HYDROLOGICAL PROCESSES
*Hydrol. Process.* **26**, 1892–1905 (2012)
Published online 23 May 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9248

# Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance

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## Abstract:

A model including slope effects on snow redistribution, interception and energetics was developed using the Cold Regions Hydrological Model platform, parameterized with minimal calibration and manipulated to simulate the impacts of forest disturbance on mountain hydrology. A total of 40 forest disturbance scenarios were compared with the current land cover for four simulation years. Disturbance scenarios ranged from the impact of pine beetle kill of lodgepole pine to clear-cutting of north- or south-facing slopes, forest fire and salvage logging. Pine beetle impacts were small in all cases with increases in snowmelt volume of less than 10% and streamflow volume of less than 2%. This small impact is attributed to the low and relatively dry elevations of lodgepole pine forests in the basin. Forest disturbances due to fire and clear-cutting affected much larger areas and higher elevations of the basin and were generally more than twice as effective as pine beetle in increasing snowmelt or streamflow. For complete forest cover removal by burning and salvage logging, a 45% increase in snowmelt volume was simulated; however, this only translated into a 5% increase in spring and summer streamflow volume. Forest burning with the retention of standing burned trunks was the most effective forest cover treatment for increasing streamflow (up to 8%) because of its minimizing of winter snow sublimation losses from interception and blowing snow. However, increases in streamflow volumes were almost entirely due to reductions in intercepted snow sublimation with decreasing canopy coverage. Peak daily streamflow discharges responded more strongly to forest cover disturbance than did seasonal streamflow volumes, with increases of almost 25% in peak streamflow from the removal of forest canopy by fire and the retention of standing burned trunks. Peak flow was most effectively increased by forest removal on south-facing slopes and level sites. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS forest; snow; Canadian Rocky Mountains; pine beetle; fire; clear-cutting

*Received 15 August 2011; Accepted 10 January 2012*

## INTRODUCTION

The mountain pine beetle (MPB) epidemic in Western Canada is a natural disaster that has affected forest canopy cover in many drainage basins, changing interception processes and the proportion of precipitation reaching the ground surface as well as the energetics of snowmelt (Winkler *et al*., 2008). MPB is moving eastward from British Columbia to Alberta, with major potential consequences for forests in the Canadian Rocky Mountain foothills of Alberta. Water supplies in the rivers draining the Canadian Rockies have been and are predicted to decline because of climate change while demand increases due to rising population and increasing consumption from downstream agriculture and industry (St. Jacques *et al*., 2010). Mountain runoff is highly sensitive to both variations in climate and forest disturbance. This is expected to be most severe in cold mountain environments that are dominated by snowmelt and frozen soils, such as the Canadian Rockies. Sublimation of intercepted snow is a major component of the water balance for western Canadian forests, ranging from 10% to 45% of seasonal snowfall (Pomeroy and Gray, 1995). Interception is strongly controlled by canopy leaf area index (LAI), and so disturbances to the forest canopy are likely to result in changes to streamflow hydrology (Pomeroy *et al*., 1998). Recent temperature and precipitation shifts have led to a decrease in annual snow extent (Groisman *et al*., 1994), an earlier spring freshet (Cayan *et al*., 2001) and an increase in winter days with positive air temperature (Lapp *et al*., 2005). These changes have been associated with increased rates of forest disturbance due to wildfire (Fauria and Johnson, 2006, 2008), insect infestation (Aukema *et al*., 2008) and disease (Woods *et al*., 2005). A comprehensive understanding of runoff generation in mountain headwater systems subject to forest change is thus critical to managing downstream water resources.

Snow hydrology response to forest management practices is highly variable, largely because of the inherent variability in management approaches across the wide range of climatic and vegetation regimes. Pomeroy and Granger (1997) found a strong response in snow hydrology to clear-cutting of the western Canadian boreal forest in which snow accumulation and melt rates were greatly increased with forest cover removal. Gelfan *et al*. (2004) found similar responses in northwestern Russia were related to changes in sub-canopy radiation to snow, snow interception, sublimation and melt rates and volumes. Ellis *et al*. (2011) showed that the magnitude and direction of the impact of forest removal on net radiation for snowmelt depends on slope

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and aspect. Stand-level and paired catchment research have been undertaken for many decades, yet results differ between specific environments given regional differences, notably, catchment wetness, temperature and topography. Buttle *et al.* (2005) stated that despite work on forestry impacts, there remained a shortage of studies on disturbance impacts (both natural and anthropogenic) on water yields and peak/low flows in Canada's various forest landscapes. Thus, models and system understanding developed in temperate environments are sometimes applied in cold regions environments in Canada where they may not be valid (Swanson, 1998).

Changes in mass and energy exchange between the atmosphere, canopy and ground surface expected as a result of forest disturbance have additional consequences for water storage and subsequent subsurface flow routing to streams. The removal of the forest canopy often (but not always) increases effective precipitation and snowmelt rates, leading to higher water table levels after snowmelt and during storms for several years after disturbance (Adams *et al.*, 1991; Dhakal and Sidle, 2003) and enhanced runoff via surface and near-surface pathways (Hetherington 1987; Monteith *et al.*, 2006a), particularly immediately after harvesting (MacDonald *et al.*, 2003). At the basin scale, Monteith *et al.* (2006b) observed a greater fraction of event water four years after harvest using classical hydrograph separation techniques, yet no differences in basin-wide residence times were observed. At larger scales, Buttle and Metcalfe (2000), in a comprehensive study of forest harvest on streamflow regimes in northern Ontario, suggested that the hydrologic impact of forest harvesting becomes equivocal due to the large natural variability of flows. Given the importance of the alpine zone in generating runoff in the Canadian Rockies and the greater potential for groundwater storage in mountain compared with boreal shield environments, this needs careful assessment in the region to determine how sensitive mountain snow hydrology really is to changes in forest cover.

Questions regarding the basin-scale hydrological impacts of forest disturbance are often addressed with numerical models, which are less costly than intensive field monitoring and can be applied to basins for which field data are unavailable (Pomeroy *et al.*, 1997, 2007; Whitaker *et al.*, 2002; Schnorbus and Alila 2004). The Cold Regions Hydrological Model (CRHM) platform is a modular modelling system that permits appropriate hydrological processes for the basin, selected from a library of process modules, to be linked to simulate the hydrological cycle as a purpose-built model (Pomeroy *et al.*, 2007). From its inception, CRHM has focused on the incorporation of physically based descriptions of cold regions hydrological processes, which make models developed using this platform particularly appropriate to application in the cold, snowy Canadian Rockies. Recent developments include options for tree line forest effects from alpine blowing snow (MacDonald *et al.*, 2010), improved soil and fill-and-spill runoff generation (Fang *et al.*, 2010) and enhanced forest modules (Ellis *et al.*, 2010). CRHM has a wide range of processes that can be relevant for Canadian Rockies forest snow hydrology studies such as direct and diffuse radiation to slopes, long-wave radiation in complex terrain, intercepted snow, blowing snow, subcanopy turbulent and radiative transfer, sublimation, energy balance snowmelt, infiltration to frozen and unfrozen soils, rainfall interception, combination-type evapotranspiration, subsurface flow and kinematic wave flow routing. CRHM uses an object-oriented structure to develop, to support and to apply dynamic model routines. Existing algorithms can be modified or new algorithms can be developed and added to the module library, which are coupled to create a purpose-built model, suited for the specific application. The model operates on the spatial unit of the hydrological response unit (HRU), which has been found optimal for modelling in basins where there is a good conceptual understanding of hydrological behaviour but incomplete detailed information to permit a fully distributed fine scale modelling approach (Dornes *et al.*, 2008). CRHM was evaluated in the recent SnoMIP2 snow model intercomparison and performed relatively quite well in modelling forest snowmelt at sites in Switzerland, USA, Canada, Finland and Japan (Rutter *et al.*, 2009).

The objective of this study is to develop a physically based mountain forest snow hydrology and use this to evaluate the sensitivity of a mountain basin to potential forest disturbance. The model is developed using the CRHM platform and our current understanding of hydrology developed from observations of snow accumulation, snowmelt, groundwater, micrometeorology and streamflow collected in Marmot Creek Research Basin in the eastern slopes of the Canadian Rockies. The model is then applied with various forest disturbance scenarios to show the sensitivity of the basin-scale hydrology to disturbances in forest cover relating to pine beetle infestation, fire and clear-cut harvesting. The response of snowmelt volume, seasonal streamflow and peak streamflow are considered in detail in response to forest disturbance scenarios.

## METHODOLOGY

### *Site description*

The study was conducted at the Marmot Creek Research Basin (MCRB) (50°57′N, 115°09′W) in Kananaskis Valley, Alberta, Canada. As shown in Figure 1, MCRB covers 9.4 $km^2$ and has three subbasins in the upper portion: Cabin Creek (2.35 $km^2$), Middle Creek (2.94 $km^2$) and Twin Creek (2.79 $km^2$). All three subbasins merge into the Marmot Creek confluence (1.32 $km^2$). Elevation ranges from 1600 m a.s.l. at the Marmot Creek outlet to 2825 m a.s.l. at the peak of Mount Allan. MCRB largely consists of needleleaf vegetation and is dominated by Engelmann spruce (*Picea engelmanni*) and subalpine fir (*Abies lasiocarpa*) in the higher part of basin, and the lower portion of basin is dominated by lodgepole pine (*Pinus contorta* var. Latifolia) (Kirby and Ogilvy, 1969). Experimental forest management in the 1970s and 1980s left large clear-cuts in the Cabin Creek subbasin and a series of small circular clearings in the

 

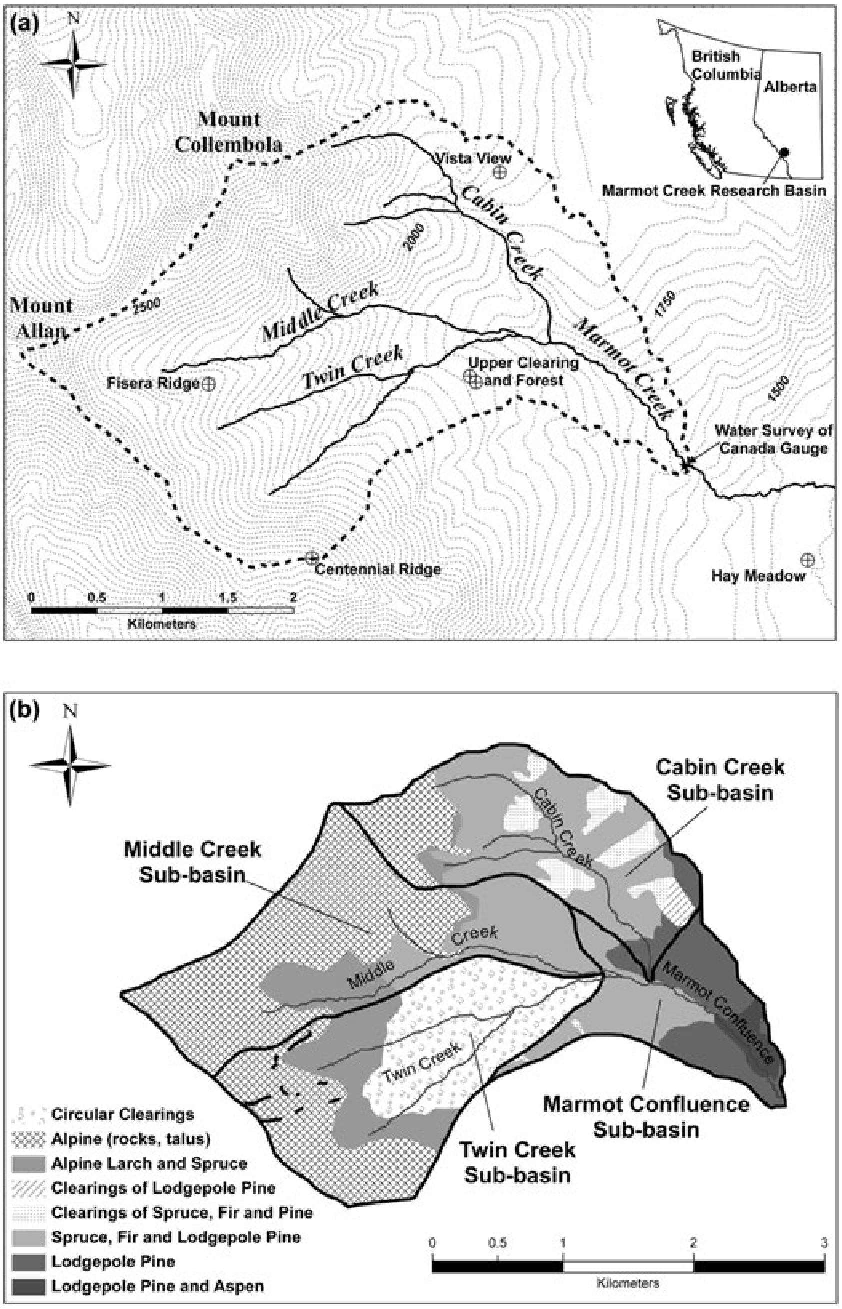


Figure 1. Study site: (a) topography, hydrometeorological stations and streamflow station and (b) land covers of the subbasins of the Marmot Creek Research Basin: Cabin Creek, Middle Creek, Twin Creek and Marmot Confluence. Note that the area where there are small circular clearings is shown, but individual clearings are too small to be shown at this scale

Twin Creeks subbasin (Swanson *et al.*, 1986). Exposed rock surface and talus are present in the high alpine part of basin (Figure 1b). The surficial soils are primarily poorly developed mountain soils consisted of glaciofluvial and till surficial deposits (Beke, 1969). Relatively impermeable bedrock is found at the higher elevations and headwater areas, and the rest of basin is covered by a deep layer of coarse and permeable soil allowing for rapid rainfall infiltration to deep subsurface layers (Jeffrey, 1965).

Continental air masses control the weather in the region, which has long, cold and relatively dry winter and a cool and wet spring and early summer. Annual precipitation in MCRB ranges from 600 mm at the lower altitudes to more than 1100 mm at the higher elevations, and approximately from 70% to 75% occurs as snowfall with the percentage increasing with elevation (Storr, 1967). Snowfall can occur in any month of the year, but primarily occurs from October through May. Mean monthly air temperature ranges from 14 °C in July to −10 °C in January.

### *Observations*

Model forcing data of air temperature, relative humidity, wind speed, precipitation and incoming shortwave radiation from six hydrometeorological stations at high and low elevations in the basin were used for hydrological simulations (Figure 1a). These stations are described in several recent publications (Ellis *et al*., 2010; MacDonald *et al*., 2010; Pomeroy *et al*., 2011). Precipitation was measured with a Geonor weighing precipitation gauge with an Alter shield at the Hay Meadow and Upper Clearing and was corrected for wind-induced undercatch. For modelling purposes, meteorological data were distributed around the basin with adjustments for temperature by environmental lapse rate (5.5 C/1000 m) and an adjustment for precipitation based on observed annual gradients from several years of observations at multiple elevations. Vapour pressure was conserved for unsaturated conditions but not allowed to exceed saturation vapour pressure when extrapolated. Radiation inputs were recalculated for slope and sky view using the various procedures outlined in the next section.

Snow surveys were conducted over the winter and spring near the meteorological stations shown in Figure 1. Surveys consisted of at least 25 snow depth measurements with a ruler and at least six gravimetric snow density measurements to calculate snow water equivalent (SWE). Environment Canada's Water Survey of Canada maintains a long-term streamflow gauge (05BF016) that defines the basin shown in Figure 1a.

### *Model structure and parameterization*

CRHM was used to develop a basin model to simulate the dominant hydrological processes for forested and alpine sites in the Canadian Rockies. The model was structured around a set of four subbasins within which were several HRUs corresponding to the major land cover/soils/topographic/drainage features. Within each HRU, a set of physically based modules was linked in a sequential fashion to simulate the dominant hydrological processes. Figure 2 shows the schematic of these modules, which include the following:

1. Observation module: reads the meteorological data (temperature, wind speed, relative humidity, vapour pressure, precipitation and radiation), providing these inputs to other modules.
2. Garnier and Ohmura's radiation module (Garnier and Ohmura, 1970): calculates the theoretical global radiation, direct and diffuse solar radiation and maximum sunshine hours based on latitude, elevation, ground slope and azimuth, providing radiation inputs to sunshine hour module, energy-budget snowmelt module and net all-wave radiation module.
3. Sunshine hour module: estimates sunshine hours from incoming short-wave radiation and maximum sunshine hours, generating inputs to energy-budget snowmelt module and net all-wave radiation module.
4. Slope adjustment for short-wave radiation module: estimates incident short-wave for a slope using measurement of incoming short-wave radiation on the level surface. The measured incoming short-wave

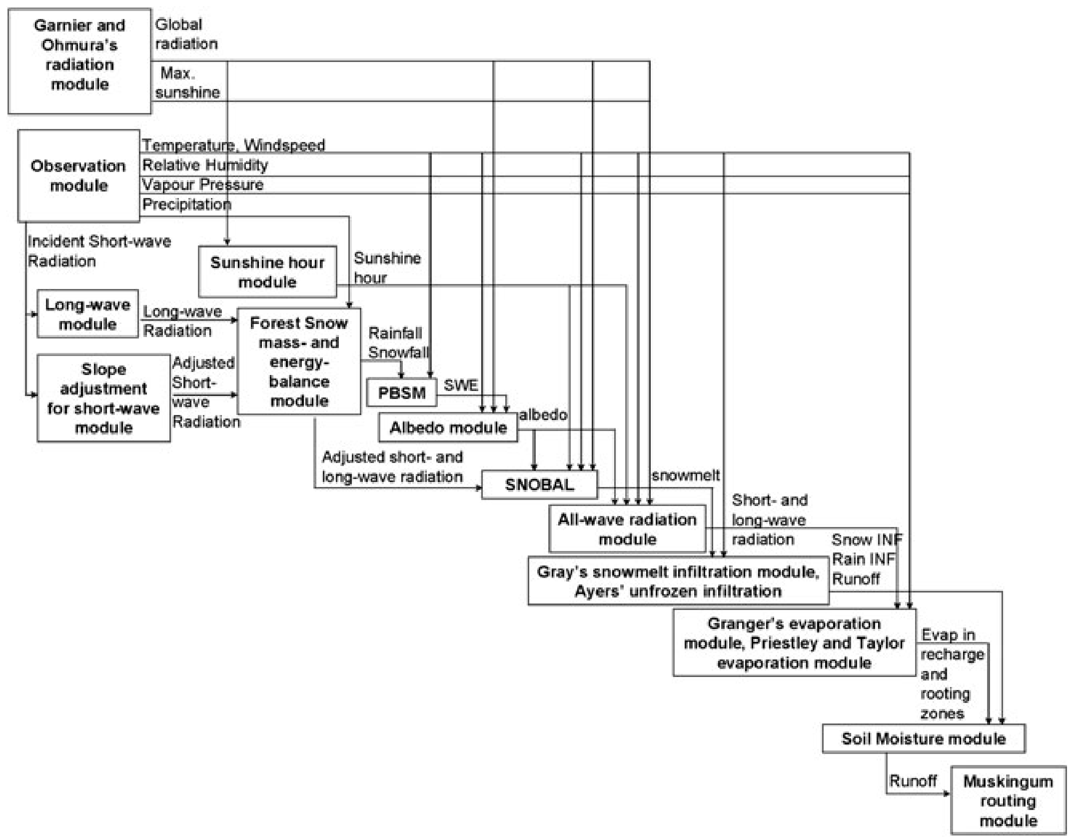


Figure 2. Flowchart of the interactions of state variables and fluxes for mountain snow hydrology calculated by physically based hydrological process modules linked using CRHM. This structure is repeated within each HRU in CRHM to create a mountain hydrology model

radiation from the observation module and the calculated direct and diffuse solar radiation from the Garnier and Ohmura's radiation module are used to calculate the ratio for adjusting the short-wave radiation on the slope.

5. Long-wave radiation module (Sicart *et al.*, 2006): estimates incoming long-wave radiation using the measured short-wave radiation and provides long-wave radiation inputs to energy-budget snowmelt module.
6. Albedo module (Essery and Etchevers, 2004): estimates snow albedo throughout the winter and into the melt period and also indicates the beginning of melt for the energy-budget snowmelt module.
7. Forest snow mass- and energy-balance module (Ellis *et al.*, 2010): estimates the snowfall and rainfall intercepted by forest canopy, sublimation and evaporation losses from the canopy and updates the under-canopy snowfall and rainfall; also provides estimation for the adjusted short-wave and long-wave radiation underneath the forest canopy. This module generates inputs for both blowing snow module (Prairie Blowing Snow Model PBSM) and energy-budget snowmelt module (Snobal) and has options for both open environments (no canopy adjustment of snow mass and energy) and forest environments (adjustment of snow mass and energy from forest canopy).
8. PBSM module (Pomeroy and Li, 2000): simulates the wind redistribution of snow and estimates snow accumulation and density changes throughout the winter period.
9. SNOBAL module (Marks *et al.*, 1998): this is a point version of the spatially distributed ISNOBAL model (Marks *et al.*, 1999) and is developed to simulate snowmelt in the mountain forest environment. This module estimates snowmelt by calculating the energy balance of radiation, sensible heat, latent heat, ground heat, advection from rainfall and change in internal energy for two layers of snowpack: a top active layer and a layer underneath it.
10. All-wave radiation module (Granger and Gray, 1990): calculates net all-wave radiation from the short-wave radiation and provides inputs to the evaporation module.
11. Infiltration module (two types): Gray's parametric snowmelt infiltration (Zhao and Gray, 1999) estimates snowmelt infiltration into frozen soils; Ayers' infiltration (Ayers, 1959) estimates rainfall infiltration into unfrozen soils based on soil texture, bedrock exposure, rooting characteristics and vegetation cover. Both infiltration algorithms are linked to the soil moisture balance module. Snowmelt or rainfall in excess of the infiltration rate forms surface runoff.
12. Evaporation module (two types): Granger's evaporation expression (Granger and Gray, 1989; Granger and Pomeroy, 1997) estimates actual evaporation (evaporation and transpiration) from unsaturated surfaces; the Priestley and Taylor evaporation expression (Priestley and Taylor, 1972) estimates actual evaporation from saturated surfaces such as wetlands or open water bodies such as stream channels and lakes. Both evaporation calculations update moisture content in the soil column, and the Priestley and Taylor evaporation also updates moisture content in the stream channel.
13. Soil moisture balance module: this module was modified (Dornes *et al.*, 2008; Fang *et al.*, 2010) from an original soil moisture balance routine developed by Leavesley *et al.* (1983) and calculates depressional storage, soil moisture balance, runoff and groundwater storage for control volumes corresponding to surface depressions, two soil layers and a groundwater layer. The top soil layer is called the recharge layer, which receives inputs via infiltration of stored surface water, snowmelt or subcanopy rainfall. Evaporation first uses water from interception and surface storage and then can withdraw moisture via transpiration from only the recharge layer or from both soil column layers depending on vegetation characteristics and is restricted to plant available soil moisture (Armstrong *et al.*, 2010). Evaporation does not withdraw soil moisture until canopy interception and surface water storage are exhausted. Groundwater recharge occurs via percolation from the soil layers or directly from depressional storage via macropores. Subsurface runoff occurs via horizontal drainage from either soil layer. Surface runoff occurs if snowmelt or rainfall inputs exceed subsurface withdrawals from saturated soils.
14. Muskingum routing module: the Muskingum method is based on a variable discharge–storage relationship (Chow, 1964) and is used to route the runoff between HRUs in the subbasins. The routing storage constant is estimated from the average length of HRU to main channel and average flow velocity; the average flow velocity is calculated by Manning's equation (Chow, 1959) on the basis of averaged HRU length to main channel, average change in HRU elevation, overland flow depth and HRU roughness.

Each subbasin was configured as a 'representative basin' in CRHM. In each representative basin, a set of physically based modules was assembled for several distinctive HRUs. Muskingum routing was used to route the streamflow output from these RBs along the main channels at MCRB (Figure 3). To define HRUs, forest cover types were derived from the existing basin forest cover type map by Alberta Forest Service (1963), and recent changes were updated from site visits. Figure 1b shows the updated cover types including alpine talus, alpine forest, mixed spruce and lodgepole pine forest, mixed lodgepole pine and aspen forest, lodgepole pine forest and forest clearings. A terrain preprocessing GIS analysis using a 2008 LiDAR derived 8-m DEM (Hopkinson *et al.*, 2011) was conducted to extract elevation, aspect and slope for the basin. Twelve HRUs were created for the relatively complex Cabin Creek subbasin, seven HRUs were extracted for both Middle

 

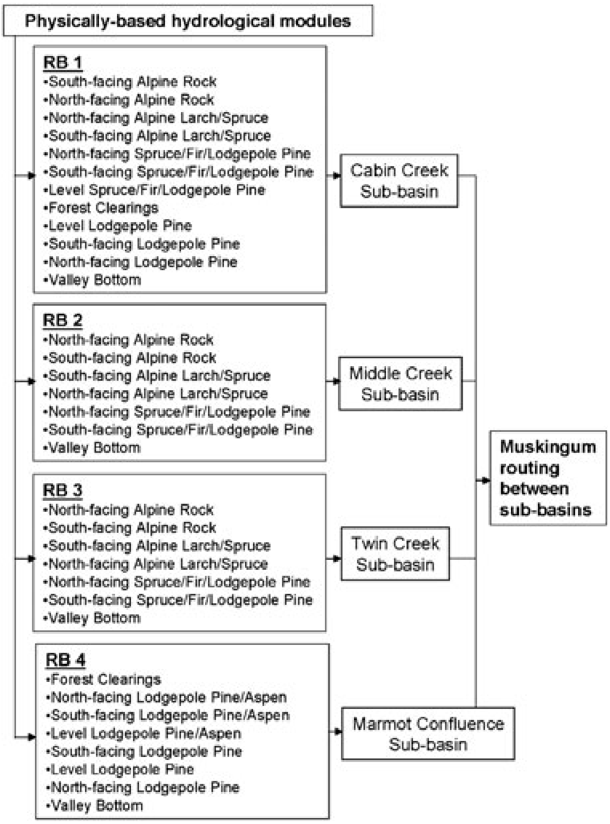


Figure 3. CRHM modelling structure. The four subbasins comprising Marmot Creek are simulated as representative basins (RBs) composed of various HRU, each HRU is composed of the internal structure shown in Figure 2; Muskingum routing connects all four RBs and routes flow to the stream gauging site

Creek and Twin Creek subbasin and eight HRUs were produced for the Marmot Creek confluence subbasin. Parameters for the snow components of the model were set on the basis of mostly field measurements of interception and blowing snow described by MacDonald *et al.* (2010) for the alpine zone and Ellis *et al.* (2010) for the forested zone. These parameterizations were informed by measurements of canopy LAI and sky view factor measured using fish-eye digital photography, vegetation species, vegetation density and height, aerodynamic fetch, snow survey observations of blowing snow redistribution and weighed suspended tree and unloaded snow lysimeter observations of intercepted snow dynamics over several seasons (Ellis and Pomeroy, 2007; Essery *et al.*, 2008; Ellis *et al.*, 2010; MacDonald, 2010; MacDonald *et al.*, 2010). Soil texture was set on the basis of soil surveys by Beke (1969). Soil depth and drainage parameters were set on the basis of field observations along road cuts and hillslopes and well level response to drainage at three groundwater observation wells in the basin and parameter estimates for forested environments (Gray *et al.*, 2001). Routing parameters were determined from the LiDAR DEM and field observations of channel conditions. No calibration was used except for trial and error setting of one parameter that controls the changing connectivity of soil to groundwater in the late summer and the subsurface runoff storage constant. Full details of the parameterization are provided by Pomeroy *et al.* (2011).

### *Model tests*

Model simulations of the snow regime were evaluated by comparing the simulations to observations from snow surveys of SWE in both forest and alpine environments during 2007–2008 and 2008–2009 seasons. The comparisons were conducted at the upper clearing and upper forest sites (see Figure 1 for locations) for evaluation of forest and clearing SWE predictions in the spruce–fir–pine zone; comparisons made at the Fisera Ridge site were used to evaluate near–tree line alpine and subalpine snow predictions. Model predictions of basin streamflow discharge were assessed by comparing the simulated and observed basin streamflow from 1 May to 30 September in 2006, 2007, 2008 and 2009. SWE tests during accumulation and ablation periods gave good results over a wide range of environments with root mean square differences ranging from 2% to 17% of seasonal mean SWE and are shown in detail in Figures 4–6. Both snow accumulation and ablation seasons were well simulated. Model bias for streamflow discharge shows annual errors of less than 15% with estimates in some years more than 3% in error. Bias in individual months ranges from 1% to 59%, but during the peak streamflow month of June, most errors were less than 6% with a maximum of 25%. Figure 7 shows observed and simulated basin streamflow for the May to September period of each simulation year. Peak flows are normally in May and June during the main snowmelt period, and the greatest volume of discharge occurs in June of each year with a recession in July and August. Despite occasional heavy precipitation events in late summer, the hydrograph is very unresponsive to meteorological inputs after the snowmelt period. Although there is not good correspondence between simulated and observed flows in every instance, the simulation is considered adequate for evaluating change of seasonal and peak flows considering that parameter calibration techniques were not used (Pomeroy *et al.*, 2011).

### *Forest disturbance scenario model runs*

Nine types of forest disturbance scenarios were developed for this study, and simulations were made for four hydrological years starting 1 October: 2005–2006, 2006–2007, 2007–2008 and 2008–2009. The scenarios are virtual changes to forest cover that range from the current forest cover to varying level of forest disturbances resulting from MPB infestation, clear-cutting or burns from major forest fires, with and without trunk retention. To simulate forest disturbance, new HRUs corresponding to the disturbed land cover were created with the same geographical, soils and topographical attributes as the original forested HRU. The original forested HRU area was reduced by the amount of increase in the new disturbance HRU. In total, there are 41 scenarios that are

 

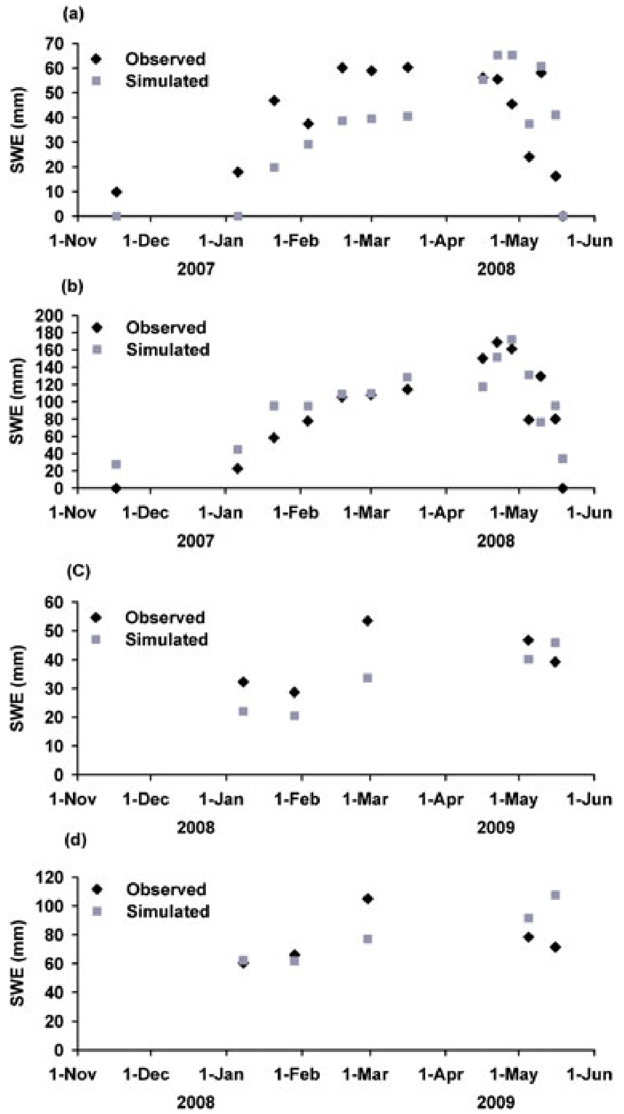


Figure 4. Comparisons of the observed and simulated snow accumulation and ablation (SWE) at the upper forest and upper clearing sites in the spruce–fir zone of Marmot Creek Research Basin. (a) Upper forest during 2007–2008, (b) upper clearing during 2007–2008, (c) upper forest during 2008–2009 and (d) upper clearing during 2008–2009

summarized in Table I. The full set of model parameters for these scenarios is provided by Pomeroy *et al*. (2011).

In both scenarios 2 to 6 and scenarios 7 to 11, the lodgepole pine forest canopy was reduced progressively from 20% to 100% by MPB; the reduction covers from 3% to 15% of total basin area. As shown in Figure 1b, lodgepole pine only occupies the lower elevations of the basin. A new HRU—MPB disturbance—was incorporated into the scenario simulation and occupied from part to all of the previous lodgepole pine HRU areas. Elevation, aspect and slope for the MPB disturbance HRU were estimated from the area-weighted average values of elevation, aspect and slope from the infested lodgepole pine. As MPB has not yet infected Marmot Creek, forest parameter values (LAI, canopy snow interception capacity) were drawn from field observations at infected sites in Western Canada (Boon, 2009; Bewley *et al*., 2010). To simulate the temporal progression of MPB disturbance to canopy (red needles, then grey needles, then needle and some stem loss) as the infection spreads, values for the LAI and canopy snow interception load capacity for the MPB disturbance HRU declined linearly as infected area increased. This simplification of a complex biological process permitted a clear scenario that is consistent with the general understanding of the impact of MPB disturbance. The infested lodgepole pine trunks remained in the scenarios 2 to 6, with the original vegetation height, but the respective values of LAI and canopy snow interception load capacity were reduced. The beetle-infested lodgepole pine was salvage logged in the scenarios 7 to 11, with the MPB disturbance HRU being given further reduced values for LAI and canopy snow interception load capacity. Transpiration was suppressed from the infested lodgepole pine in all disturbed scenarios (2–6 and 7–11).

In scenarios 12 to 16 and 17 to 21, the forest area (including all forest species at all forested elevations) was removed progressively by fire and replaced by disturbance HRUs from 20% to 100% of the forested area; the removal corresponded from 12% to 60% of the total basin area. A new HRU—fire disturbance—was added to the scenario simulation to account for formerly forested area. As Marmot Creek has not recently been burnt, parameter values for burned mountain forests were selected from nearby field studies in the Canadian Rockies (Burles and Boon, 2011). It was presumed that all subcanopy vegetation was suppressed and that transpiration was minimal but that the largely mineral soil texture was kept intact. Elevation, aspect and slope for the fire disturbance HRU were estimated from the area-weighted average values of elevation, aspect and slope from the burned forest. The burned forest trunks were permitted to remain in the scenarios 12 to 16 with the original vegetation height, and values of LAI and canopy snow interception load capacity were strongly reduced. The burned forest was completely removed in the scenarios 17 to 21, with the fire disturbance HRU values of LAI and canopy snow interception load capacity being set to zero.

In scenarios 22 to 26 and 32 to 36, a new HRU—south-facing clearing—was added to the scenario simulation, and forests on the south-facing slopes were clear-cut by logging from 20% to 100% of forested south-facing slope area and replaced with this new HRU; this modification covered approximately from 7% to 36% of total basin area. Stumps 1.5 m high and subcanopy vegetation were retained in the scenarios 32 to 36 to simulate residual 'slash', whereas the forest was cleared to bare ground with all vegetation removed in the scenarios 22 to 26. In scenarios 27 to 31 and 37 to 41, a new HRU—north-facing clearings—was incorporated into the scenario simulation; forests on the north-facing slopes were clear-cut by logging from 20% to 100% of forested north-facing slope area and replaced with this new HRU, which corresponds to from 4% to 22% modification of the total basin area. Stumps 1.5 m high were retained after the logging in the scenarios 27 to 31, whereas the forest was completely cleared with no residual vegetation in the scenarios 37 to 41.

 

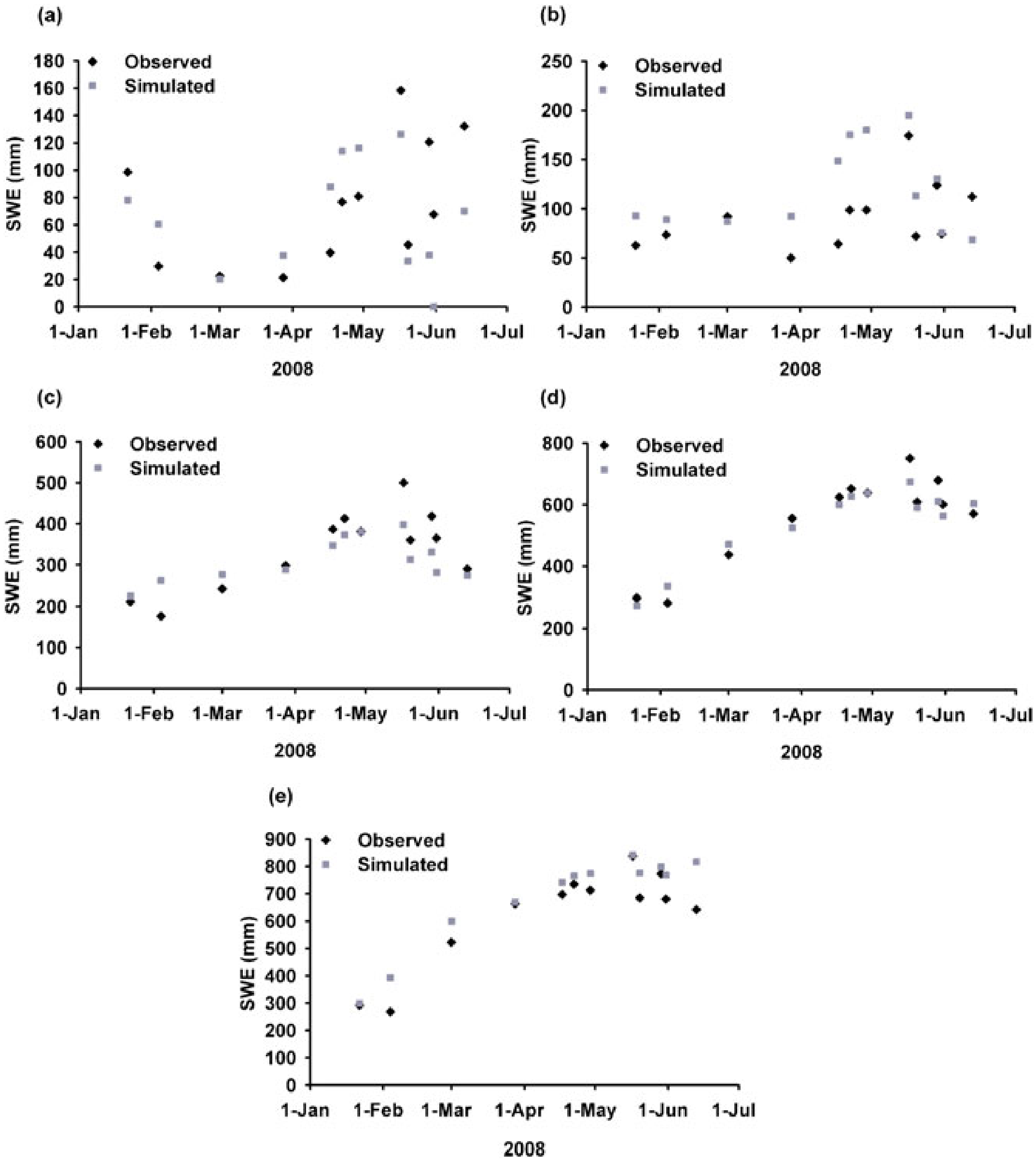


Figure 5. Comparisons of the observed and simulated snow accumulation and ablation (SWE) on differing tree line zone slopes near Fisera Ridge, Marmot Creek Research Basin, in 2008. (a) North-facing tundra slope, (b) ridge top tundra, (c) top south-facing tundra slope, (d) bottom south-facing open larch slope and (e) larch and spruce forest

## RESULTS AND DISCUSSION

### *Snowmelt volume*

Changes in modelled snowmelt volumes under the various scenarios are shown in Figure 8, where a 50% increase in snowmelt volume corresponds to 170 mm. The sensitivities are shown as the four-season averaged changes in the cumulative basin snowmelt volume against the forest cover disturbance expressed as a percentage of the total basin area. The effect of forest disturbance invariably increased modelled snowmelt volumes. However, the results suggest that MPB infestation with dead trunk retention (no salvage logging) is the least effective means to increase snowmelt because of the small area and the low elevations affected and the modest modification to canopy properties. A disturbance to forest cover corresponding to 15% of basin area results from complete pine mortality due to beetle and only results in a 5% increase in snowmelt volume. With salvage logging, the increase in snowmelt volume due to MPB infestation doubles to 10%. The low effectiveness of MPB infestation on basin scale snowmelt volume was greatly contributed to by the low elevations of most pine forests and the associated low snowfall in these forests compared with the high elevations of the basin where most snow accumulation occurs. By comparison, the removal of forest canopy at higher elevations due to clear-cutting or burns with salvage logging has almost doubled the effectiveness in increasing basin snowmelt volume. However, if clear-cutting or burning had been restricted to lodgepole pine forests, the impacts would have been more similar to that of MPB. The most effective forest removal technique for

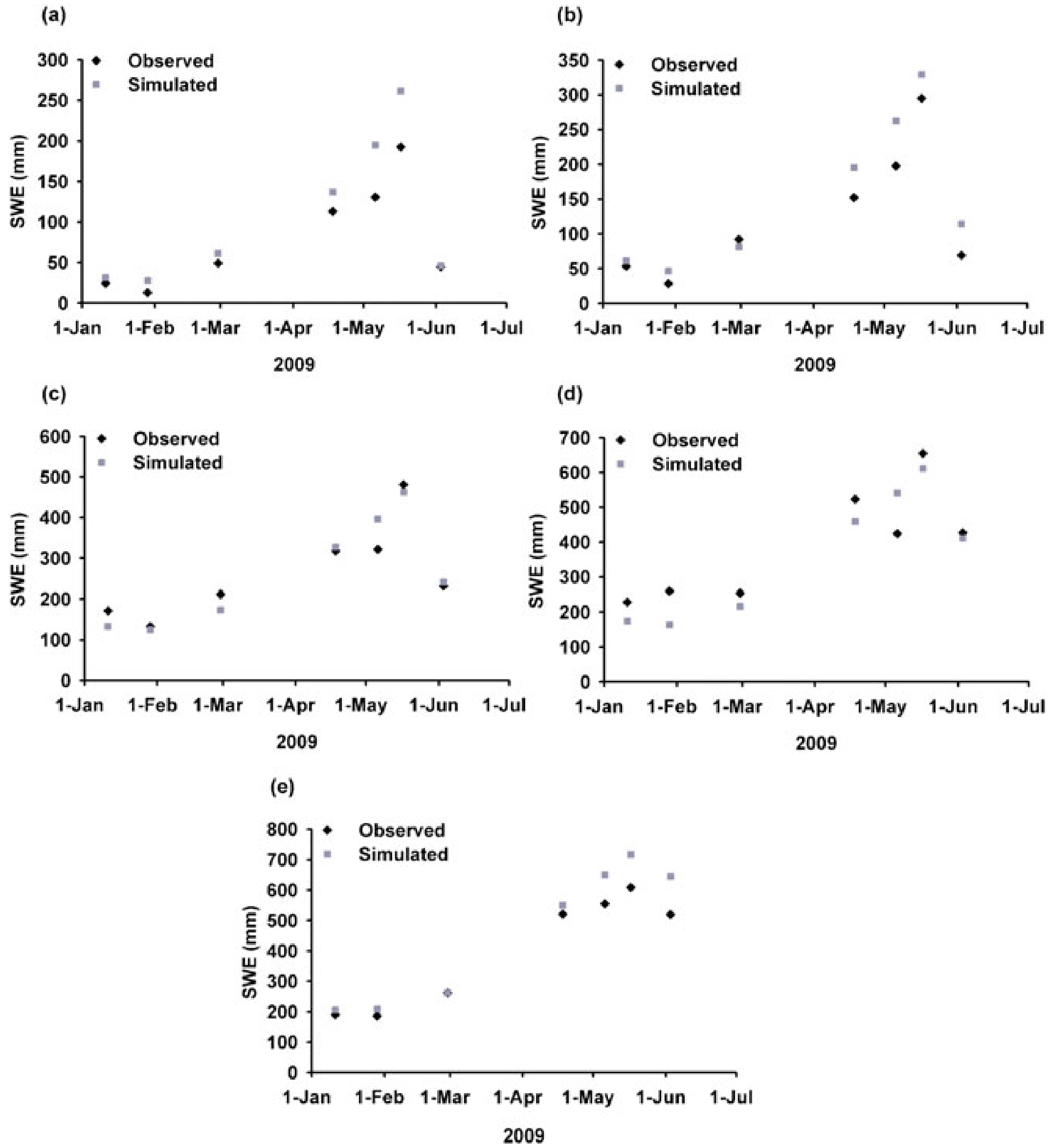


Figure 6. Comparisons of the observed and simulated snow accumulation and ablation (SWE) on differing tree line zone slopes near Fisera Ridge, Marmot Creek Research Basin, in 2009. (a) North-facing tundra slope, (b) ridge top tundra, (c) top south-facing tundra slope, (d) bottom south-facing open larch slope and (e) larch and spruce forest

increasing snowmelt volume is forest removal by clear-cutting or fire with salvage logging. When the canopy is removed from 60% of the basin area, a 45% increase in snowmelt volume can result, and even a small area of the basin with canopy removal (5%) can result in a 10% increase in snowmelt volume. There is little effect of slope on snowmelt volume changes in response to forest disturbance.

*Streamflow*

Figure 9 shows the spring and summer seasonal (1 April to 30 September) streamflow volume change compared with reduction in forest cover under various forest treatments, averaged for 4 years. Of immediate interest is the very small effect of MPB infestation on streamflow; MPB-killed forests with dead trunks standing can cover up to 15% of the basin area but cause an increase in streamflow volume of less than 2%. With salvage logging, this increases slightly to more than 2% only. By contrast, forest disturbances from fire, salvage logging and clear-cutting ranging from 5% to 35% of basin area can increase streamflow by from 3% to 5%. The lower effectiveness of MPB infestation on streamflow for a given disturbed area is due to the drier, lower elevations that lodgepole pine forests occupy and their relatively small contribution to streamflow compared with the wetter forests at higher elevations. Clear-cutting on south-facing slopes seems slightly less effective than the other treatments, suggesting these sites are less hydrologically sensitive to disturbance; this may be due to drier soils and hence lower runoff generation or to an earlier melt than the rest of the basin when these sites area cleared. The most effective method to increase streamflow was fire with the retention of burned trunks, for which complete burning of the basin

 

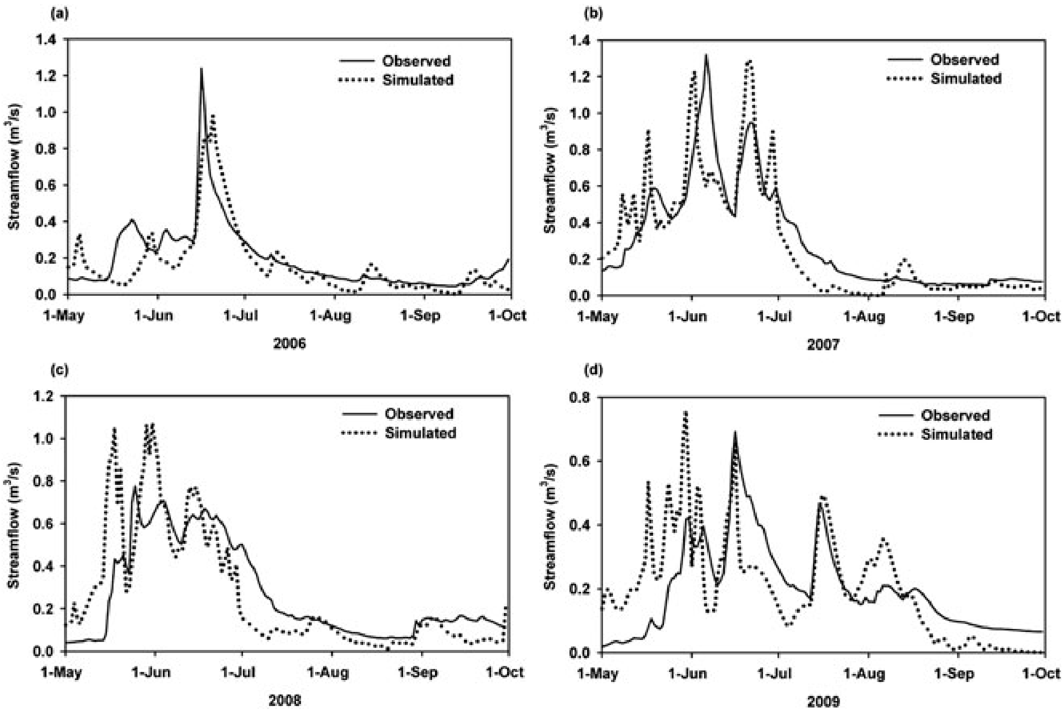


Figure 7. Comparisons of the observed and simulated spring and summer streamflow discharge rates at Marmot Creek for (a) 2006, (b) 2007, (c) 2008 and (d) 2009

forests (60% disturbance of basin area) resulted in an 8% increase in streamflow. Interestingly, only a 5% increase in streamflow was modelled for burning with salvage logging, likely because of increased blowing snow transport and sublimation and earlier snowmelt from the exposed, unsheltered clearings. Similarly, clear-cuts with the retention of stumps had slightly higher streamflow than those without stumps. Very small differences in streamflow were found with aspect despite the dramatic differences in snowmelt energetics between these slopes (Ellis *et al.*, 2011). Although the energetic differences affect timing, the volume of runoff is relatively similar between north and south aspects.

Peak streamflow occurred in May and June and showed little difference in timing with forest disturbance; however, the peak streamflow discharge rates changed substantially. Figure 10 shows the percentage change in peak daily streamflow discharge rate with the forest cover disturbance expressed as a percentage of basin area, averaged for 4 years. Again, the MPB effects are small, with a less than 4% increase in peak streamflow rate from a 15% disturbed basin area and only a slight increase due to further salvage logging of the pine beetle affected areas. This is likely due to the low elevations of the lodgepole pine forests and hence their relatively small influence on peak flow generation, which is associated with melt at higher elevations. In contrast, a clear-cut of only 5% of the basin area resulted in a 7% to 8% increase in peak streamflow rate; further increases in clear-cutting as salvage logging after burning to 60% of the basin area resulted in up to a 23% increase in peak streamflow rate. Clear-cutting on south-facing slopes increased peak streamflow rates somewhat more than that on north-facing slopes. This suggests that although south-facing slopes are hydrologically less responsive in generating seasonal flow volumes, they are important contributors to peak streamflow and hence remain hydrologically important. The retention of burned trunks somewhat reduced the peak streamflow rate increase for moderate forest area disturbances but had the opposite effect with complete forest removal, possibly because of the synchronization of melt timing under a fairly uniform dead canopy when this exceeded 50% of the basin area.

The major influence forest cover removal has on the snowmelt water balance is associated with the decrease in sublimation of intercepted snow as shown in Figure 11. Figure 11 shows the 4-year average sublimation losses over the basin from various scenarios, plotted against seasonal streamflow volume expressed in millimetre. Blowing snow sublimation, although large, is not strongly affected by decreased forest cover and so changes very little, and this change has no relationship to streamflow volume. In contrast, a change in intercepted snow sublimation is associated with a similar volumetric change in streamflow from the basin. The changes in seasonal streamflow volume are therefore almost entirely the result of reduced sublimation of intercepted snow. This is attributed to the very small streamflow quantities generated after the snowmelt freshet in this basin (Figure 7) and hence the limited influence of changes in summer evaporation on streamflow generation.

 

Table I. Description of forest disturbance scenarios at the Marmot Creek Research Basin

| Scenario | Scenario description | Basin area changed (%) |
|---|---|---|
| 1 | Current forest cover | 0 |
| 2 | MPB attack of 20% of pine forest with infested trunk retained | 3 |
| 3 | MPB attack of 40% of pine forest with infested trunk retained | 6 |
| 4 | MPB attack of 60% of pine forest with infested trunk retained | 9 |
| 5 | MPB attack of 80% of pine forest with infested trunk retained | 12 |
| 6 | MPB attack of 100% of pine forest with infested trunk retained | 15 |
| 7 | MPB attack of 20% of pine forest with salvage logging | 3 |
| 8 | MPB attack of 40% of pine forest with salvage logging | 6 |
| 9 | MPB attack of 60% of pine forest with salvage logging | 9 |
| 10 | MPB attack of 80% of pine forest with salvage logging | 12 |
| 11 | MPB attack of 100% of pine forest with salvage logging | 15 |
| 12 | Burning of 20% of all forests with trunk retained | 12 |
| 13 | Burning of 0% of all forests with trunk retained | 24 |
| 14 | Burning of 60% of all forests with trunk | 36 |
| 15 | Burning of 80% of all forests with trunk retained | 48 |
| 16 | Burning of 100% of all forests with trunk retained | 59 |
| 17 | Burning of 20% of all forests with trunk removed | 12 |
| 18 | Burning of 40% of all forests with trunk removed | 24 |
| 19 | Burning of 60% of all forests with trunk removed | 36 |
| 20 | Burning of 80% of all forests with trunk removed | 48 |
| 21 | Burning of 100% of all forests with trunk | 59 |
| 22 | Clear-cutting of 20% of all forests on south-facing slopes | 7 |
| 23 | Clear-cutting of 40% of all forests on south-facing slopes | 14 |
| 24 | Clear-cutting of 60% of all forests on south-facing slopes | 21 |
| 25 | Clear-cutting of 80% of all forests on south-facing slopes | 29 |
| 26 | Clear-cutting of 100% of all forests on south-facing slopes | 36 |
| 27 | Clear-cutting of 20% of all forests on north-facing slopes | 4 |
| 28 | Clear-cutting of 40% of all forests on north-facing slopes | 9 |
| 29 | Clear-cutting of 60% of all forests on north-facing slopes | 13 |
| 30 | Clear-cutting of 80% of all forests on north-facing slopes | 18 |
| 31 | Clear-cutting of 100% of all forests on north-facing slopes | 22 |
| 32 | Clear-cutting of 20% of all forests on south-facing slopes with 1.5 m stump retained | 7 |
| 33 | Clear-cutting of 40% of all forests on south-facing slopes with 1.5 m stump retained | 14 |
| 34 | Clear-cutting of 60% of all forests on south-facing slopes with 1.5 m stump retained | 21 |
| 35 | Clear-cutting of 80% of all forests on south-facing slopes with 1.5 m stump retained | 29 |
| 36 | Clear-cutting of 100% of all forests on south-facing slopes with 1.5 m stump retained | 36 |
| 37 | Clear-cutting of 20% of all forests on north-facing slopes with 1.5 m stump retained | 4 |
| 38 | Clear-cutting of 40% of all forests on north-facing slopes with 1.5 m stump retained | 9 |
| 39 | Clear-cutting of 60% of all forests on north-facing slopes with 1.5 m stump retained | 13 |
| 40 | Clear-cutting of 80% of all forests on north-facing slopes with 1.5 m stump retained | 18 |
| 41 | Clear-cutting of 100% of all forests on north-facing slopes with 1.5 m stump retained | 22 |

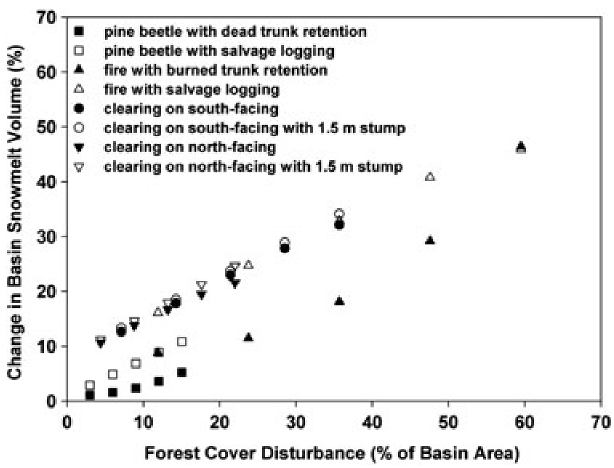


Figure 8. Change in the disturbance in forest cover as a percentage of the basin area for various forest disturbance scenarios and the basin-wide snowmelt volume averaged for 4 years for Marmot Creek

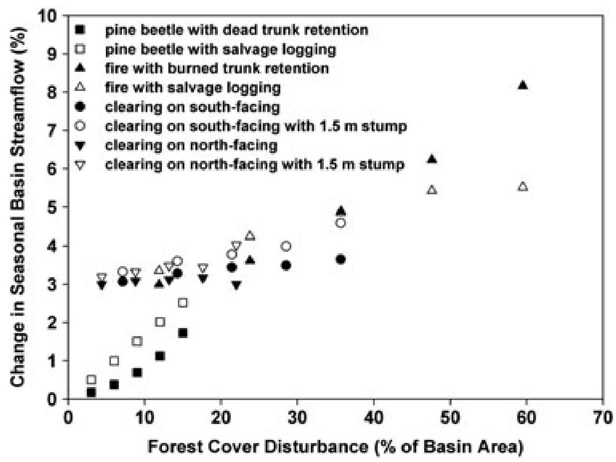


Figure 9. Change the area of forest disturbance expressed as a percentage of basin area for various forest treatment scenarios and the associated percentage change in April through September streamflow discharge volume averaged for 4 years

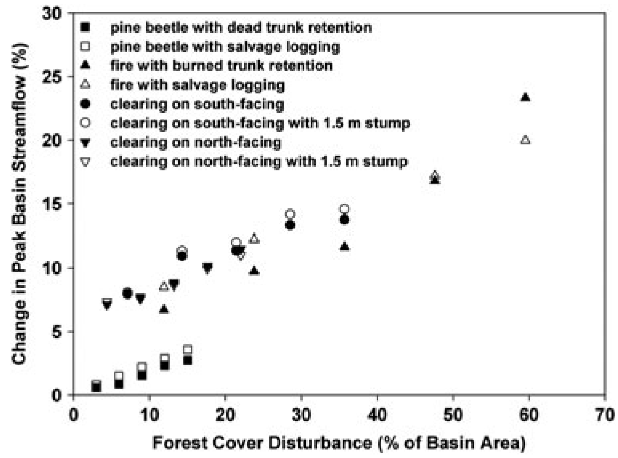


Figure 10. Change the area of forest disturbance expressed as a percentage of basin area for various forest treatment scenarios and the associated percentage change in peak annual streamflow rate averaged for 4 years.

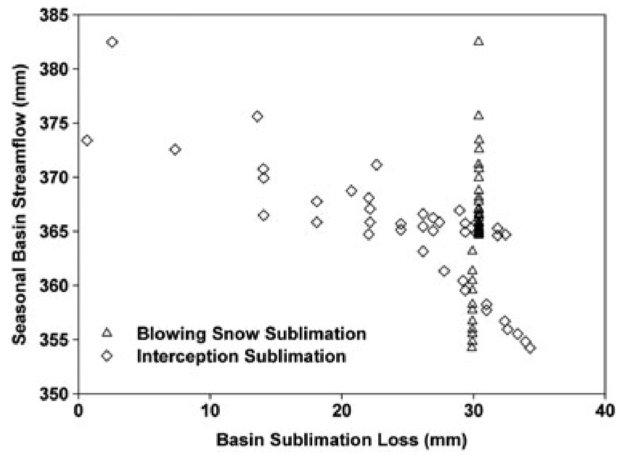


Figure 11. Seasonal sublimation losses from blowing snow and intercepted snow, averaged for the 2005–2009 period and compared with seasonal (May–September) streamflow volumes.

## CONCLUSIONS

Marmot Creek Research Basin, a typical basin of the forested east slopes of the Canadian Rockies, was the host for a physically based hydrological model, constructed using the CRHM platform, parameterized with minimal calibration and tested for 4 years of simulation. The model was found to accurately simulate snowpacks in forested and cleared landscapes and adequately simulate the timing and quantity of streamflow over the basin for use in land use scenario development and evaluation. These results are an encouraging example of a multi-objective evaluation of a physically based model with very little calibration and suggest future applications to prediction in ungauged basins. The model was manipulated to simulate the impacts of forest disturbance on basin snowmelt volume and streamflow generation. Forty forest disturbance scenarios were compared with the current land cover for the four simulation years. Disturbance scenarios ranged from the effect of pine beetle kill of lodgepole pine to clear-cutting of north or south-facing slopes, forest fire and salvage logging.

Pine beetle impacts were small in all cases with increases in snowmelt volumes of less than 10% and of streamflow volume of less than 2%. This is due to only 15% of the basin area being covered with lodgepole pine and this forest being at lower elevations, which received much lower precipitation than did higher elevations and so generated much less streamflow. Forest disturbance due to fire and clear-cutting occurred equally at all forested zones and elevations, hence affected much larger areas of the basin and greater elevation ranges, and was generally more than twice as effective as pine beetle kill in increasing snowmelt volume or streamflow. For disturbance of all forests from burning with salvage logging, a 45% increase in snowmelt volume was simulated; however, this only translated into a 5% increase in spring and summer streamflow volume. Forest fire with the retention of standing burned trunks was the most effective treatment for increasing streamflow (up to 8%), as this minimized snow sublimation. Increases in snowmelt volumes were associated with reduced intercepted snow sublimation losses due to canopy removal. The additional meltwater from reduced sublimation was primarily contributed to streamflow generation in the spring. Peak daily streamflow discharges responded more strongly to forest cover disturbance than did seasonal streamflow volumes, with increases of more than 20% in peak streamflow with the removal of all forest cover. The greatest increase in peak flow occurred with disturbances from burning with burned trunk retention. The high sensitivity of peak flows to forest cover removal is consistent with increased runoff efficiency from an increase in melt rates upon canopy removal from level and south-facing slopes as identified by Ellis *et al.* (2011). Presumably, a basin with differing topographic orientation or steepness would provide a differing hydrological response to forest cover change, and the sensitivity of these changes to basin characterization needs further examination. As such, these results should not be extrapolated to basins with differing topography, even in the same climate region, without careful considerations of how basin hydrology can mitigate the response of snow energetics and mass balance to forest cover change. A more detailed examination of the soil hydrology and groundwater hydrology response to forest cover removal is warranted before detailed hydrograph shape scenarios can be examined. The Kananaskis River valley where Marmot Creek is situated is now subject to MPB attack, and so Marmot Creek may in the near future provide real data on the effect of this type of forest disturbance that can be used to further evaluate the model and conclusions.

ACKNOWLEDGEMENTS

Funding assistance from the Alberta Sustainable Resource Development, the Canadian Foundation for Climate and Atmospheric Sciences through the IP3 Cold Regions Hydrology Network, the Natural Sciences and Engineering Research Council of Canada through discovery grants, research tools and instrument grants and the Alexander Graham Bell Scholarships, the Canada Research Chairs programme and the Biogeoscience Institute, University of Calgary, is gratefully acknowledged. Logistical assistance was received from the Nakiska Ski Area and Biogeoscience Institute. Field work by many graduate students in and visitors to the Centre for Hydrology and research officers Michael Solohub and May Guan were essential in data collection.

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