Modelling of Peak Flow Change Using the DHSVM Model

ANDREW WHITAKER, YOUNES ALILA, AND D.A.A. TOEWS

ABSTRACT

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a physically based model that uses a Digital Elevation Model (DEM) to simulate the effect of topography on hydrologic processes. The influence of the forest canopy on the accumulation and melt of snowpack is simulated in an explicit and physically based approach. Model calibration was possible through the use of snow course surveys and snowline air-photo surveys in addition to stream discharge at Redfish Creek experimental watershed near Nelson, B. C., where extensive hourly data are available. The model appears to correctly simulate the influence of forest canopy on the snowpack, and simulated and observed hydrographs are well matched in both calibration and verification periods. Subsequently, 10 harvest scenarios, with varying levels of cutting in different elevation zones, were evaluated over the 5-year period of record (1992–1997). Redfish Creek basin (26 km^2) is divided into four elevation zones based on the hypsometric curve. The three lower zones (700–1880 m) contain operable forest and make up 60% of total basin area, while the high-elevation alpine zone (1880–2300 m) forms 40% of basin area. Results show that harvesting at progressively higher elevations (especially upper forest zone and alpine) causes progressively larger increases in peak flows. There is significant variability from year to year, indicating that the magnitude of peak-flow change depends on the unique weather conditions and seasonal melt pattern in a given year. Cutting in the lowest zone (H80–H100) has little or no effect on peak flow. In the middle forest zone (H60–H80), low-intensity cutting (7% of basin) has little effect, but consistent increases in peak flows are seen with high-intensity cutting (13% of basin). In the upper zone (above H60), low-intensity cutting increased peaks by 6.7–9.5%, while high-intensity cutting produced increases of 13.1–19.4%. A scenario with low-intensity cutting in all forest zones showed a significantly reduced impact on peak flows (except in 1997) even though a greater percentage of basin area (20%) was harvested. Peak-flow change is closely related to harvest elevation(s) and also to seasonal weather patterns in snow-dominated watersheds such as Redfish Creek.

1 INTRODUCTION

Current watershed assessment guidelines in British Columbia assume that peak-flow increases depend on harvest elevation. Here modelling is used to determine changes in peak flows due to realistic harvesting scenarios in various elevation zones in southern interior British Columbia. In particular, the modelling will test current assumptions in the Interior Watershed Assessment Procedure (IWAP) (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) regarding the effects of harvesting on peak flows. One key assumption assigns different weighting to harvesting impacts above and below the H60 elevation on the watershed hypsometric curve. This is a very demanding modelling objective, and one that requires hydrologic processes to be modelled using physical rather than empirical relationships (Abbott et al. 1986). Three important process changes have been determined in considering the effects of forest harvesting; changes in snow accumulation and melt as a result of canopy removal, changes in evapotranspiration during the growing season, and changes in stream channel networks as a result of forest roads and ditches. In considering peak flows, this study is concerned primarily with the first group of processes under snow accumulation and snowmelt, while the influence of forest roads is to be included at a later date. Extensive data from the Redfish Creek experimental watershed are used to calibrate and verify the Distributed Hydrology Soil Vegetation Model (DHSVM) before evaluating forest harvest scenarios. The 5-year data set includes hourly data for several climate stations within the catchment, snow course surveys, and air-photo mapping of snow coverage patterns.

2 DHSVM

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a complex physically based model that uses a Digital Elevation Model (DEM) to simulate the effect of topography on hydrologic processes (Wigmosta et al. 1994) (Figure 1). DHSVM was chosen after a review of six pertinent hydrological models, to assess their suitability in simulating the consequences of timber harvesting on peak flows in British Columbia (Whitaker et al. 1998). The model includes the influence of forest cover and clearcutting on the accumulation and melt of snow, which determines the magnitude of peak flows in interior British Columbia. Data requirements are high and include climate,

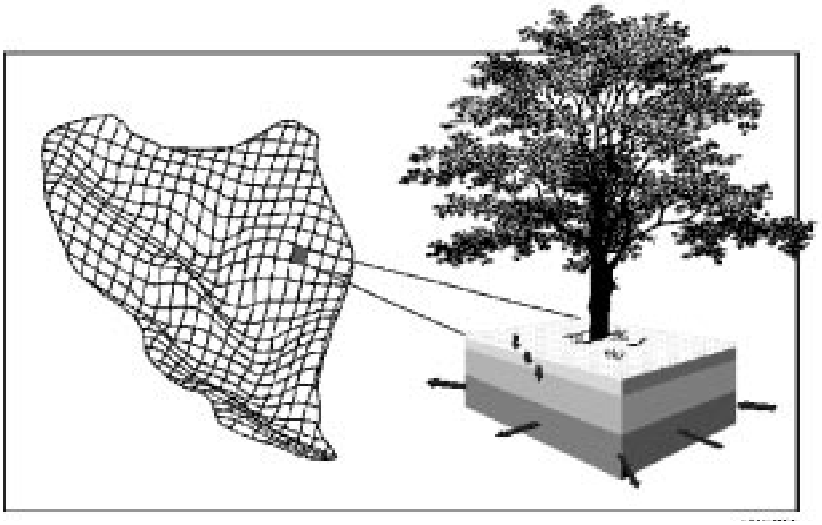

FIGURE 1 *Distributed Hydrology Soil Vegetation Model (DHSVM).*

snow cover, soil and vegetation surveys, and stream flow records. Simulation can be at daily or sub-daily time steps, and so an hourly interval was chosen in this study to allow simulation of the changes to instantaneous peak flows.

DHSVM is distinguished from other hydrologic models in that the spatial distribution of soil moisture, snow cover, evapotranspiration, and runoff production can be simulated at sub-daily time steps (Wigmosta et al. 1994). It consists of a two-layer canopy representation for evapotranspiration, a two-layer energy-balance model for snow accumulation and melt, a multilayer unsaturated soil model, and a saturated subsurface flow model. Climate data input includes precipitation, temperature, wind, humidity, and incoming shortwave and longwave radiation. Digital elevation data are used to model topographic controls on incoming shortwave radiation, precipitation, air temperature, and downslope water movement. Vegetation cover and soil properties are assigned to each digital elevation model (DEM) grid cell or pixel. For each model pixel, the land surface may be composed of overstory vegetation and/or understory vegetation, or just bare soil. As soil and vegetation characteristics are represented explicitly for each pixel across a catchment, it is possible to simulate any number of land-use change scenarios and examine the change in hydrologic response of the catchment.

3 REDFISH CREEK APPLICATION

Considerable time and resources were required in applying DHSVM to Redfish Creek. Information was gathered on the vegetation and forest cover, the soil and terrain characteristics, and multiple climate stations within the study basin. A significant amount of GIS work was involved in preparing soil and vegetation maps, and in analyzing the DEM to derive a stream channel network. A few model parameters could be estimated from standard reference texts, but many required consultation with specialists in soil science, climatology, plant physiology, hydrology, and geomorphology, and with people who have long-term field experience in the study watershed. To assemble all the information, check the quality of 5 years of hourly climate data, estimate missing values, and prepare all of the model input files, represents 9 months of work for a single worker. The model calibration and verification represents a further 3 months of work. Full details on the data preparation, model calibration, and verification may be found in the final reports submitted to the Ministry of Forests (Whitaker and Alila 2000), while this paper focuses on the modelling results and their application in practice.

The Redfish Creek basin (26 km^2) is located on the West Arm Demonstration Forest in the Kootenay Mountains near Nelson, B.C. (Figure 2). The basin has been glaciated, and ranges in elevation from 700 to 2300 m. 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. To date, approximately 10% of the basin area has been harvested. The underlying geology is granitic and is considered to give a relatively tight water balance, so that the majority of the outflow leaves the basin as surface water streamflow.

The completeness of the Redfish Creek data set allows a unique and first-time application of DHSVM in a subalpine forested watershed in interior,

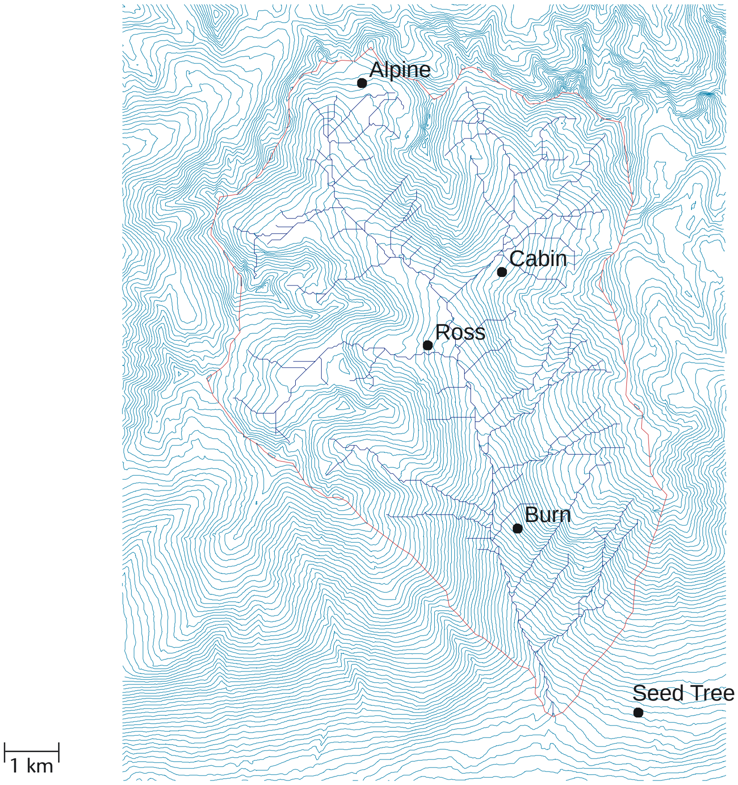

FIGURE 2 *Redfish Creek 25 m contour map derived from DEM and showing gauged basin boundary, derived stream network, and climate stations.*

snow-dominated conditions. At the Redfish Creek experimental basin, extensive hourly data were available for the 5-year period 1992–1997. The important features of the data set are that hourly data are available for both the stream discharge and several climate stations within the watershed (Figure 2). Also of significance is the availability of several snow courses and a snow pillow that allow verification of the snowpack accumulation and melt within the model. Limited data for one tributary stream also allowed the accuracy of internal runoff generation to be evaluated.

The vegetation map and forest cover characteristics for the model were derived from Ministry of Forests operational forest cover maps (FC1 series). Forest stand polygons were grouped together to give 14 vegetation types based on species composition, presence or absence of overstory and understory, vegetation height, stand age, and crown closure (Figure 3, Table 1). Measurements of leaf area index were not available, and the model values were estimated based on species composition and measurements made in the surrounding region.

Soil information was derived from detailed terrain mapping completed for the West Arm Demonstration Forest (Utzig 1997). Several hundred soil polygons were merged to create seven soil classes based on dominant genetic material. Given the absence of detailed field measurements, most soil parameters had to be derived from soil textural class and coarse fragment content that was available for four separate soil layers. Evapotranspiration could remove moisture from only the upper three layers, depending on root depths, and not the lowermost layer.

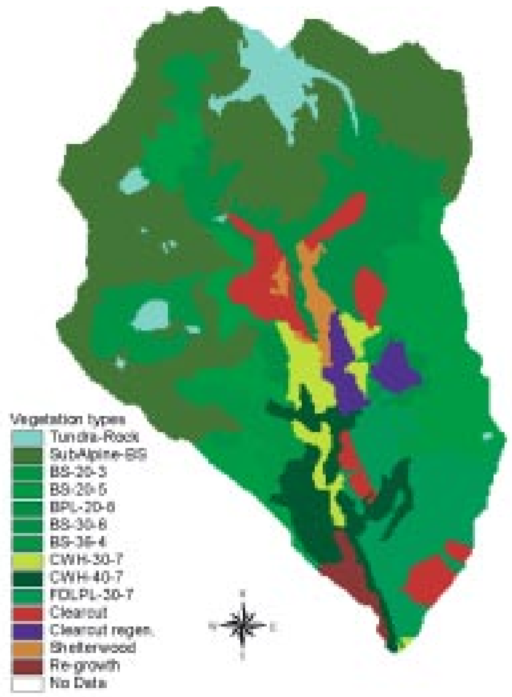

FIGURE 3 *Current vegetation cover for Redfish Creek.*

TABLE 1 *Key characteristics for each of 14 vegetation types*

Veg. type	Description / species	Stand age (years)	Overstory height (m)	Canopy closure (0–1.0)	Leaf area index (LAI)
1	Vegetation absent	N/A	N/A	N/A	N/A
2	Subalpine	200	12	0.2	2.5
3	Balsam-Spruce	180	21	0.3	3.0
4	Balsam-Spruce	140	22	0.5	3.5
5	Balsam-Pine	130	20	0.8	5.0
6	Balsam-Spruce	170	30	0.6	4.5
7	Balsam-Spruce	260	36	0.4	4.0
8	Cedar-Hemlock	160	27	0.65	7.0
9	Cedar-Hemlock	170	39	0.7	7.0
10	Douglas-fir–Larch-Pine	115	29	0.7	6.0
11	Clearcut-no overstory	8	0	0	0
12	Clearcut-early regeneration	10	3	0.1	2.5
13	Clearcut-shelterwood	10	15	0.1	2.5
14	Regenerated clearcut	38	15	0.2	3.0

The gridded DEM required by the model was derived from the 1:20 000 TRIM series or the Province of British Columbia. Gridded DEMs are available for large blocks in the form of NTS 1:250 000 quadrangles that must be subset for the desired watershed. Once within the GIS (ArcView with Spatial Analyst in this application), the DEM is analyzed to define the channel drainage network and delineate the watershed boundary (Figure 2). This is necessary because overland and subsurface flow generation is determined from DEM gradients within the model. An air-photo–derived channel map was used to edit the final channel network. The Redfish Creek DEM contains 41 331 pixels (each 25 by 25 m) with a drainage basin area of 25.83 km^2. For each Strahler channel order, mean values were estimated for width, depth, and Manning's n for channel routing. Final preparation of the channel network and input files requires the use of ArcInfo scripts written specifically for the model.

An hourly time step was chosen to best represent the rapidly changing meteorological conditions during snowmelt events, and the resultant hydrograph response of the basin. To maintain continuity in the model runs, the same two climate stations were utilized for the entire 5-year period: the Burn site, located centrally in the lower half of the watershed at 1220 m; and the Cabin site, located nearer the alpine zone at 1735 m. The key climate variables required are temperature, wind speed, relative humidity, shortwave radiation, longwave radiation, precipitation, precipitation lapse, and temperature lapse.

In conducting a continuous multi-year simulation, particular difficulty was encountered with the winter precipitation record. The accurate measurement of snowfall and rain-and-snow mixtures remains a major difficulty in cold climates. Although the Redfish basin contained a range of storage-type gauges (4-Season, Belfort), their records were too intermittent and unreliable to be of use. A tipping bucket at the low-elevation Burn site proved the most reliable instrument, although an adjustment was necessary to account for under-catch of snowfall during freezing temperatures from November to February. The measured precipitation was adjusted upwards until the simulated snow-water equivalent matched the snow-course data for the Burn and Cabin sites. Snow-pillow data for the higher Alpine site were available for the last 2 years; these data from November to February were used in place of the tipping bucket data, with adjustments for precipitation lapse rates.

4 MODEL CALIBRATION AND VERIFICATION

Calibration and verification of a fully distributed model must include examination of the simulated internal catchment processes, and their patterns and distribution across the landscape. A key advantage of fully distributed models such as DHSVM is that maps can be output for any hydrologic variable for evaluation of the model's performance. Examples include: depth to water table and the extent of soil saturation; subsurface soil moisture flow, snow coverage, and snow water equivalents; and rates of snowmelt. Simulated and observed hydrographs for internal tributaries, as well as for the basin mouth, should be compared in a complete verification of a distributed model. Such complete field data are rarely available, and very few model applications have achieved this level of verification. However, all of the above processes were evaluated in this application of DHSVM to Redfish Creek, allowing a high level of confidence in the final calibrated model and the modelling results.

The processes by which forest cover influences snow accumulation and melt within the model are of critical importance. Snow interception and release processes, and differences in the energy balance of the snowpack due to presence or absence of forest cover, all influence rates of snowmelt and the magnitude of peak flows. The most sensitive parameters are crown closure, leaf area index (LAI), and the radiation attenuation coefficient for the attenuation of shortwave radiation through the forest canopy. While crown closure is a variable that is included in routine forest inventory data, LAI and the radiation attenuation coefficient are more difficult to estimate. This uncertainty in key parameters that influence snowmelt, and potentially peak flows, is a major source of concern. Verification of simulated vegetation influences is made difficult because snow course measurements are usually made only in forest clearings. However, the modelled forest-clearcut snowpack differences look reasonable (Figure 4) and compare well with regional studies where forest and clearcut snowpacks were measured. Additionally, comparison with air-photo–derived snowline maps showed a satisfactory simulation of forest influences throughout the basin. The model closely tracked snowline recession for the available data in 1996 (Figure 5). Comparison of the simulated snowpack and the snow course data showed very good agreement for the Burn and Cabin sites, while some underestimation of snowpack occurred for the other sites (Figure 6).

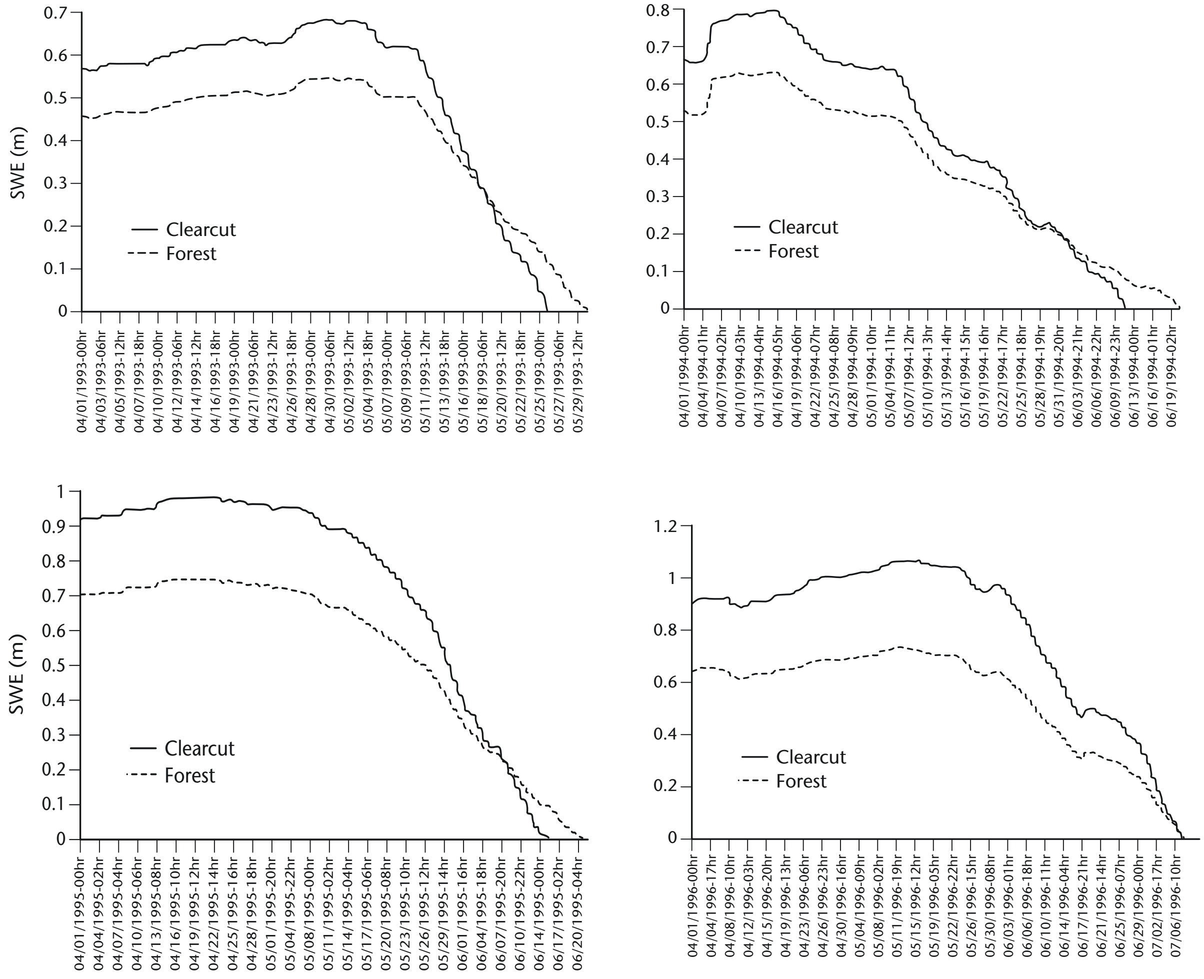

FIGURE 4 *Simulated forest-clearcut differences in snowpack for the Cabin site, 1775 m, 1993–1996.*

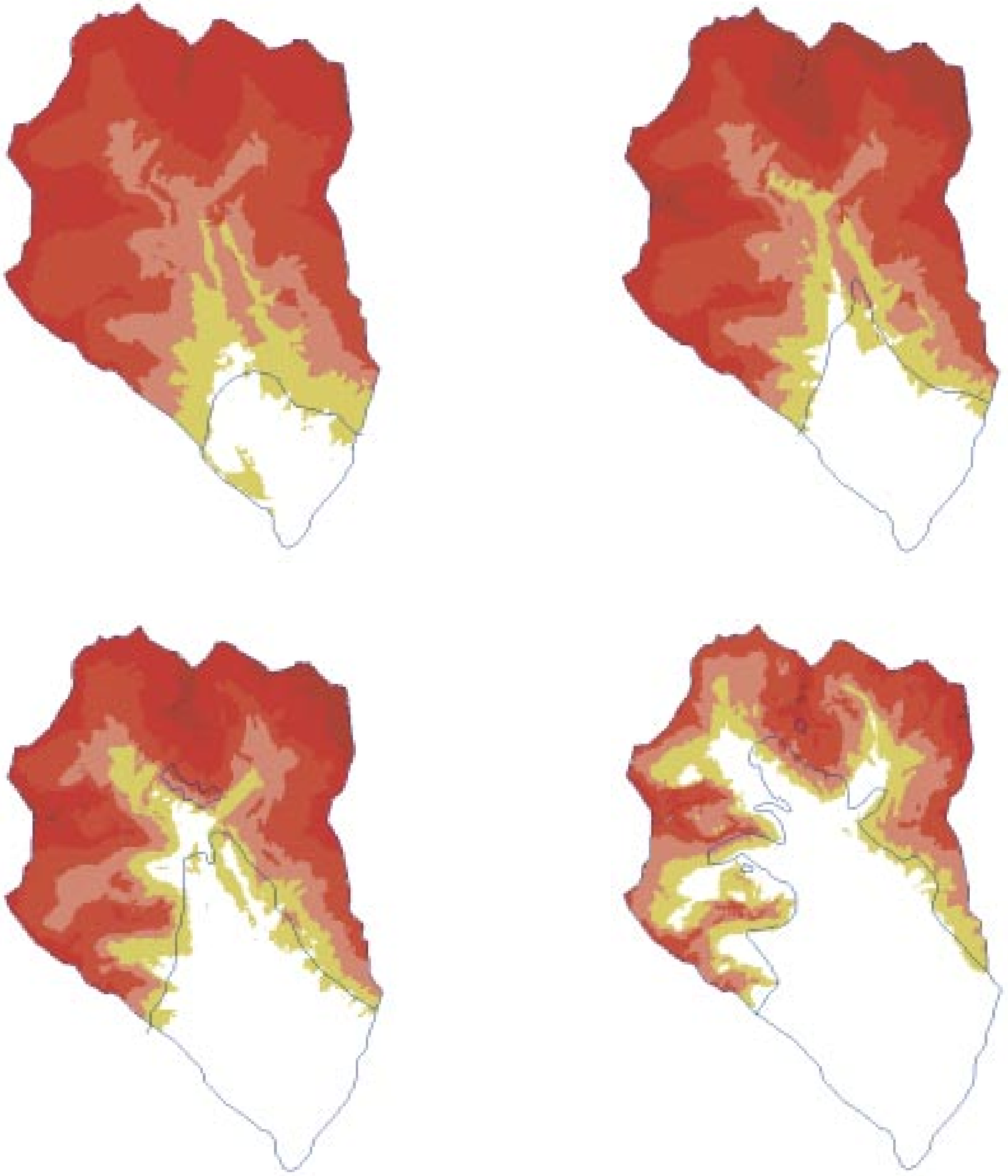

FIGURE 5 *Simulated snow water equivalents for April 14, May 27, June 10, and July 3, 1996, with snowline derived from air-photos for comparison.*

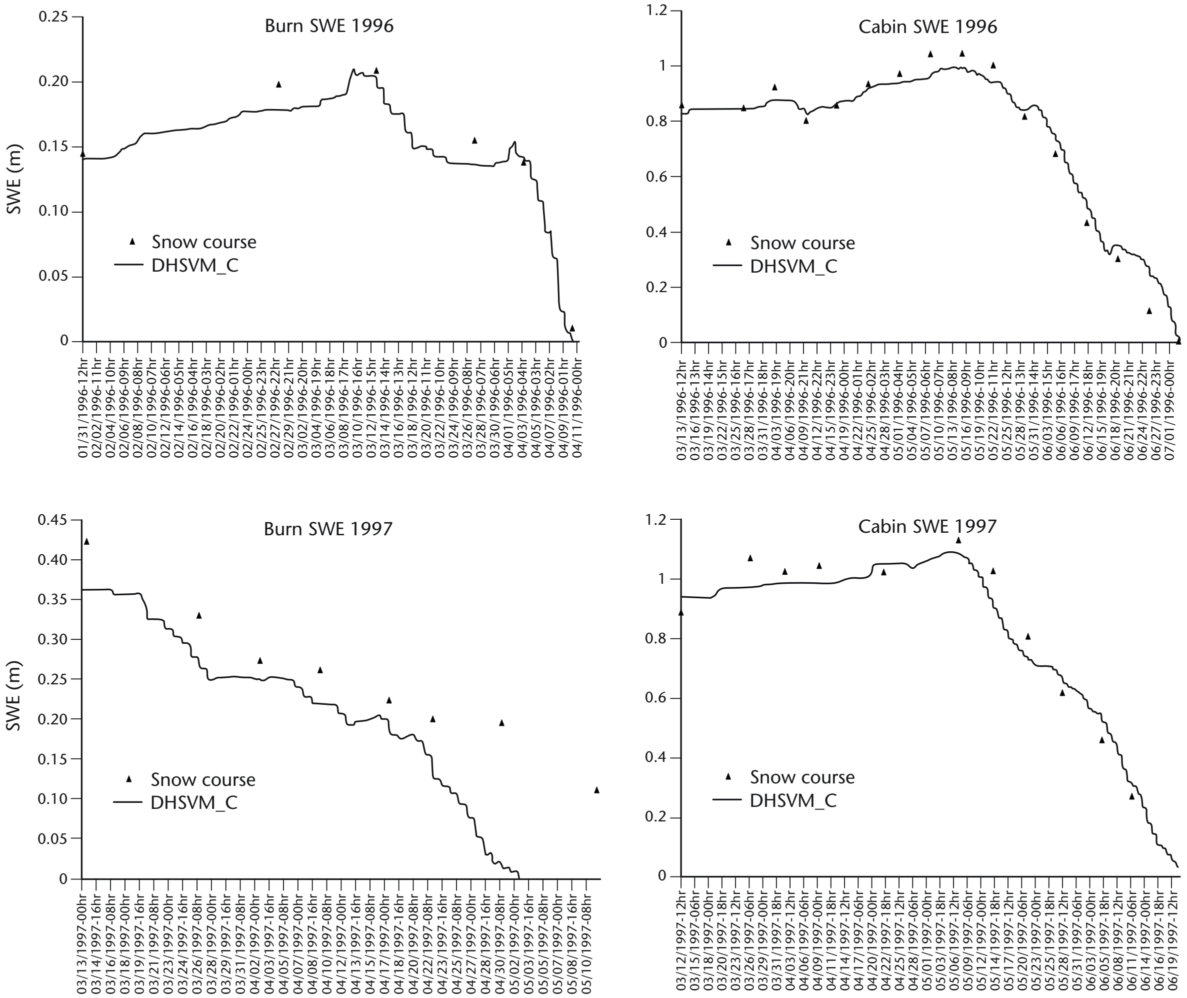

FIGURE 6 *Simulated and observed SWE for 1996–1997 at the Burn (1220 m) and the Cabin (1735 m) sites.*

A critical factor in the ripening and melt of the snowpack is the amount of solar radiation absorbed at the snow surface. This is determined by the snow albedo, which declines over time as the snowpack ages and becomes dirty. The U.S. Army Corps of Engineers (1956) albedo curves were assumed as a starting point, but some adjustment for local conditions is necessary, particularly in basins where radiation snowmelt events dominate spring runoff. Local conditions include contamination of the snow surface by forest litter and dust, shallow snow cover with protruding understory vegetation, and exposed areas of bedrock in steep and rocky terrain. Lowering the albedo curves during calibration was extremely effective in correcting the snowpack simulations and the timing of snowmelt in Redfish Creek.

Permeable forest soils, such as those of Redfish Creek, produce peak flows primarily from rapid subsurface flow and saturated overland flow rather than from infiltration excess runoff (e.g., Woods et al. 1997). Soil conductivity is therefore critical in determining rates of subsurface flow and the extent of saturation and saturated overland flow. In the model, lateral saturated hydraulic conductivity is assumed to be at a maximum at the soil surface, and to decline exponentially with depth. The model was run with a maximum saturated hydraulic conductivity ranging between 2×10^{-4} and 2×10^{-3} m/s, and exponential decay coefficients between 1.0 and 2.0. Parameter values that improved the hydrograph simulation were found to give more realistic maps of the extent of soil saturation. This was taken as confirmation that the model was generating peak flows through the correct mechanisms, and in particular, the correct proportions of surface runoff and subsurface flow. The close match between modelled and observed diurnal flow range, as seen in the hydrographs during snowmelt, is also an indication that the mix of surface and subsurface flow is reasonable.

After calibration, a continuous 5-year model run was completed for October 1992–October 1997. Bearing in mind that the water years 1993–1996 were used in the calibration, while 1997 was held back for verification, the performance of the model can be examined (Figure 7). The degree of fit from one year to the next is relatively constant, despite large differences in the magnitude and nature of the snowmelt runoff over the period of record. Most of the significant peaks are predicted to within 10% of observed flows, with several peaks predicted to within 5% or less. For the final verification year of 1997, the first two peaks are underestimated, while the third is very close. The runoff year with the least accurate simulation is 1994, which contained multiple peaks of approximately the same magnitude over an unusually long period through May and June. Each observed peak is underestimated by about 1.0 m^3/s or 20% in the model, though the pattern of rise and fall is reasonable. Early in the season, in March and April, the model appears too responsive to increasing daily snowmelt, and flows are overestimated in early and late March when the observed flows decrease more rapidly. However, given the complexities of the snowmelt process and the limitations in the climate data for such complex terrain as the Redfish basin, this is a remarkable simulation by the model.

Only after calibration was completed at the basin scale were hydrographs examined for the internal tributary of Upper Redfish. In this way, the comparison of simulated with observed hydrographs serves as an additional verification exercise to test the ability of the model to simulate internal flows and processes. Although the overall simulation is reasonable for all 3 years of record, 1995–1997, the model tends to overestimate the tributary flows and exhibit a more flashy response than observed. This could be attributed to irregularities in hillslope flow pathways, smaller-scale errors in the DEM, soil variability, and the presence of roads in the tributary.

5 ANALYSIS OF HARVEST SCENARIOS

Harvest scenarios were designed according to the delineation of hypsometric elevation zones (Figure 8). The suitability of different parts of the forest for commercial harvest operations depends on such factors as accessibility, forest productivity, regrowth potential, ecological concerns, and visual impacts. Within the Redfish basin, forested areas below approximately 1880 m are generally classed as operable forest, while above this elevation the forest and terrain is typically alpine in character and unsuitable for forest harvest activity. This alpine zone above 1880 m constitutes 40% of the total basin area (above H40 line), and is treated as a single zone in the forest harvest scenarios. Below the H40 line, the operable forest is divided at the H60 and H80 hypsometric elevations of 1740 m and 1520 m to give three additional elevation zones, each representing 20% of total basin area.

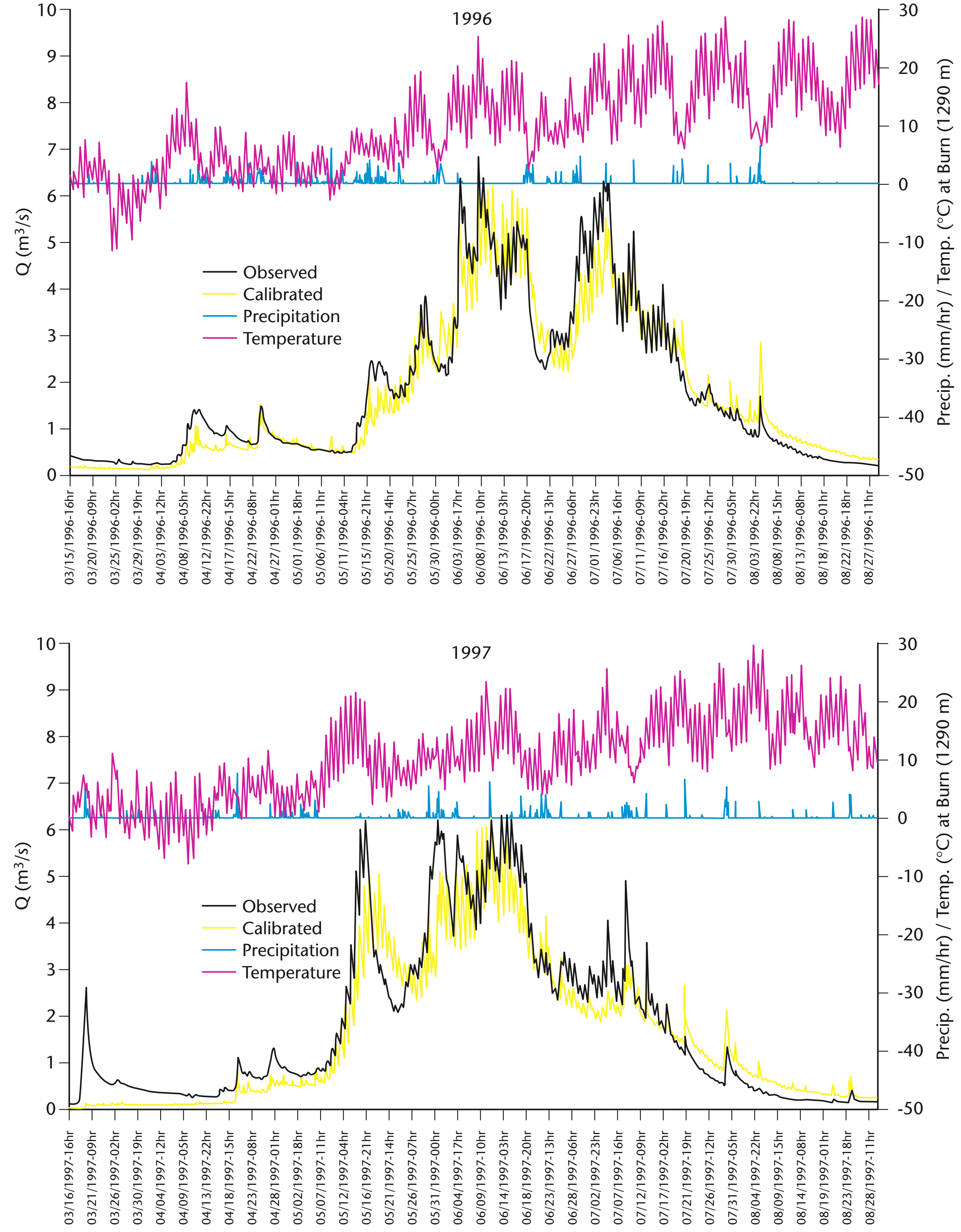

FIGURE 7 *Sample hydrographs for the calibrated model; 1996 calibration period and 1997 verification period.*

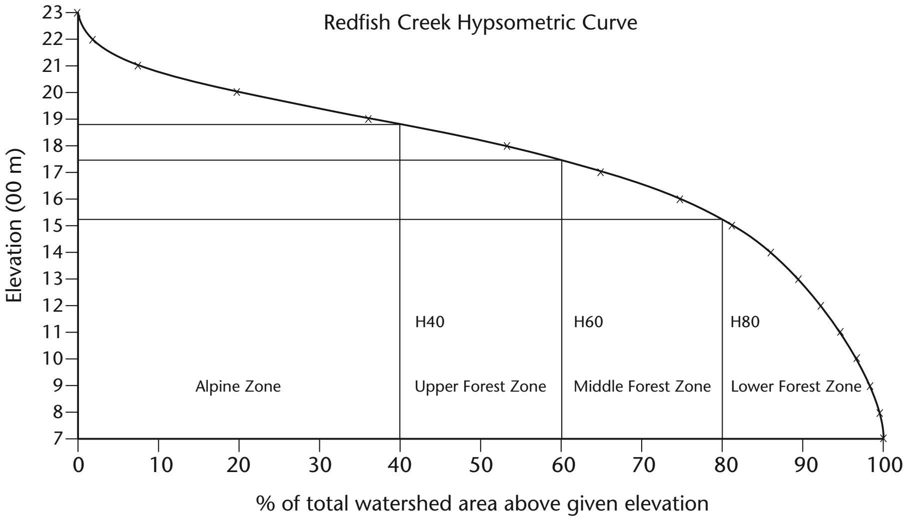

FIGURE 8 *Redfish Creek hypsometric curve.*

Ten forest harvest scenarios were designed to explore increasing levels of harvest across the various hypsometric elevation zones. Previous harvest activity in the watershed has occurred over 10% of the total area, beginning in the late 1960s and continuing on to the current time. There has been significant forest regeneration in the older clearcuts. One benchmark scenario simulated the extreme case of 100% forest canopy removal over the entire watershed, while a second benchmark scenario attempted to recreate a fully mature forest condition, as was present in the early 1960s before logging commenced. Then, for each of the lower, middle, and upper operable forest zones in turn, one-third and two-thirds harvest levels were simulated, representing 6.7 and 13.3% of the total watershed area, respectively (Figure 9). A one-third harvest in the larger alpine zone represents 13.3% of basin area. In contrast, a one-third cumulative forest harvest scenario was simulated across all three operable forest zones to give a total harvest level of 20%. Harvest scenarios were designed by first removing overstory in recovering clearcuts, and then harvesting randomly throughout the older forest stands to make up the desired clearcut area.

The simulated influence of the forest cover on stream flows is first examined for the extreme scenario of clearcutting the entire watershed area. This is compared with the current condition, which has experienced clearcutting over 10% of the basin, and the scenario for fully mature forest cover where pre-harvest conditions are re-created. The clearcut scenario increases the annual peak flow in all 5 years, with peak increases in the range of 40–94%. The largest increases occurred in 1993 and 1997; these are the years in which the hydrograph rose rapidly from the winter baseflow to the annual peak after a cool spring. Late-season peaks were less affected, and flows were reduced during the summer recession as a result of earlier snowmelt. By re-creating the mature forest canopy, peak flows were reduced by 7–11%, but with little change during the summer recession.

A clear pattern emerges for the harvest scenarios in the operable forest zone (700–1880 m). As harvesting moves from the lower to the upper elevations, the impact on peak flows changes from increasing the small, early-season peaks to increasing the late-season peaks. Harvesting in the

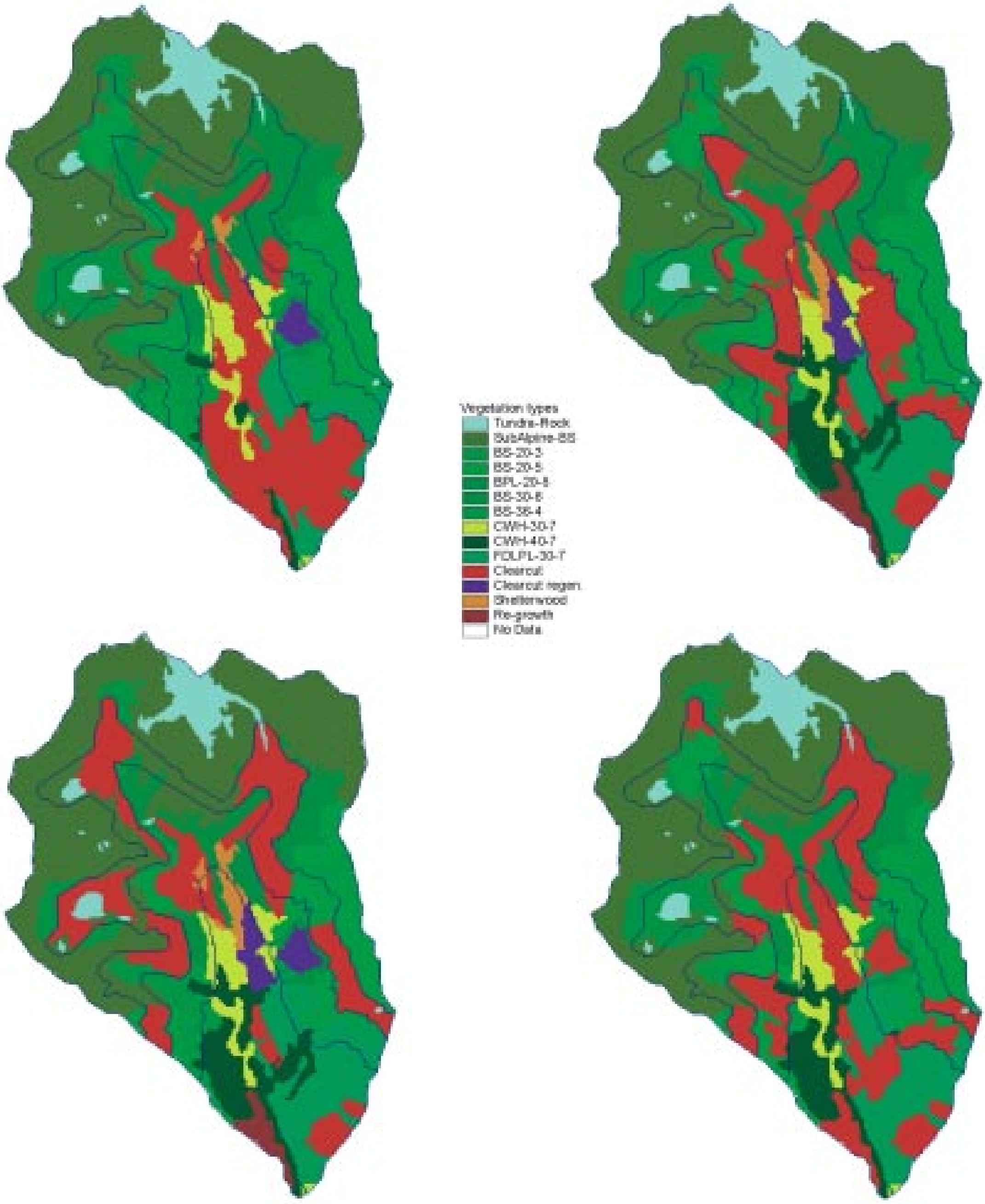

FIGURE 9 *Harvest scenarios—red shading shows 2/3 clearcut respectively in lower, mid, and upper operable zones (each 13%), and 1/3 clearcut cumulatively in each of lower, mid, and upper zones (20%).*

lower elevations tends to reduce the magnitude of the annual peak flow because it advances the melt of low-elevation snowpack so that it cannot contribute to the main melt event later in the season. This is commonly referred to as snowmelt de-synchronization, because the timing of snowmelt from different elevation zones is changed so that they are no longer synchronized. The hydrographs also show that the overall timing of the peaks is not really changed by moderate harvest activity. Only the flow magnitudes are affected.

To help in identifying the patterns of peak-flow change across the various scenarios, a 7-day period around the annual peak flow was examined in detail for each of the 5 years. Maximum percent change in the hourly peak flows was extracted in comparing the scenarios with the calibrated watershed condition (Table 2). In addition, the percent change in hourly flows averaged over the same 7-day period was also calculated (Table 3). Excluding the total clearcut scenario, the largest increases in instantaneous hourly peak flows are 19.4 and 19.8% with a 13% clearcut area. When averaged over the 7 days, the peak-flow increases for the same scenarios become 10.6 and 12.3%. These peak-flow changes have the potential to significantly affect sediment transport processes. When considering the impact of peak-flow changes on the stream-channel environment, it is important to consider both the instantaneous peaks and the average flows over several days. Bank erosion and

TABLE 2 *Annual maximum flows from radiation-snow-melt-events—maximum percent change in hourly flows over a 7-day period for the scenarios compared to the calibrated model. Calibrated current condition has approximately 10% harvested over past 30 years.*

Scenario	**1993** **5/14–5/20**	**1994** **5/7–5/13**	**1995** **5/26–6/1**	**1996** **6/7–6/13**	**1997** **5/15–5/21**	**Mean**
Fully mature forest cover	-11.3	-9.0	-6.9	-11.0	-10.6	-9.8
Total clearcut (100%)	82.3	48.0	39.8	51.0	93.9	63
1/3 cut lower H80–H100 (7%)	-2.8	-1.7	-1.1	-3.5	1.3	-1.6
2/3 cut lower H80–H100 (13%)	-2.4	-1.3	-0.7	-3.3	4.4	-0.7
1/3 cut middle H60–H80 (7%)	1.7	-1.7	-2.0	-2.8	9.2	0.9
2/3 cut middle H60–H80 (13%)	8.8	8.6	5.5	8.0	19.8	10.1
1/3 cut upper H40–H60 (7%)	9.5	7.0	6.9	6.7	8.0	7.6
2/3 cut upper H40–H60 (13%)	19.4	14.2	13.1	13.7	16.7	15.4
1/3 cut alpine H0–H40 (13%)	16.6	10.6	13.4	10.3	13.0	12.8
1/3 cut lower, mid, and upper (20%)	7.6	4.7	5.7	4.3	16.6	7.8

TABLE 3 *Annual maximum flows from radiation-snow-melt-events—percent change in hourly flows, averaged over 7 days, for the scenarios compared to the calibrated model. Calibrated current condition has approximately 10% harvested over past 30 years.*

Scenario	1993 5/14–5/20	1994 5/7–5/13	1995 5/26–6/1	1996 6/7–6/13	1997 5/15–5/21	Mean
Fully mature forest cover	-4.8	-5.7	-4.6	-6.9	-7.1	-5.8
Total clearcut (100%)	43.2	33.7	32.6	33.3	59.2	40
1/3 cut lower H80–H100 (7%)	-0.6	-1.1	-0.5	-1.6	-0.1	-0.8
2/3 cut lower H80–H100 (13%)	-0.4	-0.8	-0.2	-1.5	1.4	-0.3
1/3 cut middle H60–H80 (7%)	-1.1	-1.3	-1.2	-1.5	4.2	-0.2
2/3 cut middle H60–H80 (13%)	2.0	2.2	1.4	2.4	12.3	4.1
1/3 cut upper H40–H60 (7%)	5.8	4.5	5.0	4.5	5.8	5.1
2/3 cut upper H40–H60 (13%)	10.6	9.2	9.4	9.5	11.8	10.1
1/3 cut alpine H0–H40 (13%)	11.2	7.9	9.6	7.8	8.5	9.0
1/3 cut lower, mid, and upper (20%)	4.0	2.2	3.3	1.4	9.9	4.2

entrainment of bed materials may be more dependent on the peak, while overall sediment transport and channel morphology is determined more by high flows over several days or longer. A third analysis looked at changes in the fall-season peak flows that are caused by rainfall and rain-on-snow (Table 4). However, the relatively poor simulation of these fall peaks makes it difficult to draw accurate conclusions from the results of the harvest scenarios. For Redfish Creek, these fall peaks are almost always smaller and less significant than the spring peaks. The following discussion focuses on the instantaneous peak-flow changes (Table 2).

The results show that harvesting above the H60 elevation (upper forest zone, 1740–1880 m) produces a bigger impact on peak flows than does harvesting in the lower elevation zones. Again there is significant variability from year to year, indicating that the magnitude of peak-flow change depends very much on the particular weather conditions and seasonal melt pattern in a given year. Cutting in the lowest zone (H80–H100) has little or no effect on peak flow, and causes a small decrease in peak flows except for the year 1997. Low-intensity cutting (one-third of zone, 7% of basin) in the middle forest zone (H60–H80) has little effect, except for the year 1997 when peaks increased by 9%. Consistent increases in peak flows across all years are seen with high-intensity cutting (two-thirds of zone, 13% of basin) in the middle zone, and in all the harvest scenarios in the upper and alpine zone. In

TABLE 4 *Peak flows from rainfall and rain-on-snow events in the fall—percent change in maximum hourly flow for the scenarios compared to the calibrated model. Calibrated current condition has approximately 10% harvested over past 30 years.*

Scenario	**10/26/94**	**10/10/95**	**11/29/95**	**9/17/97**	**Mean**
Fully mature forest cover	-0.8	0.3	3.2	0.8	0.9
Total clearcut (100%)	3.3	-1.6	14	-9	1.7
1/3 cut lower H80–H100 (7%)	0.6	0.9	5.1	0.2	1.7
2/3 cut lower H80–H100 (13%)	1.4	2.1	10	0.3	3.5
1/3 cut middle H60–H80 (7%)	1.1	0.2	3.2	-0.1	1.1
2/3 cut middle H60–H80 (13%)	2.9	0.1	3.0	-0.8	1.3
1/3 cut upper H40–H60 (7%)	0.4	-1.1	-1.5	-1.3	-0.9
2/3 cut upper H40–H60 (13%)	-0.7	-1.9	-2.4	-2.2	-1.8
1/3 cut alpine H0–H40 (13%)	-1.5	-1.3	-1.8	-2.8	-1.9
1/3 cut lower, mid, and upper (20%)	2.1	0	6.9	-1.3	1.9

the upper zone (above H60), low-intensity cutting increased peaks by 6.7–9.5%, while high-intensity cutting produced increases of 13.1–19.4%. Harvesting in the alpine zone had a slightly smaller effect than in the upper forest zone. A scenario with low-intensity cutting in all three forest zones showed significantly smaller impacts on peak flows (except in 1997) even though a greater percentage of basin area (20%) was harvested.

The year-to-year variability in peak-flow increases seems to be related to the pattern of seasonal melt in a given year, and the occurrence of secondary peaks on the rising limb. The greatest peak-flow increases are seen for 1993 (upper and alpine zone cutting) and 1997 (middle zone cutting); these are years in which the hydrograph rose rapidly from base flow to the annual peak without the occurrence of secondary peaks on the rising limb. In other years characterized by rising-limb, secondary peaks, the peak-flow increases were smaller. A cool early spring followed by a sudden warming shows the potential for the greatest peak-flow increases. There is no clear relationship to snowpack volume, with 1993 having the lowest snowpack of the 5 years, and 1997 the greatest.

6 CONCLUSIONS

The model results show that peak-flow change is closely related to harvest elevation in snow-dominated watersheds such as Redfish Creek. Harvesting at higher elevations above approximately 1500 m can cause a significant increase in peak flows of 10–20%, while harvesting at the lower elevations causes little or no change. The same pattern is seen throughout the 5-year simulation period, but there is significant year-to-year variability in the magnitude of peak-flow change. Longer-term simulations would be required to improve quantitative estimates of peak-flow change. Additional snow courses are also required in Redfish Creek to characterize snowpack dynamics beneath the forest canopy. The lack of snow-course data for sites beneath the forest canopy was a major limitation in the verification of simulated canopy influences in this study. However, the model is shown to simulate the snowpack in the openings and the snowline retreat on forested slopes very closely.

Harvesting in the upper elevations has a significantly greater impact on the annual peak flows than harvesting at lower elevations. Harvesting in the lowest elevation (H80–H100) zone had no impact of peak flow. Harvesting in the next highest (H60–H80) zone had a minimal effect at 7%, but a considerable effect at 13%. Harvesting effects are considerable in the H40–H60 zone in all years, and the increase is proportional to the amount harvested. The percent increase is considerably greater in this zone than in the zone below. This more consistent increase in peak flow in this zone with timber harvested, and the greater increase as a ratio of percentage harvested, would lend justification to weighting harvesting above the H60 line more than below. The results of Gluns (2001), where he follows the snow-retreat line during peak flow, also adds some justification to the H60 line, because the snow tends to be disappearing at this elevation when the peak occurred. However, in some years with an early peak, there is still considerable snow left below the H60 elevation.

There has been some question as to the applicability of the H60 concept to throughout the interior of British Columbia. The model results are likely applicable to watersheds with a similar hypsometric curve and a substantial alpine area. In an area with a flat hypsometric curve, there would likely be less differentiation between elevation zones because accumulation and melt would not increase as much with altitude. In a watershed without an alpine area, the harvesting effects would likely be greater because all elevations, including the highest elevations, would be subject to harvesting. It would be useful to continue this type of modelling work to consider the alpine effect, the effects of roads, the longer-term effects of harvesting, and the effects of harvesting in watersheds with differing hypsometric curves.

The importance of individual watershed topographic characteristics must be stressed in determining snowmelt and peak-flow generation. Examination of the hypsometric curve may reveal a high proportion of total basin area within a narrow elevation range; for example, where there is plateau terrain. Peak flows will be particularly sensitive to harvesting in these areas of gentle slopes, because snowmelt is simultaneous across the entire zone. There is a danger that such individual watershed characteristics will be overlooked if an across-the-board threshold elevation is adopted in management guidelines.

7 REFERENCES

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell, and J. Rasmussen. 1986. An introduction to the European Hydrological System - Systeme Hydrologique Européen, "SHE." 1. History and philosophy of a physically based, distributed modelling system. Journal of Hydrology 87:45–59.

British Columbia Ministry of Forests and British Columbia Ministry of Environment. 1999. Coastal watershed assessment procedure guidebook (CWAP), interior watershed assessment procedure guidebook (IWAP). 2nd ed. Forest Practices Branch, B.C. Ministry of Forests, Victoria, B.C. Forest Practices Code of British Columbia Guidebook. http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/wap/index.htm

Gluns, D.R. 2001, this publication. Snowline pattern during the melt season: evaluation of the H60 concept. *In* Watershed assessment in the southern interior of British Columbia. Proceedings of a workshop, March 9 and 10, 2000, Penticton, B.C. D.A.A. Toews and S. Chatwin (editors). Research Branch, B.C. Ministry of Forests, Victoria, B.C. Working Paper 57/2001.

U.S. Army Corps of Engineers. 1956. Snow hydrology, summary report of the snow investigations. N. Pacific Division, U.S. Army Corps of Engineers. Portland, Oreg.

Utzig, G.F. 1997. Terrain and soil inventory - West Arm demonstration forest (WADF). Unpublished maps and report prepared for the B. C. Ministry of Forests, Nelson, B.C. by Kutenai Nature Investigations Ltd., Nelson, B.C.

Whitaker, A.C. and Y. Alila. 2000. Distributed hydrologic modelling in Redfish Creek, West Kootenays, British Columbia. Part 1: application, calibration and verification using internal catchment data. Part 2: sensitivity of peak flows to clear cut forest harvesting across different elevation zones. Unpublished reports by Faculty of Forestry, University of British Columbia, Vancouver, B.C., submitted to B.C. Ministry of Forests, Nelson Region, Nelson, B.C.

Whitaker, A.C., Y. Alila, P. Calvert, and D.A.A. Toews. 1998. Evaluation of existing hydrological models for use in assessing the impact of forest management on peak flows. *In* Mountains to sea: human interaction with the hydrologic cycle: proceedings, Canadian Water Resources Association, 51st annual conference, June 10–12, 1998, Victoria, B.C. Y. Alila (editor), pp. 67–71.

Wigmosta, M.S., L.W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research 30:1665–79.

Woods, R.A., M. Sivapalan, and J.S. Robinson. 1997. Modeling the spatial variability of subsurface runoff using a topographic index. Water Resources Research 33 (5):1061–73.

Click here for next page