The Effect of Mountain Pine Beetle Attack and Salvage Harvesting On Streamflows

Special Investigation

Forest
Practices
Board

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Executive Summary

The Mountain Pine Beetle (MPB) epidemic, and the large-scale salvage logging of beetle-infested trees, are resulting in large areas of dead pine forest and clearcuts in watersheds across the central interior. These disturbances have potential effects on water yield (the total amount of water flowing out of a watershed in a year), peak flows (the highest stream flows of the year) and flood timing.

Forests regulate streamflow by four processes. First, the forest canopy intercepts a percentage of the snowfall and returns it to the atmosphere, reducing the amount of snow reaching the ground to become runoff. Secondly, the forest provides shade, reducing snowmelt rates. In addition the reduction in wind speed in a forested stand also reduces snow melt rates. Finally, trees transpire water during growth.

The effects of a MPB- attack on these processes are different from forest harvesting. The insect-killed trees remain in place, and have a residual canopy that can intercept a portion of the snowfall. Also, the mortality is never 100% and individual trees continue to intercept water. The standing dead trees also provide considerable shade, reducing radiation and snowmelt rates. Forest harvesting contributes to increased spring peak flows by removing the intercepting canopy and removing shade.

In order to determine the scale of these hydrological changes, peak streamflow magnitude, and timing and water yield were simulated using a computer model for Baker Creek, a 1570-square kilometre watershed tributary to the Fraser River at Quesnel, British Columbia.

Four scenarios were modeled:

1) Baseline, prior to harvesting
2) Conventional harvesting
3) The MPB attack of 75% of the mature pine and past harvesting
4) Salvage harvest of 80% of the watershed with 20% of the watershed retained in reserves

The model of Baker Creek showed MPB attack of 75% of the mature pine stands, plus the past conventional harvesting (scenario 3), resulted in annual peak flood increases of 60% and annual total water yield increases of 30%. Salvage harvesting of the dead pine (scenario 4) results in a further increase in annual peak streamflow compared to leaving the MPB-attacked trees standing. In Baker Creek, salvage harvesting of all pine-leading stands, (but retaining 20% of the watershed in reserves), increases annual peak flows by 92 %. Flood frequency also increases: a former 20-year interval peak flow discharge will now be expected every 3 years. These changes represent a major shift in stream flow regime.

The peak flow changes have implications on flooding, channel stability and fish habitat within watersheds similar to Baker Creek. These results also have salvage harvest management implications. The current MPB infestation has already created a substantial peak flow hazard. Any salvage harvesting of these stands will increase the peak flow hazard even more.

The FRPA legislation and the Cariboo-Chilcotin higher level plan (CCLUP) do not require landscape level watershed assessments or planning for most MPB-affected watersheds. Government needs to develop policy and strategies for protecting drinking water and fish habitat in the MPB- attacked watersheds.

Acknowledgments

The Board thanks Dr. Younes Alila (UBC, Faculty of Forestry)[1] Dr. Charles Luo (previously with UBC Faculty of Forestry and now with CH2MHILL Engineering), for calibrating and running the DHSVM model and Steve Chatwin (Forest Practices Board) for interpreting the analysis.

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[1] Contact for technical questions on DHSVM model

People living in the central Interior area impacted by mountain pine beetle (MPB) are concerned about the potential effects on future timber supply, visual quality, biodiversity and water resources of the region. To address some of these concerns, the Forest Practices Board is conducting a series of investigations into the effects of MPB attack on various forest resources, using Baker landscape unit, near Quesnel, as a case study.[2] This report addresses the potential effects of the MPB attack, and the salvage logging currently being conducted in beetle-infested stands, on water resources.

The minutes of a watershed planning meeting[3], revealed anecdotal evidence of recent changes in the runoff regime of Baker Creek. Residents within the watershed complained that:

"Flooding has changed location. Landowners have experienced flooding, channel infilling, change of course and siltation of their fields over the past few years"

and:

"Flooding has always occurred in the Baker Creek Area, but it is happening more now than in the past. In the past, areas would flood 3-4 times a year but now they are flooding 7-8 times a year. Furthermore flooding is more severe and has caused drainage pattern changes…."

Changes in streamflow can be expected following the death of trees in a MPB attack, but the magnitude of the change can't be inferred from the research literature because of the unprecedented scale of the current attack. This project is an illustration of the use of forest hydrology models in predicting changes in streamflow in the context of a major forest disturbance.

Despite uncertainties, modeling is the only practical method of studying the effects of forest disturbances over large watersheds. However, for the models to be even more useful, additional process studies at the forest stand level in mountain pine beetle areas are needed. In spite of our attempt to reduce the uncertainties in this model (Luo et al. 2006), it still reflects the limited state of knowledge of mountain pine beetle effects on hydrological processes.

That caution aside, the value of a whole watershed analysis at this time is to scope the potential magnitude of the change in water flow that might occur with MPB attack. The results indicate the peak flow changes following MPB attack may be dramatic. A forest management dilemma is that any salvage harvesting of attacked trees will lead to even higher peak flow changes. Not harvesting leaves the stands vulnerable to fire, which would have a similar hydrological impact as harvesting. Furthermore, observations of

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[2] See Terms of Reference/ Special Projects on the web site at www.fpb.gov.bc.ca

[3] Baker Creek Watershed Assessment – Phase 1 *Summit Environmental Consultants Ltd.* March 2006

stands attacked by MPB 25 years ago[4],[5] indicate that the hydrological recovery of these stands may be relatively slow. If salvage harvesting of these areas is going to take place, government, industry and forest professionals should work together to develop mitigation strategies for protecting drinking water and fish habitat.

Introduction

The MPB epidemic is creating large-scale forest disturbances across the central interior, as pine forests are killed and salvage harvesting begins. These disturbances kill and remove trees and therefore have potential effects on water yield (the total amount of water flowing out of a watershed in a year), low flows (the lowest stream flows of the year) and peak flows (the highest stream flows of the year).

The hydrologic effects of MPB infestations vary with the species in the forest, the mortality rate and the local climate. Removing the forest canopy may potentially increase streamflow by four processes. First, the forest canopy intercepts a percentage of the snowfall and returns it to the atmosphere, reducing the amount of snow reaching the ground and becoming runoff. Secondly, the forest provides shade, reducing snowmelt rates. The loss of wind speed in a forested stand also reduces snow melt rates. In addition, trees use water during transpiration.

The hydrologic effects of a MPB attack are different from forest harvesting. The insect-killed trees can remain in place, and can intercept a portion of the snowfall. Secondly, the mortality is never 100% and individual trees continue to intercept and transpire water. A recent Board report6 describes the vigorous understory beneath many MPB-killed stands and this understory will also intercept and transpire water.

The standard approach to quantifying hydrologic changes resulting from forest disturbances is usually based on on-the-ground experiments conducted at the stand level, or on monitoring pairs of small watersheds less than a few square kilometres in size. The advantage of a hydrological model is that existing climate and streamflow data can be used, and large watersheds can be simulated. In this report, the Distributed Hydrological Soil Vegetation Model (DHSVM) is used to simulate stream flow and water yield in Baker Creek following past conventional harvest, current MPB attack and future salvage harvesting.

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[4] Forest Practices Board, 2006. *Lodgepole Pine Stand Structure 25 Years after Mountain Pine Beetle Attack,* Forest Practices Board Special Report.

[5] Also see Troendle, C. and King, RM, 1985. *Effect of Timber Harvest on Fool Creek Watershed Thirty Years Later.* Water Resources Research 21(12):1915-1922 where they document recovery taking in excess of 50 years.

[6] Forest Practices Board, 2007. *Lodgepole Pine Stand Structure 25 Years after Mountain Pine Beetle Attack.* Forest Practices Board Special Report.

FRPA Requirements for Water Management in MPB-Attacked Watershed

Baker Creek is typical of many watersheds in the MPB attack zone, with a number of domestic water intakes and high value salmon habitat. Baker Creek does not qualify as a community watershed; therefore licensees do not have to address FRPA objectives for water quality or quantity in community watersheds[7]. Also Baker Creek is not on the list of 'target fish streams' identified in the Caribou-Chilcotin Land Use Plan (CCLUP) Implementation Plan, therefore CCLUP objectives for fish habitat and cumulative watershed effects do not apply.

There is a general FRPA objective for water quality in riparian areas (section 8 of the FPPR):

> The objective set by government for water, fish, wildlife and biodiversity within riparian areas is, without unduly reducing the supply of timber from British Columbia's forests, to conserve, at the landscape level, the water quality, fish habitat, wildlife habitat and biodiversity associated with those riparian areas.

The effect of the section 8 objective is that all FSPs must either specify a result or strategy in relation to the objective, or, contain an undertaking to comply with certain default practice requirements (FPPR sections 47 to 53). These sections set out restrictions that apply in riparian management areas. If a licensee chooses to specify a result or strategy in its FSP, the licensee is then exempt from most of the requirements of sections 47 to 53.

In summary, as long as a licensee complies with the riparian reserve and management zone regulations, no further management of cumulative hydrological impact resulting from mountain pine beetle attack or salvage harvesting is required.

In spite of the lack of regulation, a watershed assessment of Baker Creek will be completed by Tolko Industries by April, 2007. The watershed assessment will "assess the watershed values with respect to future forestry development" and "provide recommendations to mitigate potential negative hydrologic effects of pine mortality and/or forest development".[8]

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[7] Quesnel Forest District does not have any community watersheds

[8] Baker Creek Watersheed Asessment – Phase 1 *Summit Environmental Consultants Ltd.* March 2006

The Baker Creek Watershed

The study area is the Baker Creek watershed, a western tributary of the Fraser River, at Quesnel (Figure 1). Baker Creek watershed has important aquatic values. There are 91 licensed points of domestic water diversion: 19 on lakes, 12 on springs and 60 on small streams. It also has Chinook salmon and rainbow trout habitat.

This watershed was chosen for modeling because it is representative of a large percentage of the watersheds in the central interior with MPB attack: plateau topography, low relief, mostly pine forests. It also has an exceptional weather, streamflow and snowfall record going back to 1961. Finally the progression of the MPB attack through the watershed is well documented.

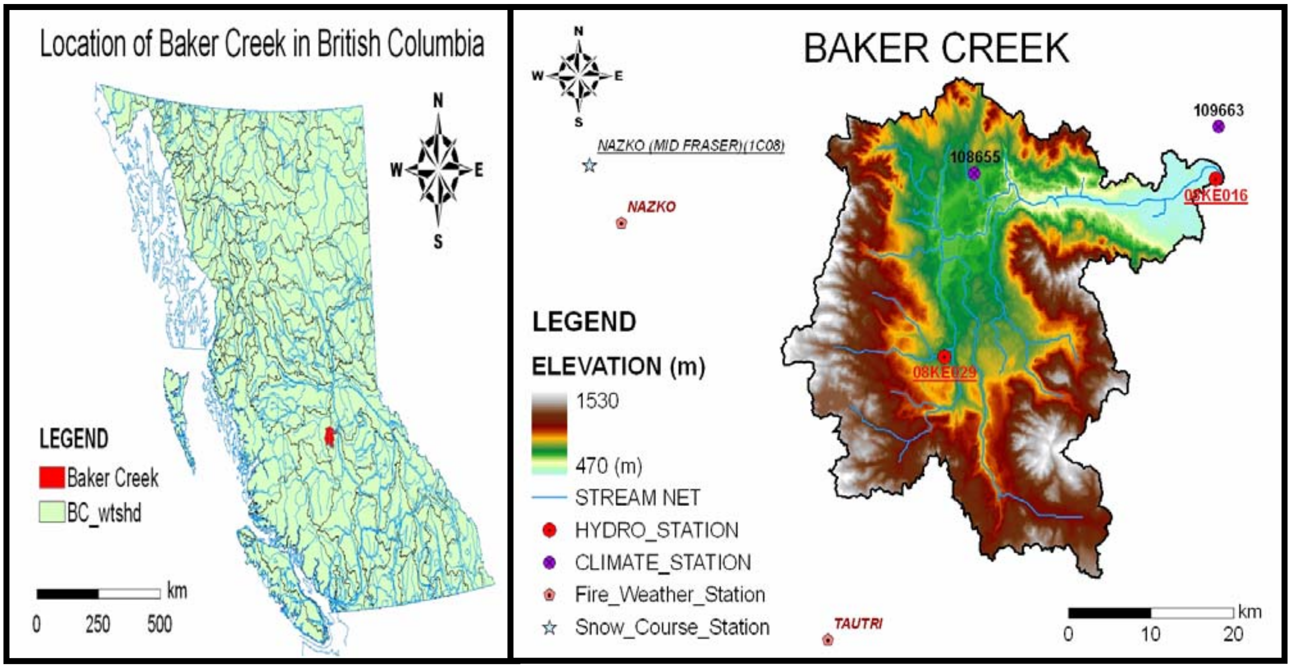


Figure 1: Location of Baker Creek study watershed in British Columbia and elevation contours

The watershed area is 1570 km2 with elevations ranging from 470-1530 m. Most of the watershed is a plateau (Figure 1). The most common biogeoclimatic units are SBPSdc (Sub Boreal Pine Spruce, dry cold), SBPSmk (Sub-Boreal Pine Spruce, moist cold) and at higher elevations MSxc (Montane Spruce, dry cold) (Figure 2). Forest cover is Lodgepole pine, with minor areas of spruce and Douglas fir. To date, 75% of the mature pine-leading stands have been infested by MPB. Pine-leading stands are 85% of the forest profile.

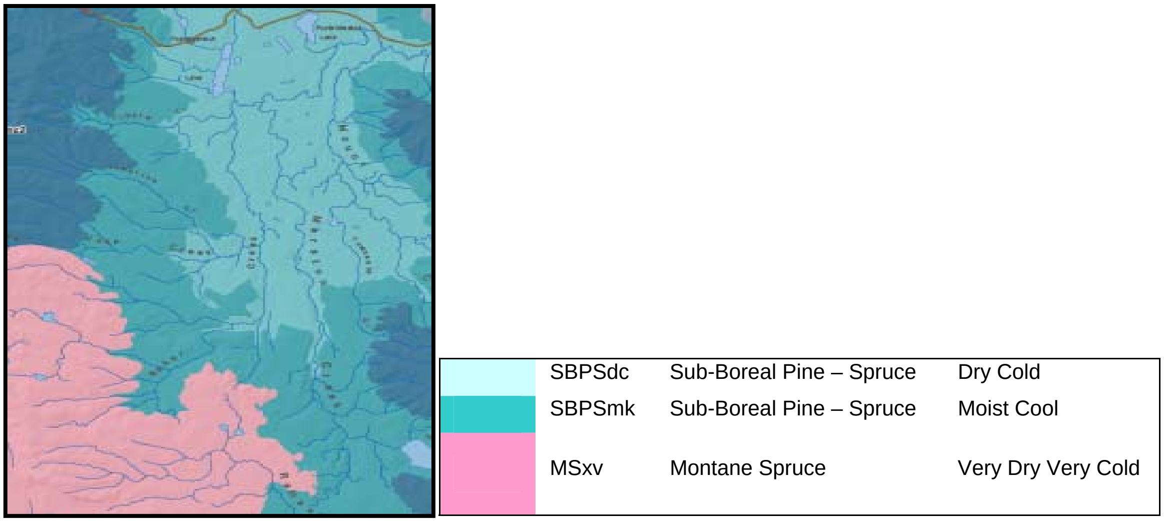


Figure 2: Baker Creek watershed biogeoclimatic variants

The watershed is semi-arid, with annual precipitation similar to the Okanagan (400 mm). Snowfall and runoff is highly variable, for example, annual runoff ranges between 20mm and 180mm over the last 30 years (Figure 3).

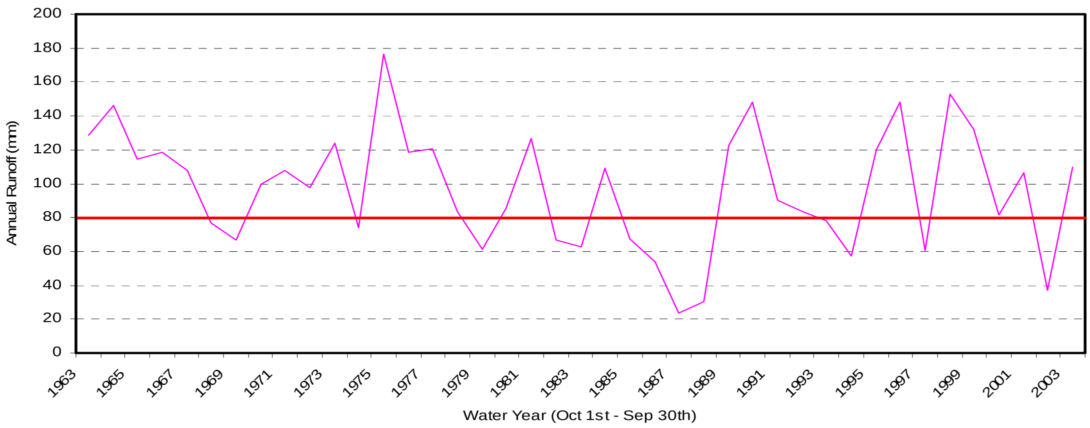
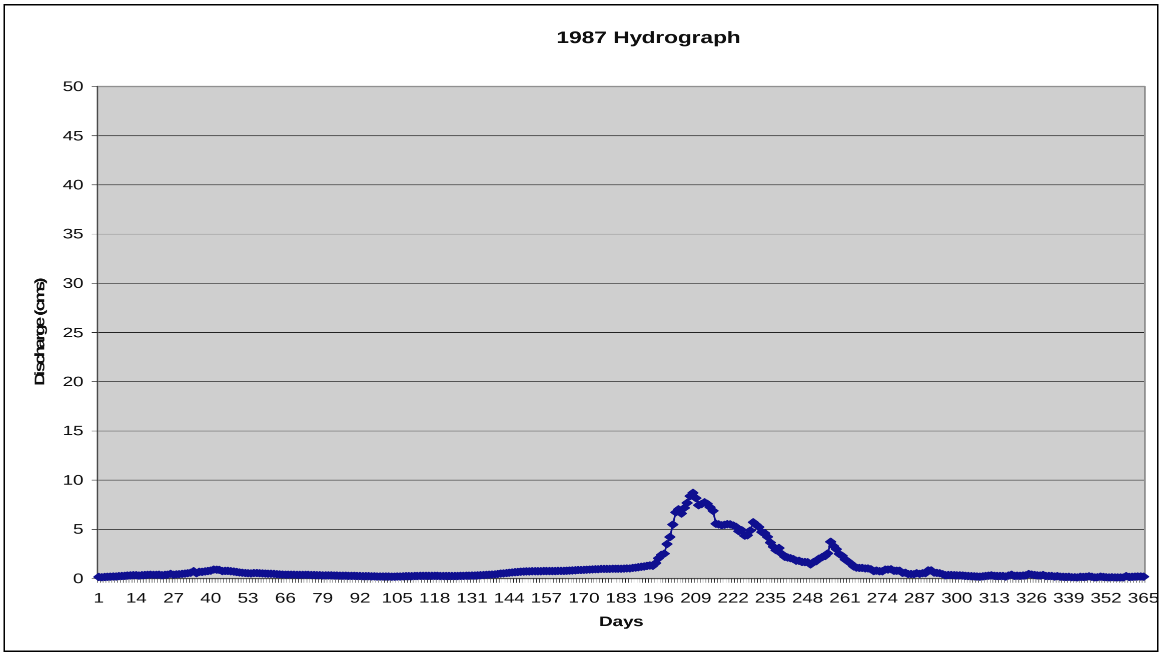


Figure 3: 1983 to 2003 annual runoff at Baker Creek near Quesnel (WSC Hydrometric Station 08KE016).The graph shows the large range of annual runoff in Baker Creek, from year to year, depending on snowfall.

The discharge record of Baker Creek is dominated by water flow from the upper elevation plateau which receives the greatest amount of snow. There is usually a single peak flow annually, in April. The peak flow magnitude is variable; in some years virtually non-existent (for example 1987 - Figure 4) and in other years high (for example 1991 - Figure 4).



1991 Hydrograph

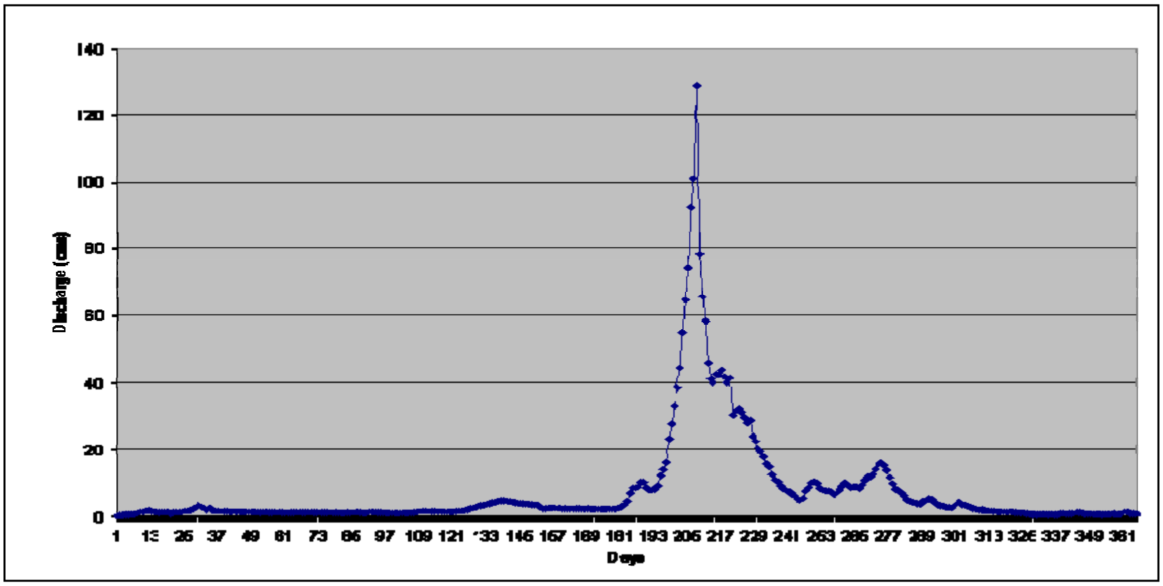


Figure 4: Daily streamflow in 1987 and 1991. The two plots of daily streamflow demonstrate the wide range of peak flows that can occur in Baker Creek from year to year depending on snowpack accumulation and melt rate. In 1987 the peak streamflow was only 10 cms. In 1991, the peak streamflow was 130 cms.

Model Development and Scenario Analysis

The model adapted for this study is the Distributed Hydrology Soil Vegetation Model (DHSVM). DHSVM was developed in Washington State (Wigmosta et al. 1994) for modeling the effects of road building and forest harvesting on stream flow. DHSVM has been successfully applied to conventional harvesting scenarios in a number of catchments in the western U.S. and Canada[9]. This model is very data-demanding, requiring continuous long-term streamflow and climate data as well as inventories of forest types, harvesting and roads, and soils. It can be adapted for any forest disturbance, including MPB attack, provided the micro-climatological processes at the stand level can be formulated.

DHSVM is a distributed model. That is, the watershed attributes, such as forest cover, topography, roads, soils, etc, are mapped as pixels over the whole watershed. Then the water balance: evapotranspiration, snow accumulation and melt, soil infiltration and groundwater flow is calculated for each pixel. The runoff from each pixel is then routed to the stream.

The effect of the mountain pine beetle attack on stand-level hydrological processes was modeled by using results from snow survey plots in northern BC under grey-attack and micro-climate studies on snow interception and melt under stands of leafless deciduous trees[10]. This is considered a reasonable analog for needle-less dead pine trees. Only the grey-attack phase of the infestation was modeled, as the red-needle-phase lasts only a couple of years. See Luo et al. (2006) or Appendix 1 for a description of the Baker Creek model development and calibration.

In summary the model uses the climate data from 1963-2005 as input to simulate the discharge in Baker Creek from 1963-2005. In order to obtain a good match with the measured hydrographs, adjustments were made to parameters such as soil hydraulic conductivity and forest canopy interception. Once the hydrographs were suitably matched for each year, further adjustments were not permitted. A land use scenario was introduced, changing the amount and distribution of clearcut, road and area of beetle attack. The calibrated model was then run with the land use changes. Each scenario is run with the same climate input of 1963-2005, generating an ensemble of 40 years of continuous streamflow record representative of post-disturbance conditions. The 40 spring peak flows under each scenario are then ranked and statistics applied to determine the expected frequency.

Scenarios

The model simulated four scenarios of harvesting and MPB attack in Baker Creek watershed:

Scenario 1: The **baseline** scenario is based on the vegetation conditions in 1970, which include 9% bare area (rock and grasslands) and 4% harvested area, for a total bare area of 13%. All other scenarios were compared to this baseline.

Scenario 2: Cumulative harvest to 1996. Before 1995, there was no significant MPB

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[9] E.g., Storck et al. 1998, Whitaker et al. 2002, Thyer et al. 2004, Beckers and Alila 2004, Bowling et al. 2000, VanShaar et al. 2002, La March and Lettenmaier 2001, Whitaker et al. 2002, Schnorbus and Alila 2004

[10] Hardy et al. 1998

infestation in Baker Creek watershed. Total area of harvest to 1996 was 15 % above baseline for a total harvested area of 28%.

Scenario 3: The situation in 2005. The total area of clearcut harvest is 21% over baseline, for a total harvested area of 34%. The MPB has infested 80 % of the pine-leading stands in the watershed.

Scenario 4: This is considered the most likely salvage scenario. It is based on a projection of salvage harvest, ten years into the future, to 2017. This scenario retains wide riparian reserves (2% of watershed area), Old Growth Management Areas (10% of watershed), wildlife tree patches (2%) and Ungulate Winter Ranges (6.5%). In total there is 20% retention. The remainder of the watershed is modeled as clearcut.

Table 1 summarizes the area in forest, the harvested area and the percentage of the watershed currently attacked by MPB. For example scenario 3 has 34% of the watershed harvested (which is 21% above the baseline). A total of 66% of the watershed is still forested, of which 80% is MPB attacked. Therefore the MPB attack area is 66% X 80% = 53% of the watershed area.

Table 1. Percentage of watershed forested, attacked or harvested for each scenario.

	Scenario	Base Year	Harvested Area (%)	Harvested area over baseline (%)	Forested area (%)(Unharvested)	MPB attacked area (% of watershed)
1	Baseline	1970	13	0	87	0
2	Conventional logging	1996	28	15	72	2
3	MPB epidemic	2005	34	21	66	53
4	Salvage logging	2017	80	67	20	17

Results

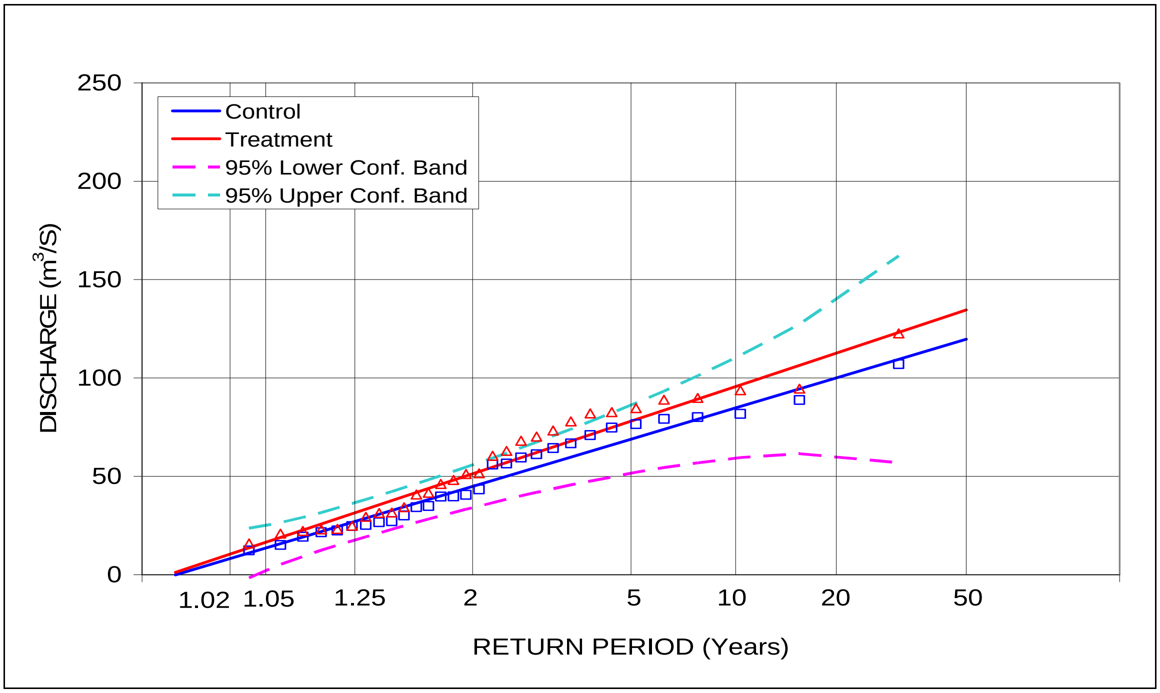
Harvesting and MPB-attack effects on peak flow and water yield

1) Flood frequency analysis

The change to the peak flow regime for each scenario was analyzed using a frequency-based comparison and not the traditional paired-event comparison. In this study, we focus on the difference between a pre-disturbance peak flow event and a post-disturbance event of the same return period (or frequency of occurrence). This approach overcomes the problem of having to index the return period of the peak flow event to the pre-disturbance conditions, as is required in paired watershed studies. The pre- and post-disturbance flood frequency curves for each scenario are compared to the baseline (Figures 6 to 8).

Figures 5-7: Return period flows for Scenario 2, 3 and 4 in comparison to the baseline (Scenario 1). The data points are the outputs of the model, before fitting to a line. The lower line (blue) is the expected discharge for various return periods (in years) for a completely forested watershed (baseline). The upper line (red) is the expected discharge for the scenario being tested.

Figure 5: Scenario 2 vs baseline



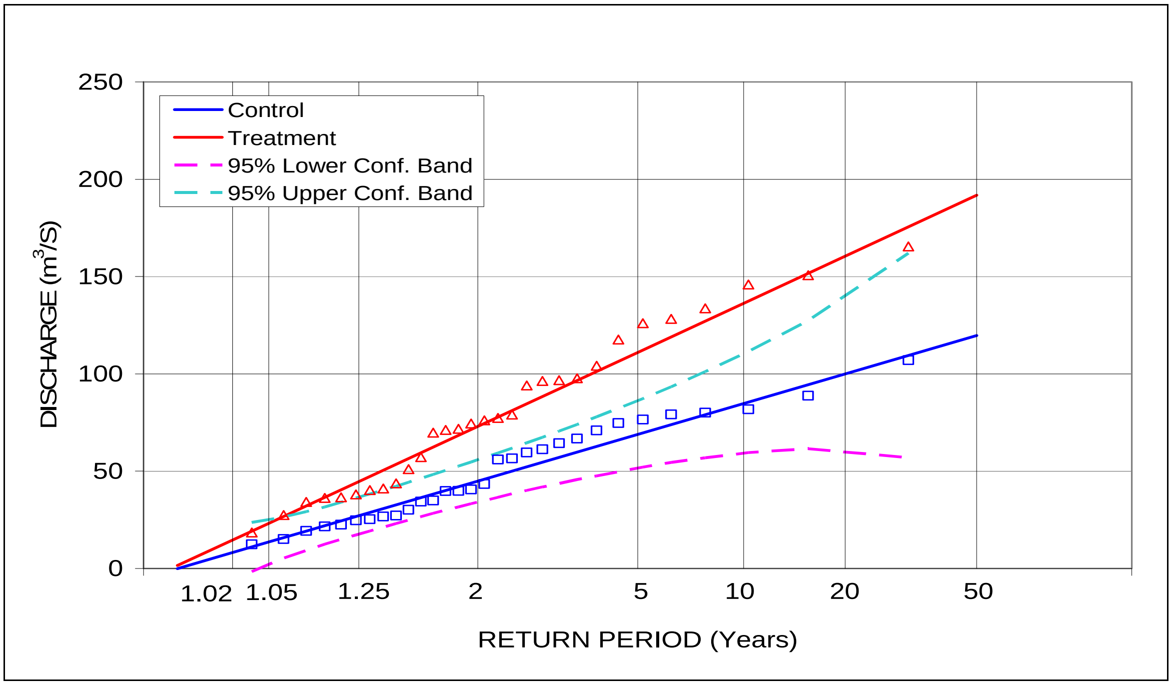


Figure 6: Scenario 3 vs baseline.

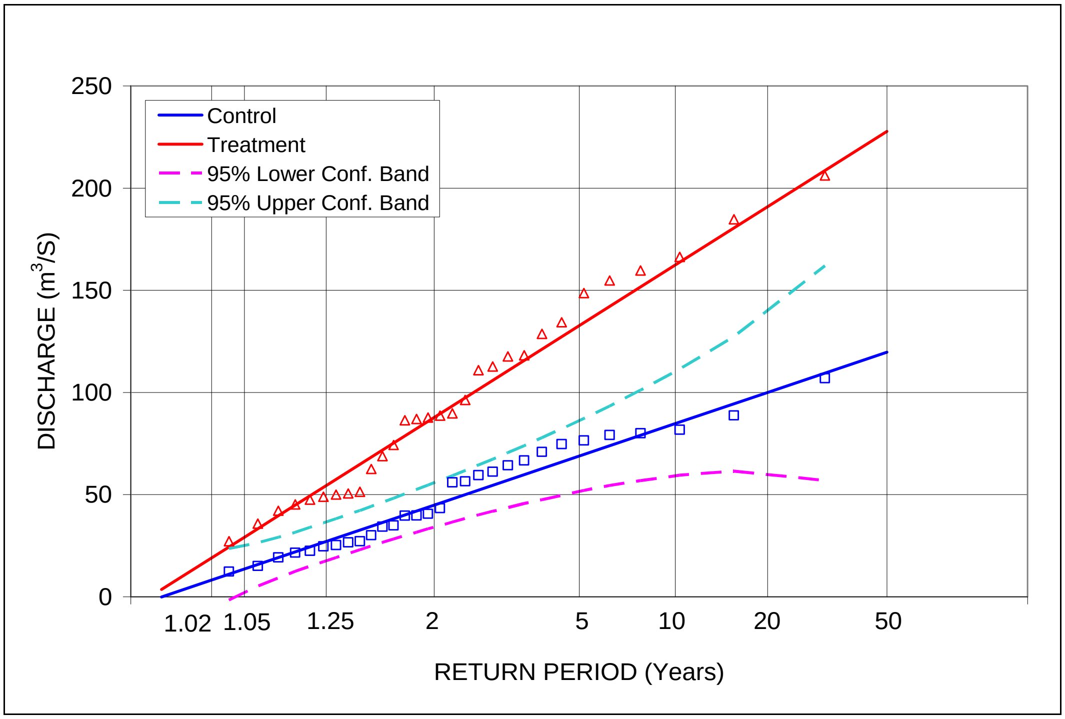


Figure 7: Scenario 4 vs baseline.

A summary table (Table 2), based on the frequency curves, summarizes the percent change in peak flow at each recurrence interval, the average peak flow change, the change in the timing of the peak event, and the seasonal water yield change for each scenario. The color shading in the table marks the changes that are statistically significant (95%).

Table 2: Predicted changes in peak flows, water yield and time of the peak flow for Baker Creek following conventional harvest, MPB epidemic and salvage harvest, compared to the baseline.

Scenario	Q_2		Q_{10}		Q_{20}		Q_{50}		Q_{Av}		WaterYield (%)	Timing (d)
	m^3/s	%	m^3/s	%	m^3/s	%	m^3/s	%	m^3/s	%	Seasonal	
2	6	14	11	13	13	13	15	12	9	13	7	2
3	28	62	52	61	61	60	72	60	41	61	31	15
4	43	95	78	92	91	91	108	90	62	92	52	16

Referring to Table 2, the percent changes to peak flows, water yield and timing were:

Scenario 2 For scenario 2 (conventional logging to 1996), the change in peak flow, for all return periods, averaged 13%. The time advance in peak flow was negligible (2 days). The water yield change of 7% was statistically insignificant.

Scenario 3 For scenario 3 (logging to 2005 + MPB beetle epidemic), the change in peak flow, for all return periods, averaged 61%. These changes were statistically significant at the 95% confidence level for the 2, 10, and 20 yr return periods. The time advance in peak flow averaged over 30 years was 15 days. The water yield change of 31% was also statistically significant. This scenario represents a dramatic change in the flow regime of the watershed, as MPB infestation changed from 2% to 80 % of mature pine.

Scenario 4 For scenario 4, (salvage logging of 80% of the watershed) the change in peak flow, for all return periods, averaged 92%. These changes were statistically significant at the 95% confidence level for all return periods. The time advance in peak flow, averaged over 30 years was 16 days. The water yield change of 52% was also statistically significant. This scenario also represents a dramatic change in watershed condition, as the watershed moves from a grey-attack watershed with standing dead pine trees to a mostly clearcut watershed.

Shift in the frequency of a flood event

Previous discussion has focussed on increases in the magnitude of floods. However figures 6-8 can also be used to determine the increased frequency with which floods of a specified magnitude are exceeded. For example, in Table 3, the shift in the frequency of a 100 $m^3 \cdot s^{-1}$ peak flow has changed from once in 20 years under baseline conditions, to once in 3 years under salvage harvesting.

Table 3: The post-disturbance return period of the 100 $m^3 \cdot s^{-1}$ (20-yr baseline flood)

Scenario	Post-Disturbance Return Period of the 100 $m^3 \cdot s^{-1}$ Flood
1	20 years
2	12 years
3	4 years
4	3 years

Discussion

Flow changes over time

The average peak flow change in Baker Creek from 1995 to 2020 is sketched in Figure 8. The peak flow hazard in 2007 is high due to the MPB attack. It will rise significantly more however, following the completion of salvage harvesting (upper line). With regeneration, the second growth will eventually reduce the peak flow hazard, but this process can take over 40 years (Troendle and King 1985). If grey-attack trees are not harvested, then the peak flow hazard may not rise much higher as the processes of dead pine fall-down over time may be matched by the growth of residual and regenerating understory[11]

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[11] Forest Practices Board (2007). *Lodgepole Pine Structure 25 years after Mountain Pine Beetle Attack*

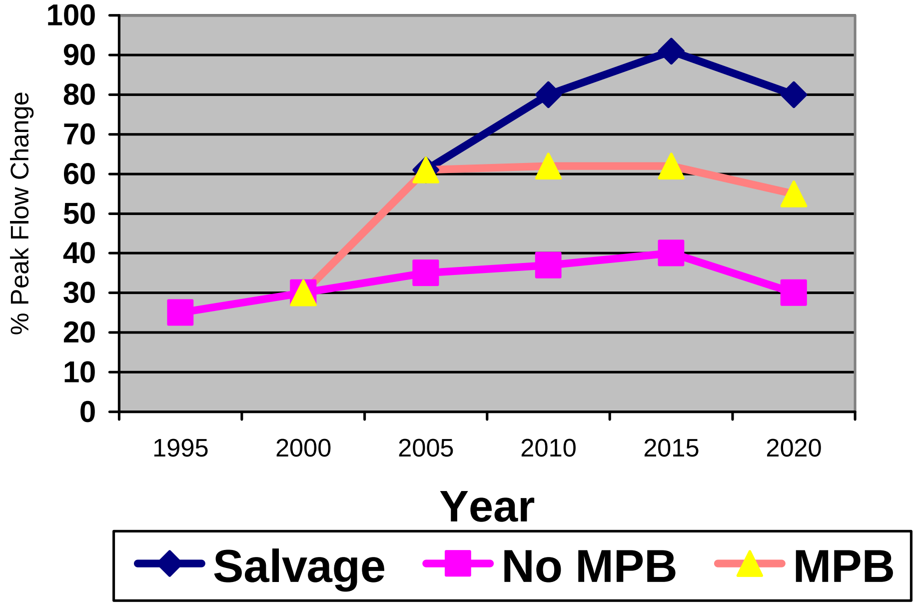

Figure 8: The percentage change in average peak flows from 1995 to 2020 as modeled. The three lines represent different management options. The upper line is 20% retention and salvage clearcutting 80% of the watershed. The middle line plots the % change in peak flow if the MPB infested trees were not salvage harvested. The lower line represents the expected changes in peak flow if there was no MPB attack and conventional harvesting took place.

The model changes in peak flow of 60% or more, for return periods ranging from 2-50 years, following MPB-attack and salvage harvesting, are high compared to other studies (Cheng 1989, Potts 1984, Bethlahmy 1975, Moore and Scott 2005). However, the other studies took place in watersheds with disturbances much less than those in Baker Creek. The magnitude of the increases can also be partly attributed to low watershed relief and the large portion of watershed area that is situated within the same elevation band. The plateau-like nature of the upper 70 percent of Baker Creek watershed amplifies the effects of larger scale disturbance because of synchronized snowmelt. Aspect also plays a role, as most of Baker Creek watershed faces north, which will also contribute to late season melting and synchronicity of flow.

Management Implications

The results of this model show that decisions to harvest MPB-affected forests must be based on achieving the optimum mix of achieving timber supply targets, biodiversity objectives and maintaining streamflows. This is particularly true for watersheds in the central interior, where a high percentage of the watershed may be attacked by MPB.

Salvage clearcut logging of grey-attack forest will affect peak flows and water yield significantly more than leaving the grey-attack forest standing. The grey-attack forest continues to play a role in snow interception, in reducing incoming solar radiation and reducing wind speed across the snowpack. As a result, the annual peak flows in the stream are delayed and of less magnitude than in clearcut watersheds. Leaving the MPB grey attack forest standing will result in lower peak flows than salvage harvesting the watershed.

However, in watersheds that have a mix of green tree stands and grey-attack stands, harvesting the grey-attack and leaving the green trees will result in a lower peak flow hazard. The grey-attack forests are less effective in delaying and controlling runoff than green forest.

The possibility of forest fire is another consideration. A MPB-grey-attack forest that subsequently burns in a hot fire will have a similar effect on streamflow as salvage logging. There may be an additional water quality impact where silt and nutrients are washed from the burned soil.

Consideration should also be made to "hardening" the drainage structures in MPB-attacked watersheds. Major culverts and bridges designed for the 50- or 100-yr flood should be examined for adequate capacity in watersheds with high levels of MPB attack. For example, the 50-yr flood capacity of a 1500 km2 watershed, such as Baker Creek with 30% harvest and 60% MPB attack will increase from 120 m3·s-1 to 220 m3·s-1, requiring a cross- sectional area increase of approximately 40 percent (under the same culvert slope and flow velocity conditions). It will be particularly important to ensure fish passage at closed bottom stream crossings, where increases in flow (and velocity) can impede passage.

Fisheries management in MPB attacked watersheds, with a combination of high MPB attack and high salvage harvesting, should be concerned about the increased frequency of major flood events. Major flood events are the main process affecting stream channel morphology and fish habitat.

The forest licensees, stakeholders and government are in the process of addressing hydrological concerns in the Baker Creek watershed through a watershed assessment, examining sediment sources, channel sensitivity, land use and hydrology. The assessment is being conducted by Summit Environmental Consultants, through Tolko Industries Limited. The watershed assessment is due by April 1, 2007 and should provide recommendations on mitigating impacts of pine mortality and salvage harvesting.

Conclusions

MPB-attack and salvage harvesting in Baker Creek, a 1570 km^2 watershed, has been modelled using DHSVM to estimate the effects on streamflow. Flood frequency analysis was carried out for the baseline and three disturbance scenarios: conventional harvest, MPB epidemic and salvage harvest.

In Baker Creek watershed, two major land use changes effect the streamflows: the MPB attack and the salvage of the attacked trees. Conventional harvesting in Baker Creek watershed before the MPB-attack did not substantially alter the streamflows. However, the combination of conventional harvesting and MPB attack, to 2006, has significantly increased the magnitude and timing of flood events. For example, former 20-year peak flow events can now be expected every 3 years. On average, peak stream flows will be 60% larger than baseline. As salvage harvesting takes place in the next few years, there will be further increases in peak flow and water yield, for example the 20-year peak flows will increase by 90% compared to baseline.

These peak flow changes have implications on the channel stability and fish habitat of the stream network within Baker Creek watershed, as channel forming flows will occur more frequently.

The government agencies are taking some steps to respond to this potential hazard. The Ministry of Forests and Range has just published a set of maps for the province that identifies those watersheds with a high proportion of mature pine that will be at risk to MPB attack and potential hydrological changes[12]. MoFR and UNBC research is underway to better understand snowmelt processes at the stand level, which will improve watershed models. The University of BC (Alila et al), under the federal MPB Initiative, is installing a network of climate and stream recorders in tributaries of Baker Creek to test and refine the DHSVM model. Also in Baker Creek, Tolko Industries is currently assessing hydrological concerns in the watershed through a watershed assessment planning process.

In addition to these initiatives however, more consideration of the hydrological effects of MPB is needed operationally. Priorities should include watershed planning, harvest scheduling, riparian retention, and assessment of the adequacy of drainage structures.

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[12] www.for.gov.bc.ca/hfp/mountainpinebeetle/stewardship/hydrology/

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Appendix 1

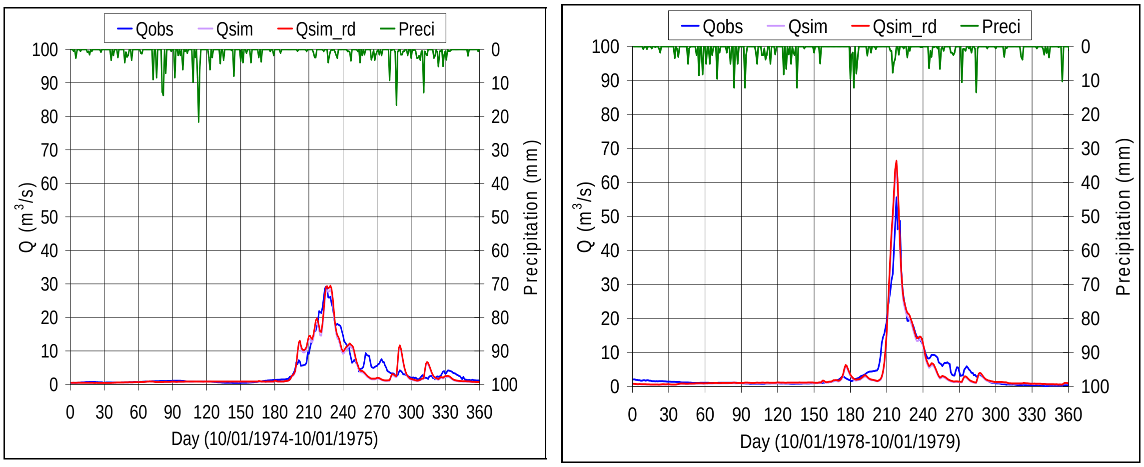
The DHSVM model was set up, calibrated and verified using these standard procedures.

Setting up the Model

The steps in model development, calibration and scenario analysis are

1. A 6400 pixel grid (500m X500 m) is draped over the watershed using the TRIM digital elevation model.
2. Slope and aspect surfaces, stream network, soil types, forest cover types, cut blocks and roads are input as distributed variables for each pixel.
3. MPB infestation spatial data, from the Canadian Forest Service and MoFR overview and detailed aerial surveys from 1970 – 2006 are added.
4. Local long-term climate data (1963-2004) is compiled and processed to provide the required meteorological inputs to the model. The main station used was Puntchesakut Lake with a 30-year record, from 1975 to 2005.
5. Stream discharge data is compiled for Baker Creek (1970-2005) and for a tributary to Baker, Little John Creek. The Baker Creek gauge (continuous, active 1931-2006) is at the outlet on the main channel; the most recent 40 year (1963 - 2005) record was used for the model.
6. The model calculates a water and energy balance for each pixel, based on the meteorological inputs and routes the runoff over the entire watershed.
7. The model is calibrated for baseline conditions, over a 4 year period, using the climate and streamflow record in Baker Creek. For example, the calibrated hydrograph for Baker Creek is compared to the actual hydrograph for 1974 (Figure 5, left graph) and then validated under different climate conditions in 1978 (Figure 5, right graph).

Figure A1: Simulated and actual hydrographs compared for calibration and validation



8. After calibration, the model simulates the streamflow of Baker Creek using various MPB infestations and harvesting scenarios over time, using the same climate inputs.

9. For each scenario, the modelled streamflow is computed for various return periods (up to 50 year return), which is statistically compared to the baseline condition.

Each of the above steps is discussed in detail in Luo, Alila and Chatwin (2006). More detail on the above steps follows:

The Grid

As the watershed is 1570 km^2, a grid size of 500m x 500m was adopted, creating a total of 6400 grid squares. (A sensitivity analysis showed there was little difference in results using a 200m grid cell. However, the 200m model application at Baker Creek is computationally more demanding, particularly for the long-term simulations.)

Topography

Topographic data was input from 20 m interval TRIM (Terrain Resource Information Management) digital maps and average elevation values were calculated for each pixel.

Forest Cover and Harvest History

Vegetation was classified into 9 classes, with the dominant class in each pixel being assigned to the entire pixel. Average values for each class were calculated for height, crown closure and leaf area index as shown in A1.

Table A1. Vegetation categories and physical parameters required by DHSVM.

	Class	Average Height (m)	Crown Closure (%)	Leaf Area Index
1	Aspen	17	37.6	5.4
2	Douglas-fir	24	43.3	2.7
3	Lodgepole pine, 0-10 years	0.8	6.6	0.1
4	Lodgepole pine, 11-30 years	6	33.2	4.0
5	Lodgepole pine, 31-60 years	14	57.0	8.5
6	Lodgepole pine, 61+ years	21	55.0	2.8
7	Grey-attack lodgepole pine	21	27.0	1.1
8	Spruce	21	41.3	2.4
9	Logged	0	0	0
10	Rock	0	0	0

The vegetation cover was obtained from forest cover maps and updated using the spatial logging history files in RESULTS (MoFR Silvicultural Database).

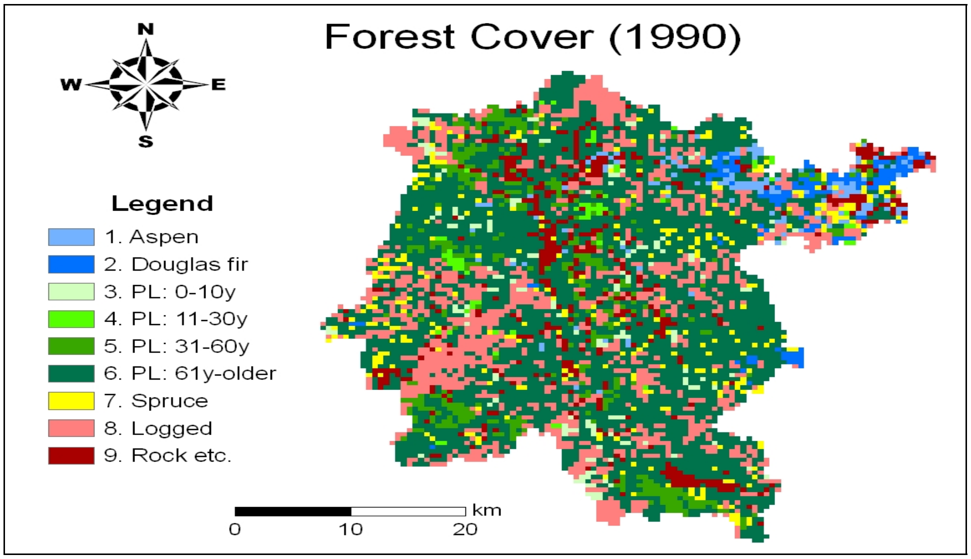


Figure A2. An example of the vegetation maps used for Baker Creek watersheds

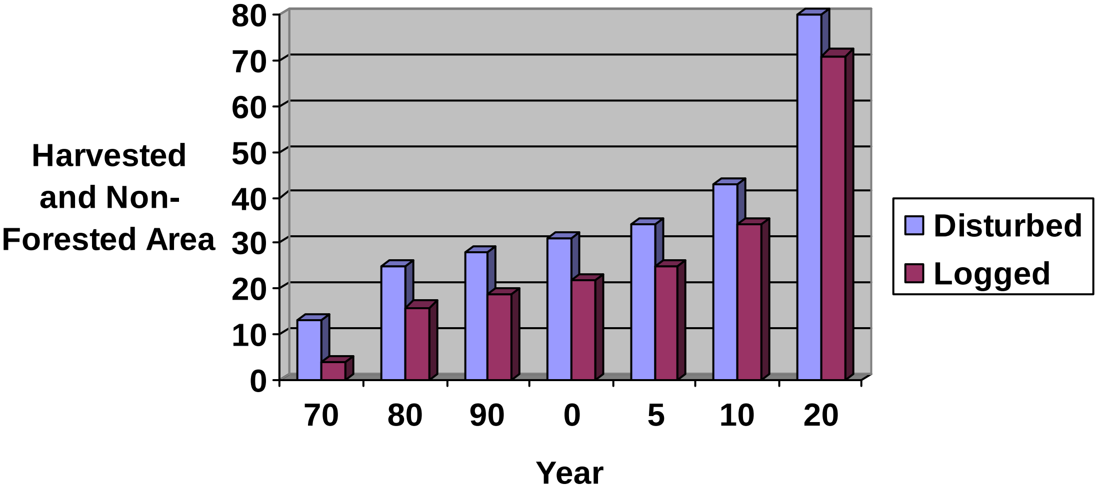


Figure A3: Harvested area and harvested+non-forested area in Baker Creek between 1970 and 2020

Mountain Pine Beetle Attack

The distribution of MPB attack in the Baker Creek watershed was obtained from the Canadian Forest Service (CFS) and the BC Ministry of Forest and Range (MoFR) aerial MPB detection surveys. Beetle attack began in this watershed in 1995 and grew to 80% of mature pine forest attacked by 2005 (Figure A3). No further beetle attack was modeled beyond 2005.

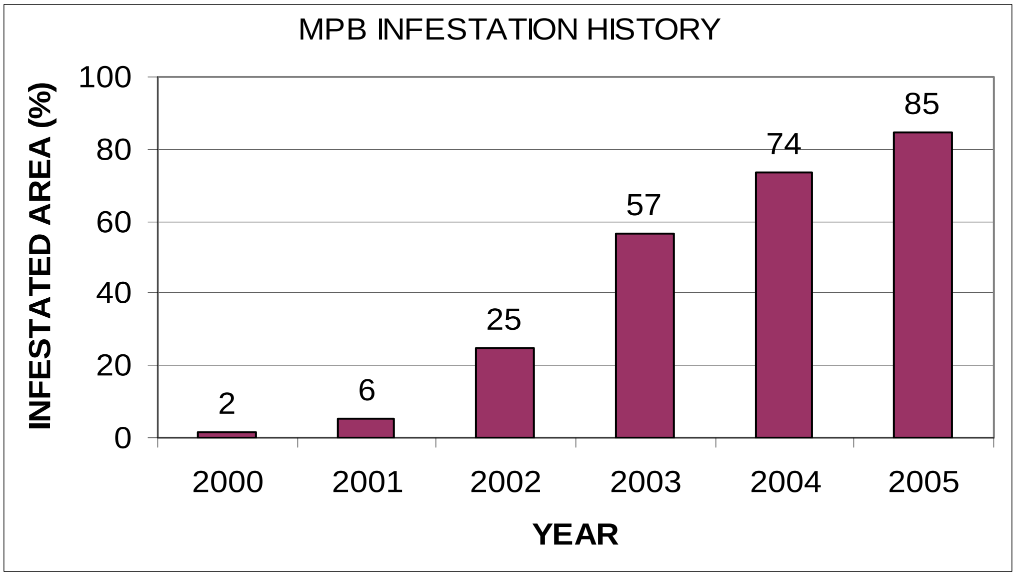


Figure A4. Percentage of mature pine forest area in Baker Creek infested with MPB

Roads

The road network was derived from the TRIM maps, but was filtered to only include main and secondary roads, and no spur roads (Figure A4). This was due to the limitations of the 500 m grid size and to reduce model processing time. Culverts were modeled at all streams shown in TRIM and otherwise at 500-meter intervals.

Soils

Nine soil series are mapped in Baker Creek (Figure A5). Typical porosity, hydraulic conductivity and bulk density values were estimated from values for similar soil types.

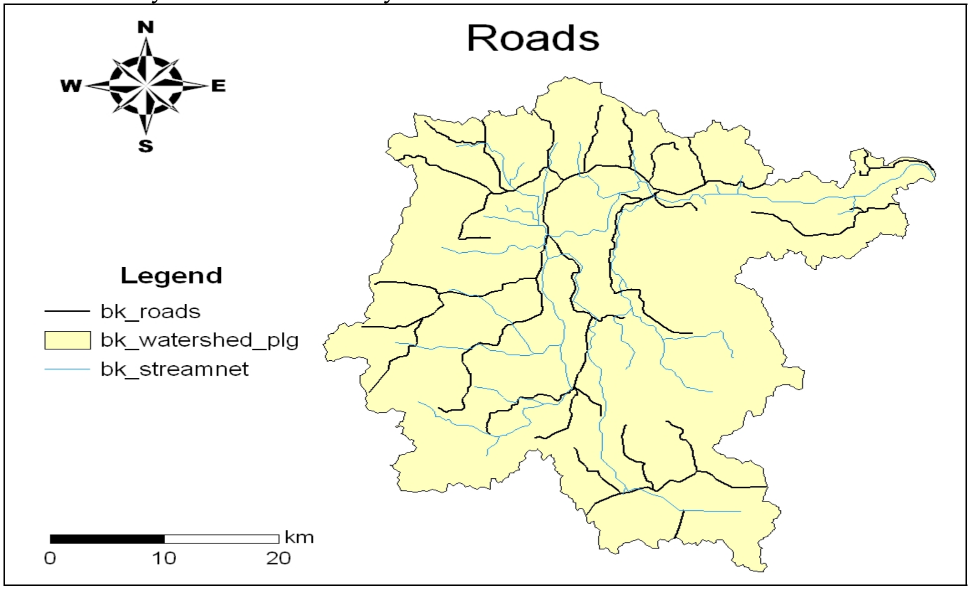


Figure A5. Forest roads in Baker Creek watershed.

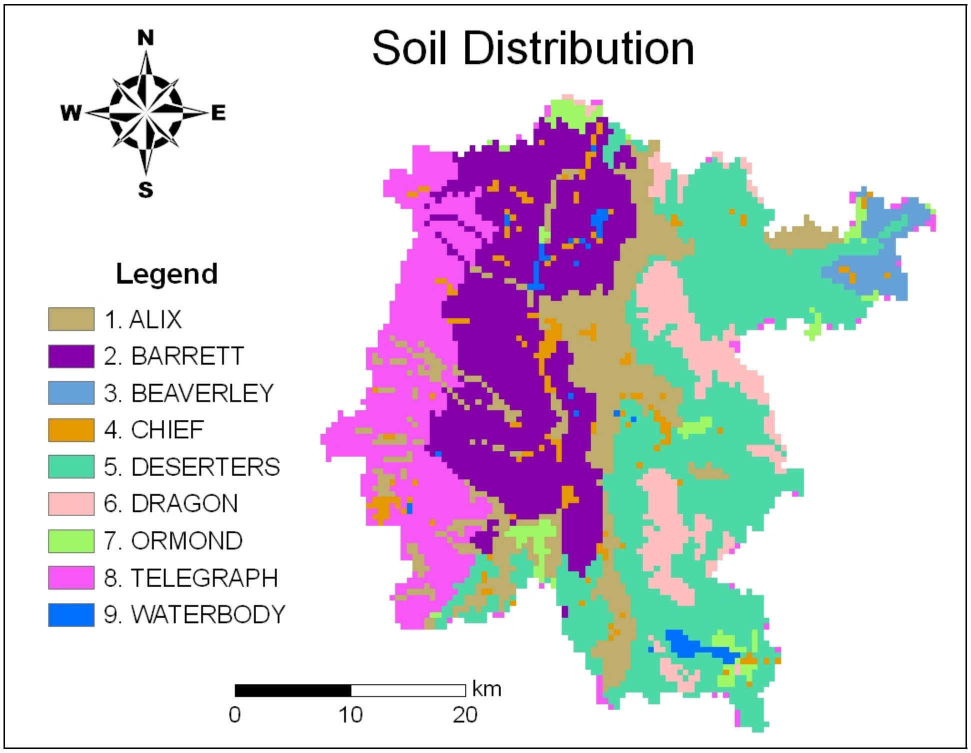


Figure A6. Distribution of soils types in Baker Creek watershed

Streamflow

There are two Water Survey of Canada (WSC) stream gauges in the watershed. Little John Creek is an inactive gauge (active 1974 to 1983) on a small tributary (169 km^2) of Baker Creek. The Baker Creek gauge (continuous, active 1931-2006) is at the outlet on the main channel, above Quesnel (Figure 1) provides a 75 year streamflow record.

Climate

Two valley bottom Meteorological Survey of Canada (MSC) long-term climate stations: near the center of the watershed and also near the outlet of Baker Creek, have records dating back to 1945 (Figure 1). The main station used was Puntchesakut Lake with a 30-year record, from 1975 to 2005. There are also two partial-record climate stations from the BC Ministry of Forest Fire Network that are representative of the hourly precipitation, temperature, wind speed and relative humidity in the period of 1990 to 2006.

Precipitation, air temperature, wind speed, relative humidity, and incoming shortwave and longwave radiation must be specified as DHSVM model inputs for each time step. The recommended time step of 1 hour was used for all simulations. Some of these data are not available from the climate stations, which only provide maximum and minimum daily temperature and total daily precipitation. For this reason, the daily data of air temperature and precipitation is disaggregated into hourly data and used to estimate the missing parameter input, such as shortwave and longwave radiation, using well established techniques.

Hourly values of air temperature were generated by computing a modified sine curve from daily minimum and maximum temperature, and the daily total precipitation was distributed uniformly to each hour since the watershed is snow-dominated and the uniform distribution of snowfall in one day in the winter season is reasonable with respect to snowpack accumulation (Waichler and Wigmosta, 2003). Waichler and Wigmosta (2003) also provided a method for estimating relative humidity using the ratio of saturation vapour pressure at dew point, which is assumed equal to the minimum temperature of the day, to the saturation vapour pressure at the temperature of the hour. When there are no fire weather station data available, the uniform wind speed is used for all year long and set to the average value (2.0 m/s) measured by Winkler (2001) in juvenile stands in Upper Penticton and Mayson Lake located in interior BC. This value (2.0 m/s) was also used by the DHSVM developers in their early application of the model to the Middle Fork Flathead River basin located in northwestern Montana (Wigmosta et al., 1994).

The estimation of shortwave and longwave radiation is complex when direct measurements are not available, as in this application. Using the same daily data of temperature provided by the Meteorological Survey of Canada (MSC) at the long-term climate stations as input, the UBC Watershed Model (UBCWM) of Quick (1995) provides the daily solar radiation as output, which is the sum of shortwave and longwave radiation. In this study, the UBCWM was employed but only to generate daily radiation, which is disaggregated into hourly values using the typical daily distribution curves of shortwave and longwave radiations measured in the interior of BC (Thyer et al. 2004).

Model Calibration

The performance of the DHSVM model, once calibrated, is evaluated visually and statistically. The visual criterion involves plotting and comparing the simulated and observed hydrographs. For example, the calibrated model reproduces reasonably well both the duration and the peaks of the flow for four typical years in Figure A6. Statistically, the coefficient of model efficiency (CE) describes how well the volume and timing of the simulated hydrograph compares to the observed one, while the coefficient of model determination (CD) measures how well the shape of the simulated hydrograph reflects the observed hydrograph (Nash and Sutcliffe 1970). The closer these coefficients are to 1.00 the better is the model performance. For the calibration and validation phases, CE was 0.73 and 0.80, respectively, and CD was 0.82.

The limitation of using two climate stations to drive DHSVM over this large watershed makes it difficult to achieve better calibration. Spring rainfall events are likely convective in nature and their spatial variability over the watershed may not be well represented by only two climate stations.

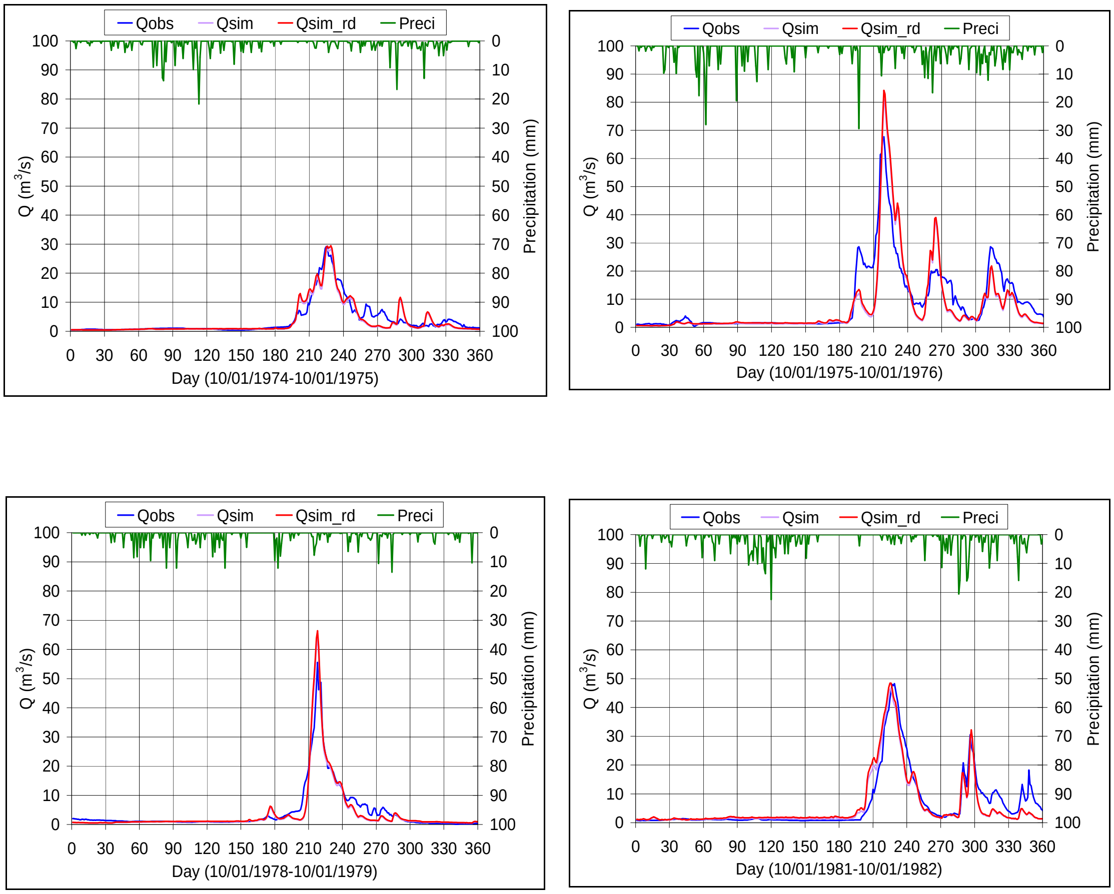


Figure A7. Simulated vs. observed hydrographs (Qsim: with roads, Qsim_rd: without roads).

Hydrological recovery of cutblocks, which gradually occurs as the stand grows in height and canopy, was accounted for during the calibration of the model by changing the age-classes of the second growth stands over time. During the post-calibration running of the model, hydrological recovery was not modeled, as recovery will be quite small over a 30 year period and a stable land use is needed to properly calculate flood frequency return intervals.

Appendix 2

Simulating the Stand Effects of Mountain Pine Beetle Grey-Attack

The standard DHSVM models hydrological processes with live green trees. In order to model the hydrologic effects of MPB-grey-attack trees, adjustments must be made to shortwave transmissivity through the canopy, interception, and evapotranspiration as a result of changes in crown closure and photosynthesis.

This model simulates only the grey-attack phase of the MPB attack, and not the red-attack phase. This is because the red-attack phase is transitory, lasting only 2-3 years, while the grey-attack phase can last 20 years or more.

Snowmelt process in clearcut, green forest, and grey-attack forests are affected by the radiative heat flux and turbulent sensible heat. Eddy fluxes of sensible and latent heat is reduced in grey-attack forests by the attenuation of wind, which is usually only 10-20% of wind speeds in the open (Adams et al, 1998).

The main driver of snow melt however, both in clearcut and the grey-attack stands is the net radiation. There are few published research results on radiation and snow melt rates in dead pine forests[13]. However, the microclimatology of leafless deciduous stands on snowmelt has been extensively reported[14]. In one of the few dead pine studies, Beaudry (2006) found snowmelt rates in a grey-attack stand to be 49% of the rate in clearcuts, based on periodic snow water equivalent measurements in pine forests near Prince George. Federer (1971) determined that the transmissivity of shortwave radiation through the leafless canopy was only 35%, due to shading by the stems and branches of a leafless hardwood forest. Hardy et al. (1998) studied stands of leafless aspen in the winter, and measured shortwave radiation transmissivity at 40% (i.e. 60 % attenuation), compared to a clearcut, through the leafless canopy. Davis et al**.** (1997) calculated that the crown closure of the leafless canopy, in the Hardy study, was 40% of the original crown closure for the green canopy. Net radiation in the clearcut averaged 86 percent more than late winter aspen below-canopy net radiation. Average clearcut to forest ratios for daily snowmelt volumes, peak melt rates and net radiation at the snowpack surface were 2.23, 2.35 and 1.86, respectively. Dewalle (1977) found daily snowmelt rates at a leafless deciduous forest site were 40-85% of those at an open site. All of these studies compare with measurements made through a 23 m tall green spruce-pine forest (with a crown closure of 54%) at Mayson Lake, B.C. (Adams et al. 1998), where the incident solar radiation was reduced by 72%.

Transmissivity τ and crown closures F have the following relation:

$$\frac{F_1}{F_2} = \frac{\ln(\tau_1)}{\ln(\tau_2)}$$

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[13] Unnila L., B. Guy, and R. Pike (2006)

[14] Hardy et al. (1998)

Substituting the measurements by Hardy et al. (1998) and Ni et al. (1997) into the equation, the equivalent crown closure of the leafless deciduous canopy is estimated at 40% of a green tree.

Field measurements of snow accumulation in grey-attacked stands are also scarce. An Equivalent Clearcut Area (ECA) of 52% for snow accumulation compared to a clearcut for grey-attacked stands was measured in snow plots near Prince George (Beaudry, 2006)[15]. A 52% ECA will result in approximately a 17% reduction in snow accumulation compared to a clearcut (Winkler and Roach, 2005). Based on these results, the Baker Creek DHSVM was run with grey-attack stands set at 40% of mature pine crown closure (55% crown closure) which is 27% crown closure.

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[15] Beaudry P. and Associated Ltd (2006), *Snow Surveys in Supply Block F, Prince George TSA*. Report Prepared for Canadian Forest Products Ltd, 5162 Northwood Pulp Mill Road, P.O. Box 9000, Prince George, B.C.