Discussion Paper

BC Journal of Ecosystems and Management

Overview of the potential effects of forest management on low flows in snowmelt-dominated hydrologic regimes

Robin G. Pike[1] and Rob Scherer[2]

Abstract

This paper reviews potential effects of forest management on low flows in snowmelt-dominated hydrologic regimes. The hydrologic response of low flows to forest management was found to be highly variable in magnitude, time, and space. Forest management generally increases water volume—no case studies relevant to snowmelt-dominated regimes reported a decrease in water quantity as a result of forest harvesting. In areas where fog drip occurs, a decrease in water volume contributing to low flows might be observed. The longevity of increased water quantity is infrequently discussed in the literature specific to snowmelt-dominated regimes. A few authors, however, have commented on expected longevity of response based upon analysis of literature not specific to snowmelt-dominated regimes. These authors generally report a return to pre-treatment low flow levels within 3–6 years with the re-establishment of vegetation.

The review identifies many knowledge, research, and extension needs. Knowledge of low flows is hampered by an incomplete understanding of generation processes, particularly those relating to subsurface flow, evapotranspiration, and the interrelated effects of forest practices and climate change. Forest management is only one of many human activities that can potentially affect a watershed's hydrologic regime. Because natural processes and human activities occur simultaneously, studying the sole effects of forest management on low flows is difficult. Limitations in low flow science around measurement methodologies, scaling of results, and inadequate research design are noted.

KEYWORDS: *low flow, forest management, forest harvest, snowmelt dominated, streamflow, British Columbia Interior, literature review, literature synthesis.*

Contact Information

1 Watershed Management Specialist, FORREX–Forest Research Extension Partnership, Suite 702, 235 1st Avenue, Kamloops, BC V2C 3J4. E-mail: robin.pike@forrex.org

2 Watershed Management Specialist, FORREX–Forest Research Extension Partnership, c/o Okanagan University College, 3333 College Way, Kelowna, BC V1V 1V7. E-mail: rob.scherer@forrex.org

Introduction

Conflicts between water withdrawals and instream uses are prominent in some watersheds in British Columbia during low flow periods of late summer and early fall. Knowledge of the influence that human activities may have on water quantity is critical in areas where streams are in a state of water shortage and (or) possess high fishery values. Conflicts over water shortages often stem from public concerns about forest harvesting effects on low flows. Forest management, however, is only one of several human activities that can potentially affect a watershed's hydrologic regime. A common perception of many natural resource managers and the public is that timber harvesting causes streams to dry up. Uncertainty around which human activities have an appreciable influence on streamflow, however, can lead to ineffective and inefficient management policies. Inadequate knowledge of low flow processes further complicates the issue. An important starting point in addressing this uncertainty is to synthesize scientific information on the topic to create a solid basis from which management can be tailored to local conditions.

This discussion paper provides:

- information on low flow hydrology;
- an overview of the potential effects of forest management on low flows in snowmelt-dominated regions; and
- a summary of knowledge, research, extension, and management needs.

This paper is an adapted portion of a detailed report produced by Scherer and Pike (2003), and includes information gathered at a technical workshop held on November 21, 2002. The Scherer and Pike (2003) report focuses on information needs relevant to the Okanagan Basin: low flows, water yield, and peak flows. Their report also introduces other watershed management issues including climate change, groundwater, assessment methodologies, water quality, scaling, and cumulative effects. Key points and recommendations pertaining to low flows generated from the workshop participants (see listing at the end of this article) are incorporated into this paper. However, readers are encouraged to refer to the Scherer and Pike (2003) document for a more comprehensive review of the effects of forest management on water quantity.

Low Flow: Background

In areas where most annual precipitation falls as snow to form a snowpack, watersheds are described as snowmelt-dominated. Peak flows in these regimes generally occur in the spring, and are defined as the maximum instantaneous discharge (maximum stage) or the maximum daily discharge (Figure 1). Peak runoff often occurs between April and mid-July as a result of melting snowpacks primarily from higher portions of a basin. In the British Columbia Interior, "this is commonly based on the location of the H60 line—defined as that elevation above which 60% of the watershed

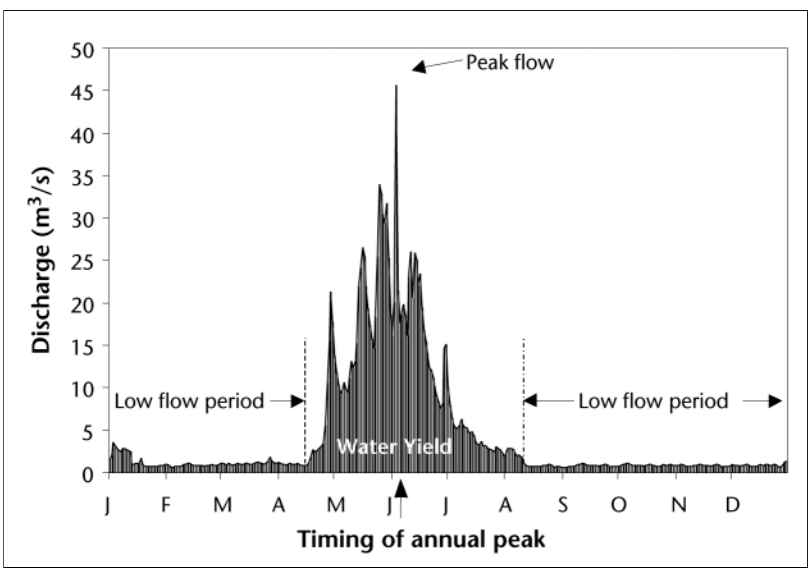

FIGURE 1. Typical annual snowmelt-dominated hydrograph. Data source: Environment Canada, Mission Creek, B.C.

lies . . . " (B.C. Ministry of Forests 2001, p. 28). The area above the H60 line is often used to denote the "source area" for peak flows (Gluns 2001) although other values can be used if justified (B.C. Ministry of Forests 2001).

Low flows are often defined as minimum flow or absence of flow in a stream during the dry season; however, no standard definition has been adopted in the literature. Unlike instantaneous peak flows, low flows are continuous and are often characterized by time period (e.g., lowest average flow over a 7-day period each year). Smakhtin (2001) details the many different methods of analyzing low flows, including percentage of mean annual runoff (MAR), percentage of mean daily flow, flow duration curves, recession analysis, and baseflow separation.

Low flows are often defined as minimum flow or absence of flow in a stream during the dry season; they are a normal part of the yearly water cycle, and are sometimes confused with drought.

In snowmelt-dominated regimes, low flows typically occur from late summer through the winter until spring snowmelt (Figure 1). Low flows are a normal part of the yearly water cycle. Drought is sometimes confused with the concept of low flows, but is distinct in that drought is a climatic trend resulting from abnormally low precipitation. Low flows are maintained in the dry season through the release of water from groundwater storage and (or) surface water discharge from melting glaciers, lakes, wetlands, and flow from channel banks (Smakhtin 2001). The low flow period ceases once spring freshet occurs with the melting of winter snow.

Low Flow Variability and Generation

Low flows are naturally variable in time and space due to the complex interaction and heterogeneity of watershed characteristics. During the dry season, many natural processes control low flow generation, including:

> *the distribution and infiltration characteristics of the soils, the hydraulic characteristics and extent of aquifers, the rate, frequency and amount of recharge, the evapotranspiration rates from the basin, distribution of vegetation types, topography and climate* (Smakhtin 2001, p. 149).

In addition, human activities can both increase and decrease low flows. Although this paper focuses on forest management, many other activities concurrent to forestry can affect low flows, including the following as discussed by Smakhtin (2001):

- groundwater withdrawals;
- drainage of valley bottom soils for agriculture or construction;
- changes to vegetation communities through clearing or planting leading to modification of evapotranspiration loss;
- urbanization through the creation of impervious surfaces;
- direct river withdrawals;
- irrigation return flow;
- industrial discharge;
- importation of water from outside of the catchment; and
- dams and impoundments.

Since low flows are a product of many natural processes and human activities that occur simultaneously in a watershed, studying the sole effects of forest management on low flow quantity can be difficult.

Importance

Low flows are a concern to watershed managers for various reasons. Water levels can be critical to fish passage, dictate the amount and quality of habitat available for fish, and ultimately determine fish survival. Low water levels can be detrimental to aquatic habitat and can dramatically affect the distribution of organisms dependent upon that habitat. Low water levels also limit the amount of water that can be withdrawn for human and agricultural activities, ultimately affecting development and other commercial activities. The importance of low flows varies with the seasons (i.e., winter, late summer, and fall) and with demands for water by people and aquatic life. While low flows are important, changes to other aspects of the streamflow regime following forest harvesting or disturbance are also important to consider (i.e., peak flows and channel stability).

Low Flow Monitoring

Measurement of low flows may be challenging or even impossible under certain conditions. For example, gauging low flows in the summer with a current meter may be difficult when flow conditions are close to zero or where inadequate flow limits sampling locations. Specifically, problems with current metering at low water levels include:

- streamflow velocities that approach or are below the meter's stall speed,
- insufficient depth of water to submerge the meter to the required depth, and
- insufficient stream width to sample an adequate number of vertical sections (D. Moore, University of British Columbia, pers. comm., 2003).

Instream structures designed for continuous measurement of higher streamflow conditions may also be inadequate and affect data quality (e.g., precision). Monitoring winter streamflow can be problematic when partially frozen stream conditions and ice formation make measurements unreliable—under these conditions, the stage–discharge relationship of any monitored stream will likely be unreliable. To deal with measurement problems under partially frozen conditions, agencies such as Water Survey Canada and the U.S. Geologic Survey often interpolate from as few as 2–3 observations during ice-covered conditions (Hamilton *et al.* 2000; Moore *et al.* 2002). It is essential that monitoring limitations are acknowledged before low flow measures are incorporated into management decisions.

Forest Management Effects on Hydrologic Processes

Low flows are the end result of many complex, interlinked hydrologic processes. While some processes reduce water quantity, others increase the amount of water available for streamflow. Unfortunately, a lack of information relevant to snowmelt-dominated regimes prohibits a systematic review of the effects of forest management by hydrologic process. It is important to understand these effects at least conceptually, however, to put research results presented later in this paper into context.

The following section presents basic concepts on the effects of forest management on individual hydrologic processes. A more comprehensive review can be found in Hetherington (1987). Where possible, conceptual ideas have been supported by references to research results. Hydrologic processes discussed include evapotranspiration, interception, snow processes, and infiltration.

Evapotranspiration

Evapotranspiration is a term used to denote the combined "loss" (return) of water to the atmosphere through evaporation and transpiration. Interception is also integral to these processes, yet is often treated separately (as below). Evaporation can occur from the soil surface, falling precipitation, water bodies, and vegetation surfaces. Transpiration is the movement of water from the ground through plant leaves (stomata) into the atmosphere. Transpiration rates vary according to levels of radiant energy, soil moisture, humidity, wind, and stomatal resistance imposed by vegetation. Many studies have demonstrated variability in daily growing-season transpiration rates. For the various tree species that can be found in the British Columbia Interior, daily transpiration rates are generally less than 3 mm of water per day (Table 1).

Forest cover directly affects "rates of transpiration, evaporation, soil freezing and patterns of snow accumulation and melt" (Hetherington 1987, p. 183). Changes in forest cover through harvesting activities can thus modify processes that control water balance in space and

TABLE 1. Transpiration rates for various forest stands (adapted from Doyle 1991)

Reference	Location	Vegetation type	Daily growing season transpiration rates (mm)	Remarks
Kaufmann (1984)	Colorado	Engelmann spruce Subalpine fir Lodgepole pine	2–3 up to 1 0.1–0.3	
Kaufmann *et al.* (1987)	Colorado	Aspen	0.1–0.3	Limited data
Knight (1987)	Wyoming	Lodgepole pine	3.3	Unlimited soil moisture
Cermak and Kucera	Czechoslovakia	Spruce Pine Hardwoods Willow	1.5 0.5 3 > 3	
Federer (1973)	New Hampshire	Hardwoods	3	
Roseboom and Figliuzzi (1986)	Saskatchewan	Riparian phreatophytes	150 m^3/day per km of channel length	50 m wide zone of phreatophytes

time. Timber harvesting decreases evapotranspiration amounts generally leading to increased soil water levels and, subsequently, increased streamflow during the growing season (Satterlund and Adams 1992).

When considering the potential effects of forest management on evapotranspiration, one must consider where the low flow source area is located. Several studies have demonstrated the effects of riparian vegetation on daily transpiration rates as reflected in streamflow. In one study, Hicks *et al.* (1991) identified reductions in low flows in two basins, 8 years and 15 years after timber harvesting. Reductions were attributed to changes in riparian vegetation, from coniferous to deciduous tree species along the stream channel. Deciduous trees most likely use more water than conifers in the summer for equivalent leaf areas (Hicks *et al.* 1991). In another experiment, Berndt (1971) documented the effects of a wildfire on streamflow in three research watersheds in the east Cascades. Prior to wildfire, streamflow oscillated daily as a result of transpiration from vegetation rooted in the streamside capillary fringe. After the wildfire, only minor daily oscillations were observed. The end result was that vegetation removal through wildfire leads to "general elevation of flow rates above extended normal depletion curves" (Berndt 1971, p. 7).

Forest harvesting differs from wildfire in the way it removes vegetation. Wildfire commonly affects the landscape in a non-contiguous manner and can indiscriminately burn riparian areas. Forestry, on the other hand, generally prescribes riparian reserves with zero to limited vegetation removal. Riparian areas are important to consider as they usually coincide with low flow source areas that could be affected the most by changes in evapotranspiration. Changes occurring in these areas will conceptually have a greater effect on flow than will activities in non-source areas of a watershed. Yet, in the British Columbia Interior, a dearth of information exists on differential transpiration rates from different forest biogeoclimatic zones and land covers at different seral stages.

Interception

As a process, interception is the interruption of the downward movement of precipitation and its redistribution. As an amount, interception is usually expressed in millimetres per year that are returned to the atmosphere. In most cases, interception denotes a "loss" of water, as temporarily stored rain or snow on vegetation surfaces evaporates before reaching the forest floor. Timber harvesting alters interception by removing intercepting surfaces of the forest canopy, thereby resulting in greater amounts of precipitation reaching the forest floor where exposure to evaporative forces is lower. Forest harvesting (including road construction) also increases the amount of solar radiation reaching the ground. Increased solar energy affects other hydrologic processes such as snowmelt, evapotranspiration, and soil freezing. Consequently, in affecting interception, forest harvesting generally results in more water available to contribute to soil moisture and (or) streamflow (Hetherington 1987).

In coastal areas, where occult precipitation (fog drip) exists, forest harvesting can reduce interception and lead to decreased water quantity. Fog drip is water from the atmosphere (fog) that is collected or deposited on vegetation surfaces and subsequently falls to the ground once vegetation storage capacities are exceeded. In studying this process, Harr (1982) attributed a reduction in low flows to a reduction in fog drip processes in coastal watersheds. Prior to timber harvesting, summer fog that was intercepted by the forest canopy subsequently dripped onto the forest floor and contributed to low flows. Upon removal of the forest canopy, the process of fog drip was eliminated, thereby reducing a source of water for summer flows (Harr 1982). Hence, in areas where occult precipitation is present, removal of vegetation can have a negative impact on water balance. Most hydrologists do not consider fog drip to be a major low flow generation mechanism in the British Columbia Interior. A few hydrologists, however, have raised the question of whether fog drip could offset evapotranspiration losses in montane areas.

Snow Processes

Alteration of the forest canopy can influence the accumulation and redistribution of snow and, subsequently, melt characteristics (Golding and Swanson 1986; Troendle *et al.* 1988; Hardy and Hansen-Bristow 1990; Winkler 1999). The effects of forest management on snow processes are complex and varied. Yet these effects are important to understand, as snowmelt can be an important source of water for low flows. In general, forest management can result in greater accumulations of snow in small openings (vs. the forest) yet larger openings can actually retain less snow due to greater exposure to winds and sublimation (Golding and Swanson 1986; Toews and Gluns 1986). Snowmelt in openings is generally faster than in an adjacent forest and some researchers suggest this contributes to an advancement in peak flow. However, in relation to low flows, no literature was located that analyzed changes in snow accumulation and melt and its direct effect on low flow generation.

Infiltration

Forests influence the routing and storage characteristics of water in a watershed. Water that reaches the ground's surface will either infiltrate the soil or move over its surface. Infiltration is the rate at which water enters the soil matrix. Most forest soils readily absorb water and as a result, surface runoff (overland flow) rarely occurs outside of stream channels in forested areas (Hetherington 1987). As noted, lower "losses" of water, as a result of forest harvesting, generally lead to higher moisture levels in the soil matrix due to higher amounts of available precipitation. The result is typically higher water tables in cleared areas, although the upper layers of the soil may appear drier due to increased evaporation.

Road building and other activities that cause soil disturbance can locally reduce infiltration and increase interception of surface and subsurface flow. If connected to the natural drainage network of a watershed, roads may then lead to quicker delivery of runoff to stream networks in certain hydrologic regimes. Conceptually, if ditchline and road surface interception leads to accelerated water delivery, this could potentially lead to lower low flows (and higher peak flows) as a result of some water bypassing the normal routing pathways. The potential effect of road interception, however, will vary according to road density, location, construction, maintenance, hydrologic regime, and other site factors.

The creation of persistent hydrophobic (non-wettable) soil conditions can also influence infiltration in a watershed. Many forest soils naturally exhibit hydrophobic characteristics when dry. However, this characteristic generally decreases once soil moisture is increased. Wildfire, on the other hand, may create more persistent hydrophobic conditions by partially volatilizing organic compounds that move down through the soil profile and condense onto cooler soil surfaces thereby creating a water repellent layer (McNabb and Swanson 1990; Wondzell and King 2003). The creation of prolonged hydrophobic conditions is important to consider as it may lead to decreased infiltration rates that affect soil and groundwater recharge. Hydrophobic conditions may also lead to decreased soil evaporation levels "as the capillary forces necessary to move water to the soil surface are lessened" (Debano 1981, p. 10). In areas where hydrophobic conditions form in the Pacific Northwest, Beschta (1990) noted that these layers are usually destroyed within the first few rainfalls following the wildfire. Dyrness (1976), however, observed increased water repellency that persisted for 5 years after a wildfire. Further discussion of the longevity and concept of hydrophobicity can be found in Wondzell and King (2003).

Overall, forest management can affect various hydrologic processes in a watershed. Evapotranspiration and interception losses associated with removal of the forest cover are the primary mechanism for increasing water available to contribute to low flows. Forest harvesting normally reduces evapotranspiration and interception "losses" by "eliminating transpiration and evaporation from the elevated canopy" (Hetherington 1987, p. 186). This generally leads to increased soil moisture conditions and less storage capacity, resulting in more water available for streamflow.

Literature Overview: Forest Management Effects on Low Flows

This review focuses on literature relevant to snowmelt-dominated regimes. Literature was selected if the study watershed met the following criteria developed by Scherer (2001):

- predominantly covered with coniferous forest types, such as lodgepole pine, Engelmann spruce, Douglas-fir, white fir, subalpine fir, ponderosa pine, and grand fir; and
- located within central British Columbia, east side of the Rocky Mountains in Alberta, eastern Washington, eastern Oregon, Utah, Idaho, Colorado, or Arizona.

At the start of the review, we attempted to divide the literature into three categories following an approach used by Reiter and Beschta (1995):

1. timber harvesting (removal of trees through clear-cut, patch cut, selection harvest, etc.);
2. road construction, maintenance, and deactivation; and
3. silviculture activities (re-establishment and tending activities, such as site preparation, prescribed burning, spacing and thinning, brushing and weeding, and tree planting).

The aim was to analyze forest management effects by specific activity. However, consistent with comments by Reiter and Beschta (1995) and Gucinski *et al.* ([editors]

2001), no studies could be identified that examined the sole influence of roads or silviculture activities on low flows. We found that studies generally group roads, silviculture, and timber harvesting together to derive an overall comment on the impact of forest management on water quantity. This grouping likely occurs as it is nearly impossible to study the exclusive effects of these activities (i.e., silviculture generally is preceded by harvesting). In addition, roads are generally constructed either concurrently or only for a short time before harvest, thereby precluding any sort of long-term (> 2 year) study. As such, this review could not determine the sole influence of roads or silviculture on low flows from the literature.

In our review of forest management's overall effect on low flows, we identified eight research studies that matched the literature-search criteria (Table 2). Four studies identified increased low flow volumes (lower number of low flow days) subsequent to timber harvesting, while the four remaining studies found non-significant or no change in low flows. None of the studies relevant to snowmelt-dominated hydrologic regimes documented a reduction in low flows (lower water volumes). Similar to Austin (1999), only general trends in the changes in low flows are presented due to the variety of low flow definitions used in the literature, which prevents detailed comparison of low flows through frequency analysis (i.e., calculation of return intervals).

Austin's work demonstrates that, in most forest types, the overriding trend is for streamflow to increase during the low flow period after forest harvesting.

The above findings are consistent with results obtained by Austin (1999) in that author's extensive review of peak flow and low flow changes as influenced by timber harvesting in snow- and rain-dominated hydrologic regimes in the United States. In summary, 16 of the studies identified an increase in low flows (increased water volume), 10 studies identified no change or non-significant change in low flows, while only two studies (Harr 1982; Hicks *et al.* 1991) identified a decrease in low flows. Because most of these studies are not representative of snowmelt-dominated regimes, Austin's research is not entirely applicable. Specifically, only three out of the 28 studies reviewed by Austin overlap with our review of snowmelt-dominated regimes: Fowler *et al.* (1987), King (1989), and King and Tennyson (1984). Nevertheless, Austin's work demonstrates that, in most forest types, the overriding trend is for streamflow to increase during the low flow period after forest harvesting. Austin concluded that:

- low flows (quantity) typically increase after harvesting,
- changes in low flows are highly variable and difficult to analyze statistically, and
- low flows rarely decrease in quantity.

Further confirmation of the general increase in summer low flows following logging can be found in Johnson's (1998) review of forestry impacts on low flows in the United Kingdom and other international studies. Johnson's review (1998) presents four main conclusions:

1. Clearcutting increases low flows, especially in the growing season, due to reduced interception and transpiration losses.
2. The magnitude of increase in low flows depends on seasonal rainfall and the amount of a forested watershed that is clearcut. Johnson suggests that 25% of a watershed's forest cover needs to be removed (i.e., clear-felled) for changes in low flows to be observed.
3. As forests grow, rates of interception and evapotranspiration increase, resulting in reduced soil moisture in forest soils. This change subsequently results in reduced low flows, especially in the summer when transpiration rates are highest.
4. Quantifying potential changes in low flows is difficult given differences in climatic and watershed factors and in forest practices.

Note that in Austin's review, two studies (Harr 1982; Hicks *et al*. 1991) reported lower water quantity after forest harvesting. These studies, however, were both from coastal rain-dominated regimes in northwestern Oregon (described previously).

Longevity of Effects

The longevity of increased water quantity after forest harvesting or natural disturbance is not generally addressed in the literature because long-term studies on low flows are rare (Reiter and Beschta 1995). In the snowmelt-dominated literature reviewed, most studies

TABLE 2. Summary of low flow data

Study	Author (yr)	Forest type	Drainage area (km^2)	Annual streamflow (mm)	Elevation range (m)	Average annual precip. (mm)	Aspect	Forest cover removed (%)	Harvest method[a]	Post-treatment study (yr)	Average low flow increase (%)	Average low flow increase (mm)
Camp Creek, southern British Columbia	Cheng (1989)	Primarily lodgepole pine	33.9	140	1070–1920	600	S	30	CC	6	38.4 (Aug.) 8 (Sept.) 14 (Oct.) 23.7 (Nov.) 18.5 (Dec.) 0.8 (Jan.) 16.5 (Feb.)	1.68 (Aug.) 0.27 (Sept.) 0.50 (Oct.) 0.76 (Nov.) 0.54 (Dec.) –0.15 (Jan.) 0.41 (Feb.)
Watershed 1, 2, 3 northeast Oregon	Fowler *et al.* (1987)	Grand fir, subalpine fir, larch, lodgepole pine, Douglas-fir	0.29 0.24 1.18	N/A	1439–1617	1429	NE	43 50 22	CC SW CC, PC	6	Not significant for any basin	Not significant for any basin
Thomas Creek, central Arizona	Gottfried (1991)	Mixed conifers	2.27	82	2545–2789	768	S	13	PC, CC	8	47.3 ± 11.0 (winter streamflow) 43.2 ± 51.3 (summer streamflow)	3 ± 3 (summer streamflow)
Horse Creek, north-central Idaho[b] Basins 8, 10, 12, 14, 16, 18	King (1989); King and Tennyson (1984)	Grand fir, western redcedar	8: 1.48 10: 0.65 12: 0.84 14: 0.62 16: 0.22 18: 0.86	~ 440	8: 1521 10: 1521 12: 1574 14: 1596 16: 1659 18: 1664	1168	8: SE 10: SE 12: S 14: S 16: S 18: S	8: 3.7[b] Due to roads/harvest 10: 2.6 12: 3.9/36.6 14: 1.8/29.2 16: 3.0/25.0 18: 4.3/33.4	CC	5	Not significant for any basin	Not significant for any basin

TABLE 2. *(Continued)*

Study	Author (yr)	Forest type	Drainage area (km^2)	Annual streamflow (mm)	Elevation range (m)	Average annual precip. (mm)	Aspect	Forest cover removed (%)	Harvest method[a]	Post-treatment study (yr)	Average low flow increase (%)	Average low flow increase (mm)
Bowron River, central British Columbia	Wei and Davidson (1998)	Lodgepole pine	3590	N/A	N/A	N/A	Variable	25	CC	14–30	0 (summer 7-day low flow) 0 (winter 7-day low flow)	0 (summer 7-day low flow) 0 (winter 7-day low flow)
Cabin Creek, Alberta, Eastern Rockies	Swanson *et al.* (1986)	Engelmann spruce, subalpine fir	2.12	310	1730–2750	840	N–NE	21	CC	8	4.0 (Aug.) 10.8 (Sept.) 11.3 (Oct.) 15.6 (Nov.) 1.3 (Dec.) 1.1 (Jan.) 1.2 (Feb.)	1.1 (Aug.) 3.0 (Sept.) 1.6 (Oct.) 1.3 (Nov.) 0.1 (Dec.) 0.1 (Jan.) 0.1 (Feb.)
Fool Creek, Colorado Rockies	Troendle and King (1985)	Spruce, fir, lodgepole pine	2.89	42	2927–3810	732	N	40	Strip cuts (1–6 tree heights wide)	30	0 (July, Aug., and Sept.)	0 (July, Aug., and Sept.)
Coon Creek, south-central Wyoming	Troendle *et al.* (2001)	Engelmann spruce, subalpine fir, lodgepole pine	16.73	N/A	2682–3322	870	W	24	Small CC (1.2–4 ha)	5	14 (Aug.) 20 (Sept.)	3 (Aug.) 3 (Sept.)

[a] CC = clear cut; PC = partial cut; SW = shelterwood.

[b] Information summarized by Austin (1999).

were carried out for no more than 8 years after timber harvesting. The two studies that examined longer time horizons (i.e., Troendle and King 1985; Wei and Davidson 1998) reported no changes in low flows 14–30 years after harvesting. It is therefore difficult to draw conclusions about longevity of effects in snowmelt-dominated regimes. However, a few authors have been able to comment on the subject of longevity based on analysis of literature not specific to snowmelt-dominated regimes. Austin's (1999) extensive work concluded that low flows generally return to pre-treatment levels approximately 3–4 years after logging. In Johnson's review (1998), low flows were estimated to return to pre-treatment levels approximately 6 years after logging. Austin (1999) noted that the longevity of increased low flows (increased quantity) is generally less than for expected changes in annual water yield, while Hetherington's 1987 literature review concluded that the expected duration of change is similar to water yield and varies depending upon rate of revegetation (3–30 years).

Natural Disturbance and Climate Change

Natural disturbances, such as insect epidemics and wildfires, influence the hydrologic role of forests. In the literature reviewed, we found three studies that addressed low flow changes associated with beetle epidemics or wildfire (Table 3). All of these studies reported an increase in low flows.

While not extensively researched for this paper, climate change is an important factor that influences low flows in a watershed. Conceptually, this makes sense, as factors that affect the recharge component (water input) in a watershed ultimately define the upper limit of water that is available for streamflow (i.e., changes in glacial melt rates, changes in seasonal precipitation totals, and snowmelt). While a significant amount of research has been conducted on climate change in regards to water quantity in the last 10 years (P. Whitfield, Environment Canada, pers. comm., 2002), no literature on the interacting effects of climate change and forest management on low flows was located for this review.

Leith and Whitfield's 1998 study provides useful insight on the topic of climate change and low flows. In the British Columbia Interior, Leith and Whitfield (1998) studied six watersheds in isolation of the confounding influences of land use (i.e., forest harvesting). In summary, their research demonstrated an "earlier onset of snowmelt runoff followed by an increasingly long and dry summer, with the possibility of water shortages in late summer" (Leith and Whitfield 1998, p. 230). Increases in winter streamflows observed in the study were attributed to a greater percentage of rain falling versus snow accumulation during this season. Hence, while research tells us that forest management may increase low flows, Leith and Whitfield's study suggests that climate change is having the opposite effect on summertime streamflow.

Because climate change often spans decades, modelling scenarios are frequently used to investigate questions around future trends. However, climate models do not always agree with one another. Specifically, while precipitation volumes have generally increased 125 mm over the last 100 years in the Okanagan, climate models are not in agreement on the direction of change for summertime precipitation (Cohen and Kulkarni [editors] 2001). Unfortunately, the uncertainty in the direction and magnitude of projected changes confounds the use of modelling results for decision making.

Overall, the effects of climate change and natural variation on water quantity are not mutually exclusive from the effects of forest management and other land-use activities. Thus, it is critical to acknowledge the complexity of low flow generation processes and confounding factors affecting those processes when attempting to quantify the overall status of low flows in any watershed.

Does Logging Dry Up Streams?

Our review shows that current scientific literature does not support the common perception that timber harvesting causes streams to dry up. Brooks *et al.* (1997) and Hetherington (1987) also reached this conclusion. The belief that timber-harvesting activities dry up streams likely stems from perception rather than physical measurement of changes in streamflow. In some cases, observations of changes in streamflow may actually be observations of changes in stream channel characteristics. For example, even if low flows remain the same or increase, buildup of gravel (aggradation in deposition zones) could result in flow becoming subsurface (Hetherington 1987). Yet other factors, such as climate variability (i.e., drought), climate change, other land uses, and natural agents of change, have a combined impact on observable water quantity and stream channel characteristics and are thus important to consider.

TABLE 3. Summary of changes in low flows associated with insect epidemics and wildfire

Watershed	Author (yr)	Forest type	Drainage area (km2)	Annual stream-flow (mm)	Elevation (m)	Average annual precip. (mm)	Aspect	Forest cover removed (%)	Cause of forest vegetation loss	Years of study after post-treatment (yr)	Low flow increase (%)	Average low flow increase (mm)
White River, Colorado	Bethlahmy 1975)	Engelmann spruce, subalpine fir	1974	N/A	N/A	N/A	W	30	Beetle epidemic (no harvest)	20	9.6 (Oct. flow)	1.6 (Oct. flow)
Yampa River, Colorado	Bethlahmy (1975)	Engelmann spruce, subalpine fir	1564	N/A	N/A	N/A	N	30	Beetle epidemic (no harvest)	20	31.4 (Oct. flow)	1.25 (Oct. flow)
Palmer Creek, southern British Columbia	Cheng and Bondar (1984)	Douglas-fir, lodgepole pine, Engelmann spruce, subalpine fir	18	71	1400–1750	1000	E	50	Severe forest fire	10	37 (Aug.–Nov.) 68 (Oct. flow)	N/A
Jack Creek, Montana	Potts (1984)	Lodgepole pine	133	305	1900–3000	347	W	~ 26	Beetle epidemic (no harvest)	5	N/A	10 (fall and winter)

Management Application and Next Steps

Many resource managers recognize that understanding local watershed condition is more important than sole reliance on generalized rules of thumb. In any management decision, science generally provides the foundation from which watersheds, hydrologic processes, and the interaction with human activities can be understood. While some generalizations on low flows may be used at face value, most are qualitative and need to be used in proper context. An illustration of this point is the generalization that timber harvesting increases water quantity available for streamflow. Yet, application of this "rule" might be in error in a coastal watershed where fog drip augments low flows. In this example, science provides the foundation for understanding yet it is up to the watershed manager to evaluate whether local watershed characteristics contradict any hydrologic generalization.

Various limitations in snowmelt-dominated case studies may detract from the successful creation of rules of thumb. These limitations include:

- Case studies based upon forest practices of the past may be limited for use in addressing current forest practices that occur under more stringent regulations (e.g., riparian reserves, rate of cut limitations).
- Comparisons between case studies are often limited due to unclear low flow definitions, different definitions, or definitions that do not match the intended application.
- Scaling of results from small watersheds (i.e., catchment areas < 10 km^2) to larger planning units may be problematic due to differing hydrologic processes at work.
- Studies that do not report detecting statistically significant change (no effect) may not accurately reflect whether a true hydrologic change has occurred.
- Studies not specifically designed to research low flows may have inadequate research design and (or) measurement methodologies.

Overall, while rules of thumb may be desired and successfully created, management should never wholly rely on a rule without understanding the system being managed.

Next Steps

Knowledge, research, and extension needs were defined through the compilation of this paper and the technical workshop held November 2002. Addressing these points will enhance understanding of hydrologic processes and, subsequently, improve management practice in relation to low flows in snowmelt-dominated regimes. The following needs are recommended starting points in future work related to low flows and forest management.

Knowledge Gaps

Several knowledge gaps became apparent through the literature review and workshop. These gaps primarily revolve around limited study in the topics of roads, groundwater, and evapotranspiration.

Information on the impacts of roads on low flows in snowmelt-dominated regimes was limited. The effect of road construction, maintenance, and deactivation on watershed functioning is a complex, highly variable, and some say poorly understood science. For the most part, researchers generally group the effects of roads and silviculture within the corresponding timber harvesting study to derive an overall comment on the impact of forest management on low flows. Conceptually, whether roads appreciably affect low flows is debatable, as response will differ depending on a watershed's hydrologic regime (i.e., snowmelt-dominated or rain-dominated) and storm history.

Several knowledge gaps became apparent through the literature review and workshop, and primarily revolve around the topics of roads, groundwater, and evapotranspiration.

> *The hydrological effects of roads depends on several factors, including the location of roads on hillslopes, characteristics of the soil profile, subsurface water flow and groundwater interception, design of drainage structures (ditches and culverts) that affect the routing of flow through the watershed, and proportion of the watershed occupied by roads* (Gucinski *et al.* [editors] 2001, p. 19).

Information regarding the effects of forest management on groundwater quantity and groundwater processes was also limited. Brooks *et al.* (1997) discuss the common perception that forest management's effect on groundwater quantity should be small based on the tenet that forest management affects only a small proportion (recharge area) of any aquifer at any one time. They note that groundwater recharge areas are vast and aquifers typically do not respond quickly or noticeably to small changes in recharge. Therefore, they conclude, changes in evapotranspiration and infiltration through forest management could be considered minor compared with natural changes in climate and precipitation. In the British Columbia Interior, there is a need for better understanding of how groundwater varies year to year and how water withdrawals interact with forest management and low flows.

We did not find any studies relevant to British Columbia Interior watersheds that examined potential differences in transpiration and evaporation rates between forest stands of different age classes. No case studies linked hydrologic response of forest management practices to stand type as represented by biogeoclimatic zone (e.g., Engelmann Spruce–Subalpine Fir, Sub-Boreal Spruce, Interior Douglas-fir). Furthermore, none of the case studies we reviewed addressed the long-term (> 40 years) trends of forest management effects on low flows (e.g., longevity or trends in low flows as a result of successive harvest rotations within a watershed). Information on evapotranspiration of a more localized nature may be important in the management of specific parts of British Columbia Interior watersheds that contribute to low flow generation (i.e., source areas).

Research Needs

Research is needed to address the above knowledge gaps, as well as the following priorities related to low flow science.

- We need a better understanding of hydrologic processes across the landscape (e.g., hillslope to valley) and the linkage between groundwater and surface water from the cutblock to the stream network.
- Long-term maintenance of data collection systems is critical to adequately assess natural variability, forest management effects, and climate trends. As a subset, more specific research is needed on the relative significance of climate change versus forest management effects, on low flows (water quantity).
- We must develop integrated, multi-disciplinary, multi-scale, long-term research programs that integrate watershed modelling, field-based process studies, and paired-watershed approaches to improve decision-support tools for natural resource managers.
- We need to clarify the effects of watershed restoration (e.g., road deactivation) on water quantity.
- We need a better understanding of the effects of wildfire and wildfire suppression on low flows.
- We need to determine the influence of surficial geology (glaciated vs. non-glaciated) on low flows and hydrologic processes. As a subset, we need a better understanding of late season water balance in relation to low flows.

Smahtkin (2001, p. 175) summed up the current state of knowledge gaps well in stating:

> *Despite the significant amount of specialist knowledge that has been accumulated in the field of low-flow hydrology, in the past decades, the understanding of specific low-flow generating mechanisms and relevance of different gain and loss processes to the wide variety of climatic, topographic and geological conditions remains rather limited. This is probably the result of limited experimental low-flow studies.*

Extension and Training Needs

While much low flow research remains to be conducted, extension of current knowledge is a critical component of forest management. We recommend focusing extension efforts in the following areas to support more effective management and to reduce misconceptions. Priority areas include:

- education of natural resource managers, policy makers, and interested public in general hydrologic principles and the interacting effects of all resource management activities on streamflow;
- education on which resource activities and natural processes have the greatest effect on streamflow quantity (i.e., water withdrawal vs. climate changes vs. forest management);
- further training of watershed management personnel in low flow survey techniques, data collection, and design of monitoring programs;
- greater awareness of the limitations of low flow data for policy and decision making related to the new British Columbia Forest and Range Practices Act; and
- greater awareness of the value of bringing researchers, operations, and decision makers together in creating science-based solutions to low flow management issues.

Operational and Management Needs

Watershed managers require tools and the best available science to assist them in planning forest management activities. While our knowledge of low flow science is currently incomplete, management decisions must still be made. Short-term as well as long-term approaches therefore need to be developed in co-operation with researchers, operations, policy, and interested public. This strategy will provide managers with appropriate decision-support tools in the short term and comprehensive adaptive-management processes over the long term. Overall, there is a need for further education on hydrologic principles and applied training on best management practices that minimize management-related impacts in snowmelt-dominated regimes.

Conclusions

Low flow generation processes are complex and vary naturally in time and space. Forest management is only one of a number of human activities that can potentially affect a watershed's hydrologic regime. Natural processes such as climate change can also affect low flows. Because these processes and activities occur simultaneously, isolating the effects of forest management on low flows is difficult. It is important to understand these interactions and appropriately manage our influences because low water levels can be detrimental to aquatic habitat and the life it supports, as well as limit the amount of water available for human use.

Does logging dry up streams? Our review has shown that current scientific literature does not support the common perception that timber harvesting causes streams to dry up. The hydrologic response of low flows to forest management was found to be highly variable in magnitude, time, and space. Water quantity generally increases or does not change meas-urably in volume as a result of forest management. No case studies relevant to snowmelt-dominated regimes reported a decrease in water quantity as a result of forest harvesting. In areas where fog drip occurs, a decrease in water volume contributing to low flows might be observed. Comments on longevity of effects of forest management in snowmelt-dominated regimes are difficult to make due to the scarcity of long-term case studies. In an analysis of literature not specific to snowmelt-dominated regimes, a few authors have commented on the subject of longevity. In general, these authors report a return to pre-treatment levels with the re-establishment of vegetation within 3–6 years for low flows. We found no case studies that examined the sole influence of roads or silviculture activities. Most research studies generally group roads, silviculture, and timber harvesting together to derive overall conclusions on the impact of forest management. As such, this review did not determine the sole influence of roads or silviculture on low flows.

Forest management is only one of many human activities that can potentially affect a watershed's hydrologic regime.

While not extensively researched for this paper, climate change is probably the most important factor that influences low flows in a watershed. Conceptually, factors that affect recharge components in a watershed should have the greatest control on the upper limit of water available for streamflow (i.e., changes in glacial melt rates, changes in seasonal precipitation totals, and snowmelt).

Numerous knowledge, research, and extension needs were identified. Ultimately, knowledge of low flows is hampered by an incomplete understanding of generation processes, particularly those relating to subsurface flow, evapotranspiration, and the interrelated effects of forest practices and climate change. While rules of thumb may be desired and successfully created, management applications should never wholly rely on a rule in absence of an understanding of the science that helped to create that rule. Limitations in low flow science around measurement methodologies, scaling of results, and inadequate research design were a few of the cautions noted.

To further understand low flow processes, short- and long-term approaches need to be developed in co-operation with researchers, operations, policy, and interested public. This strategy would provide managers with appropriate decision-support tools in the short term and comprehensive adaptive-management processes over the long term. There is also a need for further education on hydrologic principles and applied training on best management practices that minimize management-related impacts in snowmelt-dominated regimes.

Acknowledgements

Funding for the workshop, literature review, and article preparation was provided by the Province of British Columbia through the Ministry of Sustainable Resource Management (MSRM) and Forestry Innovation Investment (FII) Ltd. We thank the workshop participants listed at the end of this article for their technical input and peer assistance. We also thank the three peer reviewers whose comments greatly improved this manuscript.

References

Austin, S.A. 1999. Streamflow response to forest management: a meta-analysis using published data and flow duration curves. Unpublished MSc thesis. Colorado State University, Fort Collins, Colo.

Berndt, H.W. 1971. Early effects of forest fire on streamflow characteristics. U.S. Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oreg. PNW-148.

Beschta, R. 1990. Effects of fire on water quantity and quality. *In* Natural and prescribed fire in Pacific Northwest forests. J. Walstad, S. Radosevich, and D. Sandberg (editors). Oregon State University Press, Corvallis, Oreg. pp. 219–232.

Bethlahmy, N. 1975. A Colorado episode: beetle epidemic, ghost forests, more streamflow. Northwest Science 49(2):95–105.

B.C. Ministry of Forests. 2001. Watershed assessment procedure guidebook. Second edition. Version 2.1. Forest Practices Branch, Victoria, B.C. Forest Practices Code of British Columbia guidebook.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and L.F. DeBano. 1997. Hydrology and the management of watersheds. Second edition. Iowa State University Press, Ames, Iowa.

Cermak, J. and J. Kucera. 1987. Transpiration of fully grown trees and stands of spruce (*Picea abies* (L.) Karst.) estimated by the tree-trunk heat balance method. *In* Proceedings, Forest hydrology and watershed measurements. R.H. Swanson, P.Y. Bernier, and P.D. Woodward (editors). Vancouver, B.C., August 1987. IAHS-AISH, Wallingford, U.K. Publication Number 167, pp. 311–317.

Cheng, J.D. 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in southern British Columbia. Water Resources Research 25(3): 449–456.

Cheng, J.D. and B.G. Bondar. 1984. Impact of a severe forest fire on streamflow regime and sediment productions. *In* Proceedings, Canadian hydrology symposium No. 15, Université Laval, Quebec City, Que. National Research Council of Canada, Ottawa, Ont. Volume II:843–859.

Cohen, S. and T. Kulkarni (editors). 2001. Water management and climate change in the Okanagan Basin. Environment Canada and University of British Columbia, Vancouver, B.C.

Debano, L.F. 1981. Water repellent soils: a state-of-the-art. U.S. Department of Agriculture Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif. General Technical Report PSW-46.

Doyle, P.F. 1991. Documented autumnal streamflow increase without measurable precipitation. Water Resources Bulletin 27(6):915–923.

Dyrness, C. 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oreg. Research Paper PNW-202.

Federer, C.A. 1973. Forest transpiration greatly speeds streamflow recession. Water Resources Research 9(6): 1599–1604.

Fowler, W.B., J.D. Helvey, and E.N. Felix. 1987. Hydrologic and climatic changes in three small watersheds after timber harvest. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oreg. Research Paper PNW-RP-379.

Gluns, D. 2001. Snowline pattern during the melt season: evaluation of the H60 Concept. *In* Watershed assessment in the southern Interior of British Columbia. D.A.A. Toews and S. Chatwin (editors). B.C. Ministry of Forests, Research Branch, Victoria, B.C. Working Paper No. 57, pp. 68–93.

Golding, D.L. and R.H. Swanson. 1986. Snow distribution patterns in clearings and adjacent forest. Water Resources Research 22(13):1931–1940.

Gottfried, G.J. 1991. Moderate timber harvesting increases water yields from an Arizona mixed conifer watershed. Water Resources Bulletin 27(3):537–547.

Gucinski, H., M.J. Furniss, R.R. Ziemer, and M.H. Brookes (editors). 2001. Forest roads: a synthesis of scientific information. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oreg. General Technical Report PNW-GTR-509.

Hamilton, A.S., D.G. Hutchinson, and R.D. Moore. 2000. Estimating winter streamflow using a conceptual streamflow model. Journal of Cold Regions Engineering 14(4):158–175.

Hardy, J.P. and K.J. Hansen-Bristow. 1990. Temporal accumulation and ablation patterns of the seasonal snowpack in forests representing varying stages of growth. *In* Proceedings, 58th Western Snow Conference, pp. 23–24.

Harr, R.D. 1982. Fog drip in the Bull Run Municipal Watershed, Oregon. Water Resources Bulletin 18(5): 785–789.

Hetherington, E.D. 1987. The importance of forests in the hydrological regime. *In* Canadian aquatic resources. M.C. Healy and R.R. Wallace (editors). Department of Fisheries and Oceans, Ottawa, Ont. pp. 179–211.

Hicks, B.J., R.L. Beschta, and R.D. Harr. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. Water Resources Bulletin 27(2):217–225.

Johnson, R. 1998. The forest cycle and low river flows: a review of UK and international studies. Forest Ecology and Management 109:1–7.

Kaufmann, M.R. 1984. A canopy model (RM-CWU) for determining transpiration of subalpine forests. II. Consumptive water use in two watersheds. Canadian Journal of Forest Research 14:227–232.

Kaufmann, M.R., C.A. Troendle, M.G. Ryan, and H.T. Mowrer. 1987. Trees: the link between silviculture and hydrology. *In* Proceedings, Management of subalpine forests: building on 50 years of research, Silver Creek, Colorado. U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. RM-149, pp. 54–60.

King, J.G. 1989. Streamflow responses to road building and harvesting: a comparison with the equivalent clearcut area procedure. U.S. Department of Agriculture Forest Service, Intermountain Research Station, Ogden, Utah. Research Paper INT-401.

King, J.G. and L.C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in North Central Idaho. Water Resources Research 20(8):1159–1163.

Knight, D.H. 1987. Ecosystem studies in the subalpine coniferous forests of Wyoming. *In* Proceedings, Management of subalpine rorests: building on 50 years of research, Silver Creek, Colorado. U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. RM-149, pp. 235–241.

McNabb, D. and F. Swanson. 1990. Effects of fire on soil erosion. *In* Natural and prescribed fire in Pacific Northwest forests. J. Walstad, S. Radosevich, and D. Sandberg (editors). Oregon State University Press, Corvallis, Oreg. pp. 159–176.

Moore, R.D., A.S. Hamilton, and J. Scibek. 2002. Winter streamflow variability, Yukon Territory, Canada. Hydrological Processes 16:763–778.

Potts, D.F. 1984. Hydrologic impacts of a large-scale mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic. Water Resources Bulletin 20(3):373–377.

Reiter, M.L. and R.L. Beschta. 1995. The effects of forest practices on water. *In* Cumulative effects of forest practices in Oregon. Prepared for Oregon Department of Forestry, Salem, Oreg. Chapter 7, pp. 1–185.

Roseboom, W.A. and S.J. Figliuzzi. 1986. Carriage losses in natural channels in southern Alberta. *In* Proceedings, Canadian hydrology symposium, Regina, Sask. pp. 497–511.

Satterlund, D.R. and P.W. Adams. 1992. Wildland watershed management. Second edition. John Wiley and Sons, Inc., New York, N.Y.

Scherer, R. 2001. Effects of changes in forest cover on streamflow: a literature review. *In* Watershed assessment in the southern Interior of British Columbia: workshop proceedings. D.A.A. Toews and S. Chatwin (editors). B.C. Ministry of Forests, Victoria, B.C. Working Paper No. 57, pp. 44–55.

Scherer, R. and R.G. Pike. [2003]. Review of the potential effects of forest management on streamflow in the Okanagan Basin with an emphasis on low flows: a literature synthesis. FORREX–Forest Research Extension Partnership. Kamloops, B.C. In press.

Smakhtin, V.U. 2001. Low flow hydrology: a review. Journal of Hydrology 240:147–186.

Swanson, R.H., D.L. Golding, R.L. Rothwell, and P.Y. Bernier. 1986. Hydrologic effects of clear-cutting at Marmot Creek and Streeter watersheds, Alberta. Canadian Forestry Service, Northern Forestry Centre, Edmonton, Alta. Information Report NOR-X-278.

Toews, D.A. and D.R. Gluns. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in southeastern British Columbia. *In* Proceedings, 54th Western Snow Conference. pp. 101–111.

Troendle, C.A. and R.M. King. 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. Water Resources Research 21(12):1915–1922.

Troendle, C.A., M.S. Wilcox, G.S. Bevenger, and L.S. Porth. 2001. The Coon Creek Water Yield Augmentation Project: implementation of timber harvesting technology to increase streamflow. Forest Ecology and Management 143:179–187.

Troendle, C.A., R.A. Schmidt, and M.H. Martinez. 1988. Snow deposition processes in a forest stand with a clearing. *In* Proceedings, 56th Western Snow Conference. pp. 78–86.

Wei, X. and G.W. Davidson. 1998. Impacts of large-scale timber harvesting on the hydrology of the Bowron River Watershed. *In* Proceedings, Mountains to sea: human interaction with the hydrologic cycle conference. Canadian Water Resources Association, Victoria, B.C. June 1998. pp. 45–52.

Winkler, R.D. 1999. A preliminary comparison of clearcut and forest snow accumulation and melt in south-central British Columbia. *In* Proceedings, Confronting uncertainty, managing change in water resources and the environment. Canadian Water Resources Association, October 27–29, 1999. pp. 294–300.

Wondzell, S.M and J.G. King. 2003. Post-fire erosional processes in the Pacific Northwest and Rocky Mountain region. Forest Ecology and Management 178(1–2): 75–87.

Workshop Participants (Technical Group)*

Adam Wei, Okanagan University College

Brian Guy, Summit Environmental Ltd.

Brian Symonds, Land and Water British Columbia Inc.

Bruce McFarlane, Ministry of Water, Land and Air Protection

Dan Moore, University of British Columbia

Dave Scott, Okanagan University College

Dave Toews, Forest Hydrologist

Dean Watts, Department of Fisheries and Oceans

Des Anderson, Ministry of Water, Land and Air Protection

Eugene Hetherington, Forest Hydrologist

Karen Rothe, Ministry of Sustainable Resource Management

Karyn Sutherland, FORREX–Forest Research Extension Partnership

Paul Whitfield, Environment Canada

Phil Epp, Ministry of Water, Land and Air Protection

Rita Winkler, Ministry of Forests

Rob Scherer, FORREX–Forest Research Extension Partnership

Robin Pike, FORREX–Forest Research Extension Partnership

Roger Wysocki, Department of Fisheries and Oceans

Ron Smith, Ministry of Sustainable Resource Management

Ross Porcheron, Ministry of Sustainable Resource Management

Steve Matthews, Ministry of Water, Land and Air Protection

Victor Cumming, FORREX–Forest Research Extension Partnership (workshop facilitator)

Younes Alila, University of British Columbia

* Workshop took place at the Ramada Lodge Hotel, Kelowna, B.C., November 21, 2002.