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Development and application of a peak-flow hazard model for the Fraser basin (British Columbia)

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Abstract

The province of British Columbia, Canada, is currently experiencing the largest mountain pine beetle outbreak ever recorded in North America. The most recent surveys indicate that widespread mortality of pine trees has occurred in over 10 million ha of forest (an area roughly the size of Iceland) and the outbreak continues to kill mature pine in the province. The epicentre of the current outbreak is in the Fraser River drainage basin (230,000 km^2), where roughly 8 million ha of forest have been affected, approximately 35% of the drainage area. Due to the infestation's area and associated salvage harvest operations, the potential exists for widespread and significant local and regional hydrologic impacts within the basin. However, the scale and physiographic heterogeneity of the Fraser River basin precludes both direct observation and extrapolation of hydrologic impacts observed from a limited number of stand-level and small-basin experiments.

A peak-flow hazard model was developed for third-order catchments within the Fraser River watershed. Baseline and mountain pine beetle-infestation and -harvest scenarios were modeled for seven catchments for direct comparison with the VIC modeling results. The model is to be used in Risk-Based Hydrology modeling to produce a comprehensive knowledge of mountain pine beetle-infestation effects on the hydrology of the Fraser River watershed and its major sub-basins, in British Columbia, Canada.

Keywords: Hydrology, risk-based modeling, hydrologic modeling, peak flow, scenarios

Resume

La province de la Colombie-Britannique, au Canada, connaît actuellement la plus forte infestation par le dendroctone du pin ponderosa (DPP) jamais enregistrée en Amérique du Nord. Les derniers sondages indiquent que la mortalité des pins s'est étendue sur plus de 10 millions d'hectares de forêt (une zone correspondant plus ou moins à la taille de l'Islande), et l'épidémie continue de ravager des pins matures dans la province. L'épicentre de l'infestation actuelle se trouve dans le bassin de drainage du fleuve Fraser (230 000 km^2), où près de 8 millions d'hectares de forêt ont été touchés, soit environ 35 % de l'aire de drainage. Étant donné la zone d'infestation et les opérations de coupe de récupération qui y sont associées, il y a des risques de répercussions hydrologiques générales et considérables à l'échelle locale et régionale à l'intérieur du bassin. Cependant, l'échelle et l'hétérogénéité physiographique du fleuve Fraser excluent à la fois l'observation directe et l'extrapolation des répercussions hydrologiques observées à partir d'un nombre limité d'expériences sur le terrain et sur de petits bassins.

Un modèle de débit de pointe a été élaborés pour les captages d'eau de troisième ordre à l'intérieur du bassin versant du fleuve Fraser. Les scénarios de référence, d'infestation par le dendroctone du pin et de coupe ont été établis pour sept captages d'eau, pour permettre une comparaison directe avec les résultats du modèle à capacité d'infiltration variable. Ce modèle a été developper lors de la modélisation hydrologique fondée sur le risque pour acquérir des connaissances approfondies sur les effets de l'infestation par le dendroctone du pin ponderosa sur l'hydrologie du bassin versant du fleuve Fraser et de ses principaux bassins secondaires en Colombie-Britannique, au Canada.

Mots clés : hydrologie, modélisation fondée sur le risque, modélisation hydrologique, débit de pointe, scénarios

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1 Introduction

Recent rapid and large scale land cover changes are making the news. Yet the assessment of the impact of land cover and land-use change on the hydrologic cycle is still a challenging task, and reliable answers—for example, of the impact of the rapid changes to tropical rain forests on the hydrologic cycle—are still missing (Achard et al. 2002; Marengo et al. 1994). In North America in recent years, wildfires and insect infestations have rapidly changed the land cover. For example, the increase of large scale forest fires in the western USA has not been assessed in detail for its hydrological impacts (Miller et al. 2003). In British Columbia, Canada, the lodgepole pine forest has been decimated in the last five years by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins, MPB) epidemic. The infestation has killed more than 9 million ha of pine forest in British Columbia and scenarios predict that by 2015, 75% of the pine forest will be dead. In addition to the vast areas in British Columbia, the beetle is rapidly infesting Alberta and the Rocky Mountains in the USA. In British Columbia, the forest industry is responding by salvaging as much timber as possible before it becomes commercially unusable. Consequently, in some watersheds, more than 50% of the forested area may be logged in the future, which is higher than historical logging rates in British Columbia. Regulations do not specify which areas in a watershed should not be logged except for riparian corridors and old-growth reserves. However, other areas in the watersheds may also be hydrologically sensitive to logging. The British Columbia government is now developing tools to assess the mountain pine beetle and salvage-logging impact on peak flow, low flow, coarse sedimentation, fine sedimentation, and stream temperature for the entire province (Carver et al. 2007).

Most assessment strategies rely on either simple models using empirically-derived relations between land-cover change and hydrologic variables, or on hydrologic 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, agricultural 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 hydrologic models that simulate small-scale processes at the soil-vegetation-atmosphere interface and large-scale runoff generation processes. The models are often a detailed physically-based conceptualization of the hydrologic cycle (e.g. Distributed Hydrology Soil Vegetation Model [DHSVM]; Soil and Water Assessment Tool [SWAT]; Water Balance Simulation Model-ETH [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 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.

The main objective of this work is to estimate impacts from land-cover change on average peak flows for all third-order (1:50,000) watersheds in British Columbia because peak flows are a major concern for flood hazard, erosion and sedimentation impacts, 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 province.

The modeling approach simulates the sensitivity of peak-flow changes to land-cover modification due to mountain pine beetle 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 province of British Columbia.

2 Model Description

2.1 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) The Climate Input Module maps peak-flow–generating climate input for each defined watershed.

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

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

4) The 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.

2.1.1 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 simpler and depends mainly on elevation.

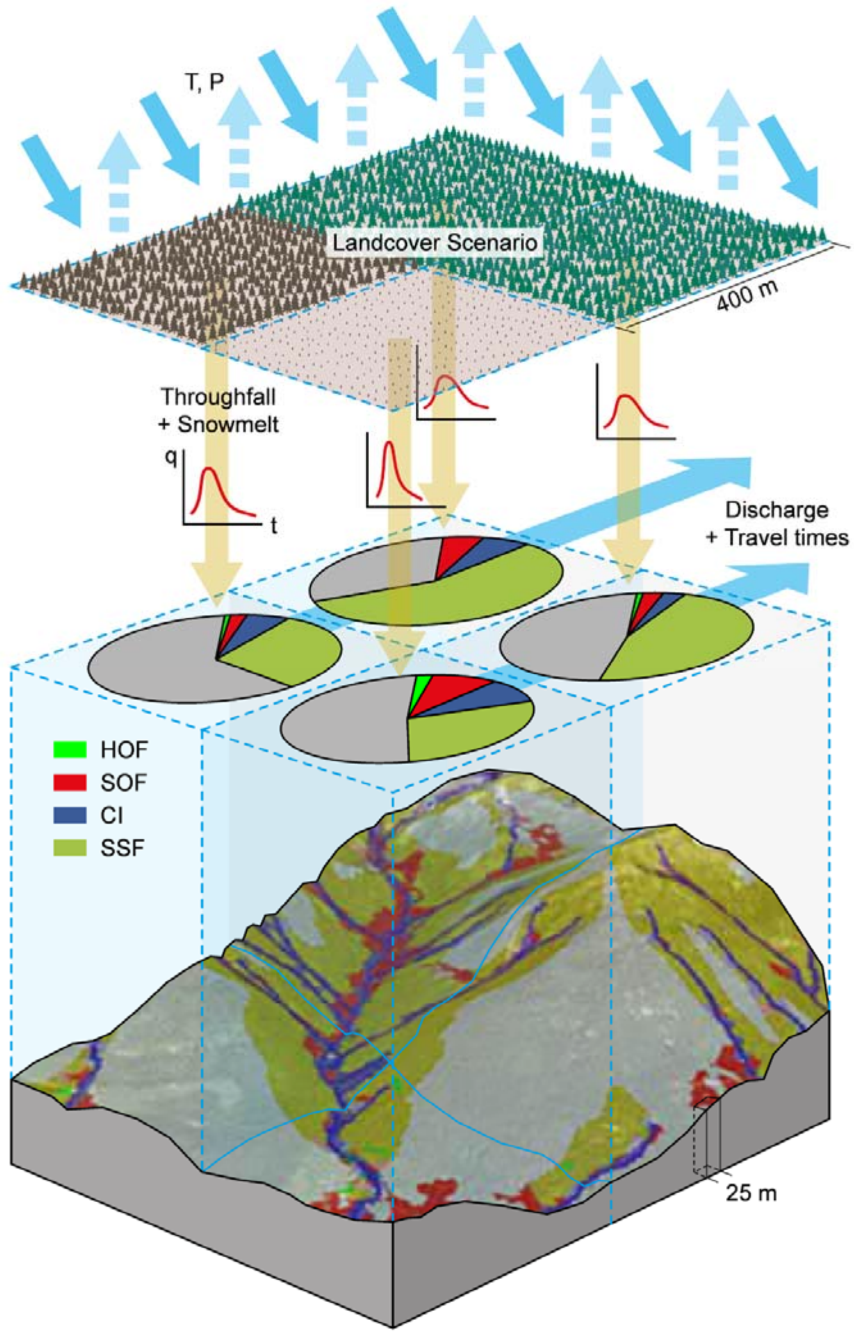


Figure 1. Schematic of the peak-flow model. HOF = Hortonian overland flow, SOF = saturation overland flow, CI = channel interception, SSF = shallow subsurface flow

The Climate Input Module uses the mean monthly climatic precipitation and temperature data available from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) methodology at a 400-m grid spacing for the province of British Columbia (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. 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 is less than T_o and as rain otherwise. Snow melts 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). 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 British Columbia characterizing the main differences in snow dynamics is chosen.

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

2.1.2 Land cover modification module

2.1.2.1 Interaction of precipitation with forest canopy

The forest canopy plays an important role in the amount of rainfall contributing to streamflow. The average rainfall reduction due to interception amounts to 15%–30% of the annual precipitation (Cheng 1989). 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, British Columbia, Canada. In the model, we apply a constant reduction of between 0%–20% depending on vegetation type to account for interception losses for months with rainfall.

Forest canopy also significantly affects snow accumulation and snowmelt—e.g., Berris and Harr (1987) found SWE was two to three times higher in open areas than under forest cover. Winkler (2001) showed that the peak SWE was 11%–32% higher in open areas than in forest. Since detailed GIS data about forest characteristics have been unavailable for meso- to macro-scale watersheds at the provincial level, a general approximation has been undertaken to account for differences in snowmelt and snow accumulation under forest. Because forests have their own microclimates, the snow melt 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 snow melt reductions between 0.4 times (mature fir stands) and 0.9 times (juvenile-thinned pine stand) in comparison to open areas. At this point in the model development, we assume a general reduction of snow accumulation of 30% and snow melt of 20% following Winkler (2001) and results from other authors (Table 1).

2.1.2.2 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—in particular, forests—on rainfall and snowmelt. Since the watersheds in the Fraser River are snowmelt-dominated, the input modification is presented for snowmelt conditions. Table 1 lists several stand-level studies, mostly in British Columbia 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 British Columbia, 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 the open over five 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 snow melt rates, Montana.
[*Toews and Gluns* 1986]	8	11	73	West Kootenay Area, in the south of British Columbia; average seasonal melt rates.
Teti 2007	3-4	5-6.5	50-65	Average melt rates in spring 2007 in lodgepole pine forest in central British Columbia.

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

The effect of mountain pine beetle infestation on the input modification was also considered. Since the beetle 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 under way. After the beetles attack a stand, the needles first turn red (red attack); after a year the needles fall off, and for several years only the tree boles and branches remain (grey attack). The parameterization for the beetle is based on the grey-attack stage since this is the more stable condition. Initial results form several studies in beetle-infested stands have revealed that grey-attack stands are closer to a healthy forest than a clearcut 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 at the larch site was even lower than at the denser cedar site. Since the research about the influence of beetle-attacked stands is not definitive, we have conservatively parameterized the snow-melt rate in grey stands to be three-quarters between that of a healthy stand and that of a clearcut.

2.1.3 Runoff generation module

The four runoff generation processes that contribute to streamflow are channel interception (CI), 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.

2.1.3.1 Channel interception (CI)

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.

2.1.3.2 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 500 m.

2.1.3.3 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 profiles, 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. In addition, riparian zones and areas close to a water body are frequently saturated since the groundwater table is near the soil surface and the moisture deficit is low (McGlynn and Seibert 2003). Arp (2005) developed a methodology to map these areas by iteratively adding 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 these areas are saturated during peak flow if the vertical distance is less than 2 m (Arp 2005).

2.1.3.4 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) claim that in most well-vegetated watersheds, subsurface flow is dominant for various storm types. In British Columbia, soils covered with forests are often shallow and characterized by impeding layers (either fine-textured moraine or bedrock). In the proposed framework, steep slopes with a 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 of 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 greater than HOF, HOF greater than SOF, and SOF greater than SSF. For example, an area that is HOF but also a channel interception area will be classified only as channel interception. Areas not mapped as one of the four processes are considered not to contribute to peak flow. Figure 2 shows an example of mapped DRPs.

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 as follows:

a) channel interception where RCF = 1.0;

b) Hortonian overland flow where RCF = 0.9;

c) saturation overland flow where RCF = 0.8;

d) subsurface flow where RCF = 0.7; and

e) where no dominant runoff generation process is defined, RCF = 0.1.

Average daily peak flow (m^3/s) for each subwatershed is calculated by multiplying the watershed area with the average peak-flow contribution of the watershed.

2.1.4 Stream routing module

The time precipitation takes to reach the outlet of a watershed depends on various factors such as the slope of the landscape and the distance to the 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 determined between each of these stations and the Mission hydrometric station. Additionally, the mean horizontal flow distance is determined for each third-order watershed. Using a regression analysis, the horizontal-flow distance is related to the determined traveling time of the selected hydrometric stations (Figure 3). The found relationship is then used to map the travel time for each third-order watershed to the Fraser outlet (Figure 4).

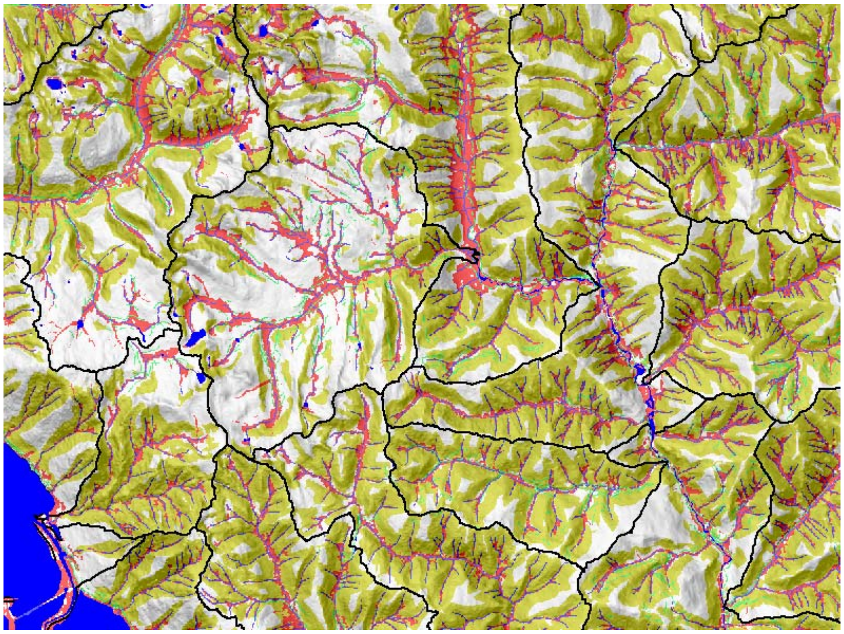


Figure 2. Dominant runoff generation process map for several watersheds along the west arm of Kootenay Lake.

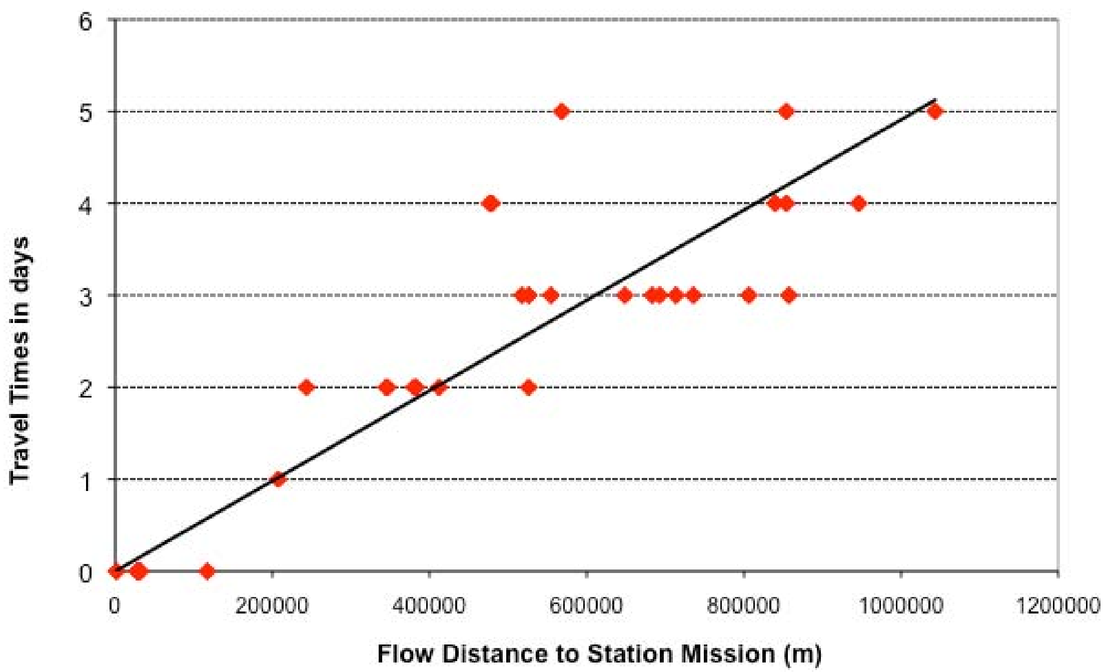


Figure 3. Relation between peak-flow travel distance and travel times to the Mission gauging station for 34 Fraser basin gauging stations.

2.2 Data Inputs

Table 2 provides an overview of key data inputs.

2.2.1 Climate data

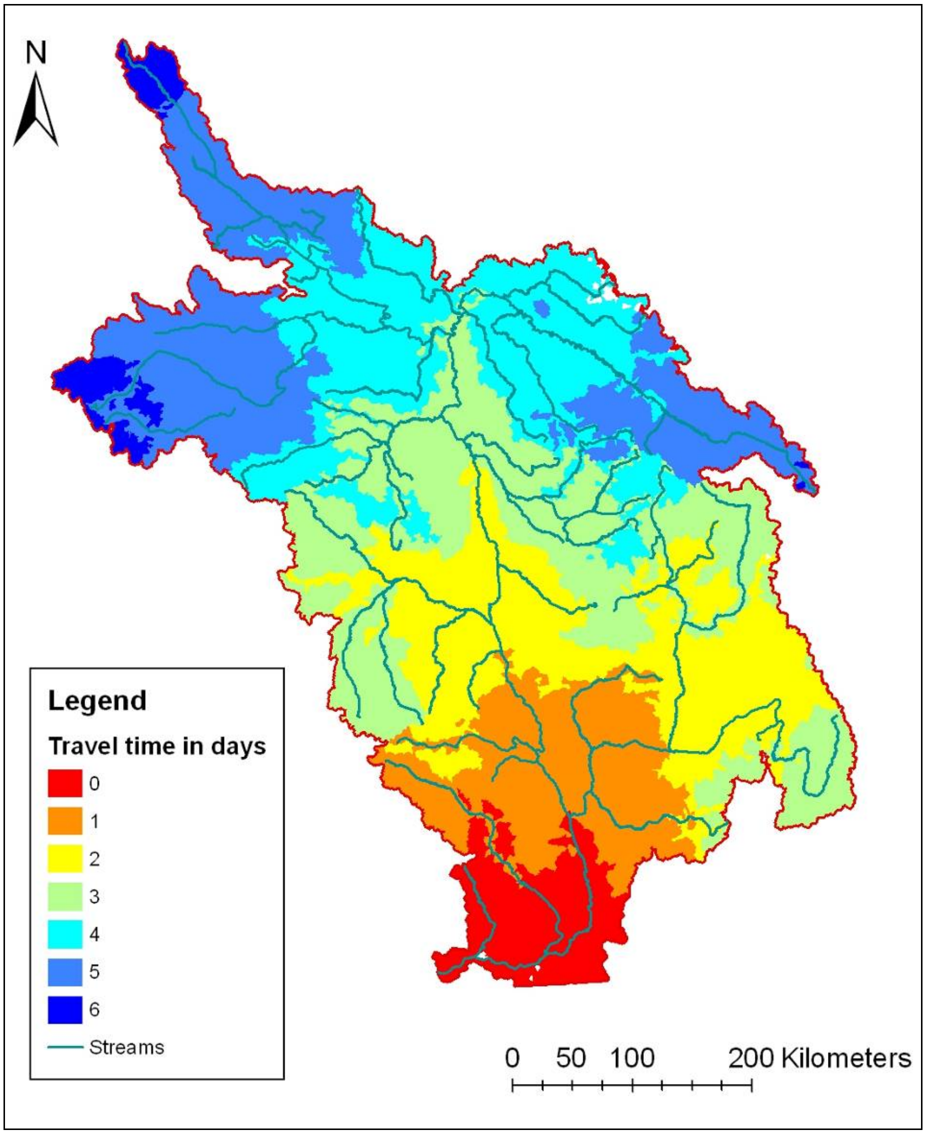
Climate data are provided as mean monthly precipitation and temperature using the PRISM methodology for a 400-m grid spacing for the province of British Columbia (Spittlehouse 2006). Mean daily temperature and precipitation at a site are interpolated from the monthly climate data whereas the monthly values are considered to represent the middle (15^{th}) of the month. The daily values between two monthly values are calculated applying a linear smoothing function between the bounding monthly values. Based on this information, the daily rate of snow accumulation and snow melt have been derived.

2.2.2 GIS data

The elevation information is derived from data from a digital elevation model (DEM). 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. As a result, a hydrologically meaningful DEM at a 25-m resolution has been generated.

For general land-use characteristics, Baseline Thematic Mapping (BTM) has been used—e.g., BCMoE (1995). This information was derived from satellite imagery from the Landsat Thematic Mapper (TM) data (BCMoE 1995). The data set contains 19 land-use classes. Also, 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 beetle 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)" (ME 2008). The Watershed Atlas includes all third-order and greater watersheds and provides a routing system for streams. The Watershed Atlas also provides the stream network used as data input.



. **Figure 4.** Predicted travel times in the Fraser River basin.

Table 2. Overview of 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	ClimateBC	Centre for Forest Gene Resource Conservation, UBC, Research Branch, MoFR	400 m	Spittlehouse (2006)	Climate Input Module
Topography	PRISM Digital Elevation Model	BC MoE, UBC	25 m		Runoff Generation Module
Vegetation	BTM1	Province of British Columbia BC MoE, Surveys and Resource Mapping Branch	1:250.000	BC MoE (Resource Mapping Branch) (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	BCMoE, Fisheries Branch	1:50.000	BC MoE (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		BCMoE	Polyline		Runoff Generation Module

2.2.3 Database development

Managing all the data described above required developing a database. The database is designed to maintain the greatest level of disaggregation but also to combine and extract information at the third-order watershed base. The database allows querying information specific to geographical area or to third-order or higher watersheds. It can also extract the necessary input data for a specific modeling scenario. By only using data for a specific scenario and region, it computes much faster than running the model on the entire provincial level dataset.

To maintain a high level of disaggregation, the province is divided into 400-m grid cells (over 6.2 million cells in total). For each cell, the input information (Table 2) was assigned. In cases of finer spatial resolution (e.g. DEM and DRPs), aggregation procedures are applied. The 25-m DEM information was aggregated using mean value over the 16 contributing cells. For the DRP information, the area percentage of each runoff process is delineated for each grid cell.

3 Model Application

3.1 Study Area

The Fraser basin covers 231,500 km^2 or 24.5% of the province of British Columbia (BCMoE 1996). Due to the high computational power required by simulating the entire Fraser basin at once, we selected eight smaller watersheds. The selection criteria were variable beetle infestation and pine coverage (Table 4) as well as watershed size (Table 3) to allow an analysis of land-cover changes over various spatial scales.

Table 3. Overview on watershed area for selected watersheds in the Fraser basin.

Station number	***Station name***	***Area in km^2***	
		Water Survey of Canada	Peak-flow Model
08MB005	Chilcotin River below Big Creek	19300	19388
08KH006	Quesnel River near Quesnel	11500	11824
08KE009	Cottonwood River near Cinema	1910	1982
08KC001	Salmon River near Prince George	4300	4259
08ME025	Yalakom River above Ore Creek	575	654
08JE001	Stuart River near Fort St. James	14600	14220
08JB003	Nautley River near Fort Fraser	6030	6518
08LG008	Spius Creek near Canford	780	777

As the table above indicates, there are differences in the watershed areas. In the peak-flow modeling, the watershed boundaries from the third-order Watershed Atlas (Province of British Columbia 1996) are used. Those watersheds are delineated using river confluences instead of hydrometric stations to determine the watershed outlet. Based on this delineation procedure, the third-order watersheds are often larger than the actual watershed of the hydrometric station. This would presumably lead to an increase in runoff. However, the model objective is to predict peak-flow changes due to land-cover modifications. In most watersheds of British Columbia, the peak flow is produced mainly in the snow-covered mountains surrounding the actual river. Therefore it can be assumed that the introduced error is negligible.

Table 4 summarizes the beetle-affected area, pine coverage, and forest coverage for the eight selected watersheds. All watersheds except Quesnel are dominated by pine tree forest cover. They vary in their severity of beetle infestation from more than 58% affected in the Chilcotin, Nautley, Cottonwood and Salmon watersheds to less than 7% in the Spius and Yalakom Rivers.

Table 4. Mountain pine beetle-affected area, pine coverage and forest cstoverage for selected watersheds in the Fraser basin.

Station number	Station name	Beetle affected** [% of area]*	Pine Coverage [% of area]*	Forest Coverage [% of area]
08MB005	Chilcotin River below Big Creek	63	77	78
08KH006	Quesnel River near Quesnel	28	34	70
08KE009	Cottonwood River near Cinema	56	58	85
08KC001	Salmon River near Prince George	63	78	84
08ME025	Yalakom River above Ore Creek	2	74	77
08JE001	Stuart River near Fort St. James	40	63	80
08JB003	Nautley River near Fort Fraser	69	78	80
08LG008	Spius Creek near Canford	7	77	90

* For this calculation, as well as in the model simulation, the 400-m grid cells were treated as homogeneous cells with no internal distribution. This leads to an overestimation of the actual area affected by mountain pine beetle or covered with pine vegetation.

** Affected area was calculated as a cumulative-area infestation over the years 1999 and 2007. The numbers represent grey-stand infestation.

3.2 Modeled Disturbance Scenarios

Six disturbance scenarios are reported. Two scenarios exclude beetle effects to provide insight into possible baseline conditions against which the mountain pine beetle results can be compared. These are

1) a hypothetical situation of a landscape with no disturbance, so that all forested sites have mature stand conditions and

2) the vegetation cover before the disturbance started (i.e., 1995 forest cover).

In addition, four 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 beetle infestation levels and total possible beetle infestation. Described in Table 4, Scenarios 3 and 4 reflect current levels of beetle-related pine death for 0% and 100% salvage, respectively, while Scenarios 5 and 6 reflect complete pine death for 0% and 100% salvage, respectively.

Table 5. Vegetation modification associated with each of the six modeled disturbance scenarios.

Scenario	Description
1	Fully forested conditions wherever a forest can grow.
2	Vegetation cover in 1995 based on data from baseline thematic mapping (equals baseline).
3	Scenario 2 plus 2007 pine death as derived from Forest Health Data (i.e.,red attack from satellite imagery).
4	Scenario 3 plus clearcut salvage harvest of 100% (by area) of the beetle-killed pine.
5	Scenario 2 plus pine death for all pine stands as derived from Eng et al. (2006).
6	Scenario 5 plus clearcut salvage harvest of 100% (by area) of all pine.

3.2.1 Undisturbed forest conditions (Scenario 1)

The undisturbed forest conditions represent a hypothetical situation in which forest cover provides the maximum protection against hydrologic hazards. Neither natural nor anthropogenic disturbances are represented in this situation. Conversely, natural disturbance regimes identified for British Columbia indicate that some portion would be in a disturbed state at any one time (e.g. Wong et al. 2003; DeLong 1998). As a result, this situation must be interpreted with caution as it represents an unattainable state, but it does provide an extreme comparison to a landscape where maximum protection against hydrologic hazards is provided by fully forested conditions.

3.2.2 Forest condition in 1995: baseline scenario (Scenario 2)

This scenario represents the baseline in our modeling approach. Therefore, 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 beetle activity.

3.2.3 Pine death and salvage based on 2007 mountain pine beetle-infestation levels (Scenarios 3 and 4)

Building on Scenario 2, Scenarios 3 and 4 introduce forest disturbance. The spatial extent of the disturbance is derived using the Forest Health Data Inventory (Eng et al. 2006). This data set uses satellite imagery to detect areas under red attack in British Columbia. The current conditions are built assuming grey attack occurs one year after red attack and thus considers the years 1999–2006. Two scenarios are modeled: Scenario 3 simulates the impact of pine death on peak flow, and Scenario 4 models the impact of salvage harvest on peak flow. We are modeling grey-attack tree harvest when 100% of the area is under grey attack.

3.2.4 Pine death and salvage based on mountain pine beetle affecting all pine stands (Scenarios 5 and 6)

This scenario incorporates the hypothetical situation in which all pine trees die from beetle attack. This scenario allows portraying the maximum effect of beetle infestation in British Columbia. Within this context, Scenario 5 represents no salvage action taken, whereas Scenario 6 reflects a complete clearcut salvage response of all pine trees.

4 Results

4.1 Dominant Runoff Processes

The mapping of the dominant-runoff-producing areas was done in close cooperation with the project "Development of a Hydrologic Process Model for Mountain Pine Beetle affected Areas in British Columbia" of the Fraser Salmon and Watershed Program. Without contribution from this project, the necessary datasets pertaining to the DRPs at a 25-m grid resolution would have been unavailable for the peak-flow simulation of this project. The 25-m resolution data were aggregated to the 400-m resolution used for the simulation with the peak-flow model (see Figure 1).

Figure 5 shows the map of the proportion of areas producing saturation overland flow (SOF). Large areas of the Interior Plateau are dominated by runoff produced from saturated areas. This relates well to the larger proportion of wetlands in this area 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 6) is much more distinct than the distribution of SOF because subsurface flow can be a relevant process only if the hillslopes are steep and connect 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.

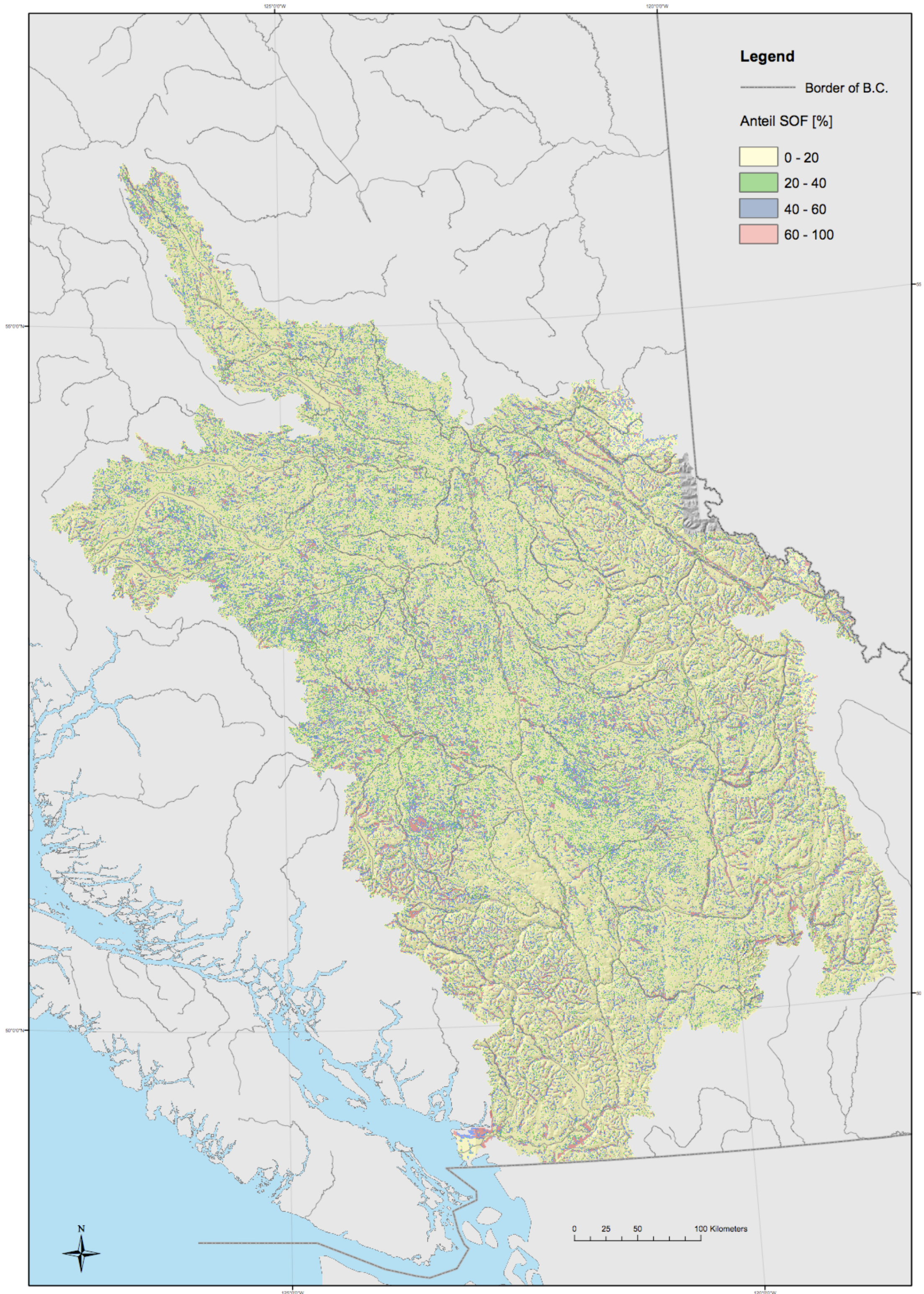


Figure 5. Proportion of area in each 400-m grid cell dominated by saturation overland flow (SOF). Map is also available as a high-resolution PDF.

Figure 6. Proportion of area in each 400-m grid cell dominated by lateral subsurface flow (SSF). Map is also available as a high-resolution PDF.

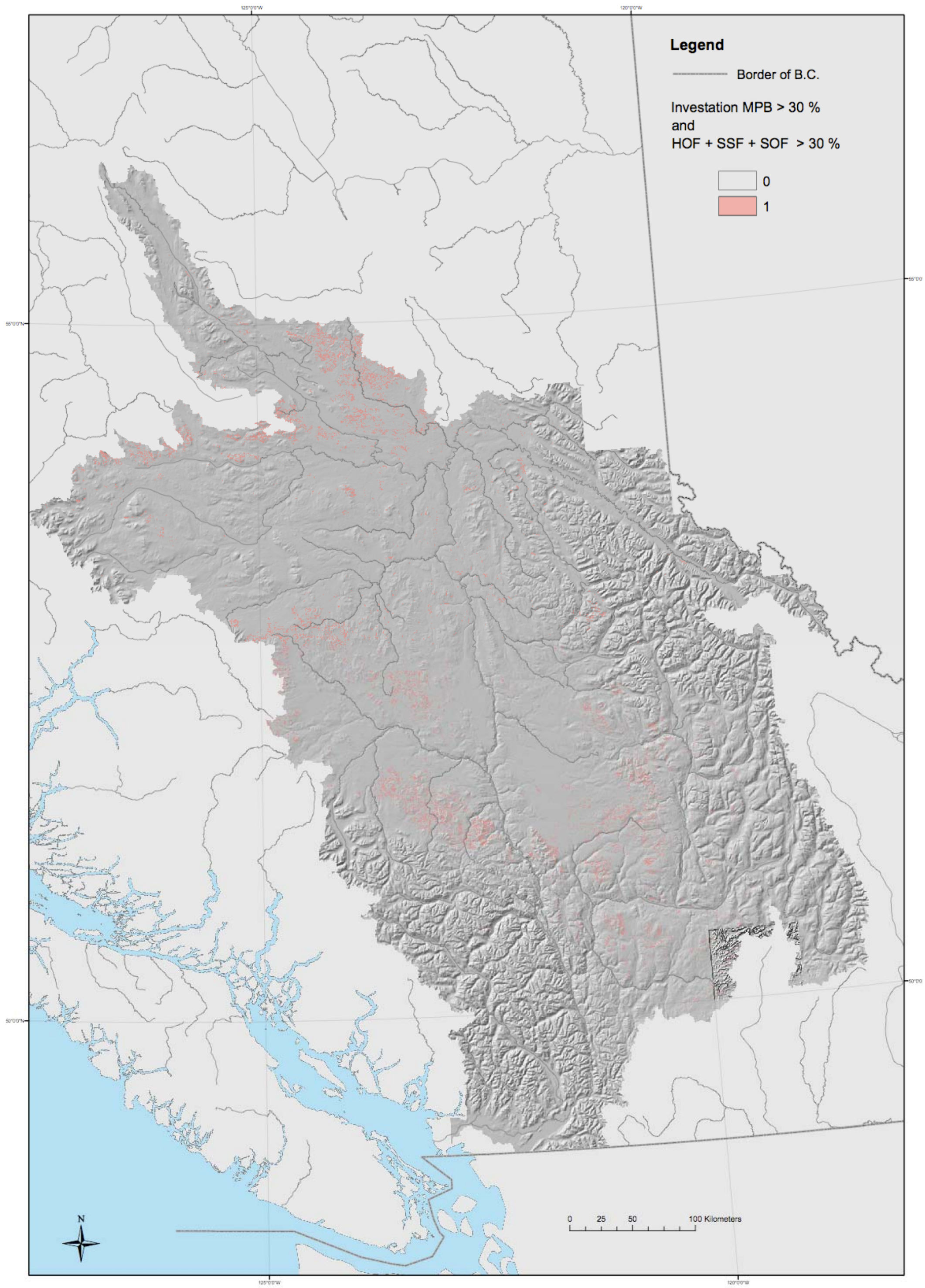


Figure 7. Areas with a high probability of being influenced by beetle infestation due to a high degree of hydrologically sensitive areas (i.e., areas with a high proportion of runoff generated in infested areas). Map is also available as a high-resolution PDF.

Already the information and distribution about dominant-runoff generation can be used to derive a hydrologic sensitivity map (Figure 7). The map shows areas in red that are infested by the mountain pine beetle with a severity greater than 30% in 2007 and could generate substantial 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 snow melt accelerated and snow accumulation increased, the runoff from these areas will also increase at a much higher rate than in other areas.

4.2 Model Validation for Scenario 2 (Baseline)

As 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 DRPs 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 six 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 6. Observed and simulated timing and volume of the peak flow for selected watersheds.

Station number	Station name	Observed		Simulated	
		Mean annual peak flow [m^3/s]	Timing (DOY)	Mean annual peak flow [m^3/s]	Timing (DOY)
08MB005	Chilcotin River below Big Creek	264.1	209	252.4	186
08KH006	Quesnel River near Quesnel	655.6	167	216.3	134
08KE009	Cottonwood River near Cinema	99.8	135	33.0	108
08KC001	Salmon River near Prince George	156.4	127	135.7	114
08ME025	Yalakom River above Ore Creek	13.2	153	14.7	135
08JE001	Stuart River near Fort St. James	309.4	185	403.2 [302.4]	118
08JB003	Nautley River near Fort Fraser	86.8	151	197.8 [89.0]	115
08LG008	Spius Creek near Canford	45.8	149	22.5	143

DOY = Day of the Year

Table 6 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 quite accurately with an error within 15%. 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 lots of water and slowly releasing it. The peak-flow model has not yet implemented lake routines and we are not surprised that the model cannot reproduce this behaviour. 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 brackets in Table 6). The Spius Creek also shows a very poor performance in the Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model model (Schnorbus et al. 2009). We believe that the gauging station is not producing correct data since the predicted total precipitation for the whole year is less than the observed annual runoff. Also, the VIC model shows a very strong negative bias for the Quesnel River which could relate to an underprediction of the precipitation or a problematic discharge record. It is also surprising that the observed mean runoff for this gauging station is 655 mm, 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 error in these cases.

The timing of the peak flow is generally predicted early on average by 5–20 days and, in the case of the Stuart River, by 67 days. This could be because the model does not include storage in lakes, which is an important process. Additionally, the fast onset of snowmelt as simulated could also be related to the use of climatic data instead of meteorological data.

4.3 Scenario Outcomes

Results presented in this section are preliminary. Medical concerns during the winter of 2008/09 postponed simulating the peak-flow changes for the entire Fraser watershed and all scenarios until the end of March. This model-development work and its implementation in R (free software) started late but will continue.

At this stage, we can present the first results for the eight selected watersheds (see study area description). In the section Next Steps, we will indicate the steps required before publishing the results.

The results given in the following paragraphs are relative values to the baseline Scenario 2. The baseline scenario defines a hydrologic situation consistent with the land cover distribution of 1995.

4.3.1 Undisturbed forest conditions (Scenario 1)

As explained earlier, Scenario 1 is a hypothetical scenario that assumes no disturbances (natural or anthropogenic) within the watershed. In this scenario, all natural and human activities (such as agriculture, burned areas and logged areas) have been eliminated and are mapped as forested areas. According to Table 7, the watersheds show a decrease in peak-flow volume of between 0.1% and 6.9%. The highest changes occur in the Salmon, Nautley and Cottonwood basins. By mapping the relative changes at the third order watershed level, a more detailed distribution is available (Figure 8). This spatial variance is caused by differences in land-cover distribution. Sub-basins having a high percentage of logging activities and agricultural areas, such as the sub-basins along the main river stem in the Cottonwood and Salmon watersheds, indicate peak-flow decreases higher than 15%.

Additionally, spatial scale effects are indicated. The Chilcotin watershed depicts nearly no change in mean annual peak-flow volume in this scenario. As shown in Figure 8, sub-basins in the southern part of the watershed show only small changes, whereas the northern parts of the watershed with rangeland and agricultural areas show decreases of up to 22%. However, those sub-basins represent only 15% of the Chilcotin watershed area whereas in the Salmon, Nautley and Cottonwood watersheds, more than 33% of the basin areas is affected. It is concluded that small vegetation changes do not have an effect on peak-flow changes.

Table 7. Peak-flow changes for each scenario for selected watersheds in the Fraser basin.

Station number	Station name	Baseline Scenario 2	Disturbance Scenario 1		Disturbance Scenario 3		Disturbance Scenario 4		Disturbance Scenario 5		Disturbance Scenario 6	
		Peak flow [m^3/s]	Peak flow [m^3/s]	% change from Scen. 2	Peak flow [m^3/s]	% change from Scen. 2	Peak flow [m^3/s]	% change from Scen. 2	Peak flow [m^3/s]	% change from Scen. 2	Peak flow [m^3/s]	% change from Scen. 2
08MB005	Chilcotin River below Big Creek	252.4	252.1	-0.1	258.3	2.3	263.9	4.5	275.2	9.0	291.2	15.4
08KH006	Quesnel River near Quesnel	216.3	214.1	-1.1	220.4	1.9	224.2	3.6	225.3	4.1	232.1	7.3
08KE009	Cottonwood River near Cinema	33.0	30.7	-6.9	39.7	20.2	43.5	31.8	40.5	22.6	44.8	35.6
08KC001	Salmon River near Prince George	135.6	129.5	-4.6	157.7	16.2	170.7	25.8	165.6	22.1	183.2	35.0
08ME025	Yalakom River above Ore Creek	14.8	14.7	-0.2	14.9	1.0	14.9	1.0	18.7	26.4	20.9	41.9
08JE001	Stuart River near Fort St. James	302.4	295.9	-2.1	330.8	9.4	347.3	14.9	351.4	16.2	379.6	25.5
08JB003	Nautley River near Fort Fraser	89.0	84.4	-5.2	102.7	15.3	110.6	24.2	105.1	18.0	114.3	28.4
08LG008	Spius Creek near Canford	19.3	18.8	-2.6	19.5	1.2	19.7	1.9	23.9	24.0	26.6	38.1

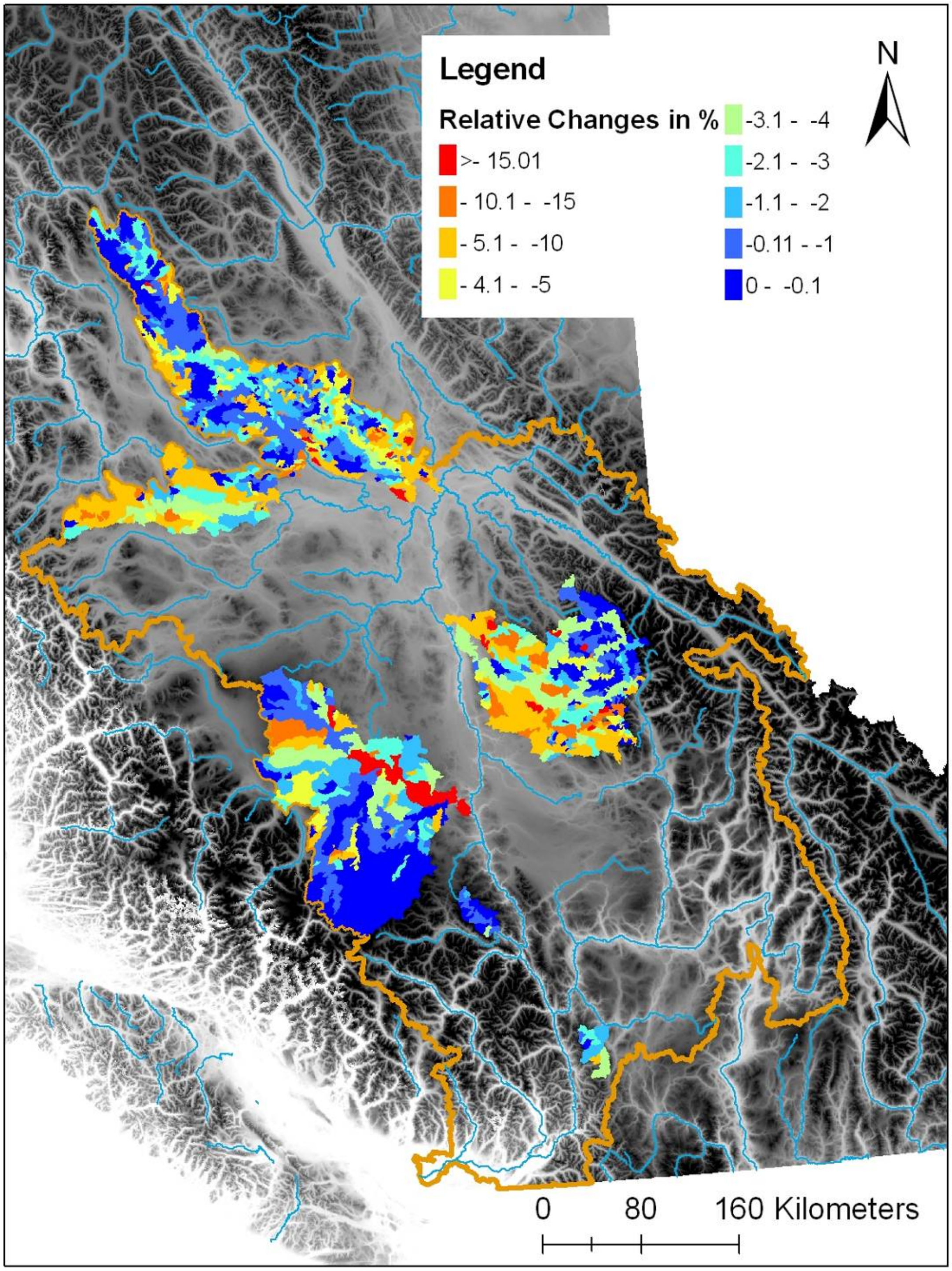


Figure 8. Peak-flow change for Scenario 1 relative to Scenario 2 baseline for selected third-order watersheds.

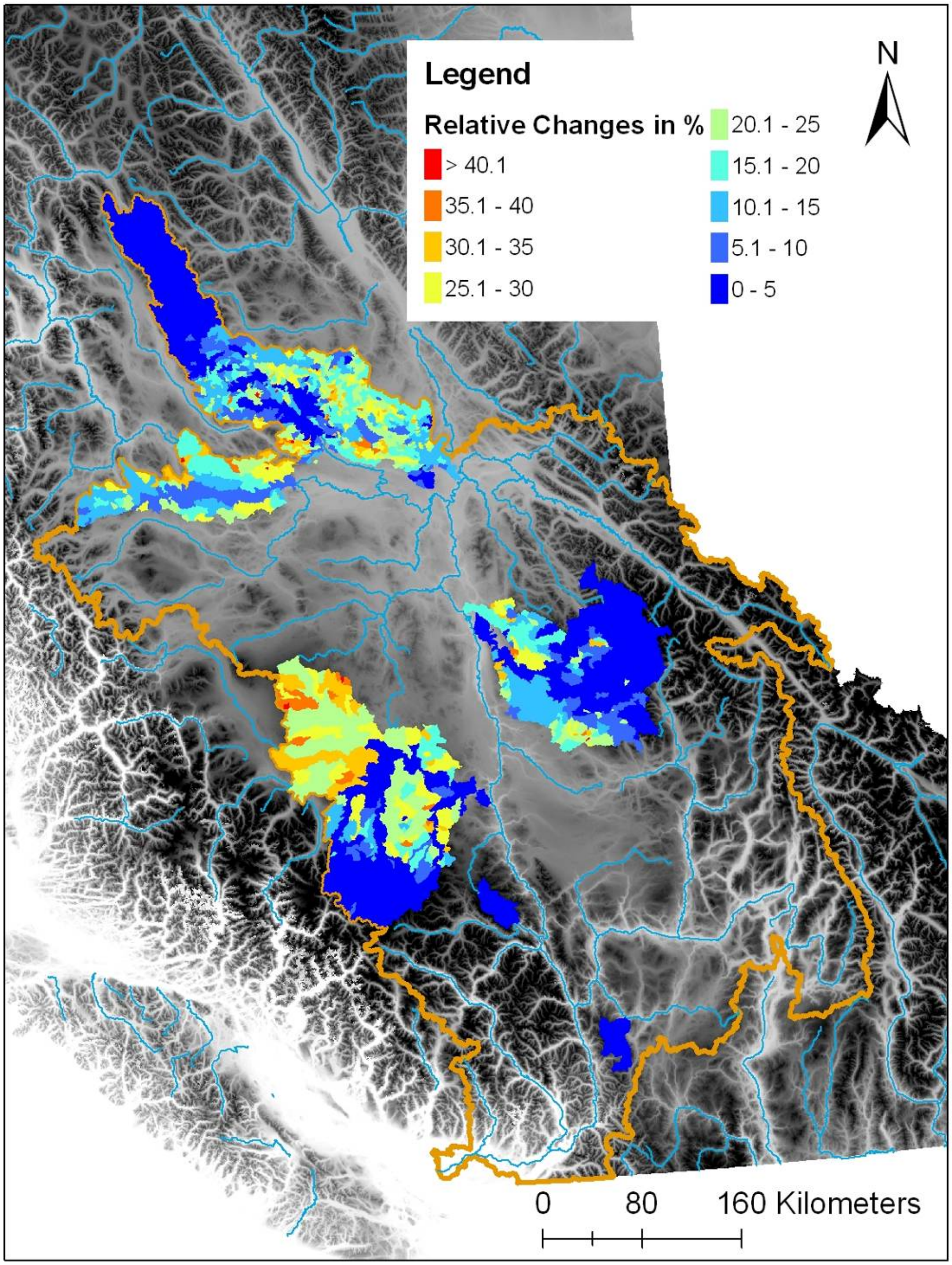


Figure 9. Peak-flow change for Scenario 3 relative to Scenario 2 baseline for selected third-order watersheds.

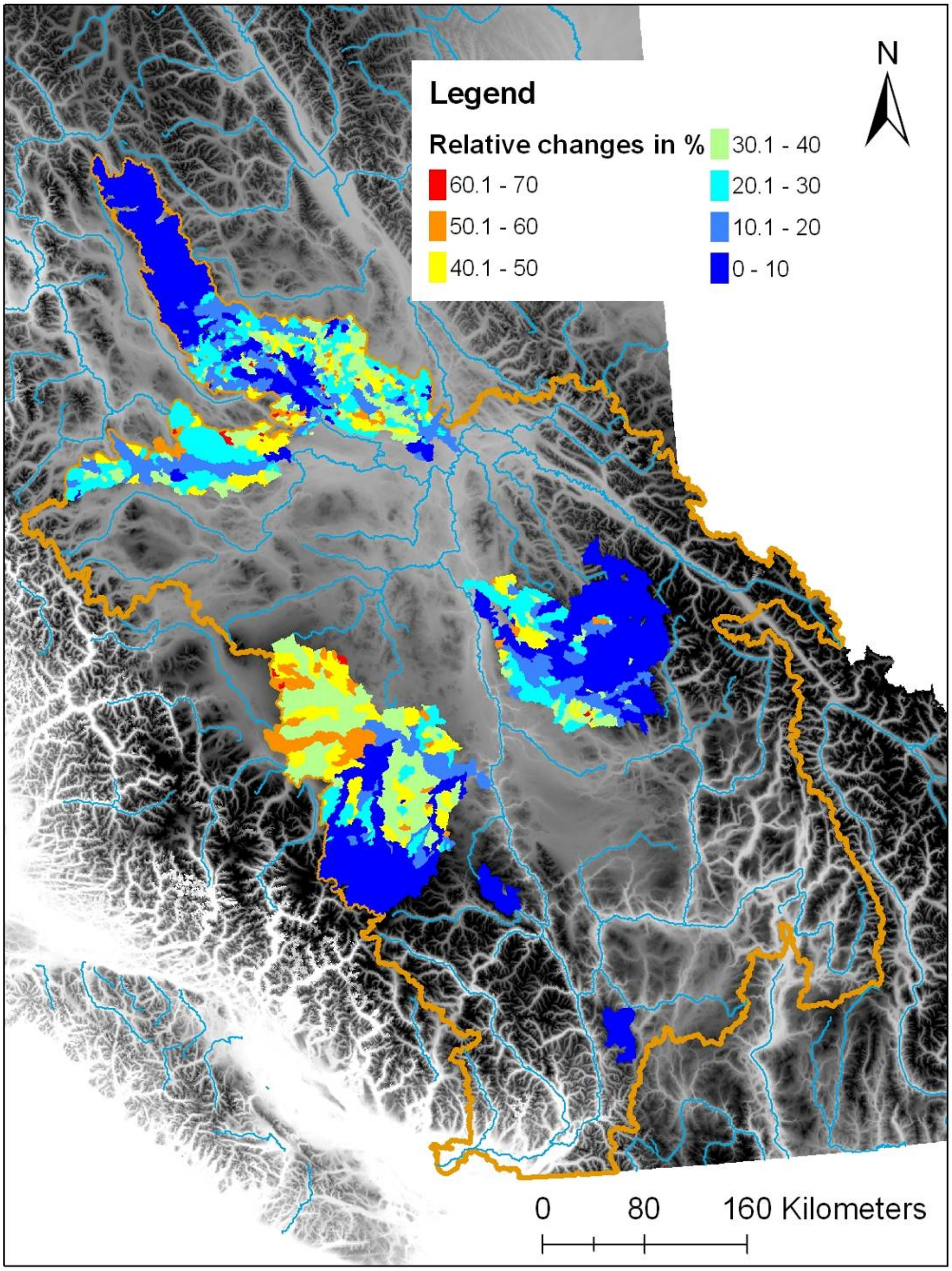


Figure 10. Peak-flow change for Scenario 4 relative to Scenario 2 baseline for selected third-order watersheds.

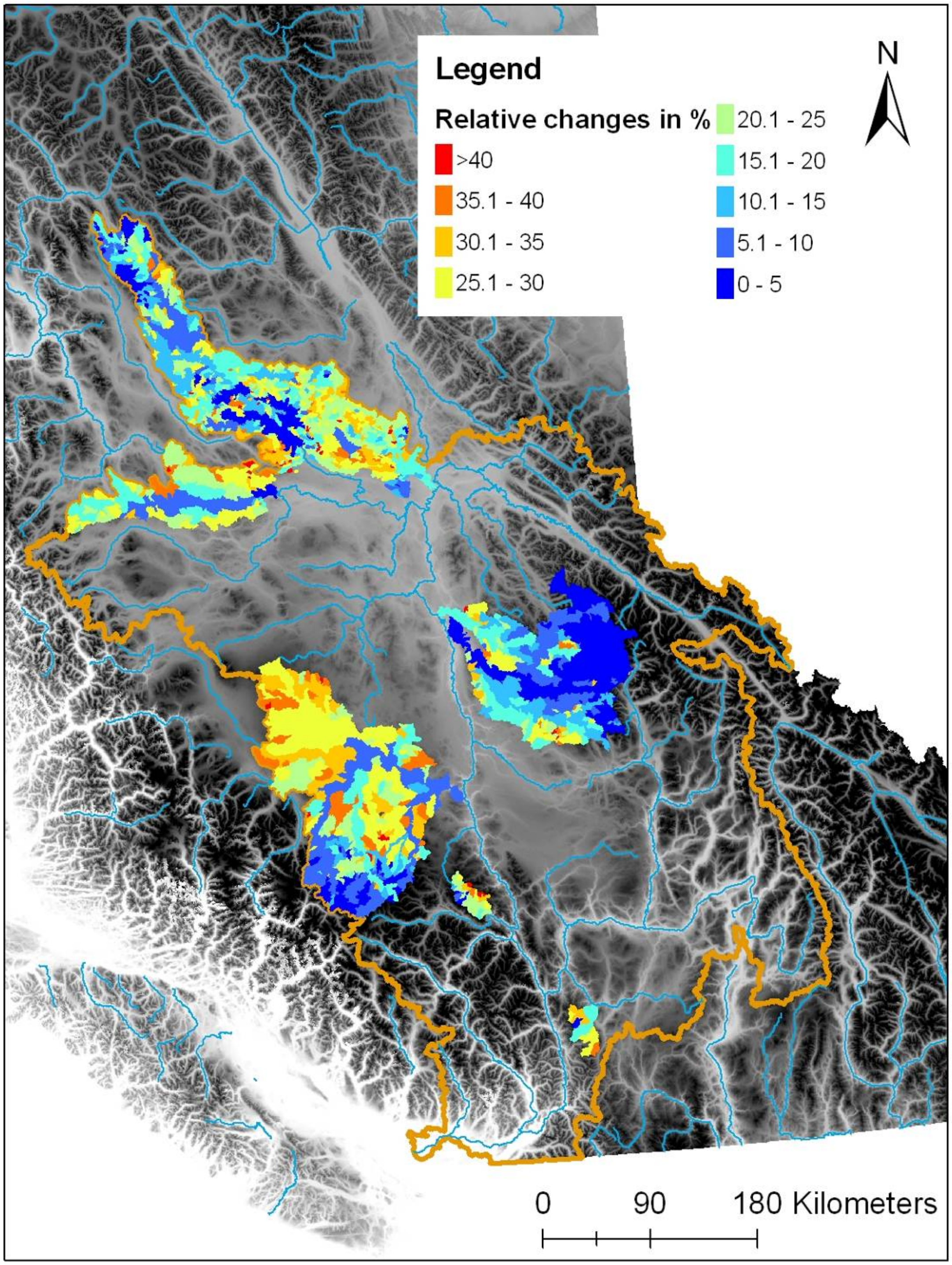


Figure 11. Peak-flow change for Scenario 5 relative to Scenario 2 baseline for selected third-order watersheds.

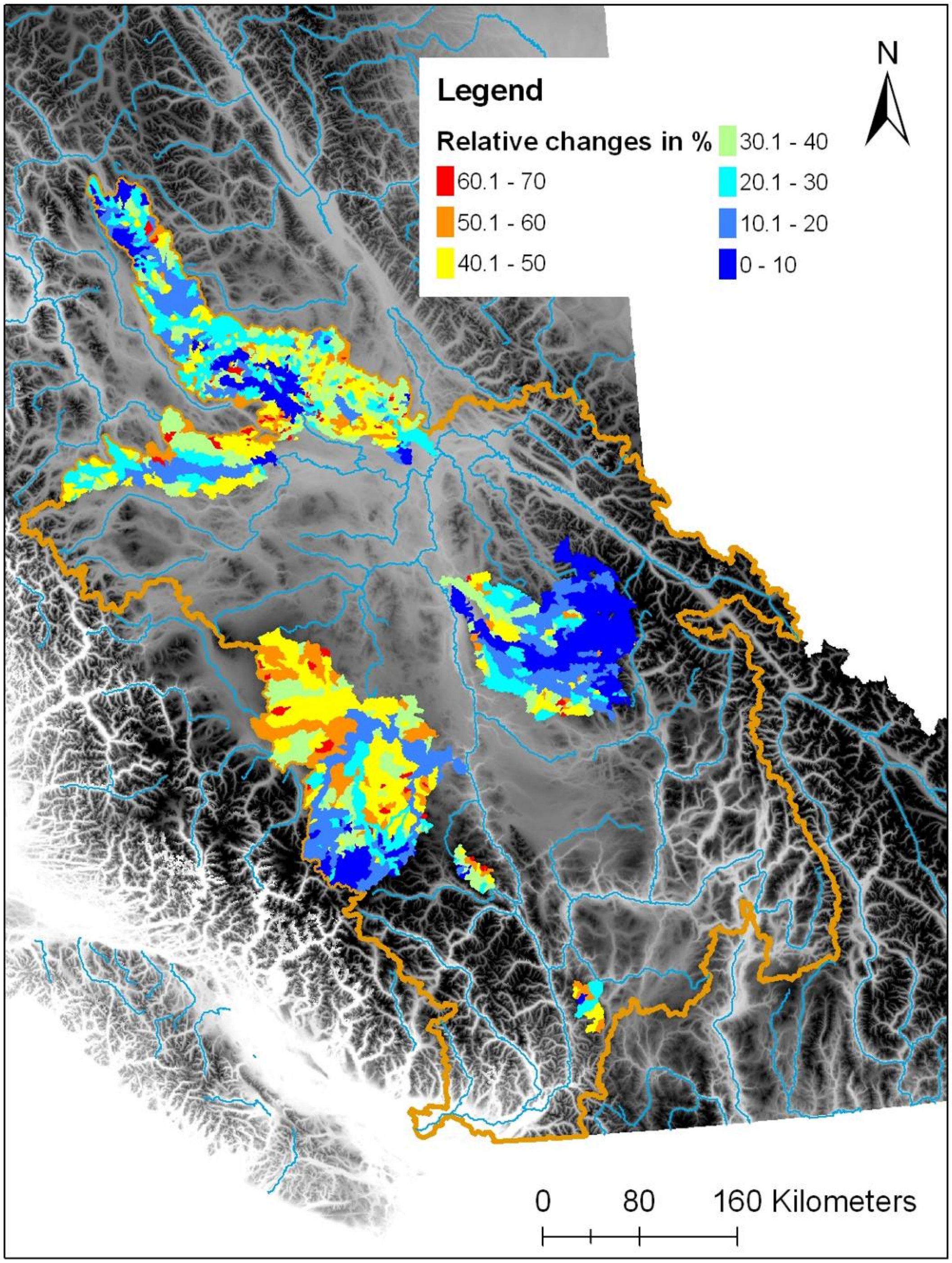


Figure 12. Peak-flow change for Scenario 6 relative to Scenario 2 baseline for selected third-order watersheds.

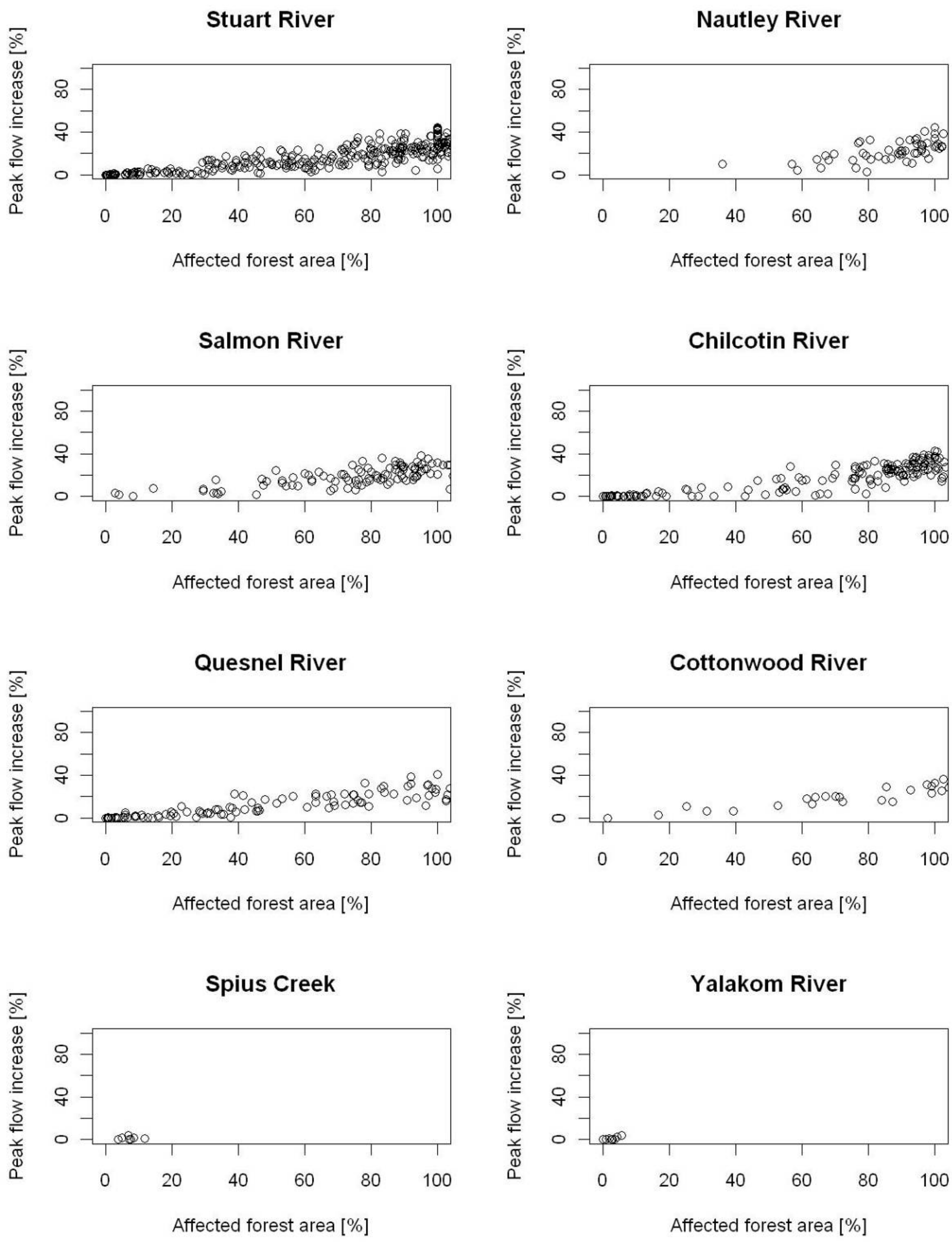


Figure 13. Scatter plots showing the beetle-affected areas (Scenario 3) against the resulting (simulated) peak-flow changes for selected drainages.

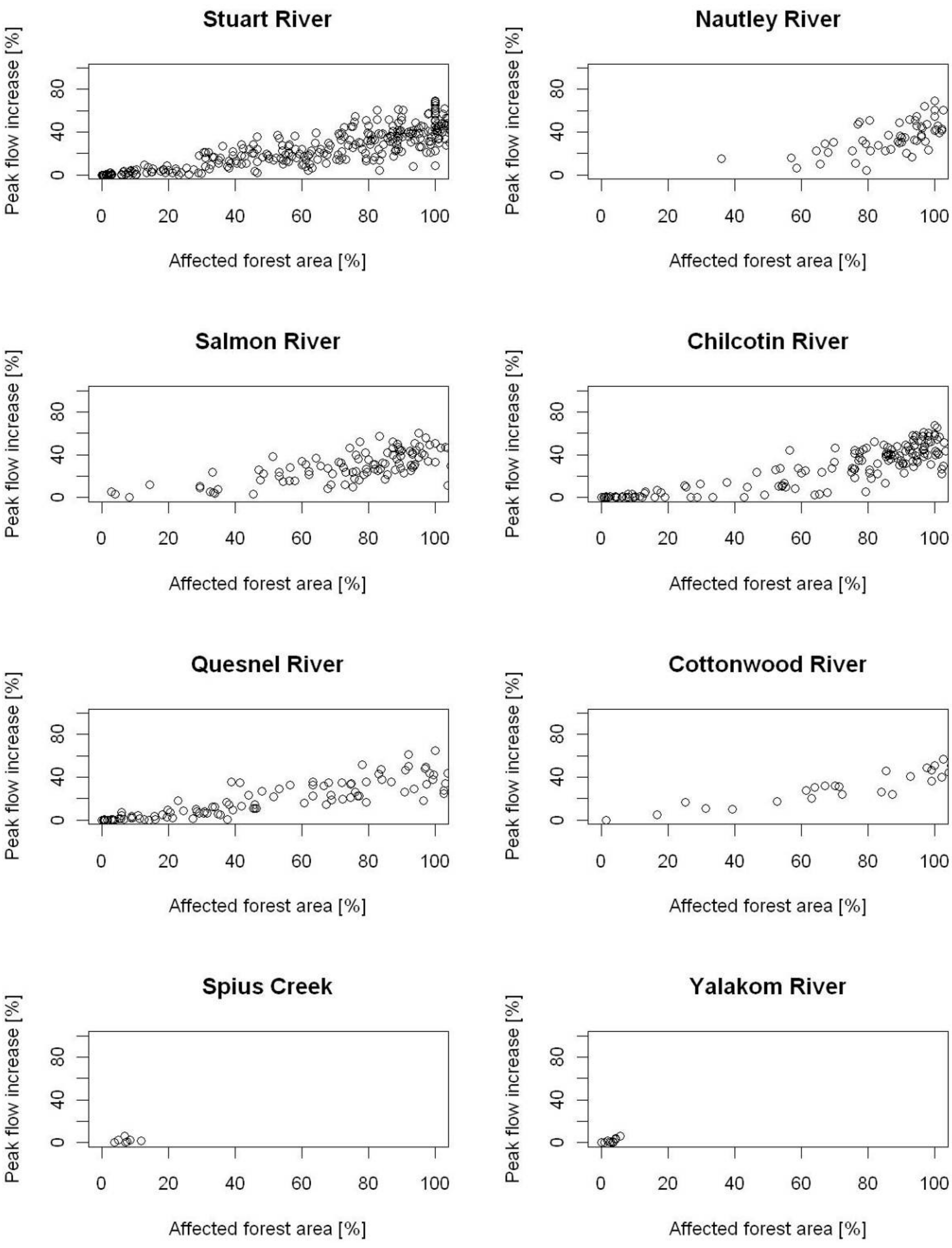


Figure 14. Scatter plots showing the beetle-affected areas (Scenario 4) against the resulting (simulated) peak-flow changes for selected drainages.

4.3.2 Pine mortality and salvage to 2007 beetle condition (Scenarios 3 and 4)

Scenarios 3 and 4 are derived based on the total effects of mountain pine beetle grey attack as of 2007. Scenario 3 assumes that the beetle-affected trees are dead (in grey stands) and Scenario 4 assumes 100% salvage harvest of these dead stands.

As expected, the model simulates an increase in peak flow when forest cover is reduced. For dead pine forests (grey-stand condition), the model predicts peak-flow increases of 0.7%–20.2%. The highest predicted changes occur in the Cottonwood, Salmon and Nautley watersheds, paralleling the high percentage of beetle attack in those watersheds (Table 4). Only small changes are shown in the Spius, Yalakom and Quesnel watersheds, with increases under 5%, due to the low area amount (less than 28%) of grey stands in these watersheds. The Chilcotin watershed plays a special role: about 63% of it is under grey attack in this scenario, yet the model predicts only a 2.3% increase in peak flow. Here, processes requiring further examination must be responsible for this spatial distribution.

In Figure 9, peak-flow increases are examined at third-order watershed base. The figure displays a spatial variance for most of the selected watersheds. It relates the peak-flow changes as a function of the affected forest cover in percent on a third-order watershed basis. The graphs indicate a link between affected forest and the magnitude of peak-flow increase for the Stuart, Nautley, Salmon, Chilcotin, Quesnel, and Cottonwood Rivers. This relationship is not obvious in the Yalakom River and Spius Creek watersheds due to the small amount of contributing third-order watersheds. The graphs also point toward an onset threshold. A reduction of forest cover of under 20% of the watershed area results in no increase or only small increases in peak flow. This behaviour was already identified by Hibbert (1967) and it seems to be confirmed in this simulation. The graphs also indicate an upper limit of peak-flow increase at 45% for grey-stand forest.

In Scenario 4, the beetle-affected area is 100% harvested. While the upward trend with the affected forest area is the same, harvesting grey-affected trees further increases peak flow. Watersheds with high beetle-kill such as Cottonwood and Salmon Rivers show a high increase in peak flow (greater than 25%) and watersheds with low beetle infestation, i.e., Yalakom River and Spius Creek, show only small increases in peak flow (less than 2%). However, the increase in peak flow from grey stand to non-forested areas does not occur linearly. The Cottonwood watershed, for instance, shows an increase of 11.6% in Scenario 4. The Stuart River, however, illustrates an increase of only 5.4%. Additionally, the increase in the mean annual peak flow is lower than the predicted changes from forest to grey stand. Figure 10 highlights the spatial distribution for peak-flow increases on a third-order watershed basis. This figure represents similar trends to Scenario 3. In Figure 13, the peak-flow increase is plotted against the forest-affected area and is comparable to the results of Scenario 3 with forest changes under 20% showing no peak-flow or small peak-flow increases, similar to Hibbert (1967). This scatterplot also indicates an upper limit for peak-flow changes: when 100% of the grey stand affected trees are removed, the maximum peak-flow increase is 70%. In these examples, the removal of 100% forest cover increases the peak flow by a maximum increase of 70%. This may be a general finding.

The simulated results show a special role for the Chilcotin watershed and its sub-basins. About 63% of the watershed area is affected by the beetle but the predicted peak-flow increase is only 2.3% (Scenario 3) and 4.5% (Scenario 4). The Chilcotin watershed is the largest selected watershed (Table 3). Due to the large catchment size, scale effects might be the reason for these small values in peak-flow change. This will be further investigated by applying the model on other larger watersheds in the Fraser basin.

4.3.3 Full pine mortality and salvage (Scenarios 5 and 6)

These two scenarios assume that the entire pine coverage in the Fraser basin is under grey attack (Scenario 5) and then harvested (Scenario 6). The results for these watersheds are displayed in Table 7 and Figure 12.

As expected, the model predicts higher peak-flow increases when higher percentages of the area are affected by vegetation reduction. The model simulates increases in the peak-flow volume of 4.1%–26.4% for grey stand pine coverage and 7.3%–41.9% when these pine stands are salvage harvested. With the exception of the Chilcotin watershed, high pine coverage also leads to higher peak-flow increases. Figure 11 and 12 display the spatial variance of increasing peak-flow volume at a third-order watershed basis. In general, more sub-basins in the watersheds show peak-flow increases. This observation can be traced back to the existence of pine stands in these sub-basins. As argued before, there is a clear relationship between affected forest area and peak-flow increase which was shown in a similar analysis undertaken for Scenarios 3 and 4. Additional analysis gives similar indications. First, reductions in forest cover of under 20% of watershed area lead to little or no increase in peak flow, as originally shown in Hibbert (1967). Second, the analysis suggests, again, an upper limit in peak-flow increase of 70% (the same as in Scenario 4.) This identical result is not a surprise because these watersheds have 100% pine and hence the scenarios are essentially the same.

4.4 Summary of Modeling Results

The modeling results can be summarized as follows:

- An increase in forest cover reduces peak flow.
- A reduction in active forest cover or the removal of forest cover increases peak flow.
- Small or no increase in peak flow occurs when forest reductions are lower than 20% (as already mentioned in Hibbert (1967).
- Preliminary analysis indicates an upper limit in peak-flow increase of 45% for grey-stand forest and 70% for complete removal of trees.
- Equal area reductions in vegetation do not lead to the same peak-flow increases and suggest the existence of scale effects and/or thresholds.
- Harvesting activities have a greater impact on peak flows than does grey attack; similar findings were published by the Forest Practices Board (2007).

5 Discussion

5.1 Data Issues

A key objective in developing this model is to make it applicable to all watersheds and, in particular, ungauged basins throughout the province. Thus, only data covering the entirety of British Columbia has been used.

5.2 Limitations

The applied model uses the concept of DRPs to determine areas which contribute more or less to watershed runoff. For simplification, a 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 landform 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 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 Spius Creek watershed, the input data are not exact. It can be assumed that data errors limit the information value derived from the simulated model results.

The model uses long-term climate averages as driving input data, which limits the information value of simulated peak-flow changes. The current model set-up allows predictions of only changes in mean annual peak flow (2.3 year return period). Larger peak-flow events, as well as changes in flood probability, are not possible to simulate.

5.3 Model Flexibility

The model can be used to derive changes on all relevant scales (third-order watershed up to larger tributaries of the Fraser River basin.) The model framework can implement new findings of stand-level research on snow accumulation and melt. In 2008, the Forest Sciences Program project Equivalent clearcut area thresholds in large-scale disturbed forests (Weiler et al. 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 this 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.

5.4 Management Implications

The model can be used to develop best-management scenarios. For example, where can a beetle-infested forest be logged while minimizing the effects on peak flow? Modeling provides direct and spatially-explicit results at a relevant scale (0.4-16 ha) to relate forest management to hydrological processes.

5.5 Next Steps

The next step in the model development is to apply the model to the entire Fraser River basin. This requires several more weeks given the computationally intensive nature of the calculations and visualisations. The goal of this step is to determine the spatial variance of the peak-flow increase and to detect watersheds which have a high sensitivity to beetle infestation.

In Section 5.2, we compared simulated and observed peak-flow values. The comparison for Stuart and Nautley River watersheds has shown that, in some instances, the model is not able to reproduce observed behaviour. Further analysis revealed that the model's 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 are treated as homogeneous cells with no internal distribution. This leads to an overestimate of the actual area affected by the mountain pine beetle as well as the area covered with pine vegetation. The next step in model development will adjust the model structure to account for a spatial variance within the grid cells.

6 Acknowledgements

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This work is part of a larger program of hydrologic risk assessment being undertaken by the Province of British Columbia. This specific component was initiated by the BC Ministry of Environment and is now being led by the BC Ministry of Healthy Living and Sport with collaboration from the University of Freiburg's Institute of Hydrology, the University of British Columbia, the BC Ministry of Environment, and the BC Ministry of Forests and Range.

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8 Literature Cited

Achard, F.; Eva, H.D. 2002. Determination of deforestation rates of the world's humid tropical forests. Science 297:999–1002.

Arp, P. 2005. Update on HSA mapping for Millar-Western's FMA and surrounding areas. Whitecourt, AB.

Berris, S.N.; Harr, R.D. 1987. Comparative snow accumulation and melt during rainfall in forested and clear cut plots in the western Cascades of Oregon. Water Resources Research 23:135–142.

Betson, R.P. 1964. What is watershed runoff? Journal of Geophysical Research 69:1541–1552.

Boehner, J.R.; Koethe, R.; Conrad, O.; Gross, J.; Ringeler, A.; Selige, T. 2002. Soil regionalisation by means of terrain analysis and process parameterisation. Pages 213–222 *in* E. Micheli, ed. Soil Classification. European Soil Bureau, Luxembourg

Boon, S. 2007. Snow accumulation and ablation in a beetle-killed pine stand, northern Interior British Columbia, BC Journal of Ecosystems and Management 8(3):1–13.

Bosch, J.M.; Hewlett, J.D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3–23.

(BCMoE) BC Ministry of Environment, Lands and Parks (Resource Mapping Branch). 1995. Baseline thematic mapping: Present land use mapping at 1:250 000. Ministry of Environment, , Release 1.0, British Columbia specifications and guidelines for geomatics. content series. Volume 6, part 1.

BCMoE 1996. An introduction to the British Columbia Watershed Atlas. Ministry of Environment, Lands and Parks (Fisheries Branch), Revision 2.1, Victoria, BC, April 1996, 23 p.

BCMoE, Fisheries Inventory. 2008. 1:50,000 BC Watershed Atlas Maps, available under http://www.env.gov.bc.ca/fish/watershed_atlas_maps/index.html

Brown, R.D.; Brasnett, B.; Robinson, D. 2003. Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. Atmosphere-Ocean 41:1–14.

Cappus, P. 1960. Bassin expérimental d'Alrance : Études des lois de l'écoulement. Application au calcul et à la prévision des débis. La Houille Blanche A 493–514.

Carver, M.; Weiler M.; Utzig, G.; Sulyma, R. 2007. Hydrologic risk assessment: Preliminary modelling results. Pages 47–50 *in* T. Redding, ed. Mountain pine beetle and watershed hydrology workshop: Preliminary results of research from British Columbia, Alberta and Colorado. 10 July 2007 Kelowna, BC. Forrex, BC. 60 p.

Chang, M. 2006. Forest Hydrology. 2nd ed. CRC Press, Boca Raton, FL. 474 p.

Cheng, J.D. 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in southern British Columbia, Canada. Water Resources Research 25(3):449–456.

DeLong, S.C. 1998. Natural disturbance rate and patch size distribution of forests in northern BC: Implications for forest management. Northwest Science 72 special issue:35–48.

Dunne, T.; Black, R.D. 1970. An experimental investigation of runoff production in permeable soils. Water Resources Research 6:478–490.

Eng, M.; Fall, A.; Hughes, J.; Shore, T.; Riel, B.; Walton, A.; Hall, P. 2006. Provincial-level projection of the current mountain pine beetle outbreak: Update of the infestation projection based on the 2005 provincial aerial overview of forest health and revisions to "the model" (BCMPB.v3). British Columbia Ministry of Forests (Research Branch), Victoria, BC. 7 p.

Fall, A.; Shore, T.; Safranyik, L.; Riel, B.; Sachs, D. 2003. Integrating landscape-scale mountain pine beetle projection and spatial harvesting models to assess management strategies. Pages 114–132 *in:* T.L. Shore, J.E. Brooks, and J.E. Stone, eds. Proceedings of mountain pine beetle symposium: Challenges and solutions. 30-31 October 2003. Kelowna, BC. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC.

(FPB) Forest Practices Board. 2007. The effect of mountain pine beetle attack and salvage harvesting on streamflow: Special investigation, FPB/SIR/16, March 2007. http://www.for.gov.bc.ca/hfd/library/documents/bib106689.pdf.

Foster, H. 2001. Landforms and natural hazards. Pages 27–44 *in:* C.J.B. Wood, ed. British Columbia: The Pacific province. Geographical essays.

Güntner, A.; Uhlenbrook, S.; Seibert J.; Leibundgut C. 1999. Estimation of saturation excess overland flow areas: Comparison of topographic index calculations with field mapping. Pages 203–220 *in* B. Diekkrüger, M. Kirkby, U. Schröder, eds. Regionalization in hydrology. International Association of Hydrological Sciences, Braunschweig, Germany.

Hardy, J.P.; Hansen-Bristow, J. 1990. Temporal accumulation and ablation patterns of the seasonal snowpack in forests representing varying stages of growth. Pages 32–34 *in* B. Shafer, J.K. Marron, C. Troendle, eds. Proceedings of the 58th western snow conference. 17–19 April 1990, Sacramento, CA. Colorado State University, Fort Collins, CO.

Hewlett, J.D.; Hibbert, A.R. 1963. Moisture and energy conditions within a sloping soil mass during drainage. Journal of Geophysical Research 68:1081–1087.

Hibbert, A.R. 1967. Forest treatment effects on water yield. Pages 527–543 *in* W.E. Sopper and H.W. Lull, eds. Forest Hydrology. Pergamon Press, New York, NY.

Jost, G.; Weiler, M.; Gluns, D.R.; Alila, Y. 2007. The influence of forest and topography on snow accumulation and melt at the watershed-scale. Journal of Hydrology 347:101–115.

Klemes V. 1986. Dilettantism in hydrology: Transition or destiny? Water Resources Research 22:177–188.

Kirkby, M.J. 1969. Infiltration, throughflow and overland flow. Pages 215–227 *in* Water, Earth and Man. Methuen, London, UK.

Kittredge, J. 1953. Influence of forests on snow in the ponderosa-sugar pine-fir zone of the central Sierra Nevada. Hilgardia 22(1):1–96.

Kuusisto, E. 1980. On the values and variability of degree-day melting factor. Finland Nordic Hydrology 11:235–242.

Maloney, D.; Bennett, B.; de Groot, A.; Banner, A. 2002. Canopy interception in a hypermaritime forest on the north coast of British Columbia. Forest sciences Prince Rupert Forest Region, Extension Note #49. 6 p.

Marengo, J.A.; Miller, J.R.; Russell, G.L.; Rosenzweig, C.E. ; Abramopoulos, F. 1994. Calculations of river-runoff in the GISS GGM: Impact of a new land-surface parameterization and runoff routing model on the hydrology of the Amazon River. Climate Dynamics 10:349–361.

McDonnell, J.J. 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes 17:1869–1875.

McGlynn, B.L.; Seibert, J. 2003. Distributed assessment of contributing area and riparian buffering along stream networks. Water Resources Research 39:1082. doi:1010.1029/2002WR001521.

Merot, P.; Squividant, H.; Aurousseau, P.; Hefting, M.; Burtt, T.; Maitre, V.; Kruk, M.; Butturini, A.; Thenail, C.; Viaud, V. 2003. Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. Ecological Modelling 163:51–71.

Miller, D.J.; Luce, C.H.; Benda, L. 2003. Time, space, and episodicity of physical disturbance in streams. Forest Ecology and Management 178:121–140.

Moore, R.D.; Wondzell, S.M. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. Journal of the American Water Resources Association 41:753–784.

Niehoff, D.; Fritsch, U.; Bronstert, A. 2002. Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. Journal of Hydrology 267:80–93.

Rango, A.; Martinec, J. 1995. Revisiting the degree-day method for snowmelt computations. Journal of the American Water Resources Association 31:657–669.

Scherrer, S.; Naef, F. 2003. A decision scheme to indicate dominant hydrological flow processes on temperate grassland. Hydrological Processes 17:391–401.

Schmocker-Fackel, P.; Naef, F.; Scherrer, S. 2007. Identifying runoff processes on the plot and catchment scale. Hydrology and Earth System Sciences 11:891–906.

Schnorbus, M.; Bennet, K.; Werner, A. 2009. Quantifying the water resource impacts of mountain pine beetle and associated salvage harvest operations across a range of watershed scales: Hydrologic modelling of the Fraser River basin. Report for Natural Resources Canada, Project #7.29, 67 p. plus appendices.

Spittlehouse, D.L. 2006. ClimateBC: Your access to interpolated climate data for BC. Streamline Watershed Management Bulletin 9:16–21.

Stednick, J.D. 1996. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology 176:79–95.

Storck, P.; Bowling, L.; Wetherbee, P.; Lettenmaier, D. 1998. Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. Hydrological Processes 12:889–904.

Teti, P. 2007. Estimating springtime solar radiation in pine stands by different methods. Poster presented at Mountain pine beetle and watershed hydrology workshop, FORREX. 10 July 2007. Kelowna, BC.

Tetzlaff, D.; Soulsby, C.; Waldron S.; Malcolm, I.A.; Bacon, P.J.; Dunn, S.M.; Lilly, A.; Youngson, A.F. 2007. Conceptualization of runoff processes using a geographical information system and tracers in a nested mesoscale catchment. Hydrological Processes 21:1289–1307.

Toews, D.A.A.; Gluns, D.R. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in southeastern British Columbia. Paper presented at the Western Snow Conference, Colorado State University, Fort Collins, Colorado.

Tuller, S. 2001. Climate. Pages 45–64 *in* C.J.B. Wood, ed. British Columbia, the pacific province: Geographical Essays. University of Victoria, Victoria, BC.

Uhlenbrook, S.; Roser, S.; Tilch, N. 2004. Hydrological process representation at the meso-scale: The potential of a distributed, conceptual catchment model. Journal of Hydrology 291:278–296.

VanShaar, J.R.; Haddeland, I.; Lettenmaier, D.P. 2002. Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. Hydrological Processes 16:2499–2520.

Walter, M.T.; Walter, M.F.; Brooks, E.S.; Steenhuis, T.S.; Boll, J.; Weiler, K. 2000. Hydrologically sensitive areas: Variable source area hydrology implications for water quality risk assessment. Journal of Soil and Water Conservation 3:277–284.

Weiler, M.; Coops, N.; Boon, S.; Teti, P. 2008. Equivalent clear cut area thresholds in large-scale disturbed forests. Project description: http://www.for.gov.bc.ca/hfd/library/FIA/HTML/FIA2008MR071.htm

Weyman, D.R. 1970. Throughflow on hillslopes and its relation to the stream hydrograph. Bulletin of the International Association of Scientific Hydrology 15:25–33.

Whipkey, R.Z. 1965. Subsurface stormflow from forested slopes. Bulletin of the International Association of Scientific Hydrology 10:74–85.

Whitaker, A.C.; Sugiyama, H. 2005. Seasonal snowpack dynamics and runoff in a cool temperate forest: Lysimeter experiment in Niigata, Japan. Hydrolological Processes 19:4179–4200.

Winkler, R.D.; Spittlehouse, D.L.; Golding, D.L. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. Hydrological Processes 19:51–62.

Winkler, R. 2001. The effects of forest structure on snow accumulation and melt in south-central British Columbia. Doctoral thesis, UBC. URL: http://www.for.gov.bc.ca/hfd/pubs/Docs/Mr/Mr114.htm.

Wong, C.; Dorner, B.; Sandmann, H. 2003. Estimating historical variability of natural disturbances in British Columbia. Land Management Handbook No. 53. BC Ministry of Forests, Research Branch and BC Ministry of Sustainable Resource Management, Resource Planning Branch, Victoria, B.C. 140 p.
URL: www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh53.htm.