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Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment

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[1] A hydrologic model of the mountainous snowmelt-dominated Redfish Creek catchment (British Columbia) is used to evaluate Interior Watershed Assessment Procedure (IWAP) guidelines regarding peak flow sensitivity to logging in different elevation bands of a basin. Simulation results suggest that peak flow increases are caused by greater snow accumulation and melt in clear-cut areas while similar evapotranspiration rates are predicted under forested and clear-cut conditions during spring high flow. Snow accumulation and melt are clearly related to elevation, but the relationship between logging elevation and peak flow change is more complex than perceived in the IWAP. Logging in the bottom 20% of the catchment causes little or no change in peak flow because of the small low-elevation snowpack and the timing of snowmelt, while clear-cut area alone appears to be a good indicator of peak flow increases due to logging at higher elevation. Temporal variability in peak flow changes due to clear-cutting is substantial and may depend more on temperatures during snowmelt than on the size of the snowpack. Long-term simulations are needed to improve quantitative estimates of peak flow change while the importance of watershed topographic characteristics for snowmelt and peak flow generation must be further examined. *INDEX TERMS:* 1803 Hydrology: Anthropogenic effects; 1860 Hydrology: Runoff and streamflow; 1863 Hydrology: Snow and ice (1827); *KEYWORDS:* forest hydrology, snow hydrology, peak flows, watershed management, British Columbia, Interior Watershed Assessment Procedure

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1. Introduction

[2] Possible connections between forest management and peak streamflows in the maritime regions of the Pacific Northwest have been intensively debated [*Jones and Grant*, 1996; *Thomas and Megahan*, 1998; *Beschta et al.*, 2000; *Jones and Grant*, 2001; *Thomas and Megahan*, 2001] because of concerns from the perspective of flooding hazards, stream morphology, water quality and fish habitat. The statistical analyses used in this debate are complicated by the many factors contributing to forest management effects on basin hydrology, including the chosen silvicultural system and logging method, the location within a catchment where timber harvesting takes place and road construction. Issues such as shortness of the streamflow records and climate variability are also of concern and not surprisingly mixed results have been obtained regarding possible impacts of logging on extreme events (i.e., 50 or 100 year flood).

[3] Timber harvesting also has the potential to increase the magnitude and frequency of peak streamflows in the snowmelt-dominated interior regions of western North America [*Troendle and Leaf*, 1981; *Troendle and King*, 1986] but research has to a large extent focused on annual yield [*U.S. Environmental Protection Agency*, 1980]. There are several ongoing paired watershed experiments in the interior of British Columbia (BC) designed to assess the consequences of forest management on watershed processes. These experiments have contributed significantly to our understanding of hydrologic processes affected by forest removal on the plot scale [e.g., *Toews and Gluns*, 1986; *Winkler*, 2000]. While these field studies recognize the influence of forest management on streamflow characteristics, linkages between plot and watershed scale hydrology are difficult to draw from data alone. Furthermore, the data record for most Canadian watershed experiments is too short for a comparison of pre-and post-logging watershed conditions against the backdrop of climate variability [*Buttle et al.*, 2000] and questions regarding the transferability of findings from these field experiments have long been recognized [*Ward*, 1971].

[4] A clear understanding of how logging affects the hydrologic regime of a watershed is necessary if land managers are expected to make decisions regarding optimal

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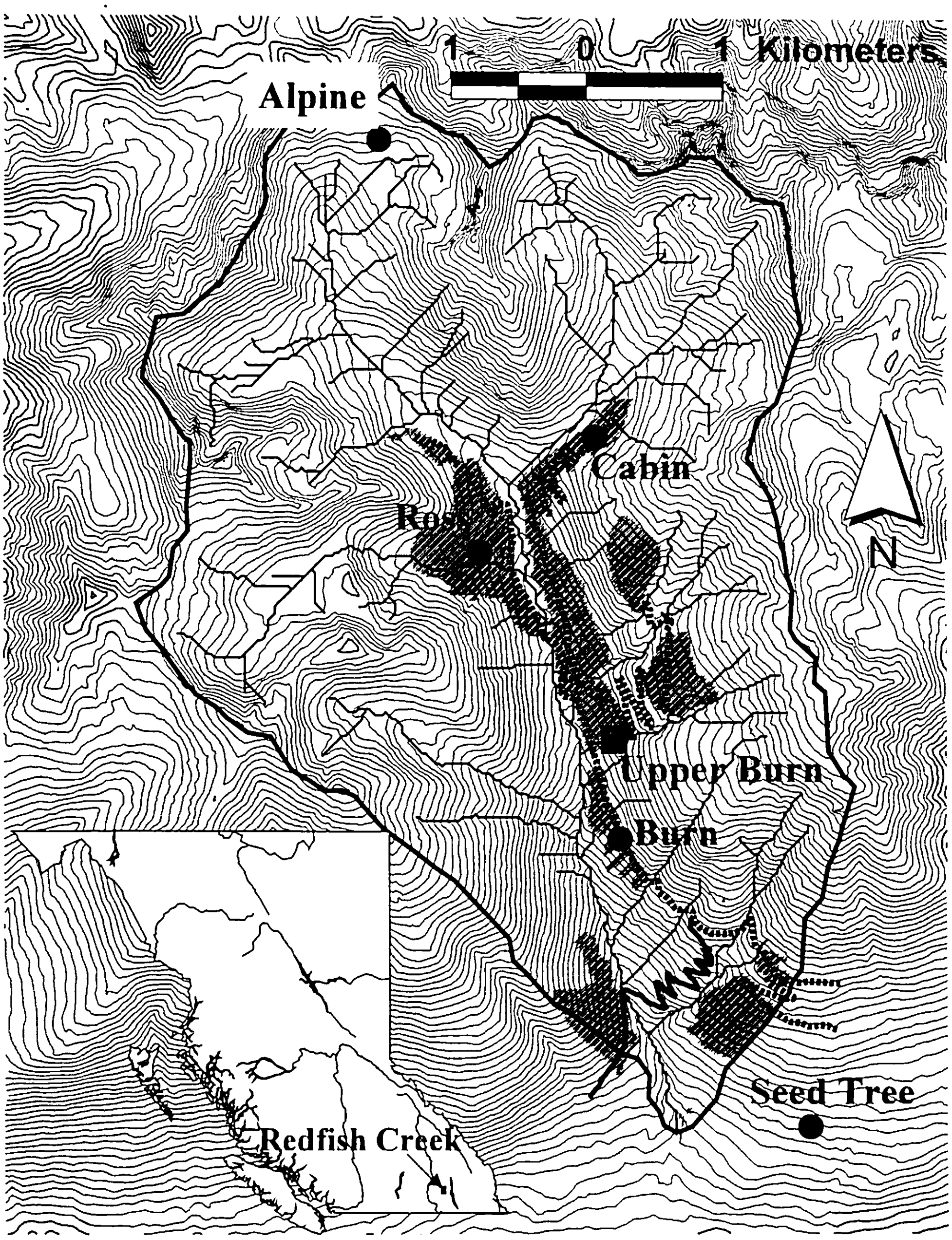

Figure 1. Redfish Creek study area with elevation contours (25 m spacing), climate stations (circles), the Upper Burn forest/clear-cut snow course (square), clear-cut areas (shading), forest roads, and the stream channel network. The insert shows the location of the study area in southeastern British Columbia.

harvest scenarios and sustainable resource management. Numerical simulation of hydrologic processes is the most useful way of supplementing information derived from paired watershed experiments [*Leaf*, 1975; *U.S. Environmental Protection Agency*, 1980] and for linking physical processes measured at the stand level to basin scale hydrology. Experience has shown that hydrologic models can alleviate some of the problems associated with paired watershed experiments and statistical analysis of streamflow records by acting as a control to filter out effects of climate variability [*Bowling et al.*, 2000]. The main advantage of numerical simulation is that it can be used to explore the effects of a large spectrum of forest management scenarios. The main weakness of hydrologic modeling is that any model is a simplification of nature and measuring the

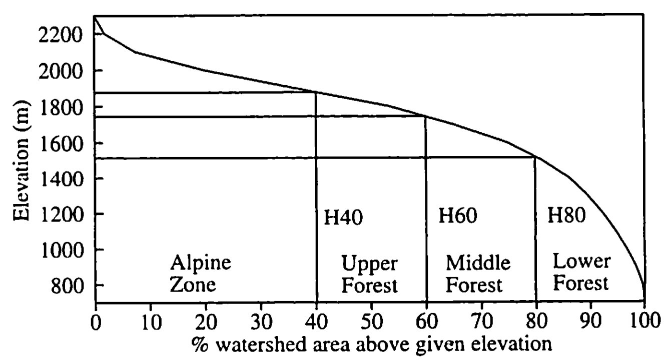

Figure 2. Redfish Creek hypsometric curve.

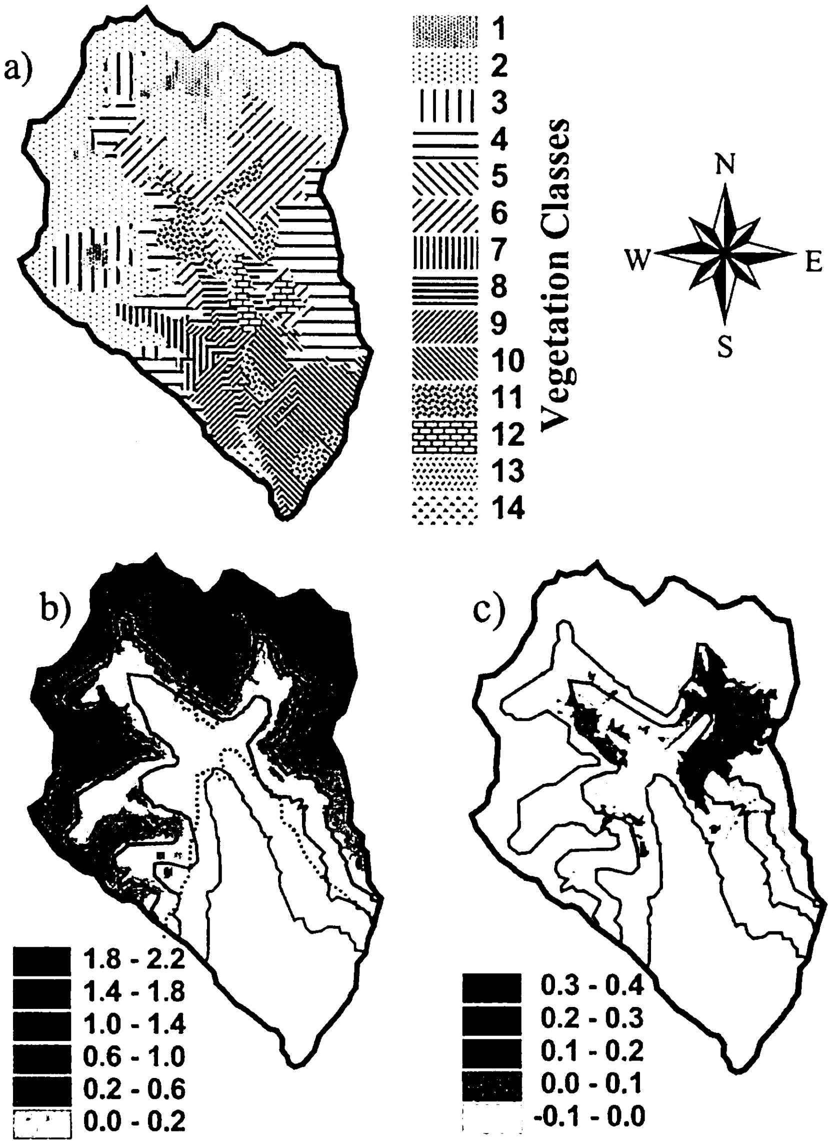

Figure 3. (a) Distribution of vegetation cover (current conditions) with vegetation classes as described in Table 1 together with (b) simulated SWE (m) on 10 June 1996 for current conditions and (c) the change in simulated SWE (m) between total clear-cut conditions and current conditions. H40, H60, and H80 hypsometric lines (Figure 2) are indicated as solid lines, and interpreted snow line from *Gluns* [2001] is drawn as dashed line on snow map (Figure 3b).

performance of models in simulating watershed processes is the only way by which the reasonableness of model assumptions can be tested. It is thus evident that watershed experiments and modeling must be closely linked if cumulative watershed effects are to be understood [*Ziemer et al.*, 1991]. Based on this premise, *Whitaker et al.* [2002] applied the Distributed Hydrology Soil Vegetation Model (DHSVM) [*Wigmosta et al.*, 1994] to the BC Ministry of Forests Redfish Creek catchment.

[5] The Interior Watershed Assessment Procedure (IWAP) was designed to assess the cumulative watershed impacts of forest management in BC's interior [*BC Ministry of Forests*, 1999]. A watershed report card (see, for example, Table 2 of *Alila and Beckers* [2001] and accompanying discussion) is used to provide a reference of consistently measurable forest-development related indicators that are used to determine hazard ratings for peak flow, sediment sources and fate of sediment, channel stability and riparian function. Peak flow hazards are determined from the size and elevation of cut blocks, hydrological recovery due to forest regrowth and road network layout. Together with field assessment results, the hazard ratings are used for making specific recommendations for future forest development.

[6] In forest management of snowmelt-dominated mountainous catchments a crucial decision factor concerns the elevation bands at which logging should take place. Melt begins earlier in the season at lower elevations and proceeds upslope. During peak flow, snow is beginning to disappear from the mid-elevations and is actively melting at the higher

Table 1. Overstory Characteristics of the 14 Vegetation Types

Class	Description/Species	Height, m	Canopy Closure (0–1.0)	Leaf Area Index (LAI)
1	lake-rock-tundra	N/A	N/A	N/A
2	subalpine balsam-spruce	12	0.2	2.5
3	balsam-spruce	21	0.3	3.0
4	balsam-spruce	22	0.5	3.5
5	balsam-pine	20	0.8	5.0
6	balsam-spruce	30	0.6	4.5
7	balsam-spruce	36	0.4	4.0
8	cedar-hemlock	27	0.65	7.0
9	cedar-hemlock	39	0.7	7.0
10	Douglas fir-larch-pine	29	0.7	6.0
11	clear-cut	N/A	N/A	N/A
12	clear-cut-early regeneration	3	0.1	2.5
13	clear-cut-shelterwood	15	0.1	2.5
14	clear-cut-regenerated	15	0.2	3.0

elevations of a watershed. This relationship between snow covered area and streamflow has long been recognized [*Garstka et al.*, 1958] and is exploited in the IWAP through the H60 concept. The H60 concept is based on the notion that in much of the BC interior snow typically covers the upper 60% of a watershed at the time of peak flow. It is assumed that timber harvesting above the H60 elevation line will thus have a greater impact on peak flows than timber harvesting below this line. The peak flow hazard index is calculated based on these assumptions, where a weight of 1 is assigned to cut blocks below the H60 line and a weight of 1.5 is assigned to cut blocks above this line. Field studies have been initiated to test IWAP peak flow guidelines in the field [*Toews*, 1999; *Gluns*, 2001]. In this paper, these field investigations are supplemented by using the DHSVM model for Redfish Creek to evaluate the sensitivity of peak flows to logging in different elevation bands of the catchment and to test the IWAP guidelines in this respect.

[7] The Redfish Creek hydrology and the ability of the DHSVM model to reproduce crucial catchment hydrologic characteristics are discussed in Section 2. The role of various hydrological processes in affecting changes in streamflow characteristics due to clear-cutting is discussed in Section 3 by comparing current catchment conditions to the hypothetical case of a totally clear-cut basin. In Section 4, specific clear-cut scenarios are developed to test IWAP guidelines with regard to the sensitivity of peak flows to logging in different elevation bands of a basin. The main findings of this study will be summarized in Section 5.

2. Basin Hydrology and Redfish Creek Model

[8] The Redfish Creek catchment (26 km^2) is part of the West Arm Demonstration Forest paired watershed experiment in the Kootenay Mountains near Nelson, British Columbia (Figure 1). The basin ranges in elevation from 700 to 2300 m (Figure 2). Slopes are heavily forested with the lower elevations falling within the interior cedar- hemlock and the upper elevations within the Englemann spruce-subalpine fir biogeoclimatic zones. In the model, the basin is divided into 14 vegetation classes based on species composition, presence or absence of overstory and understory, canopy closure, Leaf Area Index (LAI) and tree height (Figure 3a and Table 1). Understory height and LAI are assumed to be invariant between vegetation types with values of 0.3 m and 2.0, respectively. Forested slopes are limited to approximately 1880 m, while above this elevation the terrain is alpine in character with sparse tree cover (vegetation class 2) or no vegetation at all (class 1). This alpine zone constitutes 40% of the total basin area (Figure 2). Logging activity occurred in the watershed between 1969–1972 and to date 9.9% of the basin is in various states of recovery with significant regeneration in the older clear-cuts (Figure 3a, vegetation classes 12–14).

[9] Hourly climate data have been measured since 1992 at the Burn (elevation 1290 m) and Cabin (elevation 1735 m) climate stations (Figure 1) and are used as model input. Temperature and precipitation change significantly with elevation. For the October 1992 to October 1997 data record used in the calibration of the Redfish Creek model, average annual precipitation measured at Burn was 1101 mm, 19.6% of which (216 mm) was in the form of snow. During these 5 years, the average recorded temperature at Burn in the November–April snow accumulation period was −2.5°C. In contrast, Cabin was characterized by an average annual precipitation of 1584 mm during this period, with snowfall accounting for 1057 mm or 66.7% and a mean November–April temperature of −4.8°C.

[10] Elevation differences in snow accumulation and melt rates are thought to have important consequences for forest management in interior BC and the performance of the model in reproducing measured snow water equivalent (SWE) therefore deserves attention. SWE data as measured in clear-cuts and forest openings for 1993–1997 reveal a strong increase in maximum snowpack (peak SWE) between the low elevation Burn site, the middle elevation Cabin and Ross sites and the high elevation Alpine site (Figure 4). Although SWE at the Alpine and Ross stations is somewhat under-predicted in the model, elevation increases in peak SWE between the snow course sites are simulated with reasonable accuracy.

[11] Forest clear-cut ratios in peak SWE and melt rates, as measured in BC by *Toews and Gluns* [1986], *Winkler* [2000] and others, are taken to be important indicators of changes in the quantity of streamflow that may be expected following timber harvesting. At Redfish Creek, the Upper Burn snow course in the lower forest zone (Figure 1, elevation 1435 m), is the only site where SWE data have been collected in a clear-cut and an adjacent forest stand (Figure 5). On average, model-predicted peak SWE is 0.65

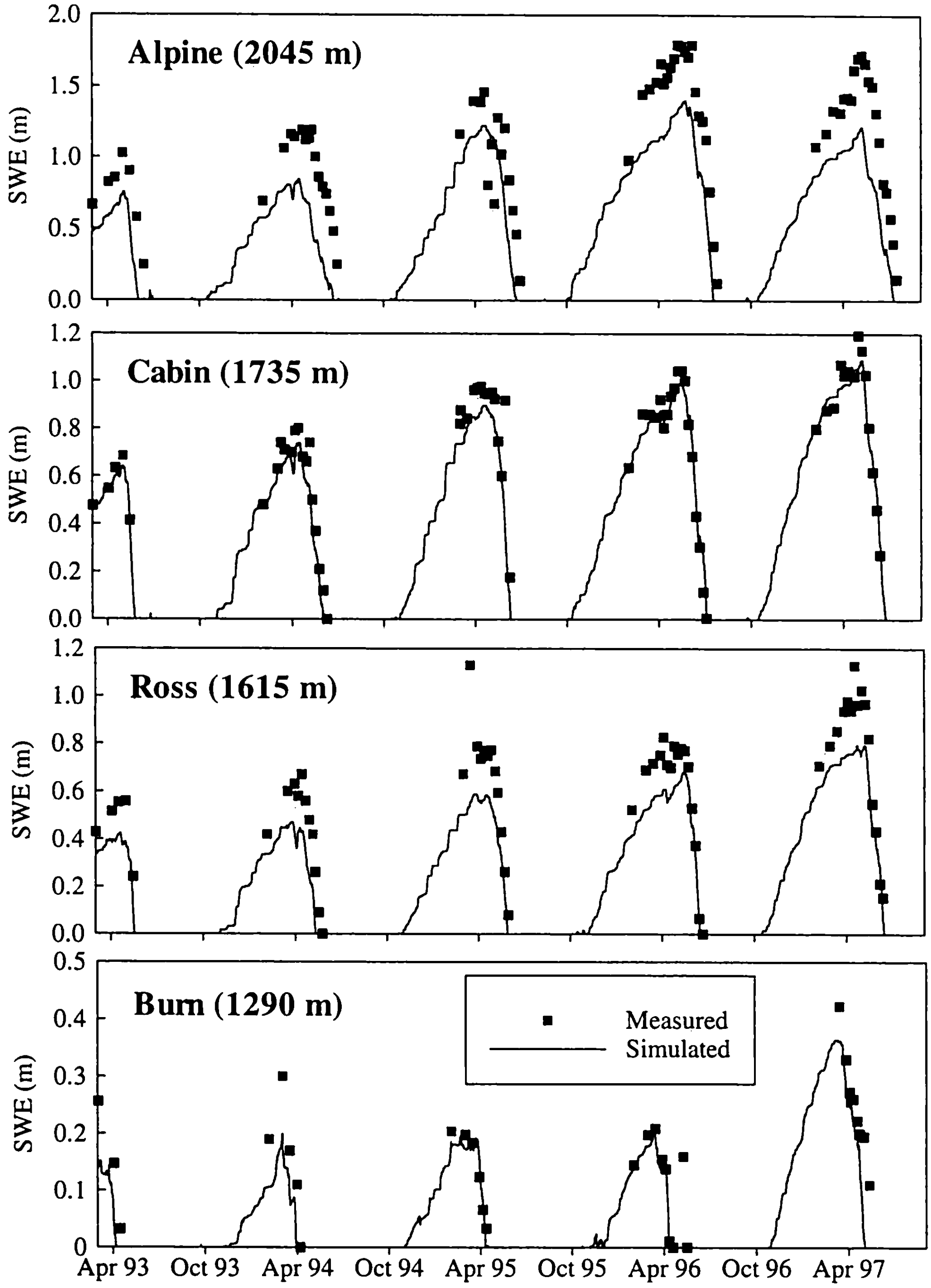

Figure 4. Comparison of 1993–1997 measured and simulated SWE at four climate stations. Note the marked increase in SWE with elevation.

times that in the clear-cut, while the data suggest a ratio of 0.67. Model-predictions regarding peak SWE were also examined for forest and clear-cut areas at Ross and Cabin (Figure 1) as elevation and canopy closure for these two sites (Table 2) are characteristic of the middle and upper forest zones, respectively (compare to Figures 2 and 3a and Table 1). Model-predicted forest clear-cut ratios in peak SWE are closer to unity in the middle and upper forest zones than in the lower forest zone, with characteristic values of 0.87 for Ross and 0.84 for Cabin. This trend is expected because with increasing winter accumulation at higher elevation, the fraction of snowfall that can be intercepted by the canopy decreases [*Bunnell et al.*, 1985] and because of the lower canopy closure values at Ross and Cabin as compared to the Upper Burn site (Table 2). Model assumptions regarding canopy snow interception are discussed in the appendix.

[12] Snowmelt rates have not been measured directly at Redfish Creek. Instead, linear regression of the SWE measurements between peak snow accumulation and snowpack disappearance (Figures 4 and 5) was used to determine average rates of snowmelt for the entire spring season. Because of the sparseness of the SWE measurements in time and occasional snowfall during the early melt season, it

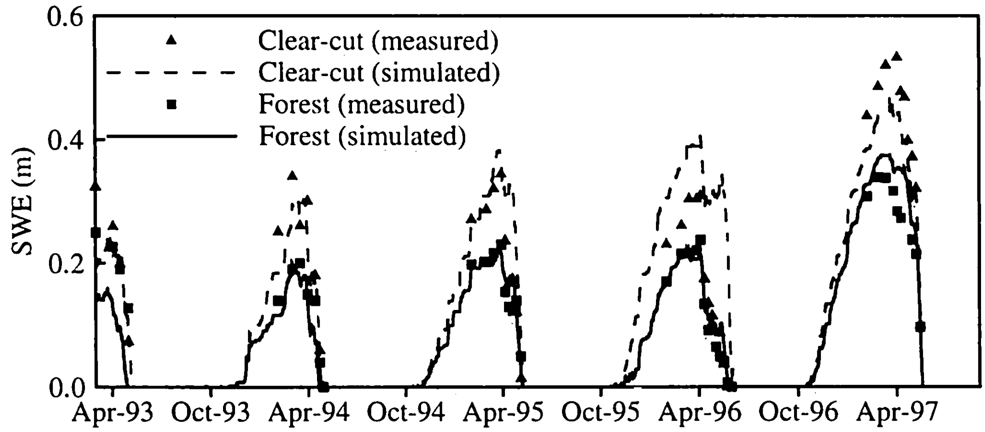

Figure 5. Upper Burn 1993–1997 forest and clear-cut measured and simulated SWE.

is not possible to reliably determine snowmelt rates over shorter time periods. The SWE measurements suggest that average spring clear-cut melt rates M^c for the 1993–1997 simulation period are 0.79 cm/d at Upper Burn, 1.96 cm/d at Ross and 2.17 cm/d at Cabin. This increase in clear-cut melt rates with elevation is a reflection of higher late season (mid-June) melt rates at Ross and Cabin, when the snowpack at Upper Burn has already disappeared, and is reasonably reproduced in the model (Table 2).

[13] The SWE measurements at Upper Burn further suggest that spring melt rates are on average 0.61 times lower in the forest than in the clear-cut, while the model results indicate an average ratio of 0.64. Both data and model suggest that the combined effects of reduced accumulation and melt rates below the canopy tend to result in a nearly simultaneous snow disappearance in forest and clear-cut (Figure 5). Model-predicted forest clear-cut snowmelt ratios M^f/M^c are substantially higher for Ross and Cabin than for Upper Burn (Table 2). Overall, the simulated melt ratios at the three sites compare well to the average ratio of 0.72 thought to characterize the Kootenay region [*Winkler*, 1999]. While forest clear-cut differences in snowmelt rates may be expected to decrease with decreasing forest cover density, it is difficult to anticipate exact site-specific effects of forest cover removal on snowmelt rates because of the complex interaction between the controlling forest cover parameters and topographically controlled meteorological conditions. Model assumptions regarding forest influences on snowmelt rates are discussed in the appendix.

[14] The model-predicted snow cover depletion was compared with 1994–1998 air photograph observations by *Gluns* [2001], where the simulated percent snow cover is averaged over the 1994–1997 period (Figure 6). While the overall rate of snow line retreat is reasonably simulated, noticeable differences between the interpreted and model-predicted snow coverage occur mid-May to mid-July. Significant year-to-year variability in the snow line retreat and the fact that simulated SWE and snow cover photographs have been averaged over short and different time periods may play a role in explaining this difference. Simulated SWE and the observed snow line for 10 June 1996 are in good general agreement (Figure 3b).

[15] Energy flux measurements in the BC interior [*Adams et al.*, 1998] suggest that long wave radiation, which is closely linked to air temperature, is the largest source of energy for snowmelt in forested environments. Because the outflow hydrograph is snowmelt-dominated, a good correlation between spring air temperatures and flow rates may be expected. In 1993, the very rapid increase in basin outflow mid-May coincided with a sudden rise in temperature at the Burn climate station from just above the freezing mark to a daily average of around 12°C (Figure 7a). This sudden rise in temperature caused the below-average 1993 snowpack (Figure 4) to disappear rapidly, resulting in an earlier-than-normal recession of the outflow hydrograph in June. Spring temperatures in 1995 and 1996 increased more gradually than in 1993 and this is reflected in a slower rise of the hydrograph (Figures 7b and 7c). Reduced basin outflow between the double peak in the hydrograph for 1996 appears to be correlated with a drop in temperature over several days in the third week of June.

[16] Rainstorms and rain-on-snow events occasionally cause periods of high streamflow and a number of such events are evident in Figure 7. For the period of record, 1995 was driest during the high-flow season with only 20 mm of precipitation between mid-May and mid-June while for 1996 this period was relatively wet with 141 mm of rainfall. Distinct high flows recorded for 31 May 1993, 24 June 1995, and 3 June 1996 can be directly correlated to high rainfall events as measured at the Burn climate station

Table 2. Model-Predicted Clear-Cut and Forest Snowmelt Rates Averaged Over the 1993–1997 Period[a]

Location (Elevation Band)	Elevation, m	Canopy Closure	M^c, cm/d	M^f, cm/d	M^f/M^c
Upper Burn (H100-H80)	1435	0.7	0.73	0.47	0.64
Ross (H80-H60)	1650	0.5	1.78	1.41	0.79
Cabin (H60-H40)	1781	0.6	2.06	1.69	0.82

[a]These melt rates are compared with observed rates of decline in SWE in section 2.

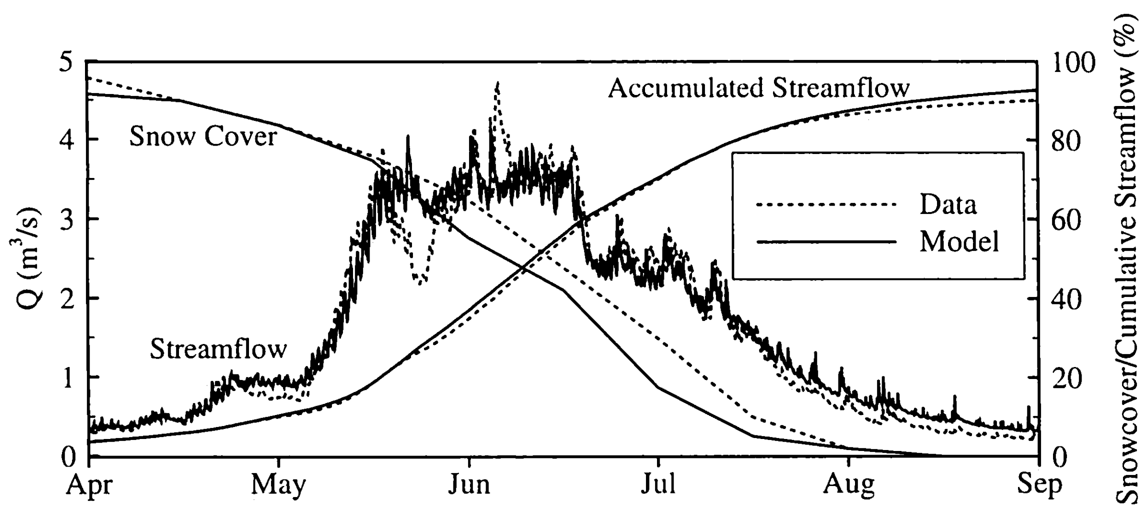

Figure 6. Recorded and simulated basin outflow hydrograph and accumulated streamflow, averaged over 1993–1997 period together with computed percent snow cover for 1994–1997 and observed percent snow cover depletion for 1994–1998.

and are simulated with reasonable accuracy. Rainfall and rain-on-snow events in the fall are less significant than these spring peaks as basin outflow is generally lower.

[17] The analysis of the outflow hydrograph for 1993, 1995, and 1996 (Figure 7) illustrates that the model is able to reproduce climate-controlled year-to-year variability in streamflow characteristics with reasonable accuracy. At Redfish Creek, total flow volume (V) out of the catchment provides the only measure of the accuracy with which the basin water mass balance is simulated. Total outflow is well simulated with volume errors $(V_{model} - V_{observed})/V_{observed}$ of 0.160 for 1993, 0.110 for 1995 and −0.024 for 1996 and a 5 year averaged error of 0.011 [*Whitaker et al.*, 2002]. Assuming that precipitation is accurately distributed over the catchment, this close agreement between observed and simulated flow volumes suggests that the total amount of water lost to the atmosphere through evapotranspiration and snow sublimation is well simulated. However, this does not preclude that a bias in either of these two atmospheric loss components may be offset by an opposite bias in the other component.

[18] *Gluns* [2001] investigated the relationship between snow line retreat and streamflow generation at Redfish Creek by comparing air photographs of snow cover and the recorded outflow hydrograph. Gluns' analysis showed that the annual peak in the outflow hydrograph early June coincided with a snow covered area of 64% while the simulated snow cover for 10 June 1996 occupies approximately 65% of the catchment (Figure 3b). The simulation results further suggest that the snow covered basin area drops from 80% to 35% during the mid-May to mid-June high-flow period (Figure 6). These model results are in good agreement with Gluns' conclusion that at Redfish Creek the generation of peak flow is concentrated around the 80–40% snow coverage range with the critical area near 65% snow coverage.

[19] Data and model results thus suggest that clear-cutting in the lower forest zone near Burn will have little consequence for peak streamflows, given the moderate size of the local snowpack and because this snow has already disappeared around the time of peak streamflow. On the other hand, the greater snowpack in the upper forest zone near the Cabin climate station around the H60 hypsometric line is thought to be quite important for peak flow generation because it is releasing meltwater during the period when annual maximum flows occur.

3. Logging Impacts on Basin Hydrology

[20] A loss of tree cover will cause snow accumulation and melt rates to increase and evapotranspiration to decrease. Little is known regarding the relative importance of these two factors for timber harvesting related changes in basin hydrology and for peak flow generation in particular. To link information about stand level forest influences on snow accumulation and melt (Figure 5) to timber harvesting effects on basin hydrology and peak streamflows, simulations are compared for current catchment conditions (calibrated model) and for total clear-cut conditions. Total clear-cut conditions are simulated by completely removing the forest canopy (overstory) from the basin.

[21] Differences in SWE between current and total clear-cut conditions on 10 June 1996 (Figure 3c) are indicative of logging-induced snowpack changes around the time of peak streamflow. These SWE differences are related to the initial thickness of the snowpack (Figure 3b) and the density of the cut forest stands (Figure 3a and Table 1) and are therefore correlated both with elevation and vegetation type. Existing clear-cuts (vegetation class 11), alpine regions devoid of forest cover (class 1) and the lower reaches of the basin, where the snowpack has already melted, appear as areas of no change. In subalpine areas with a 20% balsam-spruce cover (class 2), the snowpack under total clear-cut conditions is unchanged or slightly reduced (−0.1 m SWE) compared to that under forested conditions. In this elevation range, higher melt rates caused by the removal of the sparse forest cover are apparently more important than increased accumulation rates due to the lack of canopy snow interception. A large percentage of the basin is alpine or subalpine in character and because of the large snowpack

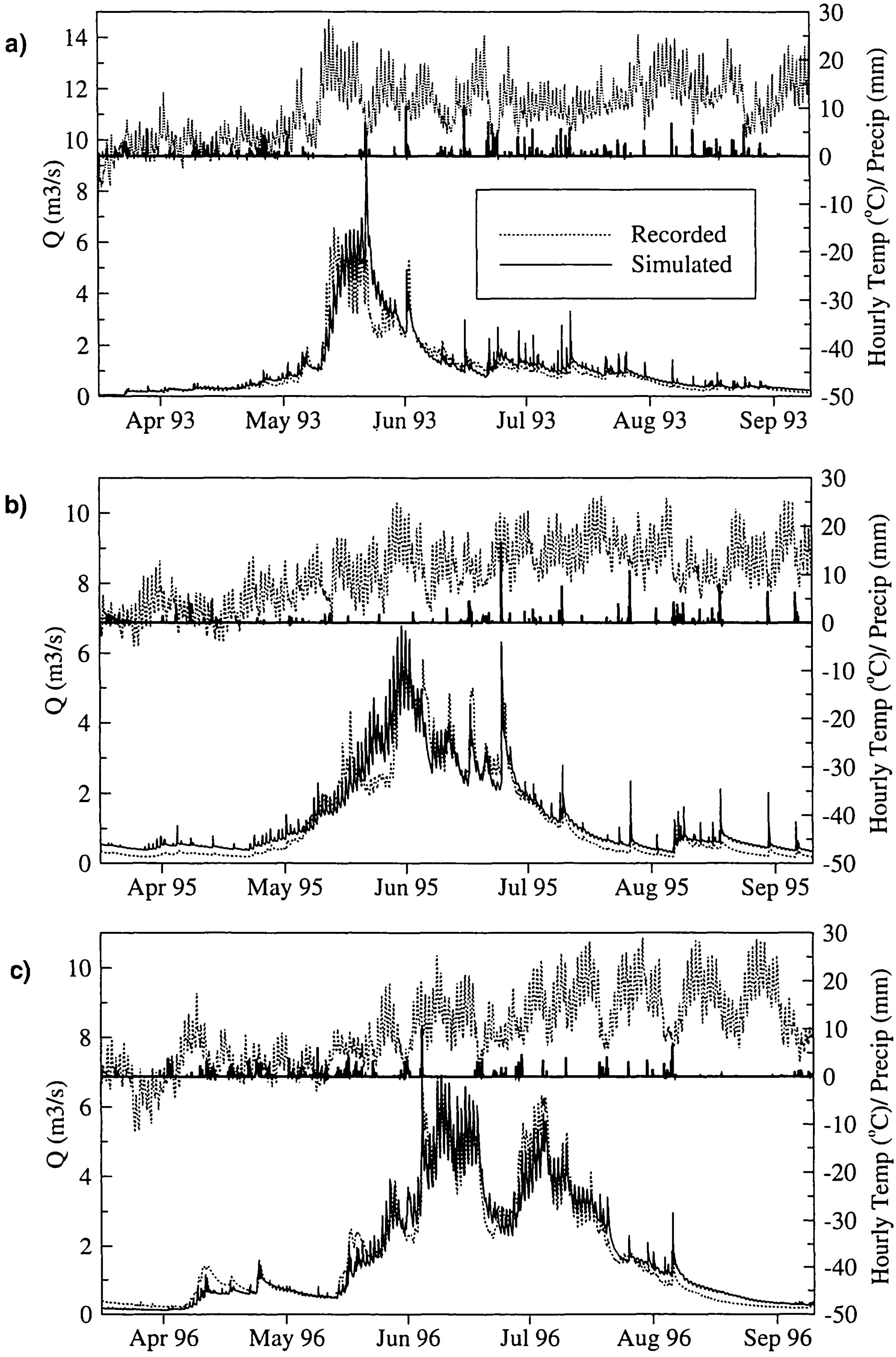

Figure 7. Sample hydrographs for (a) 1993, (b) 1995, and (c) 1996 together with hourly temperature and precipitation as recorded at the Burn climate station.

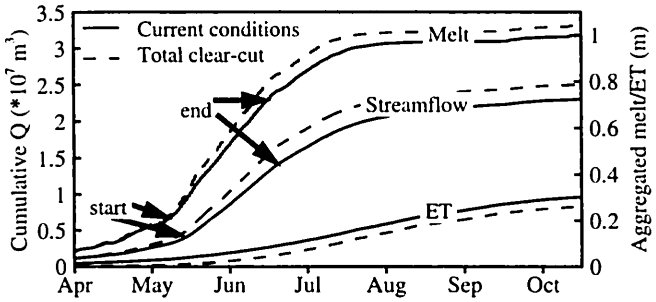

Figure 8. Comparison of simulated cumulative streamflow Q, basin aggregated melt, and evapotranspiration (ET) under current and total clear-cut conditions, averaged over the 1993–1997 period. The start and end of the mid-May to mid-June high-flow period are marked by arrows.

in this zone (Figure 3b), substantial melt will be delivered during the high-flow period, lessening the effect of timber harvesting in the rest of the basin on peak flows. Near the Cabin climate station, the removal of dense stands of balsam spruce with canopy closure values of 0.6–0.8 leads to snowpack increases of 0.2–0.3 m SWE, suggesting that logging in this area has the greatest potential for affecting snowmelt delivery during the peak flow period.

[22] For the October 1992 to October 1997 period, average annual precipitation over the basin (rain and snow) amounts to 1498 mm per unit area. Under current conditions, model-predicted evapotranspiration (ET) accounts for 314 mm (21% of precipitation) of water annually while cumulative snowmelt amounts to 1051 mm SWE or 70% of precipitation (Figure 8). Under total clear-cut conditions model-predicted annual ET decreases by 50 mm (–16%) to 264 mm. Total yearly snowmelt increases by 43 mm (4%) to 1094 mm SWE. These simulation results suggest that the net increase in snowpack due to clear-cutting accounts for 46% of the increase in basin water surplus (precipitation minus atmospheric losses), with lowered ET making up the remaining 54%. In comparison, based on long-term monitoring data following a 40% clear-cut in the Fool Creek watershed in Colorado under similar climate conditions, *Troendle and King* [1986] propose that the contribution of increased SWE to increased streamflow is 1/3 with depositional differences and growing season ET reductions comprising the other 2/3. When multiplied by the basin area, the combined effects of increased snowmelt and reduced ET would lead to an annual increase in basin water yield of 0.24×10^7 m^3. Simulated cumulative streamflow on the other hand increases by 0.21×10^7 m^3 (from 2.30×10^7 m^3 under current conditions to 2.51×10^7 m^3 under total clear-cut conditions; Figure 8), the difference being caused by increased soil moisture storage in the basin under total clear-cut conditions. The modest increase in soil moisture storage as compared to the increase in flow volume is expected given that the thin coarse-grained soil layers [*Whitaker et al.*, 2002] and steep terrain of Redfish Creek favor runoff over storage.

[23] Lowered annual ET under total clear-cut conditions appears to result from a delayed onset of this process compared to current conditions (Figure 8), explained by the DHSVM assumption that the understory is completely snow covered and does not contribute to ET when snow is present on a model pixel. Simulation results further suggest increased streamflow under total clear-cut conditions during the mid-May to mid-June high-flow period to be caused by increased meltwater delivery while the rate of ET during this period is virtually unchanged compared to current conditions. In DHSVM, transpiration by understory and overstory is calculated separately using Penman-Monteith equations [*Wigmosta et al.*, 1994]. These equations express that transpiration from vegetative surfaces is either climate-controlled by net radiation inputs and atmospheric moisture demand, plant-controlled by the resistance of each story to vapor transport, or soil moisture limited. Model results suggest that the latter factor does not play a role during spring high flow and this seems reasonable, as meltwater delivery is high. Climate controls on ET are equal under current and clear-cut conditions. The resistance of each story to vapor transport depends on leaf area available for ET, adopted minimum stomatal resistance values (rs_{min}) and the aerodynamic resistance (r_a) to vapor transport according to a ratio $rs_{min}/(r_a LAI)$, where a smaller ratio translates into larger transpiration rates. Adopted rs_{min} values are 125 s/m for the understory and 175 s/m for the overstory [*Whitaker et al.*, 2002]. Using 10 June 1996 as a proxy (Figure 3), calculations indicate that rs_{min}/LAI is nearly equal for overstory and understory cover, when LAI values for both stories are averaged over the snow-free zone and accounting for fractional forest cover (canopy closure, Table 1). If the tree cover in the 65% snow covered zone is also taken into account, then rs_{min}/LAI is a factor 1.6 smaller for overstory than for understory, but the contribution of this zone to basin-aggregated ET is limited due to the colder conditions. Because of its smaller height, r_a for the understory under clear-cut conditions is about a factor 2 larger than r_a for the overstory under pre-logging conditions. The above calculations suggest that the mechanism by which the understory can compensate for the lack of overstory ET following clear-cutting is its lower resistance to vapor transport. However, the model-predicted lack of sensitivity of spring ET to clear-cutting hinges on the adopted model parameters and the reader is reminded that simulated ET is currently poorly constrained by available data (section 2). Present model results suggest that the focus of the IWAP on the relationship between increased snow accumulation and melt in cut areas and logging-related changes in peak streamflows is justified.

[24] The model-predicted rate of snowmelt is quite uniform throughout the peak flow period mid-May to mid-June (Figure 8) despite a retreating snow line. The initial response of the basin to meltwater delivery is to replenish soil moisture lost by a lack of recharge during the winter period. Once conditions in the vadose zone equilibrate, streamflow accumulation also attains a nearly constant rate. The time delay associated with the basin response to the onset of the constant rate of meltwater delivery is approximately 10 days. The basin aggregated melt rate drops at the end of the peak flow period in mid-June around the time that the snow line retreats into the alpine upper 40% of the basin (Figure 6). The response time of the outflow hydrograph to this lowered meltwater delivery is on the order of 4–5 days (Figure 8). A time delay of this magnitude is expected given that runoff is generated predominantly

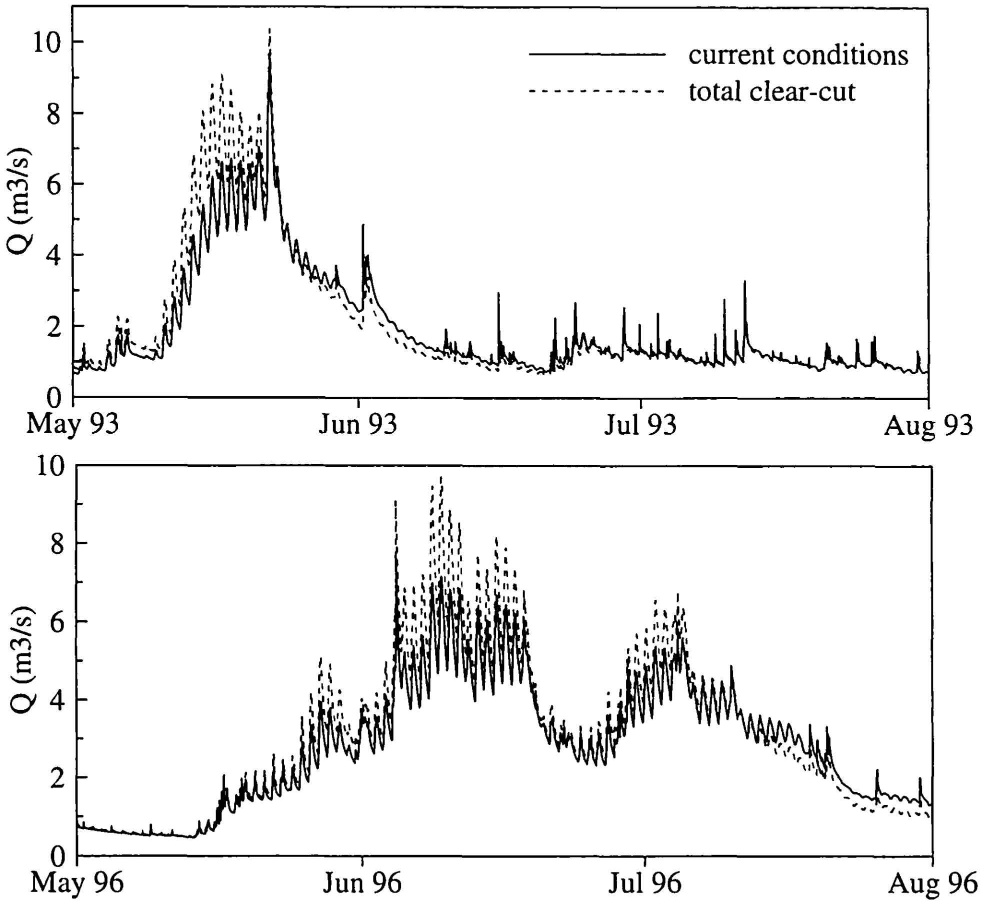

Figure 9. Simulated changes in hydrograph characteristics due to clear-cutting the entire Redfish Creek basin for 1993 and 1996.

through subsurface flow [*Whitaker et al.*, 2002]. Some faster flow routing through overland flow from near-channel saturated areas may explain why the effect of diurnal fluctuations in melt rates is reflected in the outflow hydrograph (Figure 7). This analysis illustrates that there is a strong relationship between basin aggregated snowmelt and streamflow accumulation at Redfish Creek and that ignoring runoff generation and channel routing, as done in the IWAP, may only have a moderate impact on this relationship.

[25] The 30 year post-logging record for the Fool Creek watershed [*Troendle and King*, 1986] illustrates that logging related changes in peak flows may vary significantly from year to year. At Redfish Creek, the rapid rise in the 1993 hydrograph mid-May, explained by sudden warm air temperatures (Figure 7a), is further accelerated under total clear-cut conditions (Figure 9), causing increases in hourly flow rates of up to 51% compared to current conditions. Simulated flows during the summer recession are slightly reduced as a result of this faster snowmelt. For 1996, the timing of the high-flow period is essentially unchanged between current and total clear-cut conditions as explained by the more gradual rise in spring air temperatures for this year. While 1996 was characterized by a greater snowpack than 1993, simulated peak streamflows are affected to a lesser degree by the total clear-cut with a maximum impact of up to 36% compared to current conditions. This suggests that year-to-year variability in timber harvesting effects on peak streamflows may depend more on climate conditions during snowmelt (spring temperatures) than on the size of the snowpack (winter precipitation).

4. Peak Flow Sensitivity to Logging in Different Elevation Bands

4.1. Design of Harvest Scenarios

[26] To assess peak flow sensitivity to logging in different elevation bands of the catchment, harvest scenarios were designed based on the hypsometric curve (Figure 2). The forest zone is divided using the H60 and H80 hypsometric elevations of 1740 m and 1520 m to give three elevation zones, each representing 20% of the total basin area. The

Table 3. Percent of Total Basin Cut for the Seven Harvest Scenarios and Current Conditions

Scenario	Description	Percent Basin Cut
Current	calibrated model	9.9
1	1/3 cut lower forest	11.2
2	2/3 cut lower forest	18.0
3	1/3 cut middle forest	12.3
4	2/3 cut middle forest	19.0
5	1/3 cut upper forest	15.8
6	2/3 cut upper forest	22.4
7	1/3 cut lower, middle, and upper forest	19.2

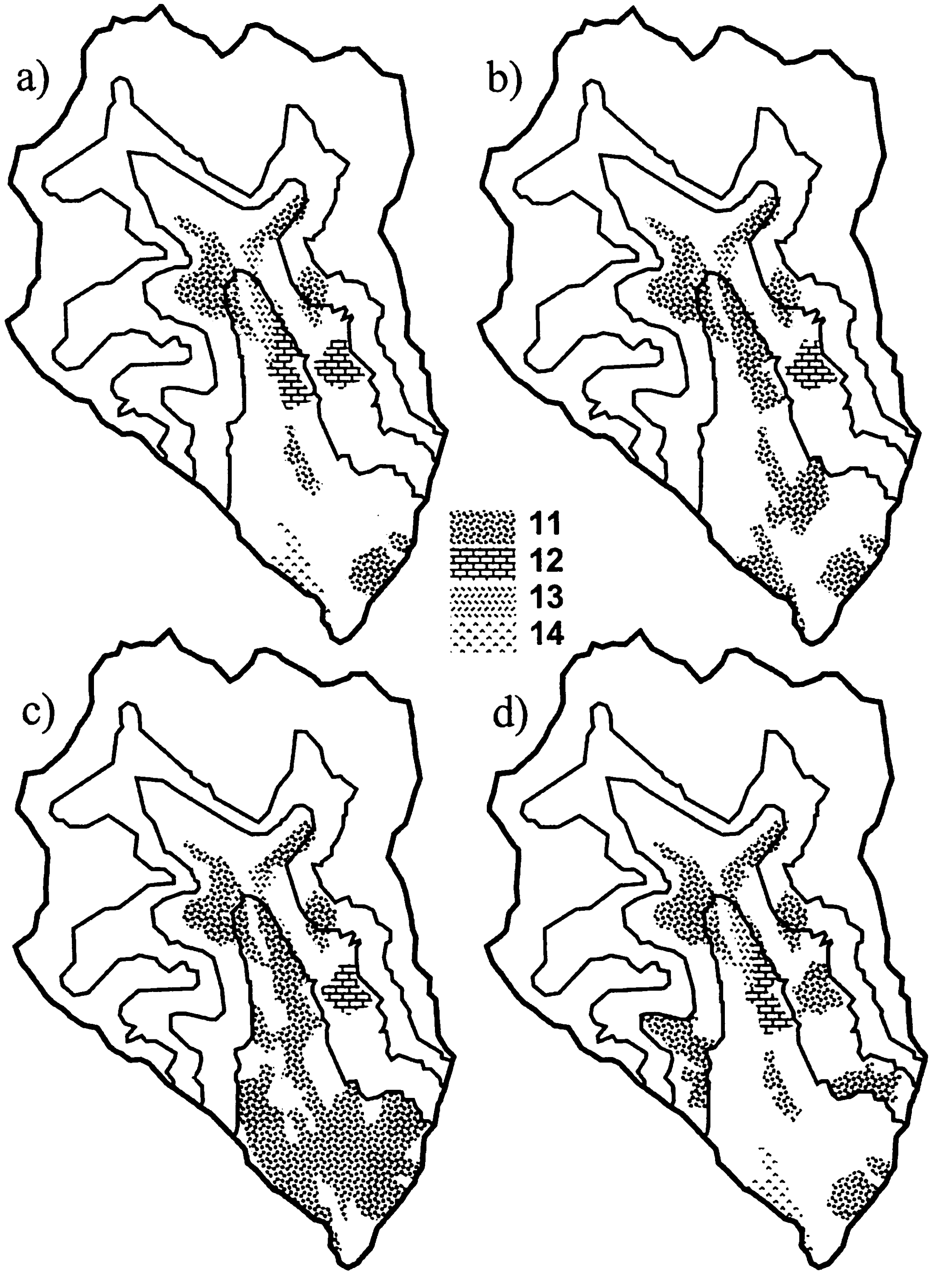

Figure 10. Distribution of new and recovering clear-cut areas for (a) current condition (calibrated model), (b) logging scenario 1, (c) scenario 2, (d) scenario 3, (e) scenario 4, (f) scenario 5, (g) scenario 6, and (h) scenario 7. Vegetation classes are described in Table 1. Percent basin cut is listed in Table 3. H40, H60, and H80 hypsometric lines (Figure 2) are indicated as solid lines.

upper 40% of the basin is devoid of merchantable trees or has no trees at all. Harvesting in this elevation band is therefore not considered in the scenario analysis.

[27] Logging scenarios were developed taking the vegetation distribution under current conditions (Figure 3a) as a starting point. Each scenario therefore considers timber harvesting in addition to the current 9.9% cut level (Table 3). The logging scenarios consider one-third and two-thirds harvest levels in the lower (scenario 1 and 2; Figures 10b and 10c), middle (scenarios 3 and 4; Figures 10d and 10e) and upper (scenarios 5 and 6; Figures 10f and 10g) forest zones, as well as a one-third clear-cut across all three zones (scenario 7; Figure 10g). The desired harvest level (area covered by vegetation type 11) in a certain elevation band was achieved by first removing the overstory in recovering clear-cuts (vegetation types 12–14) and by subsequently

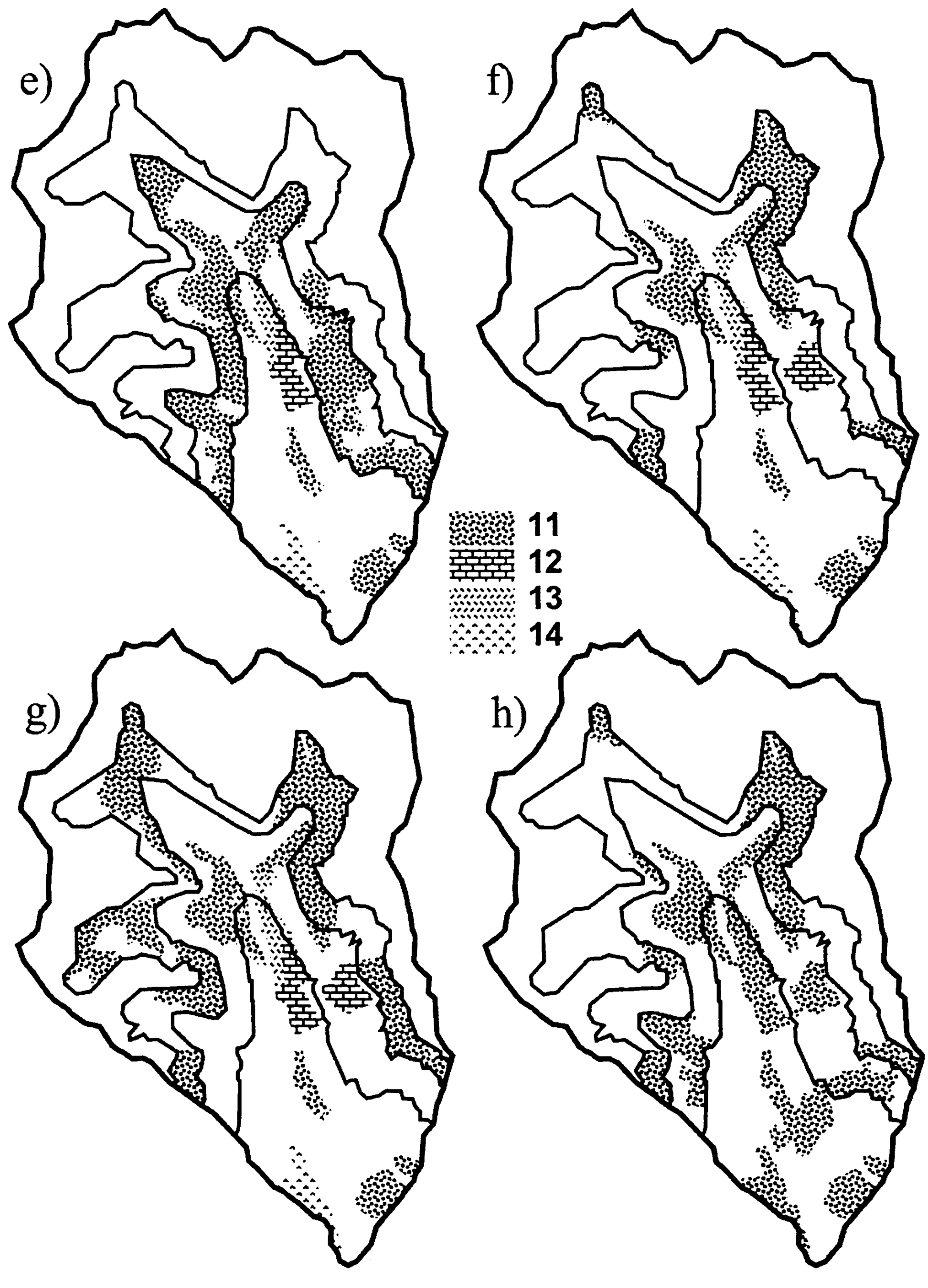

Figure 10. (continued)

removing the canopy in selected forest stands. Cumulative basin cuts corresponding to the 1/3 and 2/3 harvests in the upper forest zone are greater than those for similar harvest levels in the lower and middle forest (Table 3), given that existing clear-cuts are mostly located below the H60 line (Figure 10a).

4.2. Simulated Peak Flow Changes

[28] Because the scenarios were developed using the current harvest level as a starting point, corresponding changes in peak streamflows were originally reported using the simulated hydrograph for the calibrated model as a baseline [*Whitaker et al.*, 2001]. However, the IWAP was designed to assess the cumulative watershed effects of past and planned timber harvesting. In order to test IWAP guidelines, peak flow changes must be calculated using pristine pre-logging forest conditions as a baseline. To obtain a baseline hydrograph for pre-logging catchment conditions, a simulation was performed in which existing clear-cut areas in the calibrated model were replaced by mature forest with vegetation parameters resembling those of the surrounding forest stands (Table 4). Peak flow

Table 4. Overstory Characteristics of Vegetation Classes 11–14 Used to Simulate Hypothetical Pristine Baseline Conditions

Class	Height, m	Canopy Closure (0–1.0)	Leaf Area Index (LAI)
11	30	0.6	4
12	30	0.7	6
13	30	0.6	4
14	38	0.7	7

changes for the harvest scenarios will be reported with respect to this pre-logging baseline. Some additional model error may be introduced by replacing the existing clear-cuts with hypothetical forest cover parameters to represent pristine catchment conditions. However, because these hypothetical parameters resemble those for the surrounding forest stands and because only a small fraction (9.9%) of the catchment is affected by filling in the clear-cuts with mature forest, this additional model error is likely only small.

[29] To help in identifying patterns of peak flow change for radiation-dominated snowmelt across the various harvesting scenarios, a 7-day period with minimal precipitation around the annual peak was examined for each of the five years of simulation. Maximum percent change in hourly flow compared to pristine conditions was determined for this period (Table 5). Year-to-year variability in these instantaneous peak flow increases is significant, with greatest changes again seen for 1993 and considerably smaller increases in all other years.

[30] When considering geomorphologic impacts of changes in flow rates on the stream channel environment, it is important to consider not only the actual peaks in the hydrograph but also the sustained high flows over a period of several days. Bank erosion and entrainment of bed materials may be more dependent on the actual peaks, while overall sediment transport and channel morphology is determined to a larger extent by high flows over longer periods. Although smaller in magnitude, sustained changes in high flows for the selected 7-day periods (Table 6) follow the same trend between scenarios as maximum changes in the peaks (Table 5), as illustrated by the 5 year averaged values (Figure 11a). This suggests that any indicator designed to predict potential instantaneous changes in peak flows should also perform well in predicting sustained changes in high flows over longer periods.

[31] The potential for rain or rain-on-snow events to enhance spring peak flows depends on rainfall magnitudes and the proximity of rainfall events to the annual peak. For the period of record, only one rainfall event on 3 June 1996 occurs directly prior to the annual peak flow period (7–13 June). Maximum changes in flow rates following the 3 June peak hourly precipitation of 11 mm (Figure 7c) were calculated for each scenario (Table 7) and largely follow the same trend between scenarios as the instantaneous peak flow changes during the 7 day radiation snowmelt period (Figure 11b). A longer data record is needed to better evaluate the potential for spring rainfall and rain-on-snow to enhance peak flows.

4.3. Analysis of Instantaneous Peak Flow Changes

[32] Statistical analyses conducted in the Pacific Northwest have been used to correlate basin discharge trends to either percent basin harvested, or to the percent immature forest in a watershed which also allows for forest recovery following clear-cutting [*Beschta et al.*, 2000; *Bowling et al.*, 2000]. The IWAP utilizes similar concepts in calculating the equivalent clear-cut area (*ECA*) of a basin from the area *A* affected by logging and the percent hydrologic recovery (*R*) of that area due to forest regrowth:

$$ECA = \sum_i A(i) * \left(1 - \frac{R(i)}{100}\right) \tag{1}$$

where the sum *i* is taken over individual cut areas. The IWAP suggests values for *R* based on the height of trees in a recovering clear-cut [*BC Ministry of Forests*, 1999]. Values of $R = 0\%$, 20%, 40% and 80% have been assumed here for vegetation types 11–14, respectively. *ECA* for each scenario was calculated based on these assumed recovery values and the cut area for each vegetation type (Figure 10).

[33] Peak flow hazards related to timber harvesting are calculated based on *ECA* and by assigning a weight $W = 1.0$ to cut areas below the H60 line and a weight $W = 1.5$ to cut areas above this line. The peak flow index ($IWAP_{pfi}$) is thus calculated as [*BC Ministry of Forests*, 1999]:

$$IWAP_{pfi} = \sum_i W(i) * A(i) * \left(1 - \frac{R(i)}{100}\right) \Big/ B \tag{2}$$

where *B* is the total catchment area. $IWAP_{pfi}$ was calculated based on the assumed recovery values and the

Table 5. Logging-Induced Maximum Percent Change in Hourly Flow for Radiation-Dominated Snowmelt During a 7-Day Period in Each Year[a]

Scenario	1993, 14–20 May	1994, 7–13 May	1995, 26 May to 1 June	1996, 7–13 June	1997, 15–21 May	Mean
Current condition	30	10	8	11	7	13
Scenario 1	28	8	6	8	7	11
Scenario 2	28	8	7	8	10	12
Scenario 3	31	10	7	11	12	14
Scenario 4	37	15	11	15	19	20
Scenario 5	35	13	11	15	10	17
Scenario 6	43	17	15	20	15	22
Scenario 7	34	10	9	13	17	17

[a] Percent change is with respect to pristine baseline conditions.

Table 6. Logging-Induced Average Percent Change in Hourly Flow for Radiation-Dominated Snowmelt for a 7-Day Period in Each Year[a]

Scenario	1993, 14–20 May	1994, 7–13 May	1995, 26 May to 1 June	1996, 7–13 June	1997, 15–21 May	Mean
Current condition	11	6	5	7	4	7
Scenario 1	11	5	5	5	4	6
Scenario 2	11	5	5	5	6	7
Scenario 3	10	5	4	6	7	7
Scenario 4	13	9	7	9	12	10
Scenario 5	15	9	9	10	7	10
Scenario 6	19	11	12	13	10	13
Scenario 7	14	7	7	7	10	9

[a]Percent change is with respect to pristine baseline conditions.

cut area for each vegetation type above and below the H60 line (Figure 10). The 1.5 weight has been chosen arbitrarily and (2) is not meant for physical interpretation in terms of an expected change in peak flow magnitude corresponding to a certain harvest scenario. However, despite this lack of physical interpretation higher index values still need to correspond to greater peak flow increases and vice versa in order to be meaningful.

[34] A comparison of simulated 5-year averaged instantaneous changes in peak flow (Table 5) with *ECA/B* (Figure 12a) illustrates that this index performs well in discriminating differential impacts of one-third cuts versus two-thirds cuts in the middle (scenarios 3 and 4) and upper forest zone (scenarios 5 and 6). Furthermore, *ECA/B* performs slightly better in explaining the overall pattern of simulated peak flow changes than $IWAP_{pfi}$ (Figure 12b). The excellent correlation between *ECA/B* and model-predicted changes in peak flow for current conditions and scenarios 3–6 (Figure 12a) suggests that elevation differences in harvesting impacts play a minor role in explaining peak flow changes for these scenarios. This good performance of *ECA* alone in explaining differential peak flow increases for scenarios considering logging in the middle and upper forest zones may be somewhat puzzling in view of the marked increase in snowpack with elevation (Figure 4). However, given that changes in streamflow accumulation ($\Delta S/S$) and peak flows are strongly correlated to changes in the basin aggregated melt volume ($\Delta V_B/V_B$) (Figure 8), the following proportionality may be expected:

$$\frac{\Delta S}{S} \sim \frac{\Delta V_B}{V_B} = \frac{\sum_i \left(M_A^c(i) - M_A^f(i)\right)A(i)}{M_B{*}B} = \sum_i \left[\frac{M_A^f(i)A(i)}{M_B{*}B} * \left(\frac{M_A^c(i)}{M_A^f(i)} - 1\right)\right] \qquad (3)$$

This expresses that changes in streamflow accumulation following timber harvesting not only depend on the size of cut areas $A(i)$ and spatial variability (elevation differences) in pre-logging snowmelt rates $M_A^f(i)$ (together giving the fractional contribution of area i to the basin-aggregated melt $V_B = M_B{*}B$) but also on spatial variability in the ratio $M_A^c/M_A^f(i)$. The analysis conducted for Upper Burn, Ross and Cabin suggests that forest and clear-cut snowmelt rates increase with elevation but that $M_A^c/M_A^f(i)$ (inverse of ratios listed in Table 2) decreases with elevation. For the middle and upper forest zones, the combined effects of elevation increases in M_A^f and decreases in M_A^c/M_A^f cancel out, as expressed by the product M_A^f $(M_A^c/M_A^f - 1)$ in (3). This product, which equals the absolute increase in snowmelt rates due to clear-cutting, is 0.37 cm/d at both Ross and

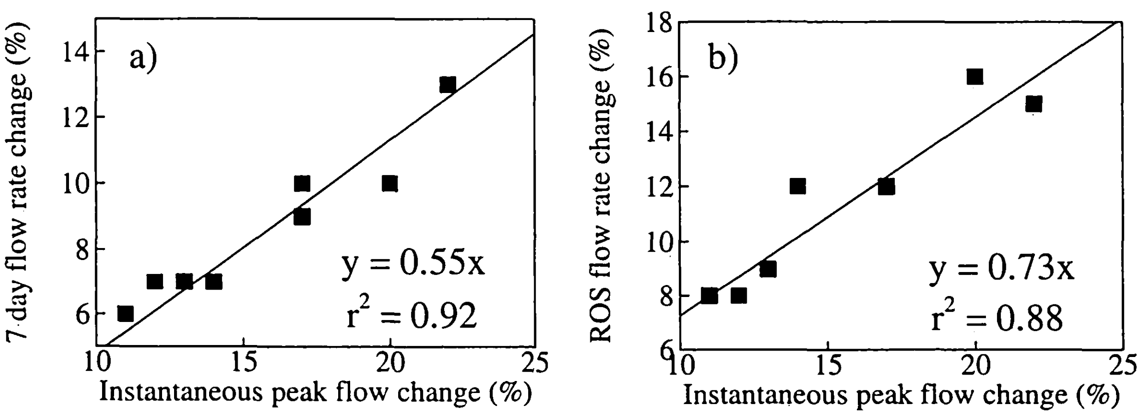

Figure 11. Comparison of simulated instantaneous peak flow changes during radiation-dominated snowmelt (Table 5) with (a) 7-day averaged flow rate changes (Table 6) and (b) the rainfall enhanced changes in flow rates for 3 June 1996 (Table 7).

Table 7. Logging-Induced Percent Change in Hourly Flow During Selected Rainfall Event Directly Prior to the High-Flow Period for 1996[a]

Scenario	3 June 1996
Current condition	9
Scenario 1	8
Scenario 2	8
Scenario 3	12
Scenario 4	16
Scenario 5	12
Scenario 6	15
Scenario 7	12

[a] Percent change is with respect to pristine baseline conditions.

Cabin. Equation (3) then suggests that cut area (*A*) alone should indeed perform well in differentiating peak flow changes for scenarios considering harvesting in the middle and upper forest zones. The scenario analysis therefore does not support the IWAP assumption that timber harvesting in the upper forest zone will have a significantly greater impact on peak flows than logging in the middle portions of the basin.

[35] Model-predicted snowmelt rates have only undergone limited evaluation against average rates of decline in measured SWE (section 2). In the above analysis we have therefore used averaged melt rates for Ross and Cabin (Table 2) as a proxy for melt rates around the 7-day peak flow window. For the middle and upper forest zones this approach may be reasonable, but at this time the snowpack has already disappeared from the lower forest zone around Upper Burn (Figure 3c). As a result of this snowmelt timing, elevation is an important factor when comparing the sensitivity of peak flows to harvesting in the middle and lower forest zones. Model-predicted peak flow changes for scenarios 1 and 2 are smaller than for scenarios 3 and 4 (Table 5). However, *ECA/B* and $IWAP_{pfi}$ do not discriminate between logging in the lower forest and middle forest zones. Instead, similar harvest levels for the 1/3 cuts (scenarios 1, 3) and for the 2/3 cuts (scenarios 2, 4) lead to similar index values (Figure 12).

[36] While scenarios 1 and 2 represent higher harvest levels than current conditions (Table 3), peak flow increases for these two scenarios are in fact slightly smaller than those predicted for the calibrated model (Table 5). The additional harvesting in the lower forest zone for these two scenarios subtly reduces the magnitude of annual peak flow compared to current conditions because increased melt rates at low elevation slightly advance the rising limb of the hydrograph and lower the annual peak. The *ECA/B* index does not account for this snowmelt de-synchronization effect, causing those scenarios that consider additional timber harvesting in the lower forest zone (1, 2 and 7) to plot on or below the regression line (Figure 12a). For 1997, the marginal snowpack in the lower reaches of the basin near Burn and Upper Burn was proportionally greater than in other years (Figure 4) and it is interesting to note that the effect of snowmelt de-synchronization is seen for all years except 1997 (Table 5).

[37] The model results thus suggest that logging in the bottom 20% of the basin causes little or no change in peak streamflows, while harvesting at higher elevation above the H80 hypsometric line may result in significant increases in these peaks. Peak streamflows at Redfish Creek are therefore sensitive as to whether harvesting takes place below or above the H80 elevation. On the other hand, harvest elevation becomes relatively unimportant above the H80 hypsometric line and cut area alone is a good indicator of peak flow changes that may be expected due to logging in the entire H80-H40 elevation band.

5. Conclusions

[38] A hydrologic model for Redfish Creek was used to evaluate Interior Watershed Assessment Procedure (IWAP) guidelines regarding peak flow sensitivity to clear-cutting at different elevation zones of snowmelt-dominated catchments and to provide insight regarding the role of various hydrological processes in this context. Harvesting related increases in peak flow during the mid-May to mid-June high-flow period appear to be caused by greater snowmelt delivery from cut areas while similar rates of evapotranspiration are predicted during this period under forested and clear-cut conditions. A strong correlation was observed between changes in spring air temperature and simulated flow rates and year-to-year variability in timber harvesting effects on peak streamflows may depend more on climate

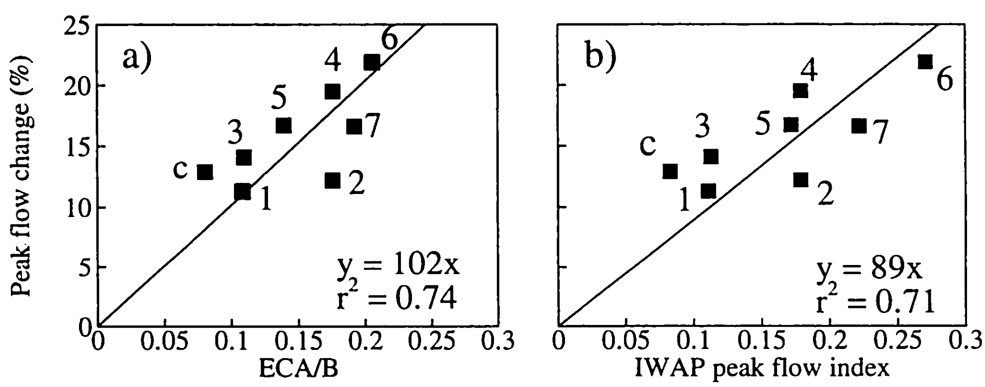

Figure 12. Comparison of model-predicted instantaneous peak flow changes for radiation-dominated snowmelt (Table 5) with (a) *ECA/B* and (b) IWAP peak flow index. Numbers refer to logging scenarios, while "c" designates current conditions (calibrated model).

conditions during snowmelt (spring temperatures) than the on size of the snowpack (winter precipitation). Model results suggest that the present 9.9% harvest level has led to instantaneous increases in annual peak flow averaging 13% for the 1993–1997 period, while sustained high flows are on average 7% higher than under pre-logging conditions. Long-term simulations of forest management scenarios would be required to improve quantitative estimates of peak flow change in the context of climate variability. Hydrologic recovery of previously logged areas is important when considering the cumulative impacts of forest management and this issue can also be addressed through long-term simulations [*Alila and Beckers*, 2001].

[39] Snow accumulation and melt are clearly related to elevation at Redfish Creek and snowmelt is strongly correlated with the outflow hydrograph but the relationship between harvest elevation and corresponding peak flow changes is more complex than suggested in the IWAP. The IWAP assumes that snow typically covers the upper 60% of a basin at around the time of peak streamflow and that timber harvesting above this H60 line will have a significantly greater impact on peak flows than logging in lower portions of the basin. While the first of these assumptions was reasonably confirmed for Redfish Creek, the second notion is not supported by the simulation results. Instead, the H80 elevation line was found to be important, while cut block elevation was found to be relatively unimportant above this line. Increasing harvest levels in the bottom 20% of the watershed caused little or no change in current peak flow magnitudes. Increasing harvest levels in the upper 80–40% of the basin resulted in significant impacts on annual maximum flows with instantaneous increases of up to 22% for a 22.4% basin cut. These results are in agreement with the small size of the low-elevation snowpack and the early season disappearance of snow in the bottom part of the basin. The important role of harvest elevation in the lower reaches of the basin has important consequences, not only for forest management decisions aimed at minimizing logging impacts on annual maximum flows but also for statistical analyses that seek to correlate peak flow changes to percent basin harvested.

[40] Care should be taken in extending the Redfish Creek results to other basins as the importance of individual watershed topographic characteristics for snowmelt and peak flow generation must be further examined. For example, the upper 40% of the Redfish Creek basin is alpine or subalpine in character, lessening the effect of timber harvesting on peak streamflows. Logging impacts in basins without an alpine zone may be proportionally greater. Furthermore, in terrain characterized by plateaus, a significant portion of the total basin area will fall within a narrow elevation range and peak flows will be particularly sensitive to harvesting in these areas of gentle slopes, because snowmelt is simultaneous across the entire zone. It is therefore worthwhile to determine the extent to which the model results obtained for Redfish Creek can be generalized for watersheds across interior British Columbia through an analysis of additional basins with different topographic characteristics. Modeling of hydrologic processes can thus provide useful information in support of forest management decisions, supplementing information derived from paired watershed experiments. Data limitations that emerged in testing model results with regard to forest clear-cut differences in snowpack dynamics and evapotranspiration may serve to guide future data collection.

Appendix A: Model Assumptions Regarding Forest Cover Effects on Snowpack Dynamics

[41] Forest cover effects on snow accumulation depend on the quantity of snow that can be intercepted by the canopy and the fate of that intercepted snow. DHSVM [*Storck*, 2000, p. 72] calculates the change in intercepted snow (ΔI) in a model time step as a fixed percentage (interception efficiency E) of snowfall (S), $\Delta I = E^*S$, until a maximum interception capacity (C) is reached: $I = \min(I + \Delta I, C)$. Intercepted snow is either removed from the canopy by snowmelt drip (D) calculated using an energy balance approach, by snow vaporization or by snow sliding off the canopy (melt-induced mass release, MR) assumed to be a fixed fraction of drip (MR/D). The forest cover also affects the snowpack energy balance and snowmelt rates. The overstory attenuates incident short wave radiation (R_s, measured), controlled in DHSVM by a canopy attenuation coefficient (k), overstory LAI and canopy closure (fractional forest cover, F). The flux R_{ss} absorbed by the snowpack is given by [*Wigmosta et al.*, 1994, p. 1669]: $R_{ss} = R_s(1 - \alpha_s)\{F\exp[-kLAI] + [1 - F]\}$, where α_s is an age-dependant snow albedo. The net long wave radiation exchange (R_{ls}) at the snow surface is given by: $R_{ls} = L_0F + \{L_d[1 - F]\} - L_s$ and depends on incident long wave radiation (L_o) absorbed by the canopy, long wave radiation fluxes (L_d) emitted downward by the canopy and the upward long wave flux from the snow surface L_s. L_o, L_d and L_s are calculated based on air temperature, canopy temperature and snow surface temperature, respectively. Sensible and latent heat exchanges at the snow surface depend on the vertical wind profile through the overstory, which in DHSVM is controlled by a canopy aerodynamic attenuation coefficient (n) and overstory height (H), F and LAI values [*Wigmosta et al.*, 1994, pp. 1677–1678].

[42] A two step approach was taken in calibrating the snow component of the Redfish Creek model [*Whitaker et al.*, 2002]. First, α_s was optimized based on inferred clear-cut snowmelt rates near the Burn and Cabin climate stations (Figure 4). Next, forest cover parameters affecting snow accumulation and melt below the canopy were determined making use of the Upper Burn SWE data (Figure 5). Values of $E = 0.35$ and $C = 4$ mm were adopted based on *Satterlund and Haupt* [1967] and *Schmidt and Gluns* [1991], while $MR/D = 0.4$ was taken from *Storck* [2000]. The appropriateness of adopted radiation ($k = 0.3$) and wind attenuation coefficients ($n = 2$) was further assessed based on energy flux measurements by *Adams et al.* [1998]. These measurements suggest that the below-canopy energy balance is dominated by net radiation, while latent and sensible heat fluxes are small, and have shown long wave radiation to be the largest source of energy in the forest. In the model, long wave radiation comprises on average 91% of total radiation fluxes absorbed by the Upper Burn below-canopy snowpack during the snowmelt period. Net radiation in turn constitutes on average 88% of snowpack energy fluxes during snowmelt. All forest cover parameters are assumed constant

between vegetation types, except for H, F, and LAI values (Table 1), which were not adjusted during model calibration.

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