Development of a Hydrologic Process Model for Mountain Pine Beetle affected Areas in British Columbia

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NOTE: All data sets and model code are currently stored on the Fisheries Center Simulation Server at UBC.

Abstract

The infestation of the Mountain Pine Beetle (MPB) has turned into a major threat to the natural habitat of British Columbia. Pine forests have been decimated in the last five years by the mountain pine beetle (MPB) (Dendroctonus ponderosae Hopk.). This infestation has impacted more than 9 million ha of pine forest in BC and models predict that by 2015, 76% of the pine forest will be dead or dying [BC Ministry of Forest and Range 2008].

A large proportion of British Columbia's pine forests occur in the Fraser River Basin, which is recognized worldwide as a watershed rich in both natural resources and cultural diversity. Within the basin, water forms a critical link between the basin and its inhabitants, whether in the form of water for fish, riparian corridors for biodiversity , reserves for drinking water or water licenses for irrigation or hydro generation . Because of these tight associations, changes to the hydrological cycle will significantly change the character and viability of many aspects of life within the basin.

Especially, forest cover is a key modifier of the watershed's peak flow regime. The peak flow generally increases when forest cover is reduced due to natural and/or man made disturbances. To determine those peak flow increases we developed and applied a hydrological model. Since some regions of the Fraser Basin have only a limited number of gauging stations (or are even ungauged), the goal was to develop a model that does not rely on complex data inputs for its validation and calibration . The model consists of an input component, a runoff generation component, a land cover modification module and a stream routing module. The input component determines the mean annual snowmelt and maximum rainfall based on climatic data. The climate input will be modified in the land cover modification module in relation to the simulated vegetation cover. The derived information is then used to determine the time and the capacity of the peak flow for every 3rd order watershed. The runoff generation component delineates the hydrologic processes such as Hortonain Overland Flow, Saturation Overland Flow and Shallow Surface Flow. This delineation is based on factors such as topography, slope, aspect, wetness index, drainage pattern and drainage density. Combining those components, the model computes a map of peak flow contribution that is used to assess sensitive areas for peak flow production. Depending on the respective spatial scale, the derived peak flow information will be used in the stream routing module to account for cumulative effects.

In this report, we modeled the impact of pine coverage in grey stand as well as pine cover harvested for the Fraser Basin. The simulated results were compared to the baseline scenario, a scenario assuming no Mountain Pine Beetle activity. Our modeling results are summarized as follows:

The reduction in active pine cover or the removal of forest cover results in an increase of peak flow whereas

1. Equal area reductions in vegetation do not lead to the same peak flow increases and suggests the existence of scale effects

2. The degree of peak flow increases due to land use changes has a clear relationship to watershed size. Peak flow increases between 23% and 88% have a higher probability at higher watershed scale.

3. Harvesting activities have a greater impact on peak flows than does grey attack; similar findings were published by the Forest Practice Board [2007].

1.0 Background

It is now generally agreed that the rapid and extensive alterations to land cover occurring in several parts of the world are the combined result of climate change and human activity. Yet, understanding the impact of these changes on critical ecosystem processes, such as the hydrological cycle, remains a challenging task. For example, hydrological analysis of the changes to tropical rain forests are still lacking [Achard, et al., 2002; Marengo, et al., 1994] as are results associated with wildfires and insect infestations in North America [Miller, et al., 2003].

In British Columbia (BC), Canada, pine forests have been decimated in the last 5 years by the mountain pine beetle (MPB) (*Dendroctonus ponderosae Hopk.*) . This infestation has impacted more than 9 million ha of pine forest in BC and models predict that by 2015, 76% of the pine forest will be dead or dying [BC Ministry of Forest and Range 2008]. To compound the problem, the infestation is progressing rapidly in Alberta and in the Rocky Mountain areas of the USA.

A large proportion of British Columbia's pine forests occur in the Fraser River Basin, which is recognized worldwide as a watershed rich in both natural resources and cultural diversity. Within the basin, water forms a critical link between the basin and its inhabitants, whether in the form of water for fish, riparian corridors for biodiversity , reserves for drinking water or water licenses for irrigation or hydro generation. Because of these tight associations, changes to the hydrological cycle will significantly change the character and viability of many aspects of life within the basin.

In response to the MPB infestation, the BC forest industry is salvaging as much timber as possible before it becomes unusable. Consequently, in some watersheds, high harvest rates are anticipated. These rates will be well beyond historical levels, and when combined with the effects of the dead pine alone, may produce unprecedented changes in the functioning of some of the basin's ecosystems .

Regulations in BC do not generally prescribe which areas of a watershed should or should not be logged (except for riparian corridors and some protected areas for wildlife). Rather, it is left to the licensees to determine the best way to achieve a number of ecosystem goals (identified in legislation), along with the extraction of timber. For Fisheries Sensitive Watersheds (a subset of watersheds with defined characteristics) these goals are identified in section 14(1) of the Forest and Range Practices act as

(a) Conserving

  (i) the natural hydrological conditions, natural streambed dynamics and stream channel integrity, and

  (ii) The quality, quantity and timing of water flow, or

(b) Preventing cumulative hydrological effects that would have a material adverse effect on fish

This flexibility has both good and bad aspects, but the significant assumption is that various patterns of harvesting could be used to better achieve non timber ecosystem goals without significantly impacting harvested volumes or profitability. Consequently tools to evaluate the results of various spatially explicit disturbance patterns could be of considerable use. The BC government is now developing tools to assess the MPB and salvage logging impact on peak flow, low flow, coarse sedimentation, fine sedimentation and stream temperature for the entire province [Carver et al., 2007].

For hydrology, most assessment strategies rely on either very simplified models using empirically derived relations between land cover change and hydrological variables, or hydrological rainfall-runoff models applied to simulate hydrographs for different land cover scenarios. Both approaches have significant disadvantages for assessing large-scale changes. The empirical models are often developed from paired-watershed experiments studying the effect of land cover on hydrological response. Smaller scale experiments study the differences in overland flow generation. Larger scale experiments analyzing the differences of watershed runoff have been mostly set-up to study the influence of forest management and logging on annual runoff and peak flow e.g. [Bosch and Hewlett, 1982; Moore and Wondzell, 2005; Stednick, 1996]. Since paired-watershed studies cannot eliminate natural variability, the results are not easily transferred and are specific to the observed climate, soils and geology.

The other strategy to assess land cover changes is to use spatially explicit hydrological models that simulate the small scale processes at the soil-vegetation-atmosphere interface and the large scale runoff generation processes. The models are often detailed physically-based conceptualization of the hydrological cycle (e.g. DHSVM, SWAT, WASIM-ETH). Their ability to simulate changes is satisfactory, but they are very time consuming to set-up, the watershed area is limited by the chosen grid-cell resolution and computing time, and most importantly, they still need to be calibrated to existing streamflow data [VanShaar, et al., 2002; Niehoff, et al., 2002; Storck, et al., 1998]. Therefore, their suitability for application to ungauged watersheds is limited and they are impractical for large areas where small scale changes have to be assessed.

The fundamental concept behind the present model is that areas that generate more runoff in a watershed during a rainfall or snowmelt event are more sensitive to land cover modification. This idea dates back to the variable source area concept [Betson 1964; Dunne and Black, 1970; Weyman, 1970] that runoff can be generated by multiple processes which do not spatially overlap. Betson [1964] demonstrated that contributing areas were almost constant during heavy rainfalls. Dunne and Black [1970] extended Betson's concept to saturation excess overland flow and Weyman [1970] to subsurface flow. Scherrer and Naef [2003] developed a decision tree to identify these different dominant runoff generation processes at the plot scale. Later, the same group introduced a procedure to identify areas of different generating processes within a GIS framework [Schmocker-Fackel, et al., 2007]. Other groups developed similar approaches using different procedures and GIS products, but focusing on the idea that runoff generation areas can be used to predict the response characteristics of watersheds [Tetzlaff, et al., 2007; Uhlenbrook, et al., 2004; Walter, et al., 2000]. As advocated by McDonnell [2003], we also believe using knowledge of first-order runoff generation processes at the basin scale is a good trade-off between experimental process knowledge and model complexity.

2.0 Objective

The overall objective of this work is to estimate impacts from land cover change on average peak flows for all in third-order (1:50,000) watersheds in the Fraser river watershed because peak flows are a major concern for flood hazard, drinking water, fish habitat and other hydrologic consequences. The goal is to provide a model that can be applied to all watersheds and in particular ungauged basins throughout the Fraser basin. This main objective has been divided into smaller working objectives:

Project Objective #1:	Peak flow generation areas and their contribution to peak flow will be mapped for each 3rd watershed within the Fraser Basin
Project Objective #2	Scenarios of current and future land-use will be simulated to predict the relative changes in peak flow in each assessment unit

Project Objective #3 A methodology will be proposed and tested to assess the cumulative effects of these changes with the Fraser River Basin

The modeling approach simulates the sensitivity of peak flow changes to land cover modification due to MPB over large areas. To guarantee applicability at the large scale, this simulation is based solely upon spatial information of a) climate input characteristics derived from monthly gridded maps and b) runoff generation processes derived from GIS data available for the entire Fraser Basin.

3.0 Model Description

3.1 Structure

The model is structured to identify and assess those areas in a watershed that are most influential in changing peak flow response in the main river channel. These sensitive areas are determined from the following model components:

1) Climate Input Module: spatially predicts peak flow-generating climate input for each defined watershed.

2) Land Cover Modification Module: modifies climate input in relation to vegetation cover.

3) Runoff Generation Module: uses delineated dominant peak flow-producing hydrologic processes to simulate runoff contribution to stream during peak flow.

4) Stream Routing Module: maps travel time from source to watershed outlet

Figure 1 provides a visual overview of the different model components and their interaction at different spatial resolutions.

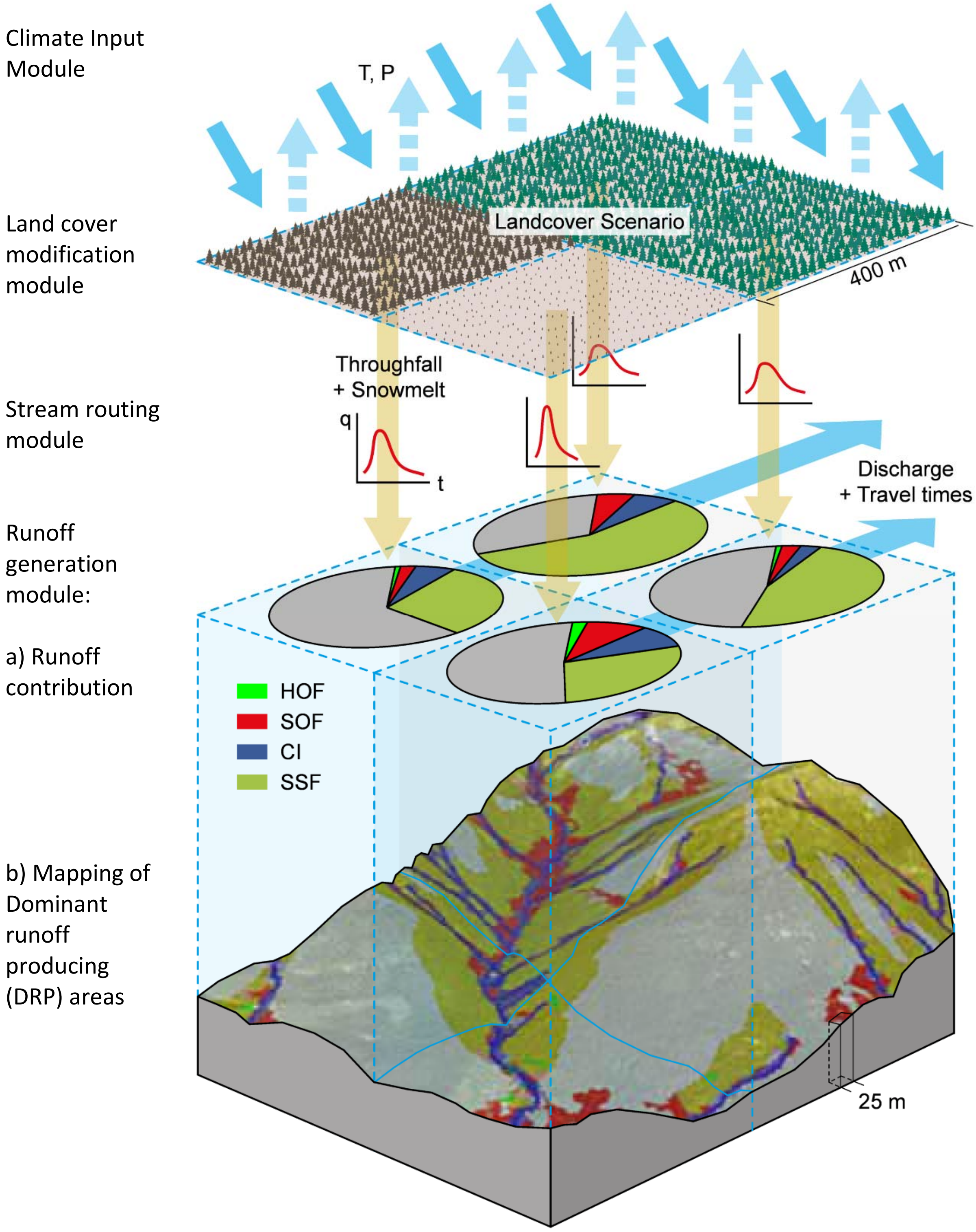


Figure 1. Schematic of the peak flow model (description in text).

3.1.1 Climate Input Module

The peak flow regime of a watershed is related to its precipitation regime (snowmelt-dominated, rainfall-dominated, and transitional). In a snowmelt-dominated watershed, peak flow is initiated by snowmelt during the spring freshet. The climate input in snowmelt-dominated watersheds is spatially and temporally highly variable with early melt in the lower portion and south-facing slopes of the watershed, and late melt in the higher parts and north-facing slopes of the basin [Jost, et al., 2007]. Hence, only certain areas in the watershed produce runoff during peak flow. The climate input in rainfall-dominated watersheds is more simplistic and depends mainly on elevation.

The climate input model uses the mean monthly climatic precipitation and temperature data available from the PRISM methodology at a 400-m grid spacing for the province of BC [Spittlehouse, 2006]. Mean daily temperature and precipitation at a site is interpolated from the monthly climatic data to define the rate of snow accumulation and snowmelt whereas the monthly values are considered to represent the middle of the month. The daily values are calculated applying a linear smoothing function between the two monthly values. Based on this information the daily rate of snow accumulation and snowmelt is derived.

Precipitation falls as snow if temperature $T<T_o$ and as rain otherwise. Snowmelts according to the degree-day factor K (mm/day/°C). T_o is set to 0°C and K to 3.0 mm/day/°C [Kuusisto, 1980; Rango and Martinec, 1995] (see Appendix: R- Model Code). The degree day factor depends on the relation of short wave to long wave radiation, elevation, topography and other factors [Rango and Martinec, 1995]. In order to avoid calibration of K to each watershed, an average factor for BC characterizing the main differences in snow dynamics is chosen and validated using snow course data of BC.

The snowmelt rate is in addition to temperature strongly influenced by incoming solar radiation which is determined by topography [Hock 2003]. The model uses the relative solar radiation to account for that local variability. The relative solar radiation was calculated for summer and winter solstices as well as for the equinox. The respective values in between those dates have been interpolated using a linear function.

The input model calculates snow-water equivalent (SWE) and hence snowmelt for each 400m grid cell for every day of one hydrological year starting on September 15^{th} and ending on September 15^{th} the next year.

3.1.2 Land Cover Modification Module

Interaction of precipitation with forest canopy

The forest canopy plays an important role in the amount of precipitation contributing to streamflow. The average rainfall reduction due to interception amounts to 15-30 % of the annual precipitation [Cheng, 2006]. Similar numbers are found in Maloney et al. [2002] who measured an average annual interception of 21 and 25 % of the annual precipitation for two test sites south of Prince Rupert, BC, Canada. In the model, we apply a constant reduction of between 0 and 20 % depending on vegetation type to account for interception losses for months with rainfall.

Forest canopy also significantly affects snow accumulation and snowmelt – i.e. Berris and Harris [1987] measured a two to three times higher SWE in open than in forested areas. Winkler [2001] showed that for open areas the peak SWE was about 11 to 32 % higher than in forest. Since detailed GIS data about forest characteristics have been unavailable for meso to macro-scale watersheds at provincial level, a general approximation has been undertaken to account for difference in snowmelt and snow accumulation under forest. Since forests have their own microclimates, the snowmelt rate is also affected by forest cover [Chang, 2003]. The snowmelt rate is much lower resulting in a longer-lived snowpack. Winkler [2001], for instance, found snowmelt reductions between 0.4 times (mature fir stands) and 0.9 times (juvenile-thinned pine stand) in comparison to open areas. At the current model settings, we assume a general reduction of snow accumulation of 30% for closed vegetation. The snowmelt reduction is currently set to 40% of open vegetation and to 25% for grey stand vegetation following Winkler [2001] and results from other authors (Table 1).

Modification of land cover according to defined scenarios

In this component, the actual runoff from each grid cell for a given scenario (see results section) is calculated based on the actual climate input due to vegetation modification and contribution from each runoff generation process. Data for the vegetation modification originate from various studies at the stand-level scale analyzing the influence of vegetation, and in particular forests, on rainfall and snowmelt. Since the watersheds in the Fraser Basin are snowmelt dominated, the input modification is presented for snowmelt conditions. Table 1 lists several stand-level studies, mostly in BC and in the USA Pacific Northwest, analyzing the difference in snowmelt between forests and open land. Only a few studies examined the melt rate difference on a short time scale (e.g. daily) and even fewer studies rely on a larger number of samples to establish more general relations between forest and open land. When focusing on the studies with larger data sets and in forests that are similar to BC, a reduction between 20% and 50% in snowmelt in the forest compared to an open area is reasonable to assume (Table 1).

Table 1: Stand-level studies comparing snowmelt rates between forested and open areas.

Reference	***Meltrate [mm/d]***		***Forest/Open***	***Description***
	Forest	***Open***	***(%)***	
[*Winkler, et al.*, 2005]	3	8	38	Measured average melt rate (snow tube and lysimeters in spruce-fir pine stands with different characteristics in Southern British Columbia).
[*Kittredge*, 1953]	7-19	12-24*	48-58	Regression analysis of daily melt rates of different forest stands (white fir, ponderosa pine, mixed conifer) against snowmelt in open over 5 freshet seasons
[*Whitaker and Sugiyama*, 2005]	6.1-7	12.3	49-57	Lysimeter study of average daily melt rates in a larch and cedar forest in Japan
[*Jost, et al.*, 2007]	4.1	6.1	67	Multiple regression analysis of average melt rate (20 days in April) including elevation, aspect and forest cover (Lodgepole pine)
[*Hardy and Hansen-Bristow*, 1990]	5.8	9.8	59	Average seasonal snowmelt rates; Montana.
[*Toews and Gluns*, 1986]	8	11	73	West Kootenay Area, in the South of British Columbia; average seasonal melt rates.
[Teti P, 2007]	3-4	5-6.5	50-65	Average melt rates in spring 2007 in lodgepole pine forest in Central BC

Since detailed and consistent GIS data about forest characteristics were unavailable at the provincial level, no differentiation in canopy structure could be been included into the model.

Additionally, the effect of MPB infestation on the input modification was considered. Since MPB kills only pine trees, we include the percentage of pine coverage to estimate the maximum proportion of trees that can be killed within a stand. Research at the stand level studying the impact of dead trees on snow accumulation and melt are just underway. After the MPB has attacked a stand, the needles first become red (red attack) and after a year the needles fall off and for several years only the tree boles and branches remain (grey attack). The parameterization for MPB is based on the grey attack stage since this is the more stable condition. Initial results form several studies in MPB-infested stands have revealed that grey attack stands are closer to a healthy forest than a clear cut in respect to snow accumulation and ablation [Boon, 2007; Teti, 2007]. A study comparing larch, cedar and open sites in Japan – a leafless larch forest should be comparable to a grey attack pine stand – showed that snowmelt rate at the larch site was even lower than at the denser cedar site. Since the research about the influence of MPB attacked stands is not definitive, we have conservatively parameterized the snowmelt rate in grey stands to be two-thirds between that of a healthy stand and that of a clear cut.

3.1.3 Runoff Generation Module

The four major runoff generation processes that contribute to streamflow during snowmelt or rainfall are channel interception, Hortonian Overland Flow (HOF), Saturation Overland Flow (SOF) and Shallow Subsurface Flow (SSF). These dominant runoff processes (DRPs) are mapped; their location in a watershed is related to a combination of factors such as relief, slope, aspect, soil properties, drainage density, drainage pattern, and hillslope curvature. The mapping procedure is based on a 25-m grid size resolution, implemented into the SAGA software and is described briefly for each DRP (see also technical details in the Interim Report 2008).

a) Channel Interception: Hewlett and Hibbert [1963] define channel interception as the process that collects water that falls directly from clouds or indirectly from vegetation on the riparian zone of the river into the stream. Channel interception is defined for all grid cells that are intersected by a stream and therefore includes the channel and part of the riparian zone.

b) Hortonian Infiltration Excess Overland Flow (HOF): Kirkby [1969] states that HOF can be understood as ‘the flow which occurs when rainfall intensity is so large that not all the water can infiltrate’. Cappus [1960] defined infiltration excess areas as roads, compacted soils, and plastered paths. The model defines roads and areas with low infiltration capacity - e.g. regions with recent fire history - as HOF areas if there is a connection to the stream network. A connection to the stream is assumed when the horizontal overland flow distance is smaller than 500m.

c) Saturation Excess Overland Flow (SOF): Due to topographic features, some zones of a catchment are more susceptible to saturation and subsequent saturation overland flow (SOF). Kirkby [1969] names these areas as adjacent to perennial streams, slopes with concave profile, hollows and hillslopes with shallow soil. The topographic wetness index has been developed and tested to delineate saturated concavities and topographic hollows where lateral flow above an impermeable bedrock layer occurs (e.g. [Güntner, et al., 1999]. We use a version that is based on a modified catchment area calculation [Boehner, et al., 2002] and replace the local slope with the slope to the downslope stream segment [Merot, et al., 2003]. Areas with a wetness index larger than 10 and underlying low permeable bedrock are mapped as SOF areas. In addition, riparian zones and areas close to a water body become frequently saturated since the groundwater table is close to the soil surface and the moisture deficit is low [McGlynn and Seibert, 2003]. Arp [2005] developed a methodology to map these areas by iteratively interpolating the elevation of all open water areas (lakes and streams). This module was implemented in SAGA and is used to calculate the vertical distance of the groundwater table to the soil surface for all grid cells. We assume that these areas are saturated during peak flow if the vertical distance is less than 2 m [Arp, 2005].

d) Shallow Subsurface Flow (SSF): Whipkey [1965], Hewlett and Hibbert [1963] and others demonstrated that subsurface flow is an important process for its contribution to fast catchment responses after rain storms or snowmelt events for areas with an impeding layer in the soil. Hewlett and Hibbert [1963] claimed that in most well-vegetated watersheds subsurface flow is predominant for various storm types. In BC, soils covered with forests are often shallow and are characterized by impeding layers (either fine textured moraine or bedrock). In the proposed framework, steep slopes with a relative short distance to the channel are defined as SSF areas, given they are underlain with an impermeable layer of soil or bedrock. With regard to steepness, the average slope to the stream – and not the local gradient - is of interest. The model defines SSF areas as those within 800 m to the stream along the overland flow pathway and with a gradient of more than 20% to the stream channel.

The Runoff Generation Module maps the DRP areas and generates a DRP map that shows the processes for a watershed or a larger area of interest. DRPs are mapped according to the following priority order: Channel Interception > HOF > SOF > SSF. For example, an area that is HOF but also a Channel Interception area will be classified only as channel interception. Areas that are not mapped as one of the four processes are considered not to contribute to peak flow. Figure 2 shows an example of mapped DRPs.

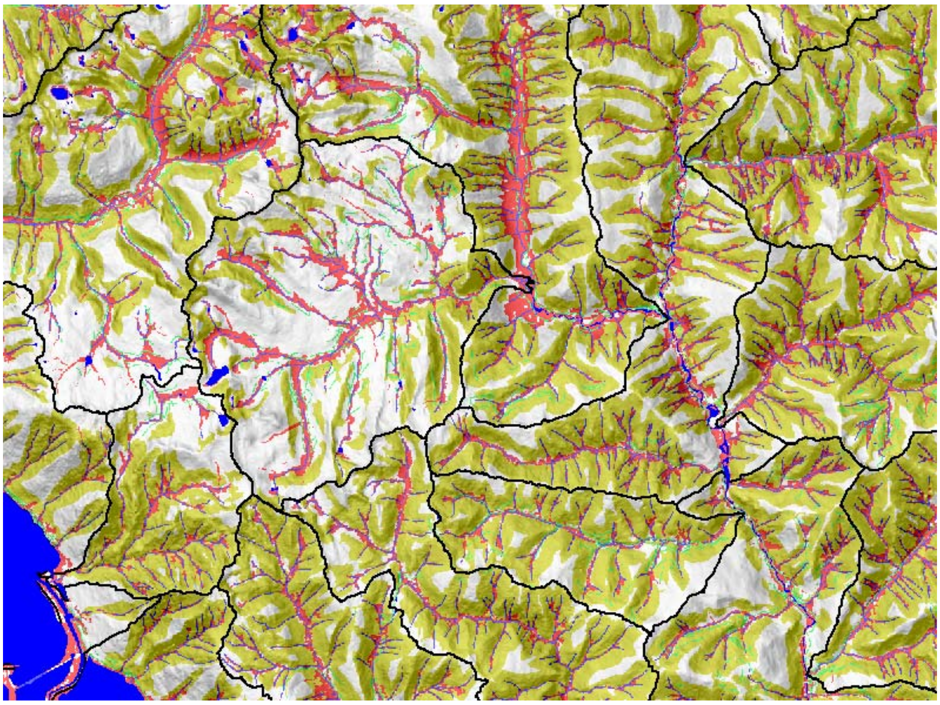


Figure 2. Dominant runoff generation process map for several watersheds along the west arm of Kootenay Lake.

The contribution from each runoff generation process area is defined based on the process understanding and its response during peak melt rate input. We define a runoff contributing factor, RCF, for each process area and multiply it with the modified input to simulate a peak flow contribution (mm/day) for each grid cell. The factors are: Channel Interception: RCF = 1.0; Hortonian overland flow: RCF = 0.9; Saturation overland flow RCF = 0.8; Subsurface flow: RCF = 0.7; where no dominant runoff generation process is defined: RCF = 0.1. The average daily peak flow (m3/s) for each sub-watershed is calculated by multiplying the watershed area with the average peak flow contribution of the watershed.

3.1.4 Stream Routing Module

The time precipitation takes to reach the outlet of a watershed depends on various factors such as slope of the landscape and distance to watershed outlet. At the current modeling stage, we consider the Mission station as the outlet to the Fraser system.

To determine the peak flow traveling time, 34 hydrometric stations along the main river stem and its tributaries have been selected and the travel time derived between each of these stations and the Mission hydrometric station. Additionally, the mean horizontal flow distance (HFD_{ws}) was determined for each third order watershed using the following equation.

$$HFD_{ws} = \frac{\sum_{i=1}^{n} HFD_{gc}}{n}$$

$$\mathrm{HFD_{ws}} = \text{3rd order watershed mean horizontal flow distance}$$

$$\mathrm{HFD_{gc}} = \text{grid cell horizontal flow distance}$$

$$\mathrm{n} = \text{grid cells per 3rd order watershed}$$

With the application of a regression analysis, the horizontal flow distance (HFD_{ws}) was related to the determined traveling time of the selected hydrometric stations (Figure 3). The found relationship was then used to map the travel time for each third order watershed to the Fraser outlet (Figure 4). For six watersheds no distance information was available due to missing values in the DEM. Here, the travel time of the surrounding watersheds was used.

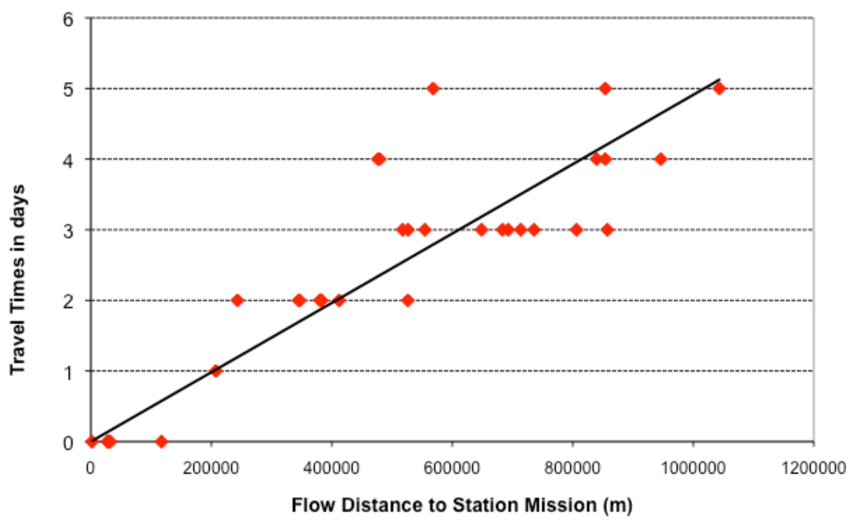


Figure 3: Relation between peak flow travel distance and travel times to the Mission gauging station for 34 Fraser basin gauging stations.

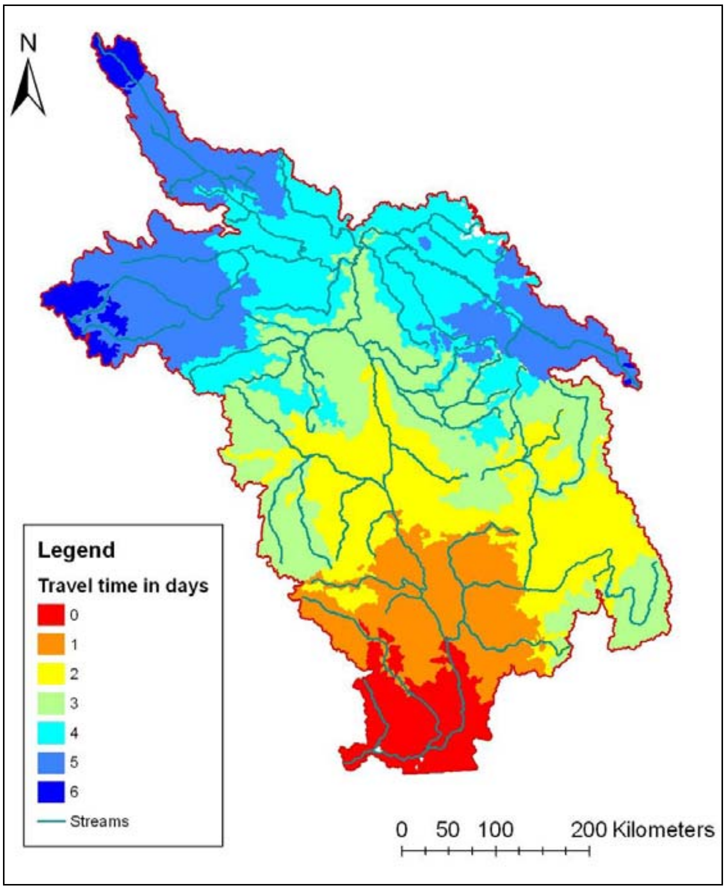


Figure 4: Predicted travel times in the Fraser basin.

3.2 Data Inputs

Table 2 provides an overview of key data inputs.

3.2.1 Climate Data

Climate data are provided as mean monthly precipitation and temperature using the PRISM methodology for a 400-m grid spacing for the province of BC [Spittlehouse, 2006]. Mean daily temperature and precipitation at a site is interpolated from the monthly climate data whereas the monthly values are considered to represent the middle of the month (equals the 15th day of the month). The daily values between two monthly values are calculated applying a linear smoothing function between the bordering monthly values. Based on this information the daily rate of snow accumulation and snowmelt has been simulated.

Table 2: Overview on Input Data

Input Data	*Data Name*	*Data Provider*	*Spatial Resolution*	*Data Citation*	*Used in Module*
Precipitation	ClimateBC	Centre for Forest Gene Resource Conservation, UBC, Research Branch, MoFR	400 m	Spittlehouse (2006)	Climate Input Module
Temperature	PRISM ClimateBC	Centre for Forest Gene Resource Conservation, UBC, Research Branch, MoFR	400 m	Spittlehouse (2006)	Climate Input Module
Topography	Digital Elevation Model	BC Ministry of Environment, University of British Columbia	25 m		Runoff Generation Module
Relative Solar Radiation		Derived from the DEM data	25m		Runoff Generation Module
Vegetation	BTM1	Province of British Columbia BC Ministry of Environment, Surveys and Resource Mapping Branch	1:250.000	Province of British Columbia et al. (1995)	Runoff Generation Module
	Pine Cover		400 m	BCMPB Eng et al. (2006)	Land Cover Modification Module
Stream connectivity hierarchy and third order watersheds	Watershed Atlas	BC Ministry of Environment, Fisheries Branch	1:50.000	BC Ministry of Environment, Land and Parks, Fisheries Branch (1996)	Runoff Generation Module
Disturbance	Mountain Pine Beetle	Forest Health Factor Data Aerial overview survey results from 1999 to present Research Branch, British Columbia Forest Service	Polygon	Eng et al. (2006)	Land Cover Modification Module
Roads		BC Ministry of Environment	Polyline		Runoff Generation Module

3.2.2 GIS Data

The elevation information is derived from a DEM data set. This DEM has been generated from the original elevation points and breaklines using a new model to homogenize the density of the elevation points and to correct for bias among mapsheet boundaries (see Appendix I). As a result, a hydrologically meaningful DEM at 25-m resolution has been generated.

For general land-use characteristics the Baseline Thematic Mapping [BTM] [Province of British Columbia et al. (1995)] has been used. This information was derived from satellite imagery from the Landsat Thematic Mapper (TM) data [Province of British Columbia et al. (1995)]. The data set contains 19 land-use classes. Additional, a pine cover data set has been used to map pine covered areas. Due to discrepancies between the BTM and pine cover data, the BTM data are updated using the pine cover data set. The Forest Health Factor data are used to determine MPB infestation. These data contain annual aerial overview survey results from 1999 to the present.

The third order watershed boundaries are used as boundaries of assessment units. These watershed boundaries derive from the British Columbia 1:50,000 digital Watershed Atlas. The Watershed Atlas is "topologically structured digital representation of all aquatic-related features (streams, lakes, wetlands, obstructions, dams, etc. and associated annotation)" [Ministry of Environment, Fishery Inventory 2008]. The Watershed Atlas includes all 3rd order and greater watersheds. It also provides a routing system for streams. The Watershed Atlas also provides the stream network used as in data input.

3.2.3 Additional Data

The BC Ministry of Environment provided detailed information on the commercial salmon value of each 3rd watershed. The salmon value hereby represents the sum over five species, whereas for each species the estimated harvest was multiplied with value in Dollar and the biological sensitivity (Eric Parkinson 2009). The following table gives an overview about the species value.

Table 3: Relative species weight in the commercial harvest score

Species	*Average Weight (kg)*	*Wholesale Price / kg ($)*	*MSY Harvest Rate [%]*	*Harvest: Escapement Numbers at MSY*	*Species Value ($/escapement)*	*Species Sensitivity*	*Relative Weights*
Chinook	8.0	4.32	63	1.7	58.8	0.82	28.6
Chum	5.2	1.66	52	1.1	9.5	0.65	3.6
Pink	1.9	2.05	47	0.9	3.6	0.47	1.0
Sockeye	2.7	7.54	56	1.28	26.3	0.65	10.1
Coho	3.5	8.57	59	1.44	43.2	0.88	22.5

MSY= Maximum sustainable yield

Source: Table was taken from BC Ministry of Environment (2006): Methods Fisheries, p.6, a document provided by Eric Parkinson Ecosystems Branch, BC Ministry of Environment.

3.2.4 Database Development

For the management of the entire GIS data described above the development of a database was required. The database is designed to maintain the greatest level of disaggregation but also to combine and extract information at 3rd order watershed base. The database allows querying information specific to geographical area or 3rd order or higher watersheds. It is also possible to extract the necessary input data for a specific modelling scenario. By only utilizing data for a specific scenario and region, computational speed is greatly increased in comparison with running the model on the entire provincial level dataset.

To maintain a high level of disaggregation, the province has been divided into 400m grid cells (in total over 6.2 million cells). For each of those cells the input information (Table above) was assigned. In case of a finer spatial resolution (e.g. DEM and dominant runoff processes) aggregation procedures had been applied. The 25m-DEM information was aggregated using mean value over the 16 contributing cells. In case of the dominant runoff process information, for each grid cell the area percentage each runoff process has been determined.

4.0 Model Application

4.1 Study Area

The Fraser basin covers 231500 km^2 which equals 24.5% of the land of BC [BC Ministry of Environment, Land and Parks, Fisheries Branch 1996]. The Fraser River Basin is therefore the largest river basin in British Columbia and home to one of the most productive salmon fisheries in the world [Fraser Basin Council 2009]. The Fraser River originates in the Rocky Mountains in central British Columbia and runs through the Interior Plateau to the Pacific Ocean. Major tributaries of the Fraser River are the Nechako, Quesnel and Thompson as well as the Chilcotin River.

The climate of the Fraser Basin varies extremely from east to west and from north to south. This is mainly caused by the geographical location and topography. The wettest climate in the Fraser River Basin can be found in the mountain ranges of the Rockies in the eastern part of the Basin with an mean annual precipitation of 801 to 1200mm and the Fraser Valley, especially the estuary of the Fraser River where mean annual precipitation can raise at over 2000mm [Natural Resources Canada 2007]. The driest climate in the basin lies in the interior plateau (MTP between 201 and 400mm) [Natural Resources Canada 2007] which is encircled by the rocky mountain ranges in the east and coast mountain ranges in the west.

The major focus of this study is the influence of land use changes on average peak flow. In British Columbia, a current major hazard is the MPB Infestation which attacks the pine vegetation of the province. The following figure illustrates the percentage of pine calculated as a percentage of each 3rd order watershed.

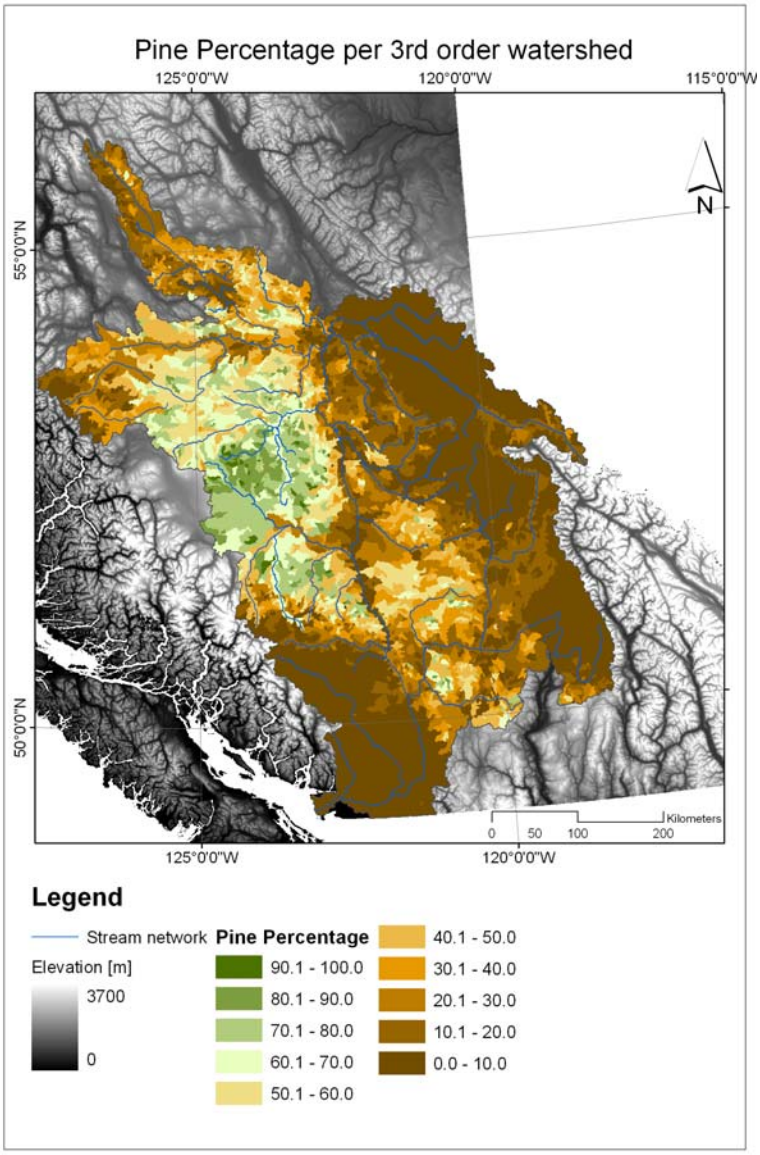


Figure 5: Percentage of pine per 3rd order watershed.

As highlighted in the figure, the pine vegetation is not equally distributed over the Fraser Basin. The highest pine volume can be found in the western part of the basin, in particular in the Blackwater River System, the Chilcotin River System and the Stuart River System. Low amounts of pine are found in the eastern part of the basin, as well as in lower area, the outlet of the Fraser.

The Fraser Basin is an important watershed for fish, in particular to salmon. The following figure highlights watersheds with a high salmon values. This salmon value is a commercial indicator for salmon production (see section data inputs).

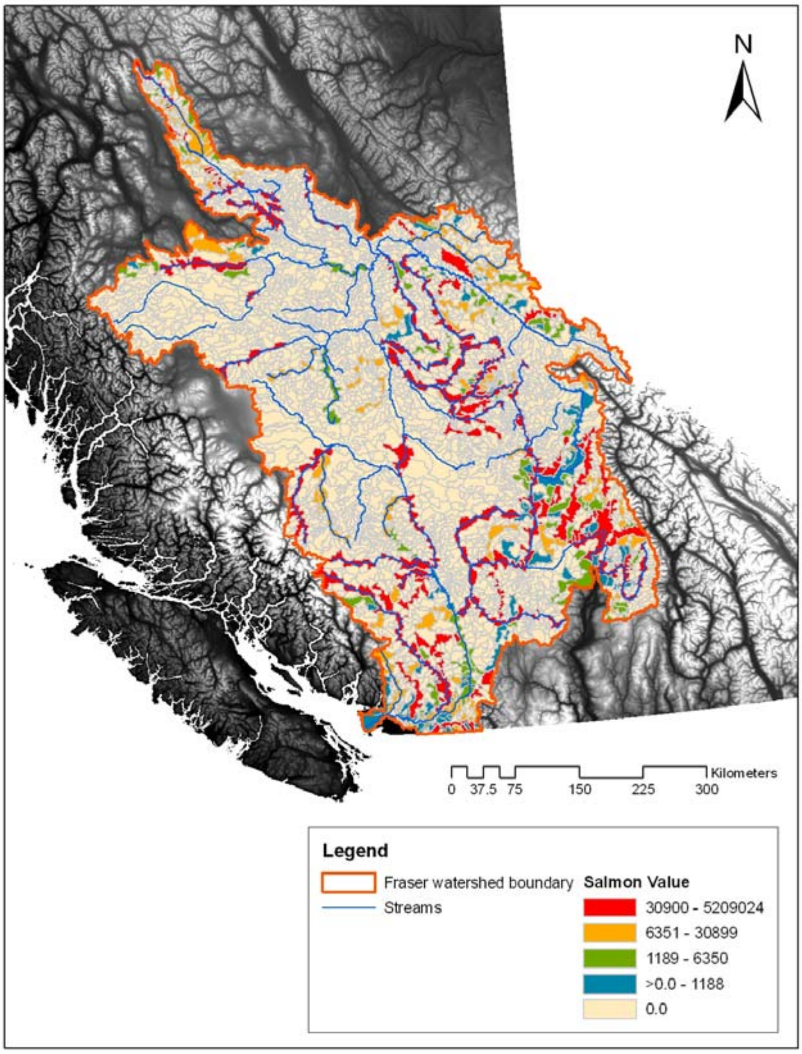


Figure 6: Salmon Value of 3rd order watersheds in the Fraser Watershed, Data Source: BC Ministry of Environment.

As shown in this figure, the most important watersheds for industrial salmon fishery are located in the Stuart-Takla subbasin, the Nechako, Lillooet- Harrison, Quesnel and Thompson River System as well as long the main stem of Fraser River. By overlying the two information, pine volume per 3rd order watershed (Figure 5) and Salmon value (Figure 6), watersheds with a high pine volume and high Ssalmon value are watersheds in the Stuart- Takla, Nechako and lower Thompson River System. It can be assumed those watersheds have a high sensitivity to land use changes.

4.2 Modelled Disturbance Scenarios

We report on three disturbance scenarios. One scenario excludes MPB effects to provide insight into possible baseline conditions against which the MPB results can be compared and is: the vegetation cover before MPB infestation started (=1995 forest cover). In addition, two disturbance scenarios build on the baseline scenario (vegetation cover in 1995) providing estimates associated with each of pine mortality and complete salvage for both current MPB infestation levels and total possible MPB infestation. Described in Table 4, scenarios 1 and 2 reflect complete pine death for zero and 100% salvage, respectively.

Table 4. Vegetation modification associated with each of the six modelled disturbance scenarios.

Scenario	Description
BL	Vegetation cover in 1995 based on data from Baseline Thematic Mapping (=**b**ase**l**ine).
1	Pine death for all pine stands as derived from Eng et al. (2006)
2	Scenario #1 plus clearcut salvage harvest of 100% (by area) of all pine.

4.2.1 Forest Condition in 1995 (Baseline scenario)

This scenario represents the baseline in our modeling approach. Herefore, the vegetation cover used is the 1995 BTM data set as well as the pine coverage [Eng et al. 2006]. Due to discrepancies between the BTM and pine cover data, the BTM data are updated using the pine cover data set. This scenario does not include pine death or any mountain pine beetle activity.

4.2.2 Pine death and salvage based on MPB affecting all pine stands (Scenarios 1 and 2)

This scenario incorporates the hypothetical bracket that all pine trees die from MPB attack. These scenarios allow analyzing the maximum effect of MPB infestation in BC. Within this context, scenario 1 represents no salvage action taken whereas scenario 2 reflects complete clearcut salvage response of all pine trees.

5.0 Results

5.1 Dominant runoff processes

The mapping of the dominant runoff producing areas was done in close cooperation with the MPBI Project #7.29 “Development and Application of a Peak Flow Hazard Model for the Fraser Basin (British Columbia)”. Without contribution from this project the development of the peak flow model would not have been possible and the scenario results shown in this report would not have been possible.

Figure 7 shows the map of the proportion of areas producing saturation overland flow (SOF). Large areas of the Interior Plateau are dominated by runoff that is produced from saturated areas. This relates well to the larger proportion of wetlands in this area which are dominated by the same runoff producing mechanism. In the mountains, the valley floors are largely covered with saturated areas. The distribution of areas dominated by subsurface flow (Figure 8) is much more distinct as the distribution of SOF. This is because subsurface flow can be a relevant process only if the hillslopes are steep and if they are connected to streams. Specifically the Coast Mountains and the mountains in the Interior are dominated by watersheds with a high proportion of areas with subsurface flow.

Figure 7: Proportion of area in each 400-m grid cell dominated by Saturation Overland Flow (SOF) – map is also available as a high resolution PDF.

Figure 8: Proportion of area in each 400-m grid cell dominated by lateral subsurface flow (SFF) – map is also available as a high resolution PDF.

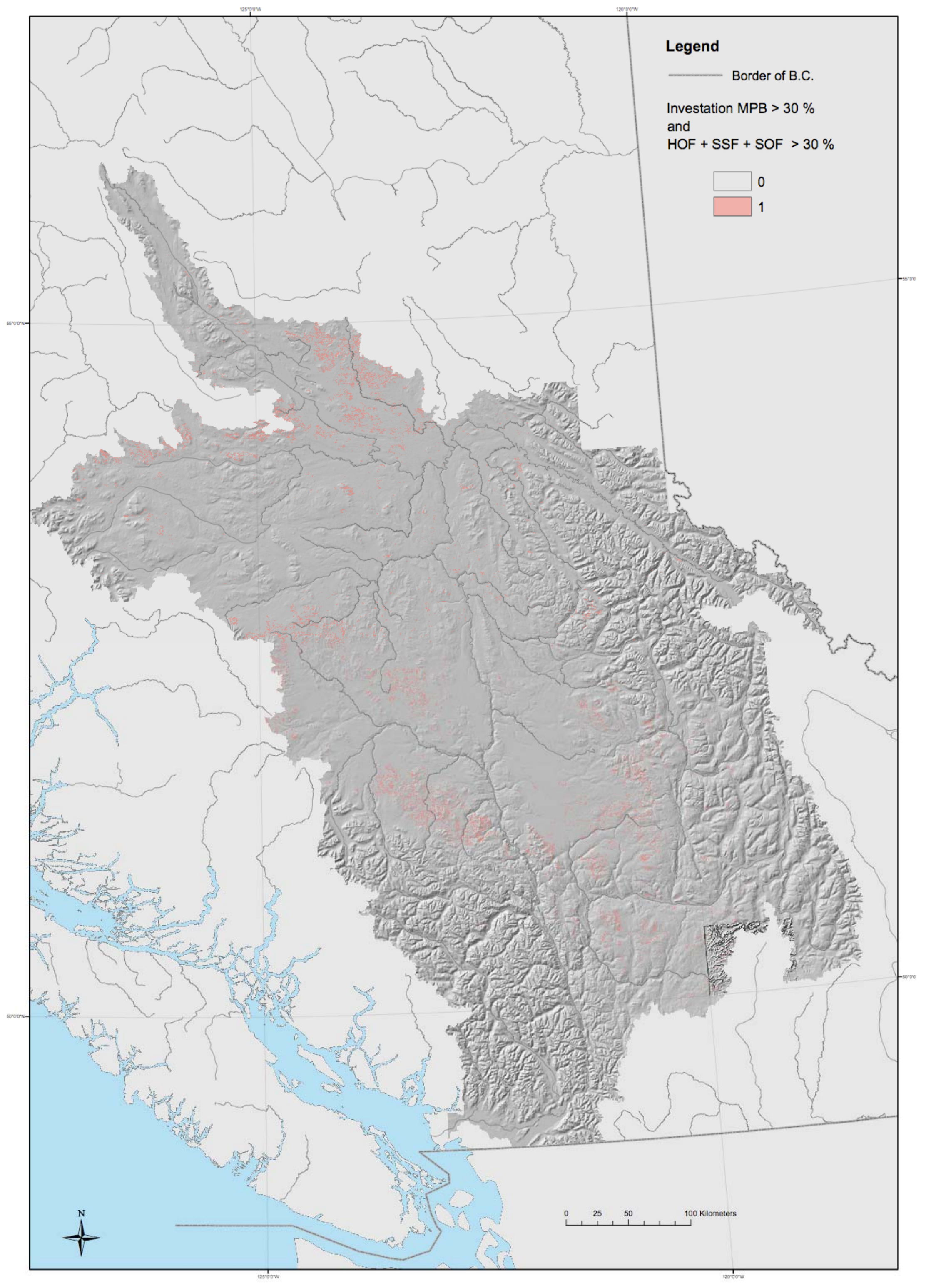


Figure 9: Areas with a high probability of being impacted by MPB infestation due to a high degree of hydrologically sensitive areas (i.e., areas with a high proportion of runoff generated in infested areas) – map is also available as a high resolution PDF.

Already the information and distribution about dominant runoff generation can be used to derive a hydrological sensitivity map (Figure 9). The maps shows areas in red that are infested by MPB with a severity larger than 30% in 2007 and that could generate substantial amount of runoff (more than 30% of the area is dominated by a dominant peak runoff producing process). If the canopy in these areas is disturbed and hence snowmelt is accelerated and snow accumulation is increased, the runoff from these areas will also increase at a much higher rate than in other areas.

The figures above show missing or incorrect dominant runoff data in the eastern part of the Fraser basin on the boarder to Alberta as well as at the outlet of the Fraser River. At the current stage the source for this error has not been found. However, the project goal is to determine the impact of land use changes, in particular effects due to pine harvesting. Those areas have no or only minor pine coverage (Figure 5) and it is therefore assumed that the introduced can be neglected for the current modeling purpose.

5.2 Model Validation for Baseline

As already mentioned in the introduction, the peak flow model is being developed to provide a hydrologic model platform to predict spatially explicit land-use change scenarios without calibrating the parameters of the model. This is accomplished by using experimental results from field studies or applying the concept of dominant runoff processes to predict the runoff contribution of areas in the watershed. The simulated peak flows can be validated against only observed runoff records. We would generally expect that the results will not be as good as with a calibrated model, but on the other hand we can ensure that the model is not right for the wrong reason [Klemes, 1986].

We are reporting on two scenarios but observed discharge values are available only for the baseline scenario and therefore only this scenario can be validated. Based on these discharge values, the mean annual runoff has been determined by calculating the daily mean for the years 1970 to 1995. From this mean annual time series the mean annual peak flow is selected and compared to the simulated peak flow value.

Table 5: Observed and simulated timing and volume of the peak flow for selected watersheds.

Station number	*Station name*	*Observed**		*Simulated (Baseline)*		*Error in %*
		Mean annual Peak flow [m3/s]	*Timing (DOY)*	*Mean annual Peak flow [m3/s]*	*Timing (DOY)*	
08MB005	Chilcotin River below Big Creek	264.1	209	250.8	180	-5
08KH006	Quesnel River near Quesnel	655.6	167	203.5	173	-69
08KE009	Cottonwood River near Cinema	99.8	135	39.6	108	-60
08KC001	Salmon River near Prince George	156.4	127	124.7	113	-20
08ME025	Yalakom River above Ore Creek	13.2	153	12.0	135	-9
08JE001	Stuart River near Fort St. James	309.4	185	402.9 [302.2]	113	-2.4

08JB003	Nautley River near Fort Fraser	86.8	151	183.0 [91.5]	113	+5.4
08LG008	Spius Creek near Canford	45.8	149	15.6	133	-66

DOY = Day of the Year

* Values provided through Water Survey Canada, mean annual average from 1970 to 1995

Table 5 summarizes the observed and simulated timing of the peak as well as the peak volume. The model predicts the mean annual peak flow for most watersheds with an error between 2.4 % to 30%. In three watersheds (Spius Creek, Cottonwood River, and Quesnel River) the model underpredicts the peak flow. At Nautley River and Stuart River the model overpredicts peak flow (fast high peak response in comparison to a slow prolonged observed peak). Large lakes and wetlands dominate the last two watersheds (over 10% of the total area) and these dampen the freshet peak by storing large amount of water that is slowly released. The peak flow model has not yet implemented lake routines and we are not surprised that the model cannot reproduce this behaviour. In order to provide a realistic prediction for the peak flow changes of the different scenarios, we implemented a simple linear lake storage and outflow relationship for these two watersheds and calculated the predicted changes based on the same relationship (the numbers in bracket in Table 5). The Spius Creek also shows a very poor performance in the VIC model [Schnorbus et al. 2009]. We believe that probably the gauging station is not producing correct data since the predicted total precipitation for the whole year is lower than the observed annual runoff. Also the VIC model shows a very strong negative bias for the Quesnel River which could be related to an underprediction of the precipitation or a problematic discharge record. It is also surprising that the observed mean annual runoff for the Quesnel River is 645 mm [Burford et al. 2009], but the total available annual precipitation for this watershed is 667 mm, which is impossible for a watershed in this climatic region. Since both models behave very similarly for these watersheds, we believe that we have a systematic measurement error in these cases.

The timing of the peak flow is generally predicted early on average by 15-29 days and in the case of the Stuart River by 72 days. This could be because the model does not include storage in lakes which is an important process. Additionally, the fast onset of snowmelt is simulated could be also related to the use of climatic data instead of meteorological data.

5.3 Scenario Outcomes

5.3.1 General summary of the results

As mentioned above, we report on three scenarios in this report whereas one scenario acts as a baseline scenario. The remaining two scenarios presented assume that the entire pine coverage in the Fraser basin is under grey attack (scenario 1) and then harvested (scenario 2). The results are shown in Figure 10 and Figure 11.

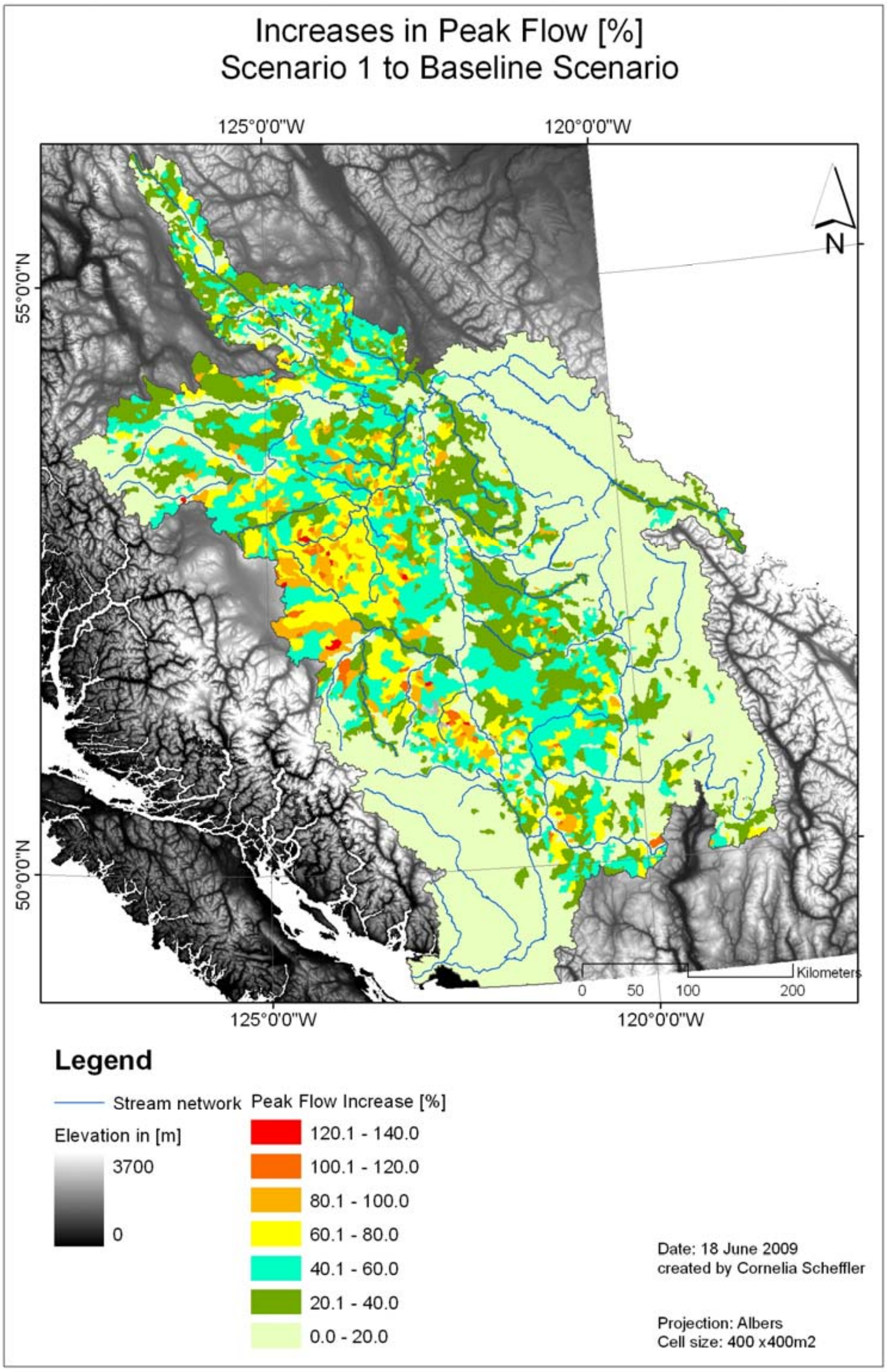


Figure 10. Peak flow change for scenario 1 relative to the baseline.

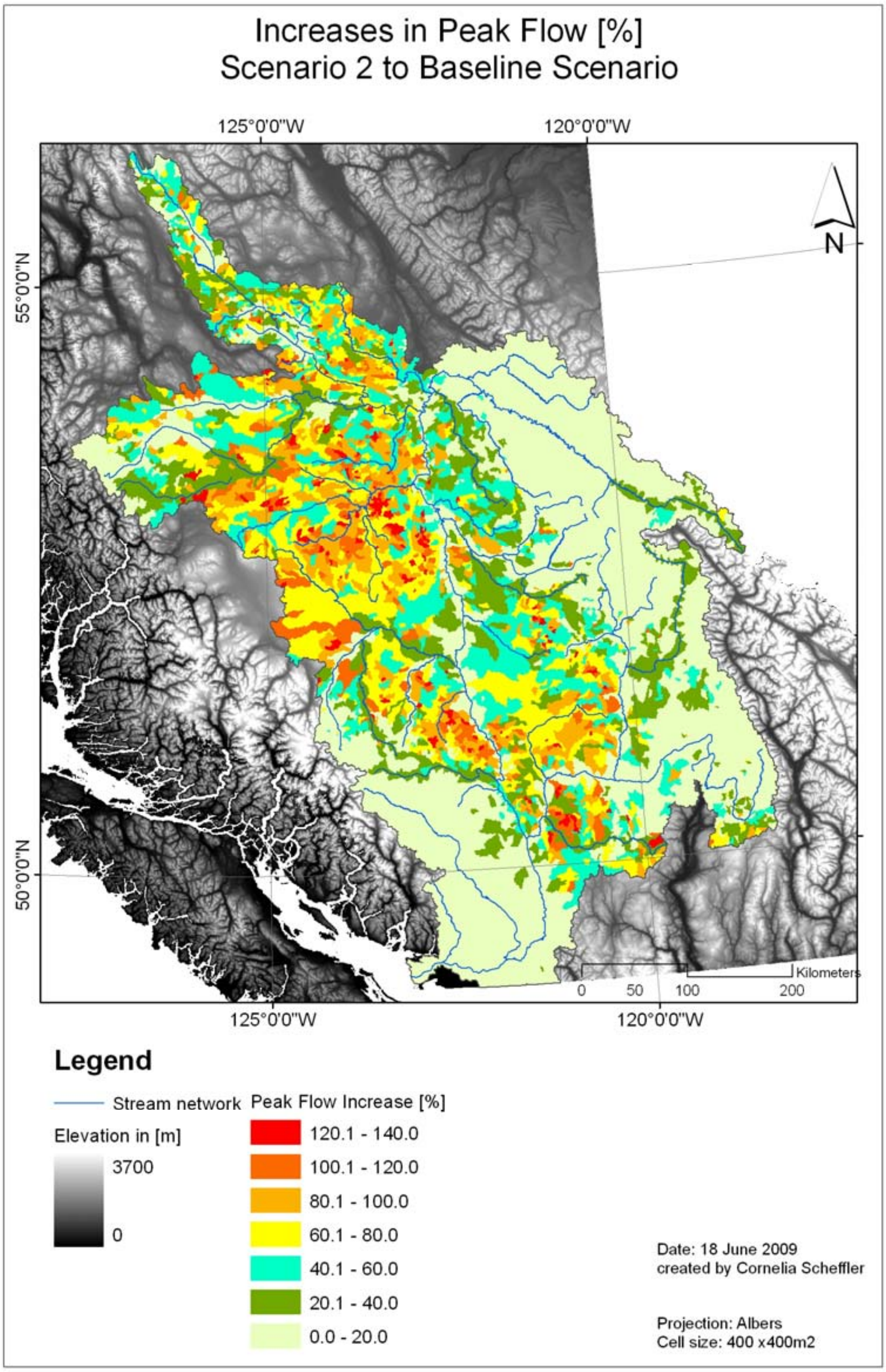


Figure 11. Peak flow change for scenario 2 relative to the baseline.

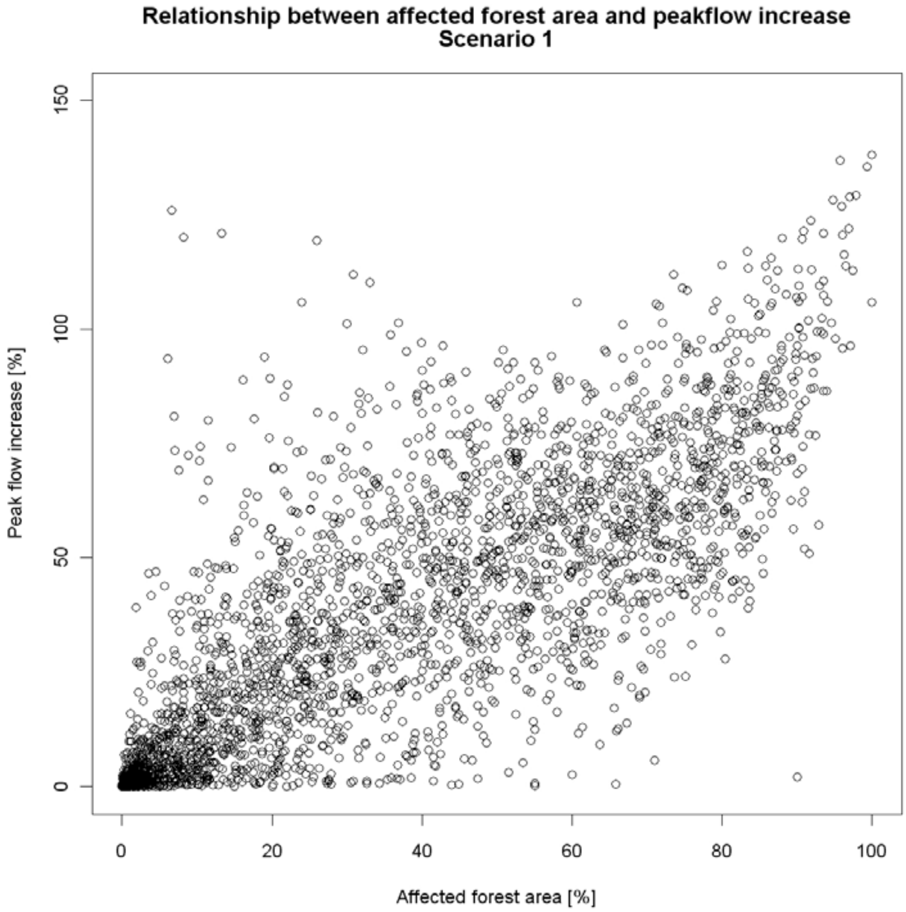


Figure 12. Scatterplot, peak flow increase in relationship to affected forest area, Scenario 1.

For the first scenario, the model simulates, as expected, an increase in peak flow when forest cover is reduced due to the MPB infestation. For dead pine forests (grey stand condition), the model predicts peak flow increases of between 0.1% and 138.1%. The highest predicted changes occur in the western part of the Fraser Basin, especially in the Chilcotin, Baezaeko, and Big Creek watershed. This aligns to the high percentage pine coverage (Figure 5) in those watersheds. Small or no peak flow increases are shown in the headwater of the Fraser River and Quesnel watersheds with mainly increases under 60%.

Figure 12, examines the proportion of affected forest against the predicted peak flow increase as a scatterplot at third order watershed base. The graph indicates a link between affected forest and the magnitude of peak flow increase and shows clearly an increase of peak flow increase with an increasing affected area. However, the impact can be very variable due to the linkage of an area that is affected by MPB and the local meteorological conditions and the runoff generation processes. For example, a watershed, which forest is affected by 40% can show close to no increase in peak flow up to 100% increase in peak flow.

In the second scenario 2, the pine covered area is considered to be completely harvested. While the upward trend with affected forest area is the same, the harvesting of grey affected trees leads to an additional increase on peak flow. Watersheds with high pine coverage such as Blackwater River, Chilcotin and Salmon River showing peak flow increases up 140% and watersheds with low pine coverage indicating no or only small increases in peak flow.

The figures above focus only on the peak flow increase at third order watershed basis. In an additional step the peak flow increase for different subbasins was examined. Therefore, the flow time between watersheds had to be taken into account. Table 6 summarizes the peak flow increase for important tributaries of the Fraser River.

Table 6: Simulated peak flow increases for important tributaries of the Fraser basin.

River System	Baseline	Scenario 1		Scenario 2	
	Peak Flow [m3/s]	Peak Flow [m3/s]	Peak Increase [%]	Peak Flow [m3/s]	Peak Increase [%]
Blackwater	168.1	268.1	59.2	299.0	77.9
Nicola	79.8	115.8	45.0	132.9	66.5
Cottonwood	39.6	55.4	40.0	61.3	54.8
Salmon River	124.7	171.0	37.2	191.8	53.8
Nechako River	1146.1	1502.3	31.1	1664.2	45.2
Stuart River	402.9	516.6	28.2	566.3	40.6
Fraser River (Outlet Mission)	3792.7	4771.1	25.8	5126.9	35.1
Willow River	79.0	94.6	19.7	99.5	25.9
Chilcotin	250.8	276.0	10.0	290.8	15.9
Bridge	158.6	171.7	8.2	176.7	11.4
South Thompson	248.5	265.4	6.8	269.6	8.5
North Thompson	386.3	411.3	6.5	420.2	8.8
Seton	83.4	87.9	5.4	89.2	6.9
Quesnel River	203.5	212.1	4.2	223.8	10.0
McGregor River	208.1	210.2	1.04	210.7	1.2
Lillooet/ Harrison	360.5	363.3	0.8	363.7	0.9

In scenario I, the change in land use leads to an increase of peak flow especially in watersheds with high pine coverage such as Blackwater, Nicola, Cottonwood, Salmon and Nechako River Systems (Figure 5). For those watersheds aveage peak flow increases over 30% were simulated. For Watersheds with low pine coverage, for example, North and South Thompson as well as Seton basin, only small increases in peak flow (< 10%) are indicated.

In Scenario 2, the grey stand affected pine area is considered to be harvested to 100%. Here, the upward trend with affected forest area is the same, the harvesting of grey stand affected trees lead to an additional increase in peak flow. However, the increase in peak flow from grey stand to non-forested areas does not occur linearly. The Cottonwood watershed, for instance, depicts an additional increase of 14.8% by harvesting the grey-stand vegetation. The Nicola River, however, illustrates an increase of only 11.5%. The table also indicates cumulative effects over when spatial scale is taken into consideration. The model simulates for the Stuart River, a tributary of the Nechako, a peak flow increase between

28.2% (scenario I) and 40.6% (scenario II). The increase predicted for the Nechako, however, is only an additional 2.9% for scenario I and 4.6% for scenario II. This implies that scale effects are in place which will be analysed further in the next section.

5.3.2 Assessment of Cumulative Effects onto Peak Flow Increases

In this analysis the cumulative effects were tested and assessed. Herefore, the peak flow was calculated for each 4th order, 5th order and 6th order watershed and the peak flow increase was determined.

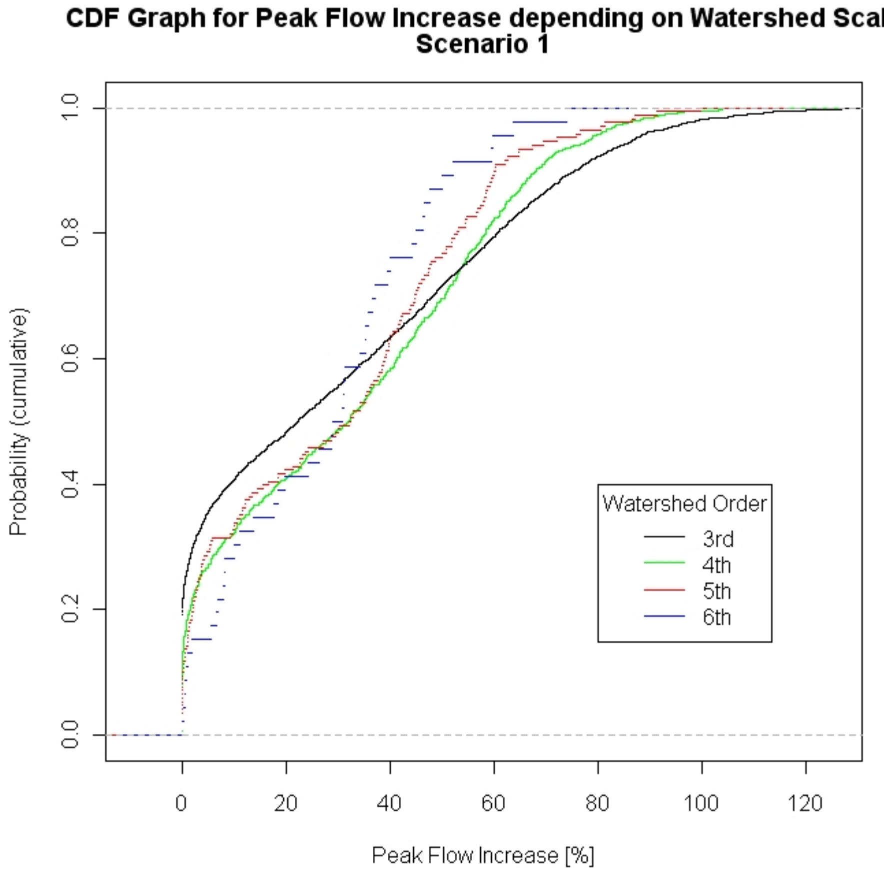


Figure 13. Cumulative distribution function for peak flow increase depending on watershed scale, Scenario 1.

Figure 13 shows the cumulative distribution function for peak flow increase depending on watershed scale for the Fraser River Basin which depicts a clear scale dependence of land use changes on the actual peak flow increase. At 3rd order watershed level, 50% of the watersheds showed an increase in peak flow over 23%. At 6th order, however, 50% of the watersheds show an increase of over 30% in peak flow. Additionally, at the 3rd order watershed level, 5% of the watersheds having an increase in peak flow higher than 88%, whereas at 6th order 5% of watersheds show peak flow increases higher than 60%. This indicates that at small watershed level(=3rd order watershed) peak flow increases below 23% and peak flow increases above 88% have a higher probability than at larger watershed size (=6th order watershed) . This can be caused due to the aggregation of smaller watersheds to larger watersheds and different runoff generation processes and timing of snowmelt. This leads to an aggregation of local events which do not have the influence at larger scale.

For scenario 2, the general behaviour of the curves stays the same, whereas the thresholds in peak flow increase are changing. At 3rd order watershed scale, 50% of the watersheds showing now an increase of peak flow higher than 31% and for 5% of the watersheds an increase of over 120% was simulated. At 6th order watershed 50% of the watersheds showed a peak flow increases over 43% and 5% of the watershed depicted increases in peak flow over 85%.

In summary, the degree of peak flow increases due to land use changes has a clear relationship to watershed size. In the next step, the degree of peak flow increase was analysed in regard to the actual affected watershed area, shown in Figure 14.

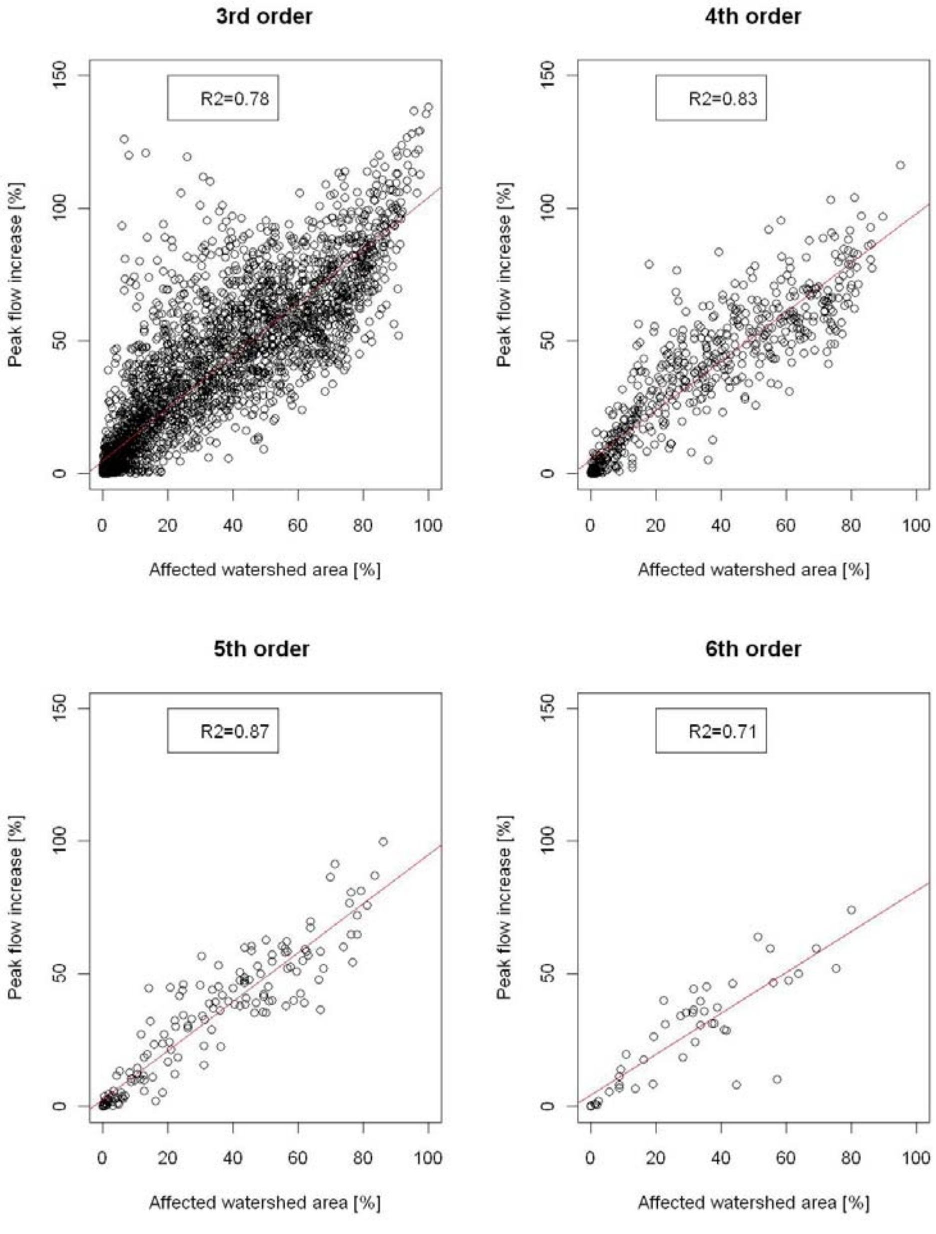


Figure 14. Scatter plots showing the affected watershed area (scenario 1) against the resulting (simulated) peak flow changes for different watershed orders.

The figure above depicts a linear relationship between the affected watershed area and the degree of peak flow increases over all respective watershed sizes. The pictures show that increasing the affected catchment area leads to increase of peak flow. Those results are not surprising since peak flow generation is directly affected by land use.

5.4 Effects on Important Salmon Watersheds

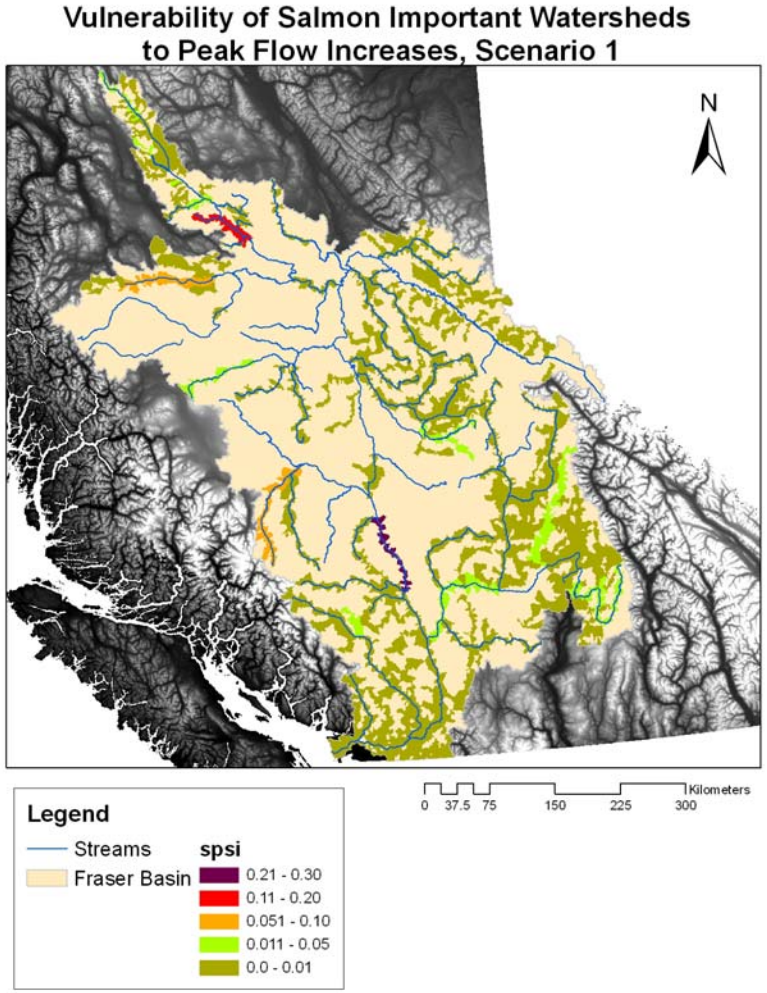
An important question to answer is, which salmon important watershed will be most affected by peak flow increase. Herefore, simulated peak flow increases were overlayed with the salmon value information. To determine the vulnerability of those watersheds, a sensitivity index has been developed. The Salmon- Peak Flow- Sensitivity Index (SPSI) takes peak flow changes as cumulative effects and therefore contributing watersheds into account. The SPSI is calculated as follows:

$$SPSI = \frac{SV}{\max(SV)} * \frac{PFI}{\max(PFI)}$$

$$\mathrm{SV} = \text{Salmon Value}$$

$$\mathrm{PFI} = \text{Peak Flow Increase[\%] over contributing watersheds}$$

The SPSI index ranges from 0 to 1, where 0 equals no vulnerability and 1 equals highest vulnerability. The figure above shows that most parts of the Fraser basin are not showing a high sensitivity. In total, 15 watersheds having a SPSI-value above 0.01 for scenario I, and for 16 watersheds a SPSI value above 0.01 was calculated for scenario 2 (Figure 15 and Table 7).



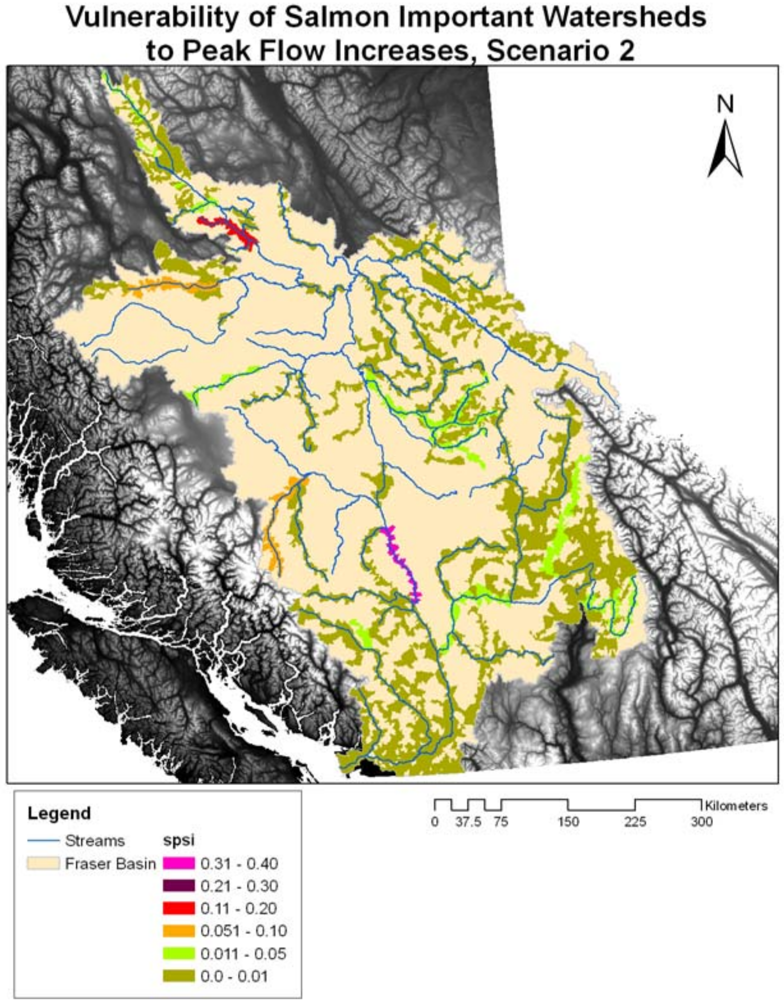


Figure 15. Salmon – Peak Flow - Index on 3rd watershed basis.

Table 7: Salmon-Peak Flow Indices (SPSI) for important Salmon watersheds, Scenario 1 and 2.

River System		Scenario I		Scenario II	
	Salmon Value	SPSI	Peak Flow Increase [%]	SPSI	Peak Flow Increase
Fraser River*	5209024	*0.29*	*25.8*	*0.30*	*35.1*
Stuart River	1806882	0.11	28.2	0.12	40.6
Stellako River	1326646	0.08	28.9	0.09	43.4
Chilko River	3801478	0.07	8.5	0.09	13.8
Horsefly River	629420	0.04	26.2	0.04	37.2
Tachie River	481309	0.03	28.7	0.03	40.4
Adams River	1470105	0.03	9.2	0.03	12.3
McKinley Creek	410409	0.02	23.8	0.02	34.3
Shuswap River	1220286	0.02	7.9	0.02	9.9
Driftwood River	445060	0.02	17.6	0.02	25.9
Blackwater River	116246	0.02	59.5	0.01	77.9
Thompson River	616808	0.01	9.7	0.02	17.5
Birkenhead River	1274345	0.01	4.0	0.01	4.9
Prince George (St. James) tributary	101713	0.01	48.8	0.01	65.8
Dusk Creek	103629	0.01	44.8	0.01	61.3
Quesnel River	1082092	<0.01		0.02	10.0

* The values for peak flow increase and SPSI are referring to the Fraser outlet.The current routing code, the PCODE provided by the Ministry of Environment, codes the entire main steam of the Fraser River with the same PCODE value (=100) which does not allow an distinction several watersheds along the river. However, it can be assumed that due to the high Salmon value the Fraser main steam has the highest SPSI.

Table 7 summarizes the SPSI values for watersheds with an SPSI higher than 0.01. For the first scenario, pine vegetation is under grey attack, 15 watersheds are showing a vulnerability whereas the highest sensitivity is depicted along the Fraser main steam, in the Stuart River, Stellako and Chilko River. In scenario 2, pine trees are completely harvested and the same river systems are showing the highest sensitivity. The SPSI- value only gives an indication about the sensitivity in the watershed but does not help to determine areas within the watershed which have a higher sensitivity than others. Herefore, an examination of the peak flow contribution at smaller scale has to be carried out.

Due to their vulnerability values and the catchment size, Adams River and McKinley River were chosen for this analysis. Figure 16 shows that Adams River basin consists of 45 contributing 3rd order watersheds and the McKinley River basin has seven 3rd order watersheds as tributaries. The figure also highlights that the tributaries are not contributing equally to the peak flow generation of the respective outlet. For example, in the McKinley River System the proportion of each watershed to the total peak flow of the outlet amounts between 0.6% and 58.2%. In Adams River system the contributing proportion of the 3rd order watersheds amounts between 0.05% and 25.4%. It can be assumed that land use changes in the watershed with the highest peak flow proportion will have a major impact on the river system's peak flow. In the McKinley basin the watershed with the highest proportion is ID = 12730 and in the Adams River system it is watershed 12890. In a following step, the change of peak flow from each individual cell in those watersheds was analyzed (Figure 17 and Figure 18) to provide an even detailed picture on sensitive areas in the watersheds.

In Figure 17, the small scale grid cell contribution to the watershed outlet is depicted for the McKinley watershed (ID= 12890). The figure 17a highlights the proportion of each grid cell contributing to the watersheds peak flow for the baseline scenario. The figure illustrates areas closest to the stream are having the highest influence (up to 0.45%) on peak flow. The surrounding hills, however, contribute below 0.1% to the watersheds peak flow. Figure 17b and c picturing the percentage of peak flow changes for pine under grey grey stand (Fig. 17b) and pine harvested (Fig. 17c). In the first scenario, the highest increase in peak flow occurs in the northwestern part of the watershed along of hillslopes alongside the river. Here, increases between 40 and 100% are simulated. In the second scenario, the same areas are now showing peak flow increase of 100 to 120%. In the Adams River similar results have been modeled. Figure 18 shows the individual grid cell proportion to the watershed's peak flow. Similar to the McKinley watershed the highest peak flow contribution (up to 0.1%) occurs along the stream (Fig. 18a). Areas most sensitive to grey pine stands are those forested areas which are close to the river valley. In those areas peak flow increases between 40 and 100% are predicted. When those grey stand pine are harvested the predicted peak flow increase rises up to over 120% in the same areas.

The comparison of increase in peak flow between scenario 1 and 2 also reveals that scenario 1 shows a higher spatial variability then scenario 2. Whereas in scenario 1, peak flow increases between 40 and 100% are simulated, scenario 2 nearly consistently predicts peak flow increase higher than 120%. This leads to the assumptions, that removing the pine trees has more severe effects on peak flow increase than pine tress in grey stand.

From these results presented above, the assumption can be made, that forest areas close to the river valleys are the most sensitive to peak flow changes. This information can be used to estimate the risk potential within the watershed and therefore, to derive harvesting and logging scenarios.

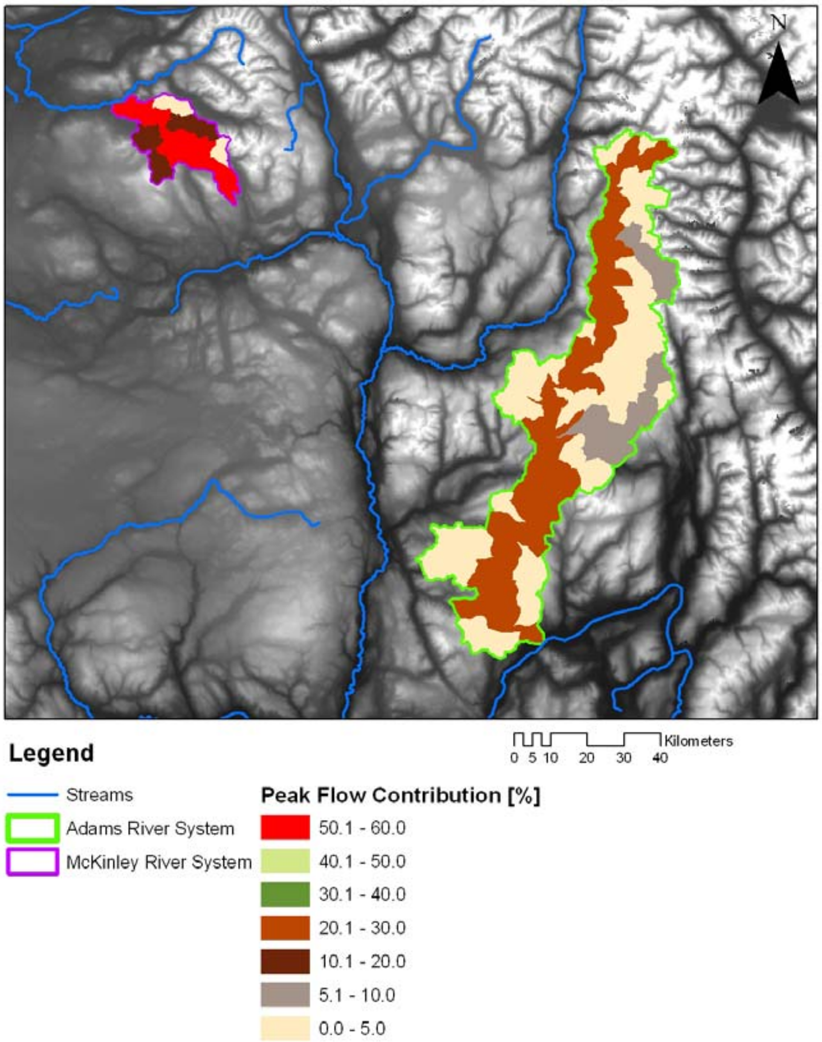
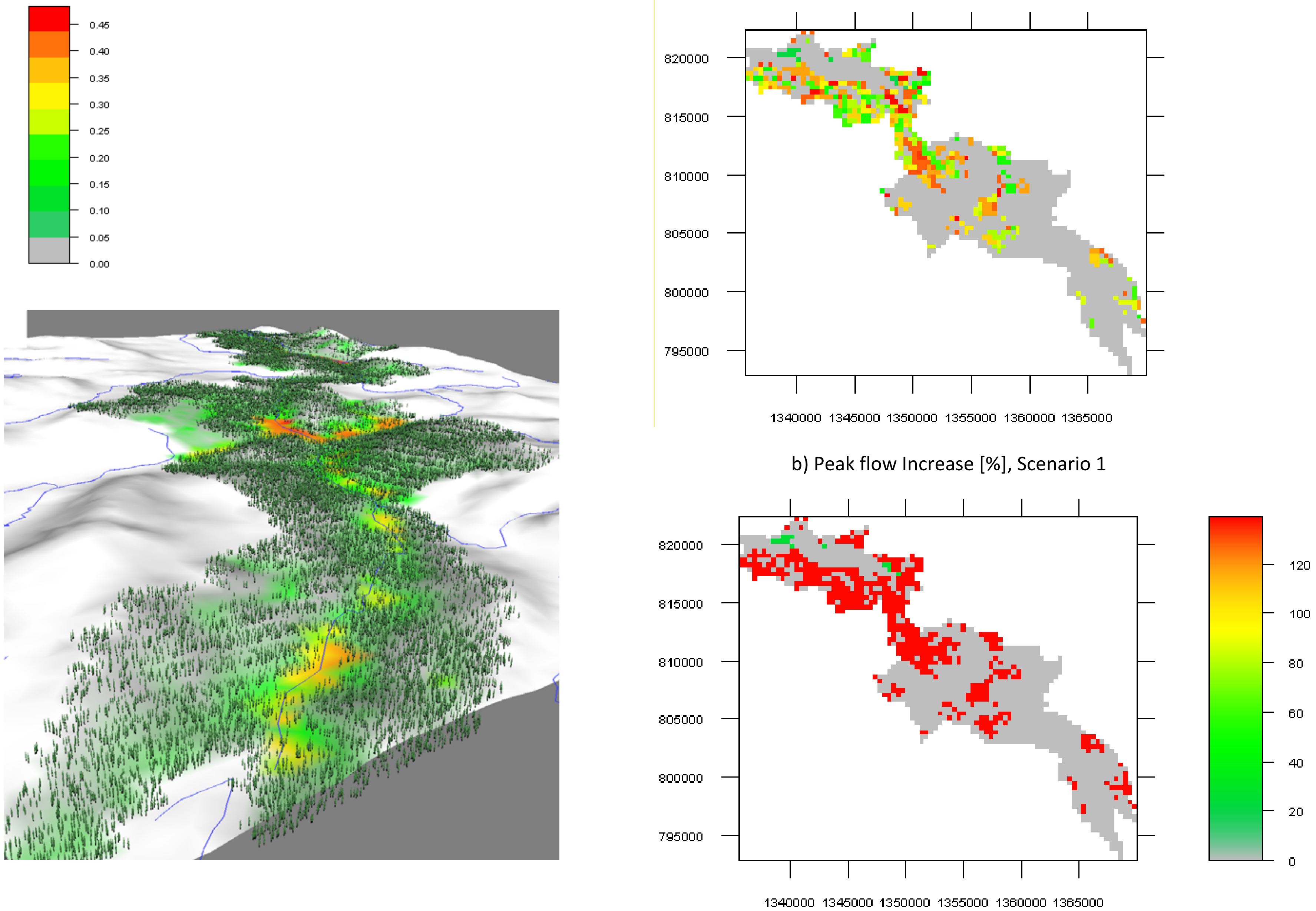


Figure 16. 3rd order Watershed Peak Flow Contribution for Adams River and McKinley River System.

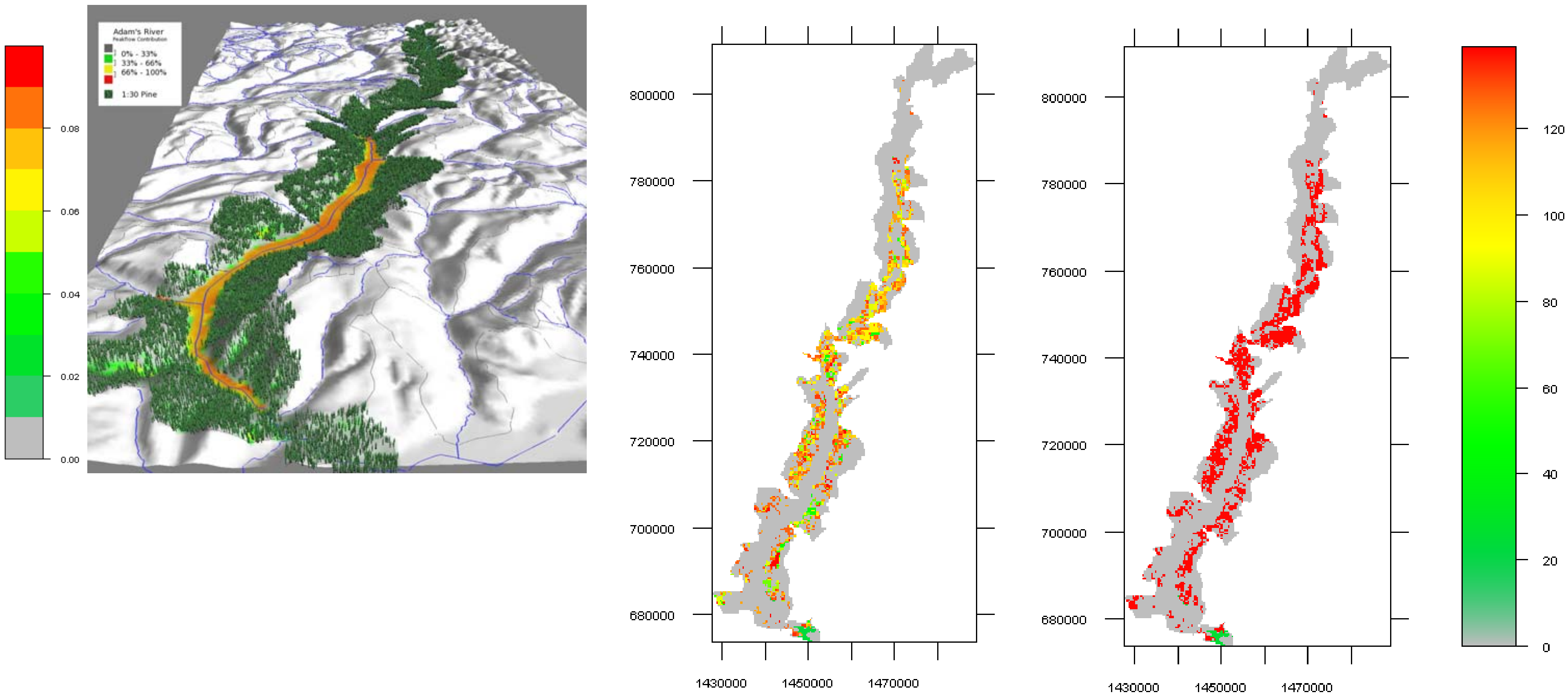


b) Peak flow Increase [%], Scenario 1

a) Baseline, Peak Flow Contribution [%] of each grid cell to the outlet

c) Peak flow Increase [%], Scenario 2

Figure 17. Peak flow increase [%] on small scale (400 x 400m^2) for McKinley River System.



a) Baseline, Peak Flow Contribution of each grid cell to the outlet

b) Peak flow Increase [%], Scenario 1

c) Peak flow Increase [%], Scenario 2

Figure 18. Peak flow increase [%] on small scale (400 x 400m^2) for Adams River System.

5.5 Summary of Modeling Results

The modeling results can be summarized as follows:

A reduction in active forest cover or the removal of forest cover results in an increase of peak flow

- Equal area reductions in vegetation do not lead to the same peak flow increases and suggests the existence of scale effects
- The degree of peak flow increases due to land use changes has a clear relationship to watershed size. Peak flow increases between 23% and 88% have a higher probability at higher watershed scale.
- Harvesting activities have a greater impact on peak flows than does grey attack; similar findings were published by the Forest Practice Board [2007].

6.0 Discussion

6.1 Data Issues

A key objective in this model development is to provide a model that can be applied to all watersheds and in particular ungauged basins throughout the province. In order to accomplish this project objective only data covering the entire area of British Columbia has been used.

6.2 Limitations

The applied model uses the concept of dominant runoff processes to determine areas which contribute more or less to watershed runoff. For simplification, one single parameter set has been used to delineate this information over the entire province. However, the province of British Columbia covers different landforms and climate regions [Foster, 2001; Tuller 2001]. Depending on local climate and land form characteristics, an adjustment of the parameter settings might be necessary.

As shown in section 3.3, the model simulates peak flow changes using different data sets, such as climate information as well as several GIS datasets (e.g. pine cover). The achieved results depend strongly on the accuracy of the climate input data. These data sets are covering an area of approximately 950,000 km^2. As shown at the example of the Spius Creek watershed, the input data are not exact. It can be assumed that there are data errors which are limiting the information value derived from the simulated model results.

The model uses long-term climate averages as driving input data. This limits the information value of the simulated peak flow changes. The current model setup allows predictions of only *changes* in mean annual peak flow (approximately 2.3 year return period). Larger peak flow events, as well as changes in flood probability, are not possible to simulate with the current set-up, but could be done if the model would be driven with continuously observed meteorological data.

6.3 Model Flexibility

The model can be used to derive changes on all relevant scales (third order watershed up to larger tributaries of the Fraser Basin.)

The model framework is flexible and therefore able to implement new findings of stand-level research on snow accumulation and melt. In 2008 the FSP project “Equivalent clear cut area thresholds in large-scale disturbed forests” [Weiler, Coops, Bon, Teti 2008] was launched. This project focuses on large-scale analysis of vegetation disturbances on snow accumulation and snowmelt using remote sensing techniques. The developed model uses that information directly as parameters in the model. Therefore, an implementation and estimation of the new findings can be easily accomplished without changing the model structure. This leads to an easy estimation of the corresponding effects.

6.4 Management Implications

As shown in Section 5.4. this model can be used to develop best management scenarios. For example, where in a watershed can MPB-infested forest be logged while minimizing the effects on peak flow? The modelling results provide a direct and spatially-explicit linkage at a relevant scale (0.4-16 ha) to relate forest management to hydrological processes.

7.0 Future Tasks and Outlook

In section 5.2, we compared the simulated to observed peak flow values. The comparison for Stuart and Nautley River watersheds has shown that the model is not able to reproduce observed behaviour. Further analysis revealed that the model stream routing module needs to include the effect of lakes. The implementation of a lake storage and outflow relationship is necessary to address this concern.

In the current model application, the 400-m grid cells were treated as homogeneous cells with no internal distribution. This leads to an overestimate of the actual area affected by mountain pine beetle as well as the area covered with pine vegetation. The future step in model development should be the adjustment of the model structure to account for a spatial variance within the grid cells.

In the current model structure the application of scenarios occurs is very static. For instance, the model does not allow the simulation of a watershed with scenario I and the neighbouring watershed with scenario II. For a more realistic respresentation of management procedures, efforts should be taken to allow a more variable application of scenarios throughout larger watersheds.

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