. 3), forests within these categories are continuously changing due to natural causes and human exploitation. From 1977 to 1981, the area of forest cover on productive forest lands in Canada was reduced by 2.2 million ha annually, while satisfactory regeneration of new trees took place on 1.8 million ha (Honer and Bickerstaff 1985). The main causes of depletion of the forest cover were fire (43%), insects and disease (23%), and harvesting (34%). These changes affect the structure and species composition of Canada's forests and have resulted in a net increase in the area of land lacking an adequate forest cover. Fire, which is common in most of Canada except for the wetter parts of coastal British Columbia, not only kills trees but sometimes consumes the organic material of the forest floor. The most destructive forest pests, the spruce budworm in eastern Canada and the mountain pine beetle in British Columbia and southern Alberta, have killed trees over extensive areas (Kondo and Taylor 1984). These changes in the pattern of forest cover have marked effects on the water cycle (Swanson 1982).

Forestry operations are concentrated in the commercially productive forest lands across southern Canada (Fig. 3), and encompass a number of practices. The principal harvesting technique is clearcutting with log removal (yarding) by ground skidding (Weetman 1983). Cable yarding systems are used in the steeper terrain in British Columbia (Toews and Brownlee 1981). Conventionally, a watershed is cut in patches over a number of years, with varying limits on the size of clearcut patch and rate of harvest. In some areas, the rate of logging is accelerated to salvage trees damaged by insect infestations (Kondo and Taylor 1984). In most provinces, special attention is given to forest management along stream and lake margins to protect these water bodies from direct disturbance or debris inputs during logging, and maintain desirable fish habitat and water quality. This may involve leaving protective buffer strips of forest vegetation along water edges (Gouvernement du Québec 1977); Toews and Brownlee 1981) or special strategies for removing streamside trees (Moore 1983; Toews and Brownlee 1981).

Silvicultural and forest protection procedures employed to varying degrees across the country include scarification to expose mineral soil to provide for regeneration of the new forest, prescribed burning, mainly to reduce fire hazard and prepare sites for tree planting, herbicide application to control brush and permit conifers to become well established, insecticide spraying to control insect damage, aerial fertilizer application to stimulate better tree growth, and thinning and tree planting to promote growth and establishment of better forests. The impacts of forestry operations on the water resource depend on the extent and severity of change in the forest cover, exposure and compaction of mineral soil, and input of materials to water systems, plus the rate of recovery of soil and vegetation after disturbance.

Most of Canada has been glaciated, which has resulted in extensive wetlands in the boreal forest region and shallow soils, often less than 1 m deep, in most areas presently occupied by forests (Dickison et al. 1981; Hetherington 1976, 1982; Jablonski 1980; Nicolson et al. 1982). In this respect, Canada differs from many areas in the United States where much of the existing body of forest hydrology research has originated.

Influence of Forests and Forestry Operations on Microclimate

The microclimate of a forest stand is the local climate in, and immediately above, or adjacent to the forest. It is determined by the ways in which the forest interacts with energy from the sun, wind, and precipitation. Forest influences on the processes of energy and precipitation distribution affect rates of transpiration, evaporation and soil freezing, and patterns of snow accumulation and melt. Changes in the forest cover, whether due to human or natural causes, also modify these basic microclimatic processes.

Radiation and Energy Balances

The sun is the primary source of energy for microclimatic processes. Solar energy (shortwave radiation) received by the forest canopy is partly absorbed and partly reflected, while some passes directly to the ground. The forest also receives energy from the atmosphere (longwave radiation and sensible heat transfer) and condensation of moisture (latent heat), and it emits energy (longwave radiation) back to the atmosphere. Much of the net energy absorbed by the forest accounts for its microclimate and the remainder is used for tree growth, resulting in an overall energy balance.

The partitioning of incoming solar radiation is dependent on the density and type of forest canopy. The amount of sunlight reaching the forest floor decreases from over 80% for a 10% canopy cover to less than 12% for complete closure for conifers (Jeffrey 1968a). In summer, the amount of solar radiation reflected by a mature coniferous forest varies from about 7% for balsam fir (McCaughey 1981) to 13% for less dense black spruce stands (Haag and Bliss 1974). One mostly deciduous forest in eastern Canada was found to reflect at least 16% (O'Kane 1983).

In forests with closed canopies, most of the energy absorbed is retained within the canopy. The net radiant energy absorbed by the ground beneath the canopy was found to be only 5% of that at the top of the canopy in one study (Spittlehouse and Black 1981). The absorbed energy is used primarily for warming the surroundings (including the melting of snow) and for the processes of transpiration and evaporation of water (evapotranspiration). When the moisture supply is adequate, more energy goes into evapotranspiration. Under drier conditions, more energy is used to warm the environment. The amount of energy stored in the vegetation and soil and used for photosynthesis usually does not exceed 5-10% of the net radiant energy on a daily basis (McCaughey 1985).

Forest harvesting and silvicultural practices alter the radiant energy balances. Clearing the forest substantially increases solar radiation reaching the ground. Clearcut and nonforested tundra surfaces reflect 2-10% more solar radiation than adjacent forests (McCaughey 1981; Petzold and Rencz 1975), although the exposure of mineral soil by logging may initially decrease the amount reflected (O'Kane 1983). With these changes, the net radiant energy absorbed by the ground in open clearcuts (or tundra areas) is considerably greater than that beneath the forest canopy. However, the net energy absorbed by the canopy still remains about 10-20% greater than that absorbed in adjacent open clearcut (McCaughey 1981) or tundra areas (Rouse 1984). In winter, snow increases the reflection of solar radiation much more from open areas than from forest canopies. For example, the reflectivity of a northern black spruce forest under snow conditions was 32% compared with 78% from a snow-covered tundra surface (Rouse 1984). The use of absorbed radiation in open areas differs from that in forests, with less energy tending to go into evapotranspiration and more into warming the environment in the open.

Evapotranspiration

Evapotranspiration includes all evaporated or transpired water. Most of the net absorbed energy used for evapotranspiration in forests goes into transpiration of soil water and evaporation from wet vegetation; evaporation from the ground and water surfaces accounts for the remainder (Fig. 1). Transpiration rates are determined not only by radiant energy but also by the temperature and humidity of the air, by soil moisture, and by physiological controls imposed by the trees themselves. The highest reported estimates of daily transpiration by individual trees in Canada are 16 L for lodge-

Forests and water are intimately associated (R. Barry, Faculté de Foresterie et de Géodésie, Université Laval, Québec, Qué.)

pole pine (1544 stems/ha) in Alberta (Swanson 1975) and 24 L for young Douglas-fir (840 stems/ha) in British Columbia (Black et al. 1980). However, maximum single-tree transpiration volumes for Douglas-fir can exceed 100 L/d in stands of lower tree density (Black et al. 1980). The maximum transpiration rates from forest stands, expressed as depth of water over the area occupied by the stand, reach 0.3-0.5 mm/h and 3-5 mm/d for both conifers and hardwoods (McCaughey 1985; McNaughton and Black 1973). These rates usually occur on sunny days.

Total evapotranspiration from forests can be even higher when the vegetation is wet. Evapotranspiration rates from wet canopies of up to 0.8-1.0 mm/h and over 5 mm/d have been reported (McCaughey 1978; Singh and Szeicz 1979). The evaporation of precipitation intercepted by tree surfaces reduces the rate of transpiration, thereby reducing the loss of soil moisture by transpiration during wet conditions (Singh and Szeicz 1979; Spittlehouse and Black 1981). The proportion of time that canopies are wet can thus strongly influence total annual losses of water by evapotranspiration. The high wet-canopy evaporation rates reported for research plots, however, are caused by the evaporative power of drier air from nearby areas moving through the canopy in addition to net radiant energy. Whether or not wind-related evaporation forces are effective in increasing total evaporation over extensive areas of wet forest remains an unresolved question (Morton 1985). In returning water to the atmosphere, the processes of evapotranspiration affect streamflow by reducing the volume of water available for runoff and by increasing the ability of the soil to temporarily store and delay runoff.

Evapotranspiration rates vary according to vegetation type. Daily summer evapotranspiration of trees was found to be greater than that of other vegetation in three Canadian studies: 10-32% higher than grass and soil in Alberta (Cohen 1977), 6-58% higher than tundra in the north (Rouse 1976), and 36% higher than grasses and shrubs in Saskatchewan (Meyboom 1967). In contrast, under relatively dry conditions, transpiration by ground vegetation (salal) exceeded that of Douglas-fir in coastal British Columbia (Black et al. 1980). Furthermore, evidence from Oregon indicates that vigorous young deciduous vegetation uses more water than mature conifers (Harr 1983). On a seasonal or annual basis, however, total evapotranspiration from coniferous forests will tend to be higher than that from other vegetation in most situations, although there are suggestions that this might not always be the case (Morton 1984; Plamondon 1981). The reasons for greater evapotranspiration from forests include the more extensive root systems of trees, longer periods of transpiration, and greater evaporation of intercepted precipitation (Calder 1982).

Evapotranspiration during the winter is small in most parts of Canada because of the cold temperatures. Annual evaporation of snowfall in forested environments could be less than 3% (Jeffrey 1968a). One exception occurs in southern Alberta, where evaporation of snow during chinook winds can account for up to 20% of annual snowfall at lower elevations (Golding 1982).

Forest harvesting reduces evapotranspiration losses by eliminating transpiration and evaporation from the elevated canopy. In Ontario, for example, maximum hourly rates of evapotranspiration were 20% greater from the forest than from an adjacent clearcut (McCaughey 1985). One result of this is wetter soils in the harvested areas than in the forest (Kachanoski and de Jong 1982). This increase in soil water content in logged areas makes more water available for streamflow by reducing the ability of the soil to store rain and snowmelt.

Soil Frost

Soil freezing within forests is impeded by the insulating qualities of the forest canopy and organic forest floor. Even in the cold winters of central Canada, soil freezing within forests can be minor (Price and FitzGibbon 1982; Sahi and Courtin 1983). Snow is also a good insulator and can be more effective in reducing the degree of soil freezing than the forest. In Quebec, for example, soil frost was less severe in the open under a deep snowpack than in the forest where the snow was not as deep (Plamondon and Grandtner 1975). Soil frost has also been observed in the forested mountains of western Canada, although it frequently disappears before spring snowmelt due to thawing from below (Harlan 1969). Forest harvesting may either increase or decrease the severity and frequency of soil freezing, depending on whether snowpack depths are lower or higher after removal of the canopy (see section on snow accumulation and melt).

In the permafrost zone (see chapter by R. O. van Everdingen in this volume), insulation provided by the forest vegetation and organic forest floor reduces the depth of summer thaw in comparison with open areas. In some locations, such as the forested lowlands of northern Quebec, snow trapped by the forests may locally prevent permafrost formation (Granberg 1973). In general, however, the forest is more efficient in preventing thawing than preventing freezing. Forest removal can cause an expansion of permafrost formation to previously unfrozen ground and an increase in the depth of summer thaw in existing permafrost.

The effect of soil frost on runoff depends on whether the soil was saturated or not at the time of freezing. Saturated soils will freeze solid and cause surface runoff if the frost persists into the snowmelt period, whereas freezing of unsaturated soils may have little effect on infiltration or runoff (Price and FitzGibbon 1982).

Wind

Wind plays an important role in the processes of evapotranspiration, snow distribution, and snowmelt. Because of their great height and surface roughness, forests induce turbulence and reduce wind speed both over the canopy and at forest/clearing edges.

The reduced roughness of low ground vegetation or isolated trees in large open areas affect wind to a much lesser extent than fully forested areas. For example, wind speeds 10 m over a forest canopy are about 50% slower than 10 m over relatively smooth open ground (Silversides 1978). Beneath the forest canopy, wind speeds may be reduced to just a few percent of those in the open (Beaudry 1984) or above the canopy (Martin 1971). The denser the forest, the lower will be the relative wind speed (Szeicz et al. 1979).

Forest harvesting changes wind patterns and the effects of wind on the environment. After clearcutting, for example, wind speeds will increase at ground level (Meeres 1977), although the change may be small in openings less than six tree heights across (Swanson 1980). Once exposed to higher wind speeds, tress along clearcut edges are more susceptible to being blown down. This possibility is an important concern in the design of protective leave strips of trees along streams, lakes, and unstable areas.

Precipitation

The forest's direct influence on water begins with the onset of precipitation (Fig. 1). Through interception, forest canopies reduce the amount of rain and snow reaching the ground and alter its distribution. Forests further alter snow accumulation and melt patterns by sheltering snowpacks from sun and wind. These initial forest-precipitation interactions help determine the quantity and timing of inputs to runoff processes.

Interception

The capture of rain by forest canopies is controlled by the type and density of trees and by rainfall intensity. On a seasonal basis, conifer stands tend to intercept more rain than hardwoods, with mixed forests falling in between (Table 1). The interception values in Table 1 represent water lost to the atmosphere by evaporation. For individual storms, light showers might be almost totally intercepted, while interception might account for as little as 5% of heavy winter rainfall (McMinn 1960). Rain interception is determined partly by the storage capacity of the canopy for rainwater and partly by continual evaporation of intercepted water during rainfall. Total storm interception, for example, has been found to exceed 10 mm for a stand with a canopy storage capacity of 2.4 mm (Singh and Szeicz 1979). Interception losses are partly offset, however, by a concurrent reduction in transpiration when the foliage is wet, as already noted. Interception of fog or cloud droplets and consequent fog drip, as observed in coastal Oregon (Harr 1983), may be locally important in immediate coastal areas.

TABLE 1. Summer rainfall interception as a percentage of total precipitation.

Forest type	Height (m)	Age (yr)	Density (no./ha)	Interception (%)	Reference
Conifers, B.C.	70	236	267	57	McMinn 1960
Conifers, B.C.	28	248	603	30	McMinn 1960
Balsam fir, Que.	15	50	4800	39	Plamondon et al. 1984b
Balsam fir, Que.		20		25	Frechette 1969
Red spruce, N.B.		46	4841	14	Mahendrappa and Kingston 1982
Hardwoods, Ont.	22	135	673	9	Foster and Nicolson 1986
Hardwoods, Que.				21	Frechette 1969
Birch, N.B.		61	4303	20	Mahendrappa and Kingston 1982
Aspen, N.B.		44	5649	8	Mahendrappa and Kingston 1982
Mixed wetland, Alta.	27	200	192	37	Rothwell 1982
Mixed, Que.		20		23	Frechette 1969

The amount of snow trapped by forest canopies, expressed in terms of its melted equivalent as water, will depend on the canopy density and whether the snow is dry or wet. Mature west coast forests can temporarily retain at least 16 mm water equivalent of wet snow (Beaudry 1984), although average values are likely much lower for the drier snow and smaller trees encountered in most other forest regions. Most of the intercepted snow is removed from forest canopies either by wind action, if the snow is relatively dry, or by melt processes when temperatures are mild. As already noted, the loss of snow by evaporation is small.

Clearcutting eliminates the elevated intercepting surfaces of the forest canopy. This permits rain or snow that would have been previously intercepted to reach the ground where it is less exposed to evaporative forces. Consequently, losses due to evaporation are reduced and more water made available for runoff processes. Even partial reductions of canopy or foliage density, such as that produced by spruce budworm defoliation of eastern conifers (Plamondon et al. 1984b) or forest fires, can reduce interception losses.

Snow Accumulation and Melt

The trees of a forest change the accumulation and distribution of snow on the ground by intercepting snow and altering wind speed and turbulence. The effect will vary depending on the characteristics of the forest canopy and the nature of the snow. Both depth and water equivalent of the snowpack are affected, although the water equivalent is more important in terms of runoff. Snow accumulation on the ground in forests usually decreases as the density of the canopy increases (Daugharty 1984). In areas with dry snow, however, more snow may accumulate in the forest than in the open due to trees trapping snow blown from adjacent open terrain (Payette et al. 1973). Leafless hardwood stands act as porous traps and accumulate more snow than coniferous forests (Daugharty 1984; Frechette 1968).

Removal of the forest cover, whether by harvesting or other causes, modifies snow accumulation patterns through elimination of interception losses and changes in redistribution processes. Small openings in the forest almost always accumulate more snow than the adjacent forest (Fig. 4). Maximum snowpack water equivalents in small clearings are usually less than 40% greater than in the forest (Golding 1982), although increases in clearings can be several hundred percent for shallow snowpacks (Jeffrey 1968a). In large open areas, late winter snowpacks are often smaller than within forests due to wind erosion of dry snow (Payette et al. 1973) or greater overwinter ablation by melting (Daugharty and Dickison 1982). In regions where milder winter temperatures prevail, snowpacks can also be greater in large openings if melt or evaporation from the canopy results in smaller snow accumulations in the forest (Beaudry 1984).

The major factors causing snow to melt are solar radiation, sensible heat and longwave radiation from the atmosphere or vegetation, and heat derived from the condensation of moisture. Forests moderate snowmelt rates by sheltering snowpacks from the direct effects of sunlight and heat transported by the wind. Consequently, melt rates of the snowpack increase with increasing exposure to sun and wind. For example, snowpacks under leafless hardwoods melt faster than those in coniferous stands (Daugharty and Dickison 1982), but snow can melt even faster while retained in the canopy (Beaudry 1984). In a lodgepole pine stand in Alberta, melting was actually slowest in very small openings about one tree height across, whereas melt rates in the forest were about the same as those in openings three tree heights in diameter (Golding 1981). Snowmelt rates were also found to be slower in small clearings in an aspen forest than beneath the canopy (Swanson and Stevenson 1971). Snow melts most rapidly, however, in large open areas (Plamondon et al. 1984a; Stanton 1966).

Removal of the forest cover by harvesting or fire usually accelerates snowmelt and runoff, and can advance the date at which the snowpack disappears. Snow in forest openings commonly disappears sooner than in the forest despite greater accumulations (Daugharty and Dickison 1982; Stanton 1966). Snowpacks in the forest have

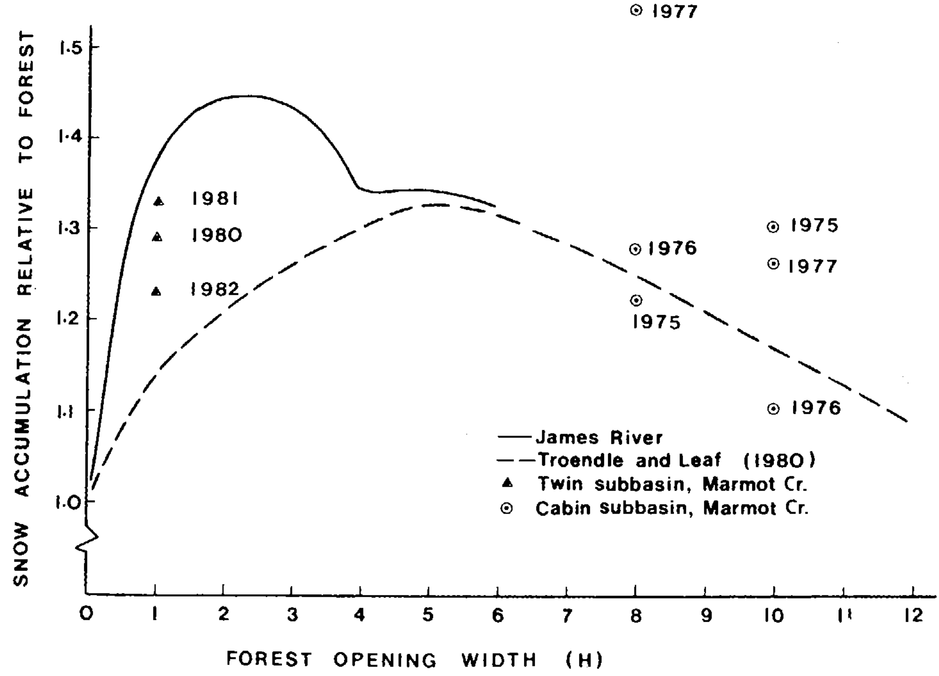


FIG. 4. Maximum snow accumulation (water equivalent) in forest openings at three locations in Alberta relative to accumulation in the uncut forest (Golding 1982). The broken line is based on data for the dry snow conditions of the subalpine zone in Colorado.

persisted for as much as 1-2 wk longer in Alberta (Stanton 1966) and 2-4 wk longer on well-shaded north aspects in Quebec (Plamondon et al. 1984a). On the other hand, because of factors such as snowmelt in the canopy or chinook wind-related processes, snow has been found to disappear sooner in lower elevation forests than in the open in coastal British Columbia (Beaudry 1984) and in Alberta (Jeffrey 1968a).

Influence of Forests and Forestry Operations on Runoff

Runoff is the product of several processes in which forest-water interactions play a key role. Following initial effects on microclimate and precipitation, forests next affect runoff by influencing the movement and storage of water on and within the soil mantle. Eventually, runoff waters move into groundwater aquifers or appear as streamflow in surface channels. Streamflow integrates the various effects of forests on runoff and also reflects changes in runoff processes caused by forestry operations.

Runoff Processes

On reaching the ground, most rain or snowmelt water will either move into and through the soil or over its surface. The processes of water movement and storage are thus conditioned by the characteristics of the soil mantle. Forest soils readily absorb water (Plamondon et al. 1972; Price and Hendrie 1983; Singh 1983), being highly permeable because of accumulations of organic matter, live tree roots, and decayed root channels and other voids (Chamberlin 1972; Foster and Nicolson 1984). As a result, surface runoff (also called overland flow by some authors) outside of stream channels is rare in most forested areas. The exceptions occur where infiltration is locally prevented because soils are saturated or frozen. Water moves more slowly through the soil than it does on the surface.

Forest soils are composed of a surface layer of organic material (called the forest floor) overlying a mantle of mineral soil, both of which can store water. The water storage capacity of a soil is the amount of space in the total soil volume not occupied by solids. Soil water storage opportunity is defined as the portion of this space not already filled with water and is created or increased by transpiration and vertical drainage. The water storage capacity of the upper 50 cm of mineral soil, which contains most of the tree roots, is typically about 250 mm. Water storage capacities of the forest floor are much lower, ranging from 13 to 23 mm (floor depth of 5–10 cm) in conifer stands in Alberta (Golding and Stanton 1972) and New Brunswick (Mahendrappa 1982), 12 to 38 mm (floor depth of 5-6 cm) in hardwood stands in New Brunswick (Mahendrappa 1982), and up to 81 mm (floor depth of 17 cm) in coastal British Columbia (Plamondon et al. 1972). Since soils under forest cover are seldom totally dry, the water storage opportunity in forest soils is usually considerably less than the maximum values for forest floors (Plamondon et al. 1972) and the mineral soil (Giles et al. 1985). The thin, very well-drained mineral soils in many forest regions in Canada further restrict soil water storage opportunity. Where the water table is close to the surface, transpiring forests also directly increase groundwater storage opportunity by lowering water levels (Rothwell 1982).

In most of the forested lands in southern Canada, peak streamflows from rain or snowmelt are generated either by subsurface flow into expanding surface channel systems (Cheng et al. 1975b) or surface runoff from zones of saturated soil near stream channels (Price and Hendrie 1983). These two processes are known as the "variable source area" and "partial area" concepts, respectively. Surface runoff on frozen ground during snowmelt is the dominant process in the permafrost zone (Price et al. 1978).

Forestry operations that remove the forest cover or disturb the soil also change runoff processes. Soil water storage opportunity is reduced by the harvesting of trees because of reduced transpiration losses of soil moisture. This results in wetter soils in cleared areas (Kachanoski and de Jong 1982), higher water tables in areas of shallow groundwater (Hetherington 1982), and increased zones of saturated soil near stream channels (Swanson and Hillman 1977). Fire may consume forest floor material, which reduces soil water storage capacity and exposes mineral soil to erosive forces (Smith and Wass 1982).

The pathways of water movement are also altered by soil disturbance. The compacted surfaces of haul roads and skid trails intercept seepage water and precipitation, creating surface runoff and speeding up water delivery to stream channels (Hetherington 1982). Yarding and scarification modify surface soil structures and block water entry to more open pathways such as decayed root channels. These changes can reduce infiltration and subsurface flow rates, cause local increases in groundwater tables during rain storms (Hetherington 1982), and could result in surface runoff. In the mountains of western Canada and particularly in coastal British Columbia, some of the steeper slopes are inherently unstable and landslides are a natural occurrence. However, the incidence of landslides can be increased by harvesting and road construction in steep terrain (Wilford and Schwab 1982). The landslide scars often become surface runoff channels, while landslide debris alters patterns of streamflow within channels.

Water Yield

Water yield is the total runoff from a drainage area through surface channels and by groundwater flow. However, it is usually taken to be the total measured streamflow over a given time period. This represents the amount of precipitation not lost to evapotranspiration or deep groundwater flow or retained in storage within the watershed. On an annual basis, water yields vary directly in relation to precipitation, since evapotranspiration is less variable than precipitation.

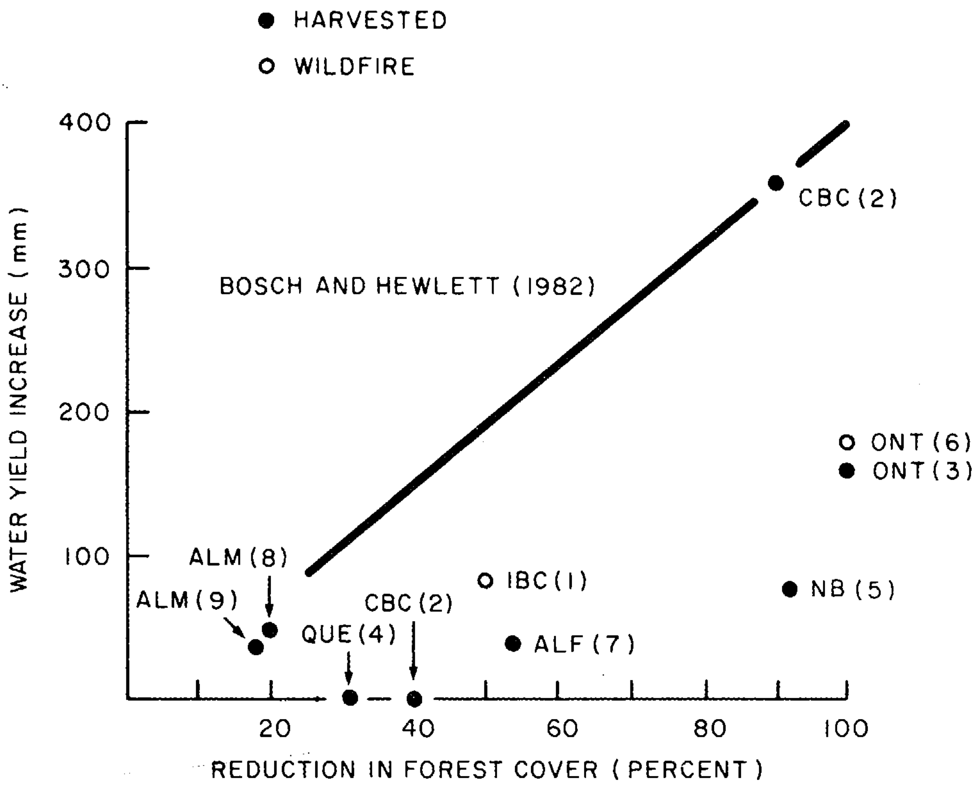


FIG. 5. Maximum annual or seasonal water yield increases within the first 4 yr following harvesting or wildfire in Canadian watersheds in comparison with worldwide averages. Values for 1, 3, and 7 are based on streamflow data for the ice-free season from spring to late fall. The regression line from Bosch and Hewlett (1982) is based on data from experimental watersheds in several countries. 1, J. D. Cheng, Ministry of Forests, Kamloops, B.C., pers. comm., the percent forest cover reduction is revised from Cheng 1980; 2, Hetherington 1982; 3, Nicolson et al. 1982; 4, Plamondon and Ouellet 1980; 5, R. B. B. Dickison and D. A. Daugharty, University of New Brunswick, Fredericton, N.B., pers. comm., a revision of data given by Dickison and Daugharty 1983; 6, Schindler et al. 1980; 7, Swanson and Hillman 1977; 8, R. H. Swanson, Canadian Forestry Service, Edmonton, Alta, pers. comm.; 9, Swanson and Golding 1982. ALF = Alberta foothills; ALM = Alberta Rocky Mountains; CBC = coastal British Columbia; IBC = interior British Columbia; NB = New Brunswick; ONT = Ontario; QUE = Quebec.

Forests reduce water yields because they are consumers of water. For the same total precipitation, a given area covered by trees will generally yield less annual runoff than an area covered with other types of vegetation, although there might be exceptions (Morton 1984). The lower yields from forests are due to greater evapotranspiration losses. However, where forest stands conserve water by trapping snow blown from open areas, forests can yield more water than adjacent treeless terrain. This occurs with drier snow in central and northern Canada.

Research studies in small (less than 25 km^2) forested watersheds in Canada have shown that reductions in forest cover by harvesting or fire usually result in higher annual water yields (Fig. 5). The increases in runoff are generally in proportion to the amount of forest cover removed, and they vary with soil depth and precipitation. These changes are mainly attributable to reductions in evapotranspiration losses from the deforested areas. Except for coastal British Columbia, observed changes in water yield are lower on average than those found elsewhere (Fig. 5). This might be partly due to the limited soil water storage capacities and rapid drainage characteristics of the thin soils found in many forested areas of Canada. The magnitude of changes in water yield from insect-damaged forests in Canada could also be limited because of reductions in evapotranspiration prior to deforestation. In areas where forests trap wind-blown snow, removal of forest stands will eliminate this trapping effect and may cause reductions in total runoff from the area affected. The rate of recovery of water yields is proportional to the rate of recovery of vegetation. With regrowth of forest vegetation and no further disturbance, water yields from deforested areas can return to predisturbance levels in only a few years on the humid west coast and in eastern Canada (Schindler et al. 1980), but recovery may take 30 yr or longer in central Canada (Swanson and Hillman 1977).

The processes that have caused observed changes in water yields in small watersheds are likely to produce similar changes in large drainages. There is evidence from large watersheds (over 700 km^2) in the United States, for example, of increases in water yield following forest harvesting (Berndt and Swank 1970) and insect damage (Bethlahmy 1974) and reductions in water yield after reforestation (Schneider and Ayer 1961). The magnitude of the change will depend on the proportion of a watershed that is deforested or reforested.

Low Flows

Forest influences on summer low flows parallel those on water yields. Forest evapotranspiration in summer can exceed precipitation inputs, thereby reducing the amount of soil water and groundwater available for streamflow. Daily flows in small streams can fluctuate in direct response to daytime water use by streamside vegetation, as observed in Washington State (Helvey 1972).

Removal of the forest cover will decrease evapotranspiration losses. Most research studies indicate that some of the extra water is translated into higher summer streamflows. For example, flows in August and September increased 10-36% after a wildfire in interior British Columbia (Cheng 1980) and 133-318% after harvesting in New Brunswick (Dickison et al. 1981) and Ontario (Nicolson et al. 1982). Minimum daily flow increased by 78% after clearcutting in coastal British Columbia (Hetherington 1982), and clearcut plot runoff doubled in Saskatchewan (Kachanoski and de Jong 1982). However, no change was detected after partial clearcutting in Quebec (Plamondon and Ouellet 1980). Even small increases in low flows can be beneficial in terms of improved fish habitat and domestic water supply. The expected durations of changes in low flows are similar to those for water yields.

Under some circumstances, low flows might be reduced in small streams following logging or fire. After initial increases, flows in west coast or eastern Canadian streams could eventually be diminished below predisturbance levels by the vigorous transpiration of new streamside deciduous vegetation (Harr 1983). Reduced fog interception could locally reduce low flows in immediate coastal areas, as observed in Oregon (Harr 1983). Even if low flows are not reduced, buildup of gravel in stream beds, such as might occur after logging, could result in flow being entirely subsurface. This change in the channel would impair its use by fish. In general, however, the evidence indicates that low flows in most of Canada are more likely to increase rather than decrease after removal of the forest cover.

Peak Flows

Peak flows are maximum stream discharges generated primarily by short-duration, localized rain showers, more extensive long-duration rain storms, spring snowmelt, and rain-on-snow events. Floods represent extreme occurrences of peak flows produced by any of these sources of runoff. The effects of forests and forestry operations on peak flows can vary considerably, depending on the source of runoff.

TABLE 2. Changes in peak flows during rain storms following logging in Canadian watersheds (nd = not detected).

Location	Change in peak flow (%)	Comments	Reference
Carnation Creek, B.C.	nd	40% clearcut	Hetherington 1982
H Creek tributary	20	90% clearcut	Hetherington 1982
Near Haney, B.C.	−22	Soil 50% disturbed	Cheng et al. 1975a
Near Hinton, Alta.	nd-230	Avg. clearcut age 10 yr	Swanson and Hillman 1977
Experimental Lakes, Ont.	Increased	After 4 yr	Nicolson et al. 1982
Nashwaak Basin, N.B.	71	1979	Dickison and Daugharty 1983
Nashwaak Basin, N.B.	38	1980	Dickison and Daugharty 1983
Nashwaak Basin, N.B.	26	1981	Dickison and Daugharty 1983

Stormflow from Rainfall

Stormflow, the rapid runoff from storm rainfall, is defined by both the peak flow and the volume of runoff. In undisturbed forested lands, stormflow is mainly affected by available soil water storage opportunity and, to a lesser extent, by canopy interception of rainfall. The effect is greatest when soils are deep and/or saturated. In general, the influence of this storage is greatest during light showers, decreases as the duration and intensity of rainfall increases, and is least during major rain storms in late fall or winter. In coastal British Columbia, for example, the proportion of rainfall appearing as stormflow has ranged from as low as 3% for small summer storms to over 90% during major winter rains (Cheng et al. 1977; Hetherington 1982).

Peak flows during rain storms increased after forest harvesting in several research watersheds in Canada (Table 2). These results apply to storms of a magnitude that is likely to occur more often than once every 5-10 yr. Stormflow volumes also increased in the Alberta and New Brunswick watersheds. The stormflow changes in Alberta and eastern Canada occurred during summer storms and were caused mainly by reductions in soil water storage opportunity after logging. The production of surface runoff by roads caused the increase in coastal British Columbia and was a contributing factor in Alberta's increases. In the west coast Carnation Creek watershed, harvesting after road construction increased peak flows from one or two early fall storms, but had little detectable impact on most runoff events in this humid environment. Peak flows may thus be increased by water reaching the stream channel faster or simply by greater volumes of runoff. The decreased peak flows in the other west coast watershed were attributed to changes in subsurface flow rates caused by extensive soil disturbance and to flow delays by logging debris in the channel.

These results indicate that stormflow runoff peaks can potentially increase after harvesting for smaller storms in small watersheds in most forest regions in southern Canada. As the severity and duration of storm rainfall increases, the proportional increase in peak flow will diminish. Changes in stormflow caused by roads are likely to be long-lasting. Those changes associated with forest cover removal will diminish as vegetation regrows and take about the same length of time as water yields to return to prelogging levels.

a. Low flow b. Peak flow

Forests influence both summer low flows and rainstorm peak flows (E. D. Hetherington, Canadian Forestry Service, Victoria, B.C.).

Snowmelt Runoff

Forests have a significant effect on snowmelt runoff through their influence on the processes of snow accumulation and melt, frost formation, and runoff generation. Peak flows from snowmelt are particularly affected by the rate and timing of melting and by soil water storage opportunity. By increasing storage opportunity through transpiration and slowing melt rates by sheltering snowpacks from the effects of sun and wind, forests help regulate the generation of runoff from snowmelt.

Forested areas composed of a mosaic of openings and tree cover, however, can generate different streamflow patterns than those arising from a complete forest cover by synchronizing or desynchronizing snowmelt (Federer et al. 1972). Peak flows are highest when heavy snowmelt runoff from all parts of a watershed is synchronized and arrives downstream at the same time. Because melt rates are higher in openings than beneath the forest canopy, the acceleration of spring snowmelt from openings may desynchronize runoff to the extent that downstream peak flows are smaller than would

TABLE 3. Changes in spring snowmelt runoff following forest harvesting and fire in Canadian watersheds (nd = no change detected).

	Change in runoff				
Location	Peak flow (%)	Volume (%)	Time of peak (d)	Treatment	Reference
Palmer Creek, B.C.	16	53[a]	−13	50% burn	Cheng 1980
Marmot Creek, Alta. (Cabin Creek trib.)	nd	24[b]	−14	20% patchcut	Golding 1980
Streeter basin, Alta:	78	41[a]	−17[c]	Patchcut	Golding 1981
Near Hinton, Alta.	57[d]	59	nd	35-84% patchcut	Swanson and Hillman 1977
Experimental Lakes, Ont.		75[a]		Clearcut	Nicolson et al. 1982
Riv. des Eaux-Volées, Que.	nd	nd	nd	31% patchcut	Plamondon and Ouellet 1980
Nashwaak basin, N.B.	Lower	Lower	−21 to −4	92% clearcut	Dickison and Daugharty 1982

[a] Runoff for April and May.
[b] Runoff for May.
[c] Occurrence of 50% of total spring snowmelt runoff.
[d] Estimated from composite hydrograph.

occur from a completely forested watershed. Accelerated melt runoff from openings at high elevations could also augment the normally earlier melt at lower elevations to increase downstream peak flows. The location of openings in forested watersheds is thus critical in determining their influence on snowmelt streamflow.

Because of the major differences in snowmelt rates between forested and open areas and the possibilities for synchronizing or desynchronizing snowmelt runoff, the effects of forest cover removal on spring snowmelt runoff are variable (Table 3). Following harvesting and, in one case, fire, spring snowmelt peak flows increased, showed no change, and decreased. In the clearcut New Brunswick watershed, early-spring runoff was increased, but the reduction in late-spring runoff was of greater magnitude (Dickison and Daugharty 1982). Spring streamflow volumes were also higher in several streams, a probable result of reduced soil water storage opportunity in cleared areas. In the New Brunswick stream, the decreased spring runoff volume resulted from greater ablation of the snowpack during the winter in the open clearcut than in the forest. In four of the studies referred to, peak runoff occurred earlier due to faster melt in open areas. However, the dispersed clearcut pattern on relatively level terrain in the Hinton, Alberta, area resulted in little difference in the timing of peak flows (Fig. 6). In summary, complete clearcutting of a watershed will usually increase peak flows from snowmelt, except in areas such as New Brunswick where winter ablation reduces the snowpack prior to spring melt. To evaluate the probable effect on snowmelt peak flows of partially harvesting a watershed, both the distribution of openings and the proportion of the drainage area to be cleared must be taken into consideration. With no further disturbance of the forest cover, changes in snowmelt runoff may persist for 30 yr or longer in central Canada (Swanson and Hillman 1977) and possibly in eastern Canada, but recovery could occur sooner on the west coast.

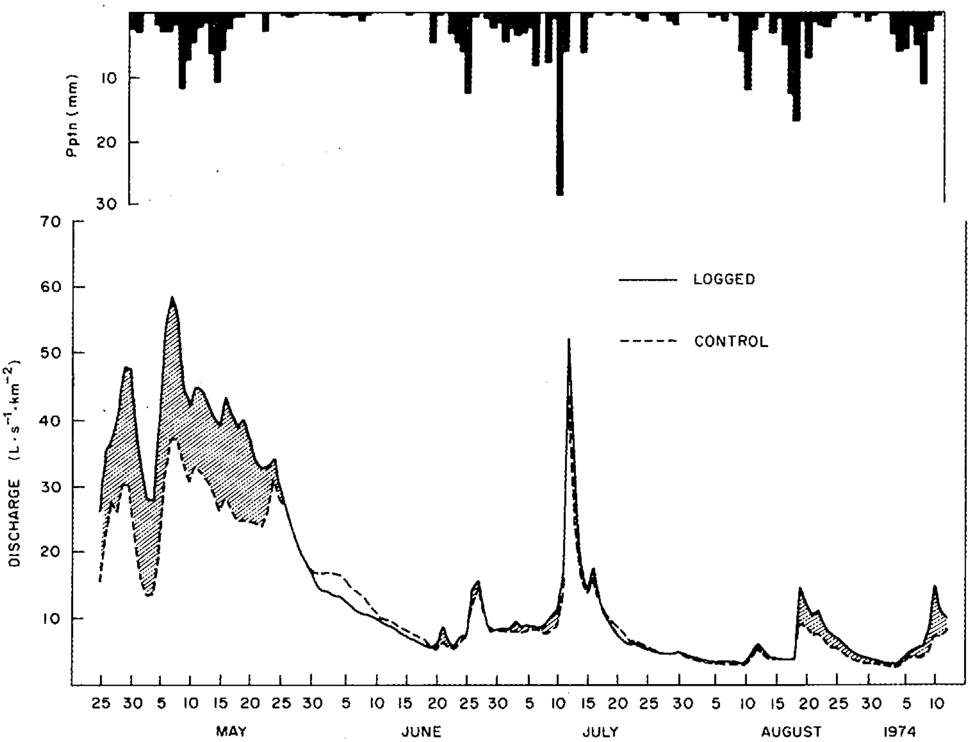


FIG. 6. Composite hydrograph for 1974 for logged and control catchments in the Hinton, Alberta, study area (Swanson and Hillman 1977). Note the increase in spring snowmelt runoff and the increases in peak flows from summer rains in the logged watershed.

Rain-on-Snow Runoff

Rain-on-snow runoff produces some of the largest peak flows in winter and spring on both the east and west coasts. However, the influence of forests on rain-on-snow runoff received little attention in Canada until recent expressions of concern over the effects of forest harvesting on peak flows in British Columbia (Toews and Wilford 1978). The presence or absence of snow in the canopy in addition to snow on the ground during rainfall can markedly affect the relative rates of runoff from forested versus open areas. With no snow in the forest canopy, rain-on-snow runoff rates and volumes were found to be higher in a clearcut than in the adjacent forest in coastal British Columbia (Beaudry 1984). When snow was present in the canopy during rainfall, peak runoff rates from the forest equalled those in the open. This result suggests that snow in the canopy melted faster than the snowpack in the open, and that temporary storage of rain and meltwater in the open snowpack exceeded that in the forest. The relative contribution of snowmelt to peak flows will diminish as the amount of storm rainfall increases. In the absence of snow in the canopy, the effects of harvesting on rain-on-snow peak flows should be similar to those for snowmelt without rain, including the duration of changes.

Floods

Floods are peak flows that rise above natural stream and river banks and flow onto adjacent areas. Damage caused by floods results from soil and debris carried by the floodwaters as well as by the water itself. In general, forests act to minimize flooding and flood damage by intercepting precipitation, increasing soil water storage opportunity through transpiration, moderating snowmelt rates, minimizing overland flow, erosion, and the effects of frost, retaining soil on steep slopes, and maintaining stream channel capacity for carrying peak flows. Forests may mitigate flood runoff from high-intensity summer showers (Anderson et al. 1976), but their influence on flood flow decreases as the duration and magnitude of rain storms increase. Snowmelt floods may also be moderated by the desynchronizing effects of accelerated melt from openings in the forest. Forest influences on extreme runoff caused by exceptional meteorological conditions, however, will be negligible (Teller 1968). In short, forests do not prevent floods, but they probably provide the best conditions for minimizing flood runoff and damage.

The effects of forest harvesting on floods have seldom been observed in experimental watershed studies and therefore must be inferred. Forestry operations that increase surface runoff through soil disturbance or more severe soil freezing can result in increased flood flows and erosion from all types of runoff. In small watersheds, flood peaks can be increased and flood damage aggravated by road-diverted runoff and localized transport of soil and debris into stream channels from landslides caused by logging operations. Direct inputs of logging debris can also create or destabilize debris jams in streams, increasing the risk of damaging surges of water and debris that can occur when the jams break up during flood flows. However, extensive and severe soil disturbance and reductions in infiltration and subsequent erosion, such as caused by cultivation or overgrazing, are not generally a problem in the forested areas of Canada.

Forest removal, apart from soil disturbance effects, might increase flood flows from high-intensity summer rain showers in smaller watersheds by reducing soil water storage opportunity. However, harvesting will have little effect on flooding caused by major long-duration rainstorms. Except for extreme events, harvesting could increase floods involving snowmelt runoff by accelerating snowmelt from clearcut watersheds or by synchronizing the melting of snow in different parts of partially cut watersheds. In most larger watersheds, however, changes in forest cover are unlikely to affect downstream flooding significantly due to natural diversity of terrain and cover conditions (Hewlett 1982). An important Canadian exception is that of basins with northward flowing rivers. Accelerated spring snowmelt following forest harvesting in the more southerly portions of such watersheds could aggravate downstream flooding if breakup has not occurred in downstream reaches (Swanson 1972).

Popular Beliefs Reviewed

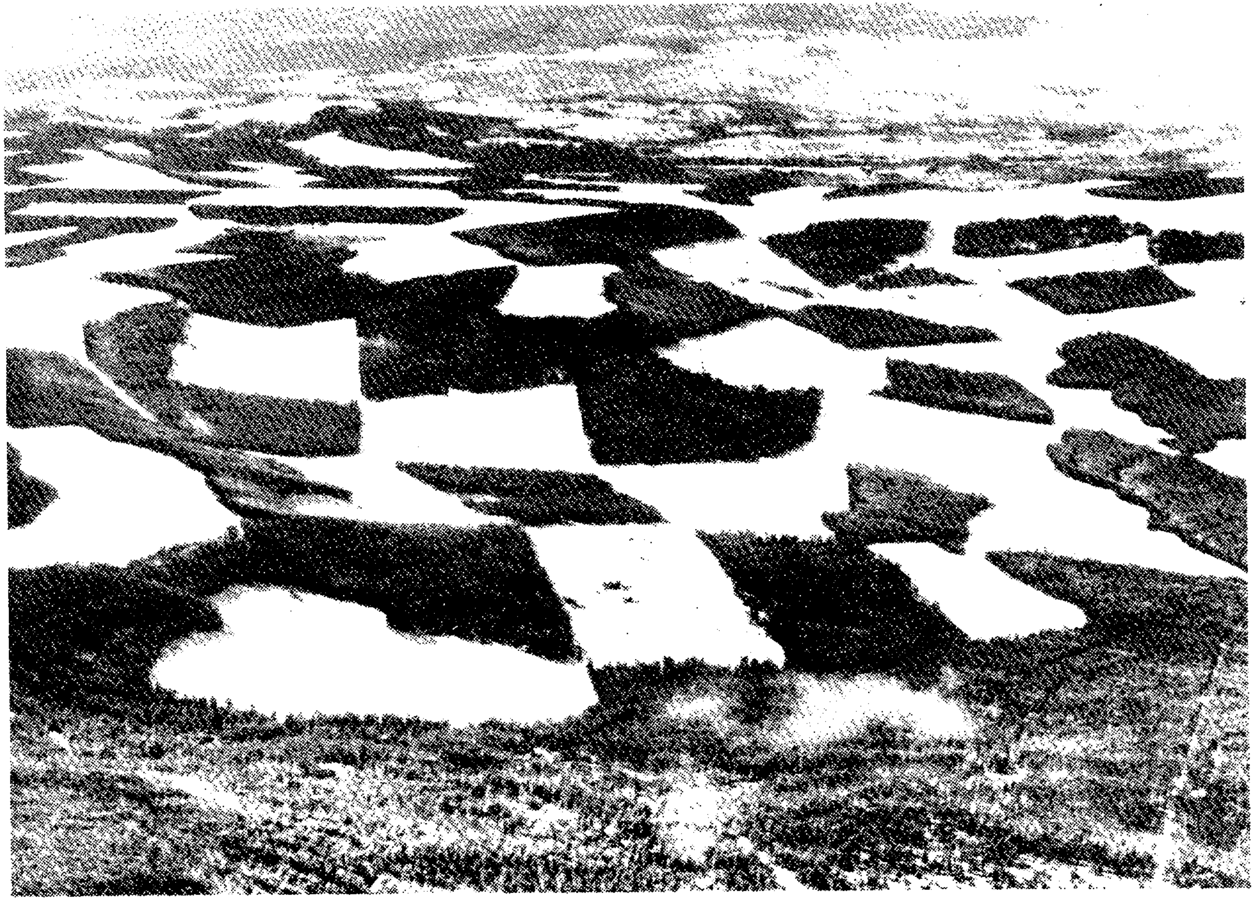
The view of forests as having positive effects on water is generally valid for healthy young or mature forests complete with undisturbed forest floor and soil. However, there are some constraints. Forests do help "regulate streamflow" by moderating spring snowmelt, but their efficacy in minimizing snowmelt peak flows can be enhanced by appropriately spaced openings in the forest cover. Forests probably provide the best cover for minimizing flood flows and damage, but they are not as effective in "protecting against floods," in the sense of preventing them as this statement implies. The role of the forest floor as a "sponge that reduces peak flows" will be minor in most areas because of limited water storage opportunity in the forest floor at the time of major runoff. With the exception of situations where trees trap wind-blown snow, forests do not "provide maximum runoff" nor are they the best cover for "sustaining summer flows." Forests are consumers rather than "conservers" of water.

The negative views of logging impacts on streamflow are mostly not substantiated. Rather than "drying up streams," harvesting usually increases summer flows and total annual runoff. The effect of earlier disappearance of snow from cleared areas on summer flows is offset by higher soil moisture reserves resulting from reduced evapotranspiration losses. Furthermore, logging, in general, does not "cause flooding." Most floods are caused by exceptional meteorological conditions. Logging may aggravate flood flows and flood damage in small watersheds through accelerated additions of soil and debris to stream channels. Harvesting might increase flood flows because of "greater snowmelt runoff from clearcuts," but flood peaks could also be reduced if this process leads to desynchronization of snowmelt runoff. In summary, forest harvesting does not cause floods, and its effects on downstream flooding are usually minor and most likely to be noticeable only in small watersheds.

Influence of Forests and Forestry Operations on Water Quality

A forest influences water quality by first modifying the chemistry of precipitation as it passes through forest vegetation and then as it moves through the soil. Trees bordering streams further affect water quality by providing shade, which moderates stream temperatures and rates of in-stream biological activity, and by furnishing inputs of leaves and other organic material. Streams draining from naturally forested lands generally contain few sediments or harmful chemicals. In some areas, however, there may be naturally high levels of deleterious substances such as mercury, or biological contamination by wildlife. Mean concentrations of most dissolved nutrients in forest streams are usually low (Feller and Kimmins 1984; Hetherington 1976; Krause 1983; Nicolson 1975; Singh and Kalra 1977). The high quality of forest stream water results from protection against erosion by the forest floor and high soil infiltration rates, soil stability provided by tree roots, the ability of forest soils to retain nutrients, and the modest organic decomposition and mineralization rates beneath forest canopies. Tree roots and logs from fallen trees also help maintain good stream water quality and desirable aquatic habitat by stabilizing stream banks and maintaining a network of pools and riffles in the channel (Toews and Moore 1982).

Forestry operations can modify the quality of stream water through direct inputs of sediment, debris, fertilizers, or pesticides, changing the rate of leaching of nutrients and other dissolved substances from the soil, and removal of streamside vegetation which allows warming of the water and subsequent biological and chemical changes (Freedman 1982; Krause 1982). Changes in water quality are most noticeable in small streams.



Conventional clearcut harvesting in patches increases water yields and modifies snowmelt runoff (R. H. Swanson, Canadian Forestry Service, Edmonton, Alta.).

Forests as Filters of Airborne Contaminants

Forest canopies are effective in collecting airborne contaminants in precipitation and in dry fallout from the atmosphere by filtering particles or moisture from air moving through the canopy and by adsorption of gases. The contaminants of current concern in North America are primarily those causing acid precipitation and acidification of streams and lakes. These include sulphur dioxide, sulphate, oxides of nitrogen, especially nitrate, hydrogen ions, and ammonium (Bangay and Riordan 1983). Other contaminants such as heavy metals, trace elements, and organic micropollutants have received considerably less attenion. Some elements, particularly nitrogen, are adsorbed by the foliage. The chemistry of precipitation is altered in passing through forest canopies by washing of deposited substances such as sulphate and leaching basic cations, primarily calcium, magnesium, and potassium, from the foliage (Morrison 1984). The resulting acidity of precipitation reaching the ground is lower in hardwoods than in the open (Foster 1984). Some conifers also lower the acidity of precipitation but to a lesser extent than most hardwoods (Mahendrappa 1983), while rainwater acidity remains unchanged or may be increased by other conifers (Foster 1984). The effect will vary with the acidity of the precipitation.

Forests soils are very important in determining the degree of protection from airborne contaminants provided water bodies by forests. Shallow, acidic soils with low basic cation content do little to modify the acidity of precipitation, while deeper soils rich in cations are highly effective in buffering or neutralizing water acidity (Foster 1984; Nicolson 1984). Soils neutralize acidic waters by exchanging basic cations for acidic cations. The result is increased leaching of calcium, magnesium, potassium, and sodium and enrichment of stream waters with these ions (Nicolson 1984). Sulphate plays an important role in cation leaching from soils low in iron and aluminum or high in organic matter, whereas soils high in iron and aluminum retain sulphate (Bangay and Riordan 1983; Foster and Nicolson 1984). As soils become more acidic, there is an increasing tendency for leaching of aluminum and manganese to occur (Bangay and Riordan 1983; Foster 1984). Nitrogen is retained by some forest soils as it is by forest canopies (Nicolson 1986) .

Sediment

Increased sediment input to streams is probably the biggest change in water quality associated with forestry operations. The three main sources of sediment in streams are surface erosion, mass soil failures (landslides), and stream bank erosion. Mineral soil is exposed to accelerated erosion through removal of the forest floor during road construction, log skidding, prescribed burning, and scarification. The major sources of sediment in most regions, however, are roads and skid trails because of the associated increase in surface runoff that causes erosion. Maximum sediment loads usually occur during construction of roads, particularly in wet weather, and reported measurements have ranged from about 200 mg/L in main streams to over 8000 mg/L in small tributaries (Krause 1982; Ottens and Rudd 1977; Rothwell 1977). Even after construction, roads continue to be sources of sediment, and concentrations from 30 to over 500 mg/L have been reported (Rothwell 1983; Slaney et al. 1977). Sediment amounts derived from soil disturbed by other forestry operations are generally lower than those from roads. More frequent landslides following logging are a major periodic source of sediment in the mountains of British Columbia. In-stream sediment production can also increase as a result of bank erosion caused by additions of logging debris and altered debris structures in the channel (Toews and Moore 1982), or the greater erosive power of increased peak flows resulting from logging.

Sediment levels can be reduced or controlled by such management practices as the use of buffer strips of vegetation along the margins of water bodies. These keep logging equipment away from streams and lakes and trap soil eroded from roads or other exposed soil, except where tributary streams or roads cross the strips (Plamondon 1982; Plamondon et al. 1976). Erosion control rehabilitation measures, such as revegetation of forest roadsides, also help speed up the reduction of sediment inputs to streams (Carr and Ballard 1980). Sediment concentrations in stream waters normally decline with time and can return to predisturbance levels within a year (Hetherington 1976). Where roads are the primary sediment source, however, sediment inputs could persist almost indefinitely. Even small increases in sediment loads may have important cumulative impacts on aquatic habitat, such as the covering or plugging of spawning and rearing gravel beds, which are harmful to the early life stages of fish (Jablonski 1980; Sabean 1978). Sediment trapped in gravel beds may also persist for considerable lengths of time.

Relatively high, short-term inputs of sediment to forest streams are possible anywhere in Canada. The conclusions of Krause (1982), however, regarding the overall potentials for stream sedimentation in Canada seem reasonable: high in the (coastal) mountains of British Columbia and the Alberta foothills, intermediate in the Rocky Mountain region, comparatively low in the Canadian Appalachians, and very low within the Canadian Shield, except for areas with fine-textured soils. During most logging operations some soil is disturbed and some increase in stream sediment levels is usually unavoidable. The belief that "logging silts up streams" therefore bears some truth. Requirements for minimizing deterioration of stream water quality or aquatic habitat by sediment include sound planning, sufficient resource data, careful and appropriate logging operations, suitable attention to road maintenance, and application of rehabilitation measures where necessary. In reality, these objectives are not always met, although improved management practices have reduced the frequency and extent of the damaging stream sedimentation of the past.

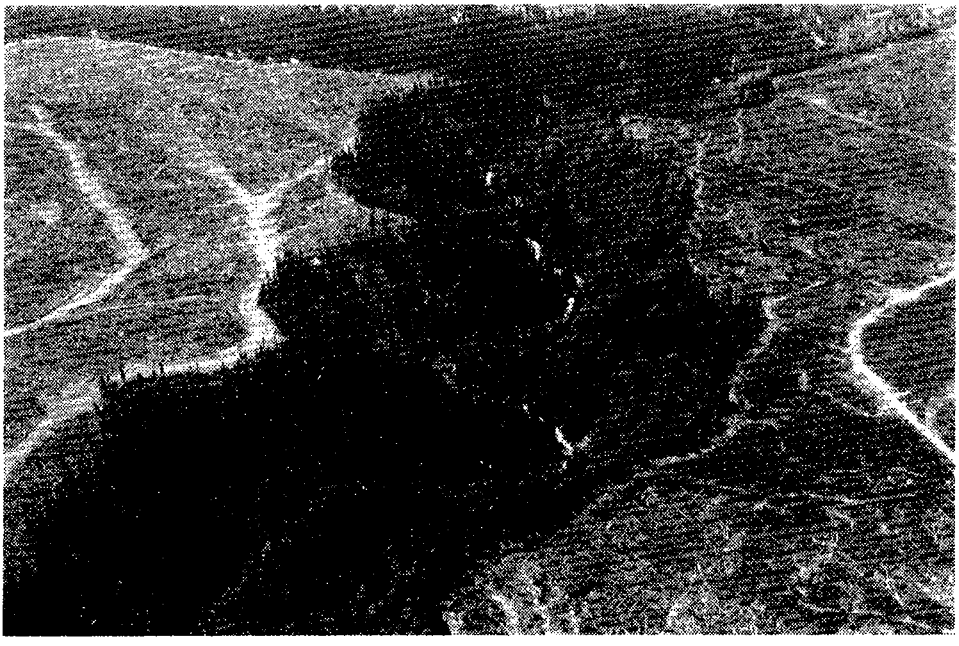
Water Chemistry

The chemistry of stream water is altered following forest harvesting and, to a greater degree, after prescribed burning or wildfire. The uptake of nutrients in vegetation is substantially reduced, decomposition of the forest floor is accelerated, and more water passes through the soil to leach these extra elements into streams. Both increased sediment and decreased leaf inputs can also affect water chemistry, while additions of organic debris can modify water quality and decrease dissolved oxygen levels as the debris decays. Changes in concentrations and total amounts of the following dissolved nutrients and chemical parameters have been measured in forest streams after harvesting or burning: calcium, magnesium, sodium, potassium, nitrogen, phosphorus, sulphate, chlorine, bicarbonate, organic substances, dissolved oxygen, colour, and pH (Feller and Kimmins 1984; Hetherington 1976; Krause 1983; Nicolson 1975; Plamondon et al. 1982; Schindler et al. 1980; Scrivener 1982; Singh and Kalra 1977). The responses have included increases, decreases, and no change in the various parameters. The changes in water chemistry and the effects of these changes, however, are usually minor. Maximum values seldom exceed drinking water standards and, then, only briefly. Decreases in dissolved oxygen could adversely affect fish. On the other hand, observed increases in dissolved nutrients will benefit nutrient-poor streams, like those in coastal British Columbia, by enhancing their biological productivity. In general, these changes in water chemistry are short-lived. Predisturbance conditions usually return within about 3-5 yr, although recorded changes have lasted as little as 1 yr in northern Ontario (Nicolson 1975) and as long as 9 yr in coastal British Columbia (Feller and Kimmins 1984).

Krause (1982) has drawn the following conclusions regarding dominant changes in water chemistry to be expected after forest harvesting in Canada: (1) increases in concentrations of calcium, magnesium, and bicarbonate in areas with conifers and soils with low acidity in British Columbia and the foothills of Alberta; (2) increases in concentrations of calcium, magnesium, sodium, potassium, and dissolved organic substances and a lowering of pH in areas with conifers and acid soils, particularly across the Canadian Shield; and (3) significant increases in nitrate-nitrogen in areas with shade-tolerant hardwoods in eastern Canada. There can, however, be considerable variability in water chemistry responses to watershed disturbance within any given region. In one west coast watershed, for example, concentrations of some nutrients that had shown initial increases or no change actually fell below preharvesting and burning levels between 2 and 8 yr later (Feller and Kimmins 1984).

Water Temperature

Once the shade of streamside trees is removed by harvesting or fire, streams are more exposed to the warming effects of the sun. In Canada, maximum summer water temperatures in small streams have increased after harvesting by up to 15° C, although most increases have been less than 10° C (Feller 1981; Holtby and Newcombe 1982; Nicolson 1975; Plamondon et al. 1982; Sabean 1977; Toews and Brownlee 1981). Shallow, slow-moving streams are more vulnerable to temperature increases than larger, deeper streams with higher flows. During winter, exposed streams could experience increased freezing and ice formation in areas where they do not normally freeze over. On the other hand, increases in winter stream water temperatures have been measured after harvesting in watersheds on the south coast of British Columbia (Feller 1981; Holtby and Newcombe 1982). Changes in water temperatures resulting from stream exposure pose little problem for most users of the water except fish. Temperature increases could be harmful to fish if streams are overheated in hotter interior regions of Canada (Toews and Brownlee 1981), but can be beneficial for fish through increased biological productivity in cool, nutrient-poor streams like those along the west coast (Holtby and Newcombe 1982). Shade given by streamside buffer strips is effective in minimizing changes in water temperatures (Plamondon et al. 1976). Furthermore, water that has been warmed in the open may be cooled upon reentering the shelter of the forest,



Buffer strips protect streams during logging and help maintain good water quality and a natural environment for fish and human enjoyment. (Pacific Forestry Centre, Victoria, B.C.).

although the reduction in temperature appears to result more from additions of cooler groundwater than from the effects of shade (Sabean 1977).

Recovery of predisturbance stream temperatures will depend on the length of time it takes for streamside vegetation to grow high enough to shade the stream. In one west coast watershed, summer water temperatures in one stream returned to prelogging levels 6-7 yr after clearcutting, but showed little decline in another stream 7 yr after both clearcutting and slashburning (Feller 1981). Winter temperature changes in the same streams lasted only 1-2 yr.

Fertilizers

The principal fertilizers used in forestry are the nitrogen fertilizers urea and ammonium nitrate. Streams can be temporarily enriched with nitrogen by direct inputs of fertilizer during aerial application or by entry of fertilizer or its breakdown products of ammonium or nitrate through surface runoff or subsurface flow (Table 4). For the most part, observed concentrations of fertilizer nitrogen have remained below acceptable limits set for public water supplies (Hetherington 1985), except for brief peaks of ammonium and, in the Nashwaak basin, of nitrate (University of New Brunswick 1976). Excess nitrogen from streams draining fertilized forest lands has the potential to unduly enrich downstream lakes, but any effects of excess nitrogen can be offset by limitations in other nutrients such as phosphorus (Perrin et al. 1984). On the other hand, nitrogen increases can enhance the biological productivity of otherwise nutrient-poor streams such as those on the west coast. By avoiding direct inputs of fertilizer to open water during application, the amounts of fertilizer nitrogen entering streams and lakes can be considerably reduced (Perrin et al. 1984).

TABLE 4. Maximum measured nitrogen concentrations and additional nitrogen in streams following forest fertilization in Canada.

	Fertilizer		Maximum concentration (mg N/L)				
Location	Type	Rate[a] (kg N/ha)	Urea	NH_4-N[b]	NO_3-N[c]	Total N[d] (%)	Reference
Coastal B.C. Lens Creek	Urea	224	14.0	1.90	9.30	14.5	Hetherington 1985
Mohun Lake Tributary	Urea	200	57.6	4.78	0.79	5.2	Perrin et al. 1984
Tributary[e]	Urea	200	0.66	0.47	0.19	2.1	Perrin et al. 1984
Montmorency, Que.	Urea	150	15.0	3.5	1.3	1.3	Gonzalez and Plamondon 1977
Nashwaak basin, N.B.	AN[f]	110		5.5	11.5	22	Univ. of N.B. 1976

[a] Rate of fertilizer application.

[b] Ammonium.

[c] Nitrate.

[d] Percentage of total nitrogen applied on the watershed that was lost in streamflow.

[e] Nonfertilized strip of forest was left along streams.

[f] Ammonium nitrate.

The duration of changes in stream water nitrogen following fertilization is variable. Urea is normally present in stream water for only a few days because it usually is rapidly converted into ammonium and nitrate. In one west coast stream, however, urea was detected up to 20 wk after application due primarily to cold temperatures and subsurface water flow through macrochannels in the soil (Perrin et al. 1984). Maximum ammonium concentrations are also usually observed at the time of fertilization, with lesser peaks occurring during rainstorms in the following few weeks. Ammonium increases lasted up to 6 wk in the two eastern streams and 12-20 wk on the west coast. Nitrate concentrations peaked during the first few rains in all streams listed in Table 4 and remained above background levels for up to 1 yr after fertilizer application in Lens Creek and the Nashwaak basin, but only for a few weeks in the other streams.

Pesticides

Forest pesticides are used primarily for suppression of unwanted deciduous vegetation (herbicides) to permit successful establishment of young conifers and for control of insects (insecticides) to protect existing forests. Pesticides are mostly applied by spraying from aircraft or from the ground, but some herbicides are injected directly into trees. The use of such chemicals often raises concerns over the risk of contaminating stream and potable waters. The most likely ways for pesticides to enter streams are by direct overspray and aerial drift during application. Secondary pathways or sources include entry by overland flow, subsurface leaching, leaf-fall, or accidental spills. Each chemical pesticide is unique in its properties, formulation, rate of breakdown, behaviour, and response in the environment. The other materials used in pesticide formulations may be much more harmful than the active ingredient itself. Any hazard associated with chemicals also results from both the amount (toxicity) and length of exposure to the chemical. Thus, while some generalities regarding pesticide impacts on the environment are possible, pesticides must be evaluated individually to obtain an accurate understanding of their effects and avoid erroneous conclusions. Because of environmental concerns about pesticides, strict federal and provincial regulations govern their registration, use, and application, including such measures as requiring unsprayed buffer zones around lakes, streams, and potable water sources.

Herbicides

The chemicals most commonly used now for forest weed control in Canada are phenoxy herbicides (e.g. 2,4-D) and glyphosate. These herbicides are applied infrequently on any given forest site, on average less than once every 40 yr. They may be used more often to clear roadside vegetation. Most herbicides decompose rapidly and do not accumulate in the environment (Toews and Brownlee 1981). Many are also strongly adsorbed on forest soils and are not readily leached.

Field evidence to date indicates that forestry uses of currently registered herbicides have not resulted in adverse effects on stream water or fish. Peak herbicide concentrations found in stream waters following operational applications have been low and transitory in nature (Wilson et al. 1983). Herbicides diminish to negligible levels within hours and disappear within days in stream water, although they may last from several days to several months on land before totally disappearing, depending on environmental conditions and chemical structure (Freedman 1982; Newton et al. 1984). Sublethal effects on fish such as impaired health, which might be caused by chronic exposure to low herbicide doses, have note been found. If streamside vegetation is killed by herbicides, aquatic habitat could be altered through changes in stream temperatures, reduction in terrestrial food supplies, and bank destabilization. However, precautions normally taken during spray applications minimize the risk of negative impacts of herbicides on aquatic resources (Freedman 1982).

Insecticides

Considerable research on the environmental effects of insecticides has been conducted in eastern Canada since the start of the spruce budworm spray program in the 1950's (Kingsbury 1984; Prebble 1975). The greatest use of insecticides has been in eastern Canada where fenitrothion, aminocarb, and the biological agent *Bacillus thuringiensis* var. *kurstaki (Btk)* are the principal insecticides employed for control of spruce budworm. Repeat application of these insecticides on any given area is much more likely than it is for herbicides. A few other chemicals are used to a lesser extent in British Columbia. Ongoing studies accompanying insecticide use have resulted in modifications to spray programs to minimize adverse effects. For example, both DDT, which was harmful to fish, and phosphamidon, which was harmful to birds, were eliminated from use during the 1960's and 1970's, respectively (Kingsbury 1984). Insecticides are normally distributed at very low concentrations (i.e. a few grams per hectare).

Field studies have indicated that operational spraying of fenitrothion and aminocarb has resulted in little effect on streams or fish. The greatest hazard is likely to come from mishandling of insecticides and their containers rather than from spraying. Concentrations of fenitrothion and aminocarb measured in streams after operational spraying have been substantially lower than levels that are toxic to fish (Morin et al. 1986). Both insecticides disappear rapidly from stream waters and usually disappear totally from the environment within a few days to a few weeks, depending on environmental conditions (Sundaram et al. 1984; Wilson et al. 1983). They also do not accumulate biologically. Where repeated insecticide applications take place, there is a risk of a gradual buildup of insecticides in the environment if the chemicals persist longer than the frequency of applications. However, no such long-term environmental accumulations have yet been documented for the insecticides in current use (Sundaram et al. 1984; Varty 1980).

Btk is a bacterial pathogen specific to caterpillars (Lepidoptera larvae), whose use in forest pest control has expanded rapidly in the 1980's. *Btk* is also applied in small amounts, and has been found to be of very low toxicity to fish and aquatic insects (Eidt 1985). It has lasted up to 100 d in water and several months in soil (Wilson et al. 1983), but is biologically inactive unless ingested by caterpillars. No adverse effects of *Btk* on aquatic life have been documented in the field.

Environmental Regulation of Forestry Operations

Forest management operations in Canada are governed by a variety of environmental regulations, many of which exist because of concern for water and fisheries resources. The primary objective of these regulations is to safeguard other resource values from adverse impacts resulting from forestry operations. The federal government, for example, is actively involved in enforcing sections of the *Federal Fisheries Act* aimed at protecting aquatic habitat and fish from possible damage resulting from such activities as forestry operations. All provinces have resource or environmental legislation which, while not necessarily addressed specifically at forestry, can be applied to forestry issues. The several laws and acts relating to stream protection in British Columbia are good examples (Dorcey et al. 1980; Toews and Brownlee 1981). At the operational level, regulations take the form of technical guidelines which specify the basic principles and procedures to be applied, such as those in Quebec (Gouvernement du Québec 1977). Resource agencies in most provinces have developed such guidelines which are implemented through interagency referral systems and incorporated into forestry use permits. In some areas, however, limitations in the capability of resource agencies to handle the large volume of forestry activity often restrict the effectiveness of these procedures. Although such practical limitations in applying some environmental regulations seem likely to persist, environmental concerns are being recognized and the level of dealing with them has improved across Canada in recent years.

Future Trends in Forest Hydrology in Canada

The next decade for forest hydrology in Canada is likely to be one of both consolidation and shift in emphasis. Forest hydrology research appears to be in a transition phase. At least two of the major experimental watershed projects are drawing to a close. The current level of research, including number of studies and researchers, will probably remain about the same, but with increasing emphasis on application of knowledge to operational watershed management (Swanson 1982). For the most part, activity will continue to focus on watershed protection. Fisheries-forestry interactions will continue to be a major focal point, primarily in relation to water quality and aquatic habitat. The demand for forest management techniques to enhance water supplies will increase because of increased need for supplies of high-quality water, increased awareness by water managers that forest and water management can be complementary, and more aggressive application of forest hydrology knowledge by hydrologists and watershed foresters.

The changing stress on forest lands will increase pressures on water resources and help focus forest hydrology attention and research. As forest harvesting continues to expand into increasingly more difficult terrain, related hydrologic problems will become more acute and the need for hydrologic input to management decisions ever more apparent. Logging in the steep, unstable mountainous terrain of British Columbia is one example. An upsurge in the management of wetlands for forestry, currently underway across central and eastern Canada, is another example. Drainage of these wetlands to improve the land for growing and planting trees significantly modifies their hydrologic regimes. Although wetlands are being studied (see chapter by T. H. Whillans in this volume), little is known about these changes and hydrologists will be increasingly called upon to investigate wetland hydrology.

A developing forestry initiative in Canada is renewal and rehabilitation of inadequately reforested land and more intensive management on highly productive forest lands. At the present time, about 10% of productive forest land in Canada is not satisfactorily reforested, and this amount has been increasing annually (Honer and Bickerstaff 1985). A renewal program has many implications for forest hydrology. Lands with minimal forest cover prolong hydrologic changes caused by harvesting or fire. Hydrologists will have an opportunity to apply their knowledge to help improve regeneration and growth of new forests (Swanson 1982) and recovery of hydrologic regimes. The concern over water quality will certainly increase, and with it, the need for hydrological input to help minimize undesirable impacts of forestry operations. Furthermore, more intensive forest management will mean more extensive road networks to maintain and a greater potential for stream sedimentation. The need to suppress or control brush in order to establish new coniferous forests on inadequately forested lands will be attended by a greater use of herbicides. Insecticides will continue to be used to ensure the survival of existing timber and of managed forest plantations. Greater use will be made of forest fertilizers to enhance tree growth in our more intensively managed forests. Fire suppression activity is also likely to increase to protect these expanded investments in Canada's forests. Each of these activities will provide an opportunity for forest hydrologists to help enhance compatible management and use of Canada's forest and water resources.

Conclusion

Our knowledge and understanding of forest hydrology and its application in Canada have advanced considerably since W. W. Jeffrey brought the subject to national attention in the 1960's. The information now available permits us to see more clearly the importance of forests in the hydrological regime. Forests and forestry operations have both positive and negative effects on stream water as perceived in relation to the fisheries resource and to human use and convenience. One of the chief values of forestry, which is often forgotten, is its role in maintaining and reestablishing healthy forests with all the positive benefits that this implies. For example, forest roads provide access for control of fire and insect damage, silvicultural improvement, recreation, and fish enhancement programs. Healthy forests with a mosaic of cover types enhance the value, use, and enjoyment of our water resources. The changing nature of our forested landscape will mean a need for continued and even expanded study and evaluation of forest-water relationships and a greater need to incorporate this knowledge into the management of both forests and water in Canada.

Acknowledgements

I gratefully acknowledge permission granted by my employer the Canadian Forestry Service to work on this chapter. The more detailed manuscript on which this chapter is based is planned for publication by the Canadian Forestry Service. I am indebted to R. B. B. Dickison, D. L. Golding, and R. H. Swanson for their reviews and to my many colleagues for their helpful comments.

References

ANDERSON, H. W., M. D. HOOVER, AND K. G. REINHART. 1976. Forests and water: effects of forest management on floods, sedimentation and water supply. U.S. For. Serv. Gen. Tech. Rep. PSW-18: 115 p.

BANGAY, G. E., AND C. RIORDAN [ED.]. 1983. United States - Canada memorandum of intent on transboundary air pollution. Impact Assessment Work Group I Final Report. Environment Canada, Ottawa, Ont. 626 p.

BEAUDRY, P. G. 1984. Effects of forest harvesting on snowmelt during rainfall in coastal British Columbia. M.F. thesis, Faculty of Forestry, University of British Columbia, Vancouver, B.C. 185 p.

BERNDT, H. W., AND G. W. SWANK. 1970. Forest land use and streamflow in central Oregon. U.S. For. Serv. Res. Pap. PNW-93: 15 p.

BETHLAHMY, N. 1974. More streamflow after a bark beetle epidemic. J. Hydrol. 23: 185-189.

BLACK, T. .A., C. S. TAN, AND J. U. NNYAMAH. 1980. Transpiration rate of Douglas fir trees in thinned and unthinned stands. Can. J. Soil Sci. 60: 625-631.

BOSCH, J. M., AND J.D. HEWLETT. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55: 3-23.

CALDER, I. R. 1982. Forest evaporation, p. 173-193. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

CARR, W. W., AND T. M. BALLARD. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. J. Soil Water Conserv. 35: 33-35.

CHAMBERLIN, T. W. 1972. Interflow in the mountainous forest soils of coastal British Columbia, p. 121-127. *In* H. O. Slaymaker and H. J. McPherson [ed.] Mountain geomorphology, B. C. Geographical Series No. 14, Tantalus Research Ltd., Vancouver, B.C.

CHENG, J. D. 1980. Hydrologic effects of a severe forest fire, p. 240-251. *In* Proc. Symp. Watershed Management, Boise, Idaho. American Society of Civil Engineers, New York, NY.

CHENG, J. D., T. A. BLACK, J. DE VRIES, R. P. WILLINGTON, AND B. C. GOODELL. 1975a. The evaluation of initial changes in peak streamflow following logging of a watershed on the west coast of Canada, p. 475-486. *In* Proc. Tokyo Symp. IASH Publ. No. 117.

CHENG, J. D., T. A. BLACK, AND R. P. WILLINGTON. 1975b. The generation of stormflow from small forested watersheds in the Coast mountains of southwestern British Columbia, p. 542-551. *In* Proc. Can. Hydrol. Symp. — 77. National Research Council of Canada, Ottawa, Ont.

1977. The stormflow characteristics of a small, steep and forested watershed in the Coast mountains of southwestern British Columbia, p. 300-310. *In* Proc. Can. Hydrol. Symp. — 77. National Research Council of Canada, Ottawa, Ont.

COHEN, S. J. 1977. Land use changes on micro-climate in central Alberta: an energy balance study. M.Sc. thesis, Department of Geography, University of Alberta, Edmonton, Alta. 263 p.

Daugharty, D. A. 1984. The effects of topography and forest cover on snow depths and water equivalents in the Nashwaak experimental watersheds, New Brunswick. M.Sc.F. thesis, Faculty of Forestry, University of New Brunswick, Fredericton, N.B. 256 p.

Daugharty, D. A. and R. B. B. Dickison. 1982. Snow cover distribution in forested and deforested landscapes, p. 10-19. *In* Proc. 50th Western Snow Conf., Reno, NV.

Dickison, R. B. B., and D. A. Daugharty. 1982. The effects on snowmelt runoff of the removal of forest cover, p. 131-150. *In* Proc. IHP Fourth Northern Research Basin Symp. Workshop, Ullensvang, Norway. Norw. Natl. Comm. Hydrol. Rep. No. 12, Oslo, Norway.

1983. Climate and water balance, p. 8-14. *In* G. R. Powell [ed.] Nashwaak Experimental Watershed Project Annu. Rep. 1981-1982. Department of Natural Resources, Forestry Branch, Fredericton, N.B.

Dickison, R. B. B., D. A. DAUGHARTY, and D. K. Randall. 1981. Some preliminary results of the hydrologic effects of clearcutting a small watershed in central New Brunswick, p. 59-75. *In* Proc. 5th Can. Hydrotech. Conf., Fredericton, N.B. Canadian Society of Civil Engineers.

Dorcey, H. J., M. W. McPhee, and S. Sydneysmith. 1980. Salmon protection and the B.C. coastal forest industry: environmental regulation as a bargaining process. Westwater Res. Centre, University of British Columbia, Vancouver, B.C. 378 p.

Eidt, D. C. 1985. Toxicity of *Bacillus thuringiensis* var. *kurstaki* to aquatic insects. Can. Entomol. 117: 829-837.

Federer, C. A., R. S. Pierce, and J. W. Hornbeck. 1972. Snow management seems unlikely in the northeast, p. 212-219. *In* Proc. Symp. Watersheds in Transition. American Water Resources Association, Urbana, IL.

Feller, M. C. 1981. Effects of clearcutting and slashburning on stream temperature in southwestern British Columbia. Water Resour. Bull. 17: 863-867.

Feller, M. C., and J. P. Kimmins. 1984. Effects of clearcutting and slash burning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resour. Res. 20: 29-40.

Foster, N. W. 1984. Neutralization of acid precipitation within a deciduous forest, p. 143-148. *In* Proc. TAPPI Res. and Dev. Conf., Appleton, WI.

Foster, N.W., and J. A. Nicolson. 1984. Acid precipitation and water quality within a tolerant hardwood stand and soil, p. 337-342. *In* Speeches and Papers, Forest Resources Management, the Influence of Policy and Law. Int. For. Cong., Quebec, P.Q.

1986. Ion transfer through a tolerant hardwood canopy, Turkey Lakes watershed, Ontario. *In* Proc. Acid Rain and Forest Resources Conf., 1983. Quebec, P.Q. (In press).

Frechette, J.-G. 1968. Accumulation de la neige sous divers types de couverts forestiers. Cah. Géogr. Qué. 12: 141-144.

1969. Interception de la pluie par une sapinière laurentienne. Nat. Can. 96: 523-529

Freedman, B. 1982. An overview of the environmental impacts of forestry, with particular reference to the Atlantic provinces. Institute for Resources and Environmental Studies, Dalhousie University, Halifax, N.S. 219 p.

Giles, D. G., T. A. Black, and D. L. Spittlehouse. 1985. Determination of growing season soil water deficits on a forested slope using water balance analysis. Can. J. For. Res. 15: 107-114.

Golding, D. L. 1980. Calibration methods for detecting changes in streamflow quantity and regime, p. 3-7. *In* Proc. Helsinki Symp. IAHS Publ. No. 130.

1981. Hydrologic relationships in interior Canadian watersheds, p. 107-115. *In* D. M. Baumgartner [ed.] Proc. Symp. Interior West Watershed Management. Coop. Ext., Washington State University, Pullman, WA.

1982. Snow accumulation patterns in openings and adjacent forest, p. 91-112. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

Golding, D. L., and C. R. Stanton. 1972. Water storage in the forest floor of subalpine forests of Alberta. Can. J. For. Res. 2: 1-6.

Gonzalez, A., and A. P. Plamondon. 1977. Urea fertilization of natural forest: effects on water quality. For. Ecol. Manage. 1: 213-221.

Gouvernement du Québec. 1977. Guide d'aménagement du milieu forestier. Ministère des Terres et Forêts, Québec, Qué. 158 p.

Granberg, H. B. 1973. Indirect mapping of the snowcover for permafrost prediction at Schefferville, Quebec, p. 113-120. *In* PERMAFROST: The North American Contribution to the Second International Conference, National Academy of Sciences, Washington, DC.

Haag, R. W., and L. C. Bliss. 1974. Functional effects of vegetation on the radiant energy budget of boreal forest. Can. Geotech. J. 11: 374-379.

Harlan, R. L. 1969. Soil-water freezing, snow accumulation and ablation in Marmot Creek experimental watershed, Alberta, Canada, p. 29-33. *In* Proc. 37th Western Snow Conf., Salt Lake City, UT.

Harr, R. D. 1983. Potential for augmenting water yield through forest practices in western Washington and western Oregon Water Resour. Bull. 19: 383-393.

Helvey, J. D. 1972. First-year effects of wildfire on water yield from mountain watersheds in north-central Washington, p. 308-312. *In* Proc. Symp. Watersheds in Transition. American Water Resources Association, Urbana, IL.

Hetherington, E. D. 1976. Dennis Creek, a look at water quality following logging in the Okanagan Basin. Can. For. Serv. Inf. Rep. No. BC-X-147: 33 p.

1982. Effects of forest harvesting on the hydrologic regime of Carnation Creek experimental watershed: a preliminary assessment, p. 247-267. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

1985. Streamflow nitrogen loss following forest fertilization in a southern Vancouver Island watershed. Can. J. For. Res. 15: 34-41.

Hewlett, J. D. 1982. Forests and floods in the light of recent investigation, p. 543-559. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

Holtby, B., and C. P. Newcombe. 1982. A preliminary analysis of logging-related temperature changes in Carnation Creek, British Columbia, p. 81-99. *In* G. F. Hartman [ed.] Proc. Carnation Creek Workshop, a 10 year review. Pacific Biological Station, Nanaimo, B.C.

Honer, T. G., and A. Bickerstaff. 1985. Canada's forest area and wood volume balance 1977-1981: an appraisal of change under present levels of management. Can. For. Serv. Inf. Rep. BC-X-272: 84 p.

Jablonski, P. D. 1980. Pretreatment water quality of the TriCreeks experimental watershed. Alta. Energy Nat. Resour., For. Land Use Branch, Watershed Manuscr. Rep. No. 7: 67 p.

Jeffrey, W. W. 1967. Forest hydrology research in Canada, p. 21-30. *In* W. E. Sopper and H. W. Lull [ed.] Proc. Int. Symp. For. Hydrol. Pergamon Press, Oxford.

1968a. Snow hydrology in the forest environment, p. 1-19. *In* Snow Hydrology, Proc. Workshop Seminar, Fredericton. Can. Natl. Comm. Int. Hydrol. Decade, Ottawa, Ont.

1968b. Watershed management problems in British Columbia: a first appraisal. Water Resour. Bull. 4: 58-70.

1970. Hydrology of land use. *In* D. M. Gray [ed.] Handbook on the principles of hydrology. Sect. XIII. 57 p. Can. Natl. Comm. Int. Hydrol. Decade, National Research Council of Canada, Ottawa, Ont.

Kachanoski, R. G., and E. de Jong. 1982. Comparison of the soil water cycle in clearcut and forested sites. J. Environ. Qual. 11: 545-549.

Kingsbury, P. D. 1984. Environmental impact assessment of insecticides used in Canadian forests, p. 365-376. *In* W. Y. Garner and J. Harvey, Jr. [ed.] Chemical and biological controls in forestry. American Chemical Society, Washingon, DC.

Kondo, E. S., and R. G. Taylor. 1984. Forest insect and disease conditions in Canada 1983. Environment Canada, Canadian Forestry Service, Ottawa, Ont. 73 p.

Krause, H. H. 1982. Effect of forest management practices on water quality — a review of Canadian studies, p. 15-29. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

1983. Effect of clearcutting on stream-water quality and nutrient balance, p. 15-17. *In* G. R. Powell [ed.] Nashwaak Experimental Watershed Project Annu. Rep. 1981-1982. New Brunswick Department of Natural Resources, Forestry Branch, Fredericton, N.B.

Mahendrappa, M, K. 1982. Effects of forest cover type and organic horizons on potential water yield, p. 215-224. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

1983. Chemical characteristics of precipitation and hydrogen input in throughfall and stemflow under some eastern Canadian forest stands. Can. J. For. Res. 13: 948-955.

Mahendrappa, M. K., and D. G. O. Kingston. 1982. Prediction of throughfall quantities under different forest stands. Can. J. For. Res. 12: 474-481.

Martin, H. C. 1971. Average winds above and within a forest. J. Appl. Meteorol. 10: 1132-1137.

McCaughey, J. H. 1978. Energy balance and evapotranspiration estimates for a mature coniferous forest. Can. J. For. Res. 8: 456-462.

1981. Impact of clearcutting of coniferous forest on the surface radiation balance.

J. Appl. Ecol. 18: 815-826.

1985. Energy balance storage terms in a mature mixed forest at Petawawa, Ontario — a case study. Boundary-Layer Meteorol. 31: 89-101.

McMinn, R. G. 1960. Water relations and forest distribution in the Douglas-fir region on Vancouver Island. Can. Dep. Agric. For. Biol. Div. Publ. 1091, Ottawa, Ont.

McNaughton, K. G., and T. A. Black. 1973. A study of evapotranspiration from a Douglas fir forest using the energy balance approach. Water Resour. Res. 9: 1579-1590.

Meeres, L. S. 1977. A preliminary study of changes in wind structures produced by a commercial-appearing cut in a mature forest, p. 220-236. *In* R. H. Swanson and P. A. Logan [ed.] Proc. Symp. Alberta Watershed Research Program. Can. For. Serv. Inf. Rep. NOR-X-176.

Meyboom, P. 1967. Groundwater studies in the Assiniboine River drainage basin Part II: Hydrogeologic characteristics of phreatophytic vegetation in south central Saskatchewan. Geol. Surv. Can. Bull. 139: 64 p.

Moore, G. C. 1983. A report on the feasibility of harvesting timber within buffer zones: a literature review. New Brunswick Department of Natural Resources, Fredericton, N.B. 138 p.

Morin, R., G. Gaboury, and G. Mamarbachi. 1986. Fenitrothion and aminocarb residues in water and balsam fir foliage following spruce budworm spraying programs in Quebec, 1979 to 1982. Bull. Environ. Contam. Toxicol. 36: 622-628.

Morrison, I. K. 1984. Acid rain, a review of literature on acid deposition effects in forest ecosystems. Commonw. For. Bur. For. Abstr. 45: 483-506.

Morton, F. I. 1984. What are the limits on forest evaporation? J. Hydrol. 74: 373-398.

1985. What are the limits on forest evaporation — reply. J. Hydrol. 82: 184-192.

Newton, M., K. M. Howard, B. R. Kelpsas, R. Danhaus, C. M. Lottman, and S. Dubelman. 1984. Fate of glyphosate in an Oregon forest ecosystem. J. Agric. Food Chem. 32: 1144-1151.

Nicolson, J. A. 1975. Water quality and clearcutting in a boreal forest ecosystem, p. 733-738. *In* Proc. Can. Hydrol. Symp. — 75. National Research Council of Canada, Ottawa, Ont.

1984. Ion concentrations in precipitation and streamwater in an Algoma maple-birch forest, p. 123-135. *In* Proc. Can. Hydrol. Symp. No. 15, 1984. National Research Council of Canada, Ottawa, Ont.

1986. Ion movement in terrestrial basins in the Turkey Lakes forest watershed. *In* Proc. Acid Rain and Forest Resources Conf., 1983, Quebec, P.Q. (In press).

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* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

O'Kane, T. 1983. The effect of clearcutting on the forest albedo..B.Sc.F. thesis, University of New Brunswick, Frederiction, N.B. 40. p.

Ottens, J., and J. Rudd. 1977. Environmental protection costs in logging road design and construction to prevent increased sedimentation in the Carnation Creek watershed. Can. For. Serv. Inf. Rep. BC-X-155: 28 p.

Payette, S., L. Filion, and J. Ouzilleau. 1973. Relations neige-végétation dans la toundra forestière du Nouveau-Québec, Baie d'Hudson. Nat. Can. 100: 493-508.

Perrin, C. J., K. S. Shortreed, and J. G. Stockner. 1984. An integration of forest and lake fertilization: transport and transformations of fertilizer elements. Can. J. Fish. Aquat. Sci. 41: 253-262.

Petzold, D. E., and A. N. Rencz. 1975. The albedo of selected subarctic surfaces. Arct. Alp. Res. 7: 393-398.

Plamondon, A. P. 1981. Écoulement et modification du couvert forestier. Nat. Can. 108: 289-298.

1982. Augmentation de la concentration des sédiments en suspension suite à l'exploitation forestière et durée de l'effet. Can. J. For. Res. 12: 883-892.

Plamondon, A. P., T. A. Black, and B. C. Goodell. 1972. The role of hydrologic properties of the forest floor in watershed hydrology, p. 341-348. *In* Proc. Symp. Watersheds in Transition. American Water Resources Association, Urbana, IL.

Plamondon, A. P., A. Gonzalez, and Y. Thomassin. 1982. Effects of logging on water quality: comparison between two Quebec sites, p. 49-70. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

Plamondon, A. P., and M. M. Grandtner. 1975. Microclimat estival d'une sapinière à *Hylocomium* de la forêt Montmorency. Nat. Can. 102: 73-87.

Plamondon, A. P., R. Leprohon, and A. Gonzalez. 1976. Exploitation forestière et protection de quelques cours d'eau de la Côte Nord. Les Cahiers de Centreau. Vol. 1, No. 6. Université Laval, Québec, Qué. 43 p.

Plamondon, A. P., and D. C. Ouellet. 1980. Partial clearcutting and streamflow regime of ruisseau Eaux-Volées experimental basin, p. 129-136. *In* Proc. Helsinki Symp. IAHS Publ. No. 130.

Plamondon, A. P., M. Prevost, and R. C. Naud. 1984a. Accumulation et fonte de la neige en milieu boisé et déboisé. Géogr. Phys. 38: 27-35.

1984b. Interception de la pluie dans la sapinière à bouleau blanc, forêt Montmorency, Can. J. For. Res. 14: 722-730.

Prebble, M. L. [ed.] 1975. Aerial control of forest insects in Canada. Environment Canada, Ottawa, Ont. 330 p.

Price, A. G., and L. K. Hendrie. 1983. Water motion in a deciduous forest during snowmelt. J. Hydrol. 64: 339-356.

Price, A. G., L. K. Hendrie, and T. Dunne. 1978. Controls on the production of snowmelt runoff, p. 257-268. *In* S. C. Colbeck and M. Ray [ed.] Proc. Modeling of Snow Cover Runoff. U.S. Army Cold Reg. Res. Eng. Lab., Hanover, NH.

Price, J. S., and J. E. FitzGibbon. 1982. Winter hydrology of a forested drainage basin, p. 347-360. *In* Proc. Can. Hydrol.Symp. '82. National Research Council of Canada, Ottawa, Ont.

Rothwell, R. 1977. Suspended sediment and soil disturbance in a small mountain watershed after road construction and logging, p. 285-300. *In* R. H. Swanson and P. A. Logan [ed.] Proc. Symp. Alberta Watershed Research Program. Can. For. Serv. Inf. Rep. NOR-X-176.

1982. Water balance of a boreal forest wetland site, p. 313-332. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

1983. Erosion and sediment control at road-stream crossings. For. Chron. 59: 62-66.

Rouse, W. R. 1976. Microclimatic changes accompanying burning in subarctic lichen woodland. Arct. Alp. Res. 8: 357-376.

1984. Microclimate at arctic treeline. 1. Radiation balance of tundra and forest. Water Resour. Res. 20: 57-66.

Rowe, J. S. 1972. Forest regions of Canada. Can. For. Serv. Publ. No. 1300. Ottawa, Ont. 172 p.

Sabean, B. 1977. The effects of shade removal on stream temperature in Nova Scotia. CAT/77/135/150. Nova Scotia Department of Lands and Forests, Halifax, N.S. 31 p.

1978. Sediment: a preliminary investigation of the problem in Nova Scotia streams. Unpubl. Rep. Nova Scotia Department of Lands and Forests, Halifax, N.S. 12 p.

Sahi, S. V., and G. M. Courtin. 1983. Anthropogenic reduction in overstory tree canopy as a critical factor in cryopedogenesis, p. 177-179. *In* Proc. 40th Eastern Snow Conf., Toronto, Ont.

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

Schneider, J., and G. R. Ayer. 1961. Effect of reforestation on streamflow in central New York. U.S. Geol. Surv. Water-Supply Pap. 1602: 61 p.

Scrivener, J. C. 1982. Logging impacts on the concentration patterns of dissolved ions in Carnation Creek, British Columbia, P. 64-80. *In* G. F. Hartman [ed.] Proc. Carnation Creek Workshop, a 10 year review. Pacific Biological Station, Nanaimo, B.C.

Silversides, R. H. 1978. Forest and airport wind speeds. Atmos.-Ocean 16: 293-299.

Singh, B., and G. Szeicz. 1979. The effect of intercepted rainfall on the water balance of a hardwood forest. Water Resour. Res. 15: 131-138.

Singh, T. 1983. A proposed method for preliminary assessment of erosion hazards in west-central Alberta. Can. For Serv. Inf. Rep. NOR-X-251: 17 p.

Singh, T. and Y. Kalra. 1977. Impact of pulpwood clearcutting on stream water quality in west central Alberta, p. 272-284. *In* R. H. Swanson and P. A. Logan [ed.] Proc. Symp. Alberta Watershed Research Program. Can. For. Serv. Inf. Rep. NOR-X-176.

Slaney, P. A., T. G. Halsey, and A. F. Tautz. 1977. Effects of forest harvesting practices on spawning habitat of stream salmonids in the Centennial Creek watershed, British Columbia. B.C. Fish Wildl. Branch, Fish. Manuscr. Rep. No. 73. Vancouver, B.C. 45 p.

Smith, R. B., and E. F. Wass. 1982. Changes in ground-surface characteristics and vegetative cover associated with logging and prescribed broadcast burning, p. 100-108. *In*

G. F. Hartman [ed.] Proc. Carnation Creek Workshop, a 10 year review. Pacific Biological Station, Nanaimo, B.C.

SPITTLEHOUSE, D. L. AND T. A. BLACK. 1981. A growing season water balance model applied to two Douglas fir stands. Water Resour. Res. 17: 1651-1656.

STANTON, C. R. 1966. Preliminary investigation of snow accumulation and melting in forested and cut-over areas of the Crowsnest forest, p. 7-12. *In* Proc. 34th Western Snow Conf., Seattle, WA.

SUNDARAM, K. M. S., P. D. KINGSBURY, AND S. B. HOLMES. 1984. Fate of chemical insecticides in aquatic environments: forest spraying in Canada, p. 253-276. *In* W. Y. Garner and J. Harvey, Jr. [ed.] Chemical and biological controls in forestry. American Chemical Society, Washington, DC.

SWANSON, R. H. 1972. Forest hydrology in Canada — more water probably not wanted, p. 4301-4304. *In* Proc. 7th World For. Cong., Vol. III, Buenos Aires, Argentina.

1975. Water use by mature lodgepole pine, p. 264-277. *In* D. M. Baumgartner [ed.] Proc. Symp. Management of Lodgepole Pine Ecosystems, Vol. 1. Coop. Ext. Serv., Washington State University, Pullman, WA.

1978. Increasing water supply through watershed management. Can. Water Resour. J. 3: 85-93.

1980. Surface wind structure in forest clearings during a chinook, p. 26-30. *In* Proc. 48th Western Snow Conf., Laramie, WY.

1982. Problems and opportunities in Canadian forest hydrology, p. 1-13. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

SWANSON, R. H., AND D. L. GOLDING. 1982. Snowpack management on Marmot watershed to increase late season streamflow, p. 215-218. *In* Proc. 50th Western Snow Conf., Reno, NV.

SWANSON, R. H., AND G. R. HILLMAN. 1977. Predicted increased water yield after clearcutting verified in west-central Alberta. Can. For. Serv. Inf. Rep. NOR-X-198: 40 p.

SWANSON, R. H., AND D. R. STEVENSON. 1971. Managing snow accumulation and melt under leafless aspen to enhance watershed value, p. 63-69. *In* Proc. 39th Western Snow Conf., Billings, MT.

SZEICZ, G., D. E. PETZOLD, AND R. G. WILSON. 1979. Wind in the subarctic forest. J. Appl. Meteorol. 18: 1268-1274.

TELLER, H. L. 1968. Impact of forest land use on floods. Unasylva 22: 18-20.

TOEWS, D. A. A., AND M. J. BROWNLEE. 1981. A handbook for fish habitat protection on forest lands in British Columbia. Department of Fisheries and Oceans, Vancouver, B.C. 172 p.

TOEWS, D. A. A., AND M. K. MOORE. 1982. The effects of three streamside logging treatments on organic debris and channel morphology of Carnation Creek, p. 129-152. *In* G. F. Hartman [ed.] Proc. Carnation Creek Workshop, a 10 year review. Pacific Biological Station, Nanaimo, B.C.

TOEWS, D. A. A., AND D. WILFORD. 1978. Watershed management considerations for operational planning on T.F.L. #39 (Blk 6A), Graham Island. Fish. Mar. Serv. Manuscr. Rep. No. 1473. Vancouver, B.C. 32 p.

UNIVERSITY OF NEW BRUNSWICK. 1976. Nashwaak Experimental Watershed Project. Annu. Rep. 1975-1976, p. 17-19. Faculty of Forestry, Fredericton, N.B.

VARTY, I. W. 1980. Summary overview of environmental surveillance in 1978 and 1979, p. 1-4. *In* I. W. Varty [ed.] Environmental surveillance in New Brunswick 1978-1979: effects of spray operations for forest protection against spruce budworm. Faculty of Forestry, University of New Brunswick, Fredericton, N.B.

WEETMAN, G. F. 1983. Forestry practices and stress on Canadian land, p. 259-301. *In* W. Simpson-Lewis, R. McKechnie, and V. Neimanis [ed.] Stress on land in Canada. Environment Canada, Lands Directorate, Ottawa, Ont.

WILFORD, D. J., AND J. W. SCHWAB. 1982. Soil mass movements in the Rennell Sound area, Queen Charlotte Islands, British Columbia, p. 521-541. *In* Proc. Can. Hydrol. Symp. '82. National Research Council of Canada, Ottawa, Ont.

WILSON, R. C. H., W. R. ERNST, G. JULIEN, AND S. E. HALL. 1983. Brief to the Nova Scotia Royal Commission of Forestry. Vol. II, Sect. 3. Environment Canada, Environmental Protection Service, Halifax, N.S. 148 p.