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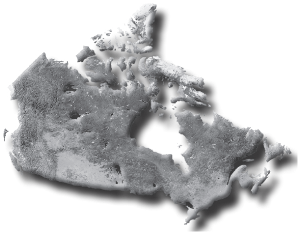

Review and Synthesis of Potential Hydrologic Impacts of Mountain Pine Beetle and Related Harvesting Activities in British Columbia

J.F. Hélie; D.L. Peters; K.R. Tattrie; J.J. Gibson

Mountain Pine Beetle Initiative
Working Paper 2005–23

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Abstract

The current mountain pine beetle outbreak in British Columbia started in 1994 and is the most important historically recorded episode. As of 2003, an estimated 164 million m^3 of pine had been killed by this infestation in BC and projections estimate that another 70 million m^3 per year will be killed until 2008 and more than 30 million m^3 per year until 2015. Many economic and environmental impacts of the infestation have been postulated, however, no studies have looked in detail at the effects of MPB infestations on water quantity and quality. The present document is a review of existing literature on large scale bark beetle epidemics and their possible impacts on hydrology and biogeochemistry. It also identifies and discusses probable hydrological and biogeochemical impacts of MPB infestations in BC as well as key knowledge gaps and recommendations for future investigations. In light of the present review of the literature, the current MPB infestation in the interior of BC is likely to damage and/or kill enough trees to significantly change interception and transpiration rates in affected watersheds and thus induce changes in annual water yields, peak flows and low flows. Furthermore, it seems reasonable to expect some nutrient losses in central BC forests through streams and rivers following an MPB infestation. This literature review revealed the importance of the nitrogen cycling as changes in this cycle triggers losses of cations. Nevertheless, it is clear that there are very few studies published on the effects of beetle attacks on the hydrological and biogeochemical cycles of forested watersheds.

Keywords: bark beetle, hydrology, biogeochemistry, impacts, recommendation

Résumé

L’infestation de dendroctones du pin qui ravage actuellement la Colombie-Britannique a débuté en 1994 et constitue la plus importante épiphytie du genre jamais enregistrée. En 2003, on estimait à 164 millions de mètres cubes le volume de peuplements décimé par cette infestation sur le territoire de la Colombie-Britannique, et on prévoit que le taux de destruction annuel atteindra les 70 millions de mètres cubes d’ici 2008, puis plus de 30 millions de mètres cubes jusqu’en 2015. Il a beaucoup été question jusqu’ici des conséquences économiques et environnementales de cette infestation, mais aucune étude ne s’est encore penchée en détail sur les effets des infestations par le DPP sur la quantité et la qualité de l’eau. La présente étude passe en revue les articles scientifiques consacrés aux grandes épidémies de dendroctones et à leurs impacts hydrologiques et biogéochimiques éventuels. On y traite aussi des répercussions hydrologiques et biogéochimiques probables des infestations par le DPP qui sévissent en Colombie-Britannique, et des aspects du problème pour lesquels on manque de données et qui mériteraient d’être mieux étudiés. À la lumière de cet examen de la littérature, il semble que l’infestation actuelle des peuplements du centre de la Colombie-Britannique pourrait endommager ou tuer un nombre suffisant de sujets pour modifier sensiblement les taux d’interception hydrique et de transpiration des bassins concernés et entraîner des modifications du régime hydrographique, notamment au niveau des crues et des étiages.

De plus, on peut raisonnablement prévoir des déperditions de la masse nutritive dans les forêts du centre de la Colombie-Britannique, par le biais du réseau hydrographique. Cette étude documentaire a mis en lumière l'importance du cycle de l'azote et de ses perturbations au niveau cationique. À l'évidence, il existe très peu de publications sur les effets des infestations de dendroctones sur les cycles hydrologiques et biogéochimiques des bassins occupés par la forêt.

Mots clés : scolyte, hydrologie, biogéochimie, impacts, recommandations.

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1 Introduction

Similar to forest fires, bark beetle outbreaks have long been a part of the natural regeneration cycle of forests in British Columbia. The recent outbreak of the mountain pine beetle (MPB) that started in 1994 is the most important historically recorded episode for two key reasons (MOF, 2003). First, fire regulation policies have increased the proportion of mature trees in BC forests (Taylor and Carroll, 2003) providing a large stock of mature and/or weakened trees vulnerable to MPB attack. Second, the low winter temperatures required to kill MPB have been less frequent in recent years, a condition which may worsen under impending climatic change (Wilson, 2003). Together, these factors have contributed to increase the severity of the 1994 infestation. Many economic and environmental impacts of the infestation have been postulated, however, no studies have looked in detail at the effects of MPB infestations on water quantity and quality. These issues are not only important for harvesting operations, but for wildlife habitat, human water consumption and protection of infrastructure in the impacted areas.

The objective of the present document is to compile and review existing literature on large scale bark beetle epidemics and their possible impacts on hydrology; to identify and discuss the probable near-term and long-term impacts of the current MPB epidemic on hydrological processes and related biogeochemical/ecological processes in British Columbia; and to identify key knowledge gaps, including areas of particular need, for further investigation. First, we will provide general background information on forest hydrology and biogeochemistry as well as on the effects of MPB on forest stands; second, we will review available literature on the effects of bark beetle attacks on both hydrology and biogeochemistry of pine forests around the world; third, we will discuss the probable near-term and long-term impacts of the current MPB epidemic on hydrological processes and related biogeochemical/ecological processes in British Columbia.

2 Background

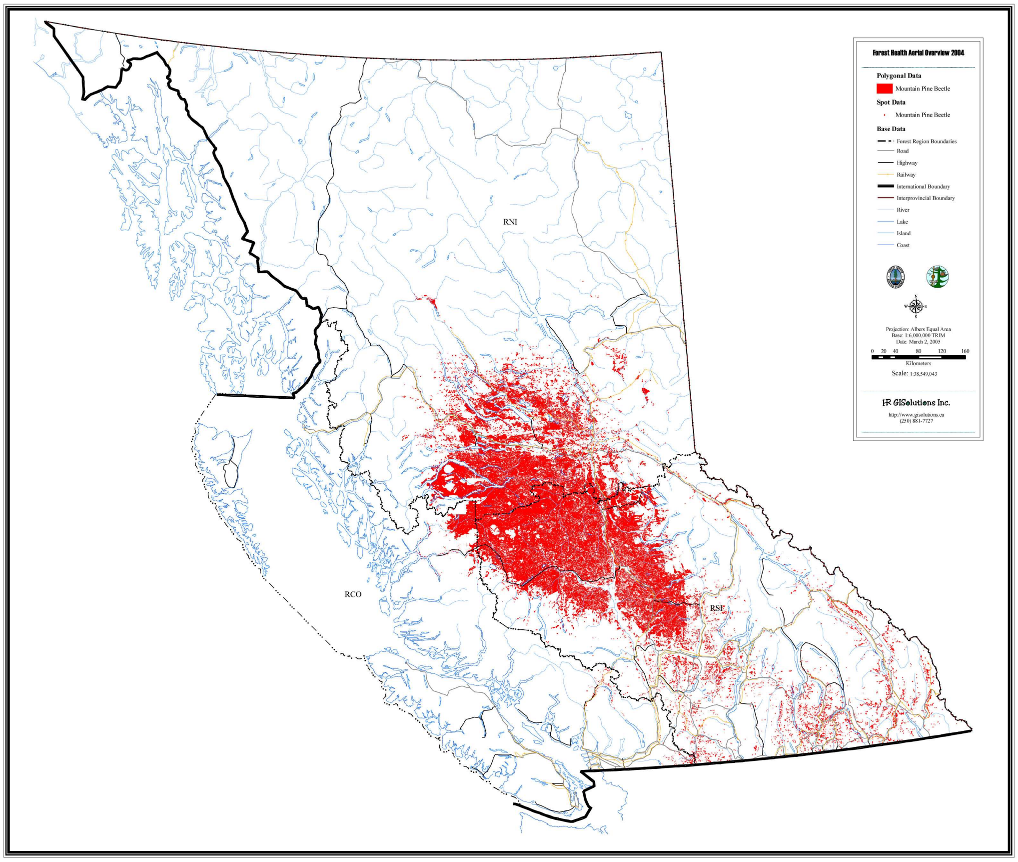
2.1 Geographical settings

British Columbia's forests cover an area of about 60 million hectares (Anonymous, 2005) and include 14 million hectares of economically harvestable pine stands (British Columbia Ministry of Forests, 1995). Lodgepole pine is by far the most abundant species but British Columbia's forests also include ponderosa, western white, white bark and limber pines (Taylor and Carroll, 2003). In this region, pine forests are disturbed by a number of different natural agents but are currently sustaining a MPB infestation. Of the 10,618,639 hectares of forest in British Columbia that were affected by forest damaging agents in 2004, 9,180,126 hectares were affected by bark beetle attacks, over 75% of which were due to MPB (Westfall, 2004). Consequently, MPB infestations are currently the most important damaging agent for this province's forests and about half of the pine stands here are currently affected by MPB. The current extent of the MPB infestation is shown in Figure 1. As of 2003, an estimated 164 million m^3 of pine had been killed by this infestation in British Columbia and projections estimate that another 70 million m^3

per year will be killed until 2008 and more than 30 million m^3 per year until 2015 (Eng et al., 2004).

The region most impacted by the current MPB infestation is the central interior of British Columbia (see fig. 1), which includes the Sub-Boreal Pine-Spruce, Sub-Boreal Spruce, Montane Spruce and Interior Douglas-Fir biogeoclimatic zones. Wedged between the Coast Mountain Range to the west, and the Rocky Mountain Range and Columbia Mountain Range to the east, this plateau region has moderate elevations (500 m to 1000 m) and is characterized by long cold winters and short dry summers. Mean annual temperatures vary between 4 and 5°C and annual precipitation is typically between 450 to 700 mm (Weather Service of Canada, unpublished data).

Figure 1. Current extent of Mountain Pine Beetle infestation (in 2004) in British Columbia. Red areas indicate area affected by MPB (from Westfall, 2004).



2.2 General forest hydrology

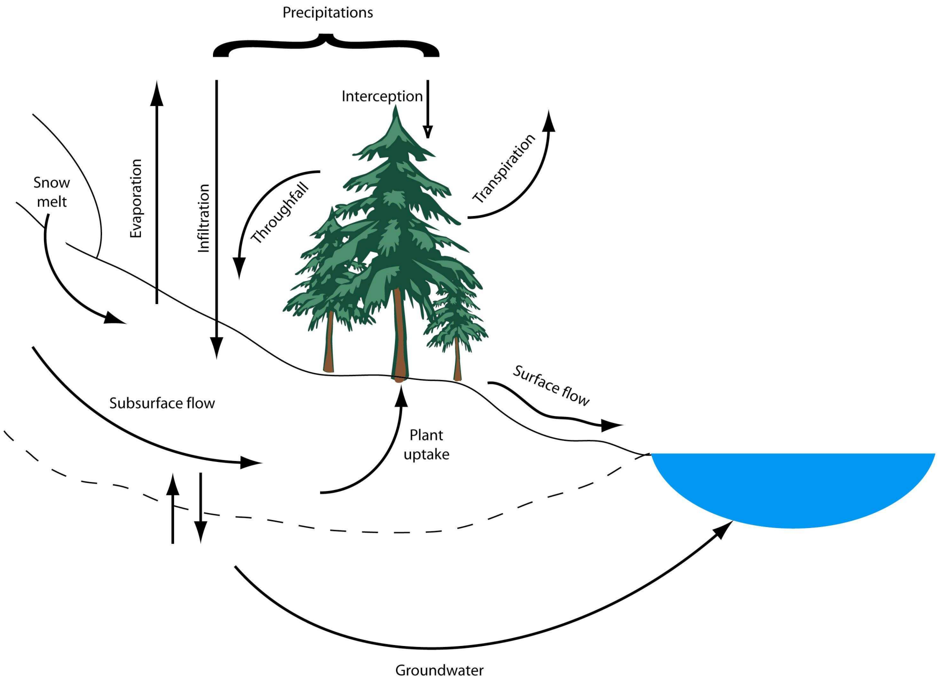
2.2.1 Forest hydrological cycle

The hydrological cycle, which is principally driven by solar radiation and gravity, provides a model for understanding the movement of water in a forested environment (Figure 2). The hydrological processes that affect the quantity and timing of water available for streamflow generation include precipitation, interception, evaporation and transpiration, and changes in water storage within a watershed. The reader is encouraged to consult "Principles of Forest Hydrology" by Hewlett (1982) and "Forest Hydrology: An Introduction to Water and Forests" by Chang (2002) for theory on each of these parameters.

Depending on the prevailing meteorological conditions, water falls to the earth as rain, snow, or less frequently as hail and sleet. In cold regions, precipitation is stored on vegetation and ground surfaces during the winter until snowmelt in the spring. In forested environments interception of precipitation by vegetated surfaces is an important process that can significantly affect the amount of water reaching the ground surface. In most cases, intercepted water is returned to the atmosphere and is thus a reduction of the portion of precipitation available for streamflow generation. An exception to this is found in coastal regions where the condensation of fog on vegetation results in an increase in the amount of water reaching the ground, increasing the water available for streamflow generation. Evaporation and transpiration are usually combined in a single term, evapotranspiration, due to difficulties in differentiating between the water lost to the atmosphere by evaporation (vegetated and soil surfaces, lake and river surfaces) versus through stomata in plant leaves by transpiration. Water that is not returned to the atmosphere may be temporarily stored in lakes and wetlands or become part of soil and groundwater reservoirs. Precipitation that is not evapotranspired back to the atmosphere or stored within the watershed will contribute to the generation of streamflow via a number of flow pathways shown in Figure 2.

As is depicted in this figure, the forest cover directly influences a number of hydrological processes. Changes in the forest structure, either by naturally occurring (e.g., wind throw, fire, and pest infestation) or anthropogenic (e.g., road construction and harvesting), can modify processes that control amount and timing of water reaching a stream, as well as the water quality within watersheds.

Figure 2. General forest water cycle.



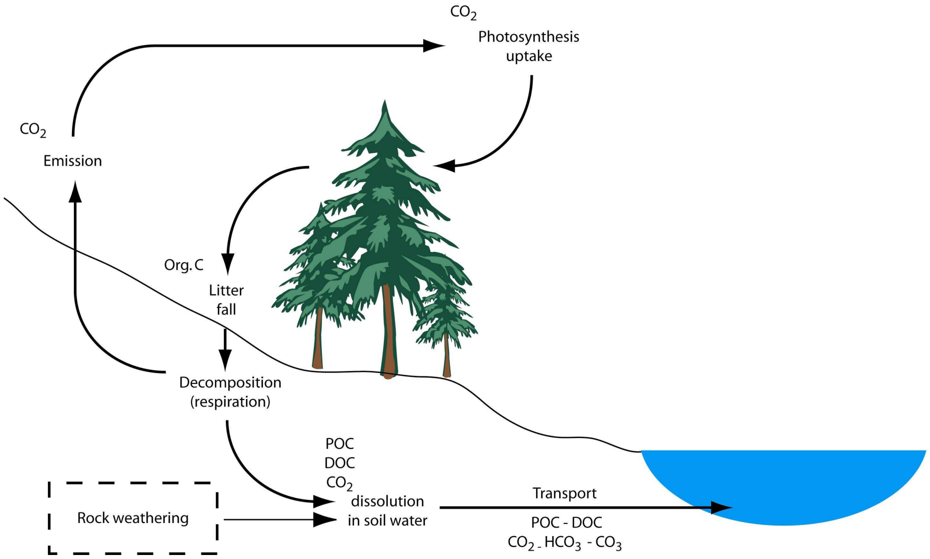
2.3 General forest biogeochemistry

A complete review of the complex biogeochemical cycles of forested areas is beyond the scope of this document. Here, we will focus our review on the carbon and nitrogen cycles, which have the greatest relevance to nutrient availability and water quality.

2.3.1 Forest carbon cycle

The typical forest carbon cycle begins with the photosynthetic uptake of atmospheric carbon dioxide (CO_2) by plants and trees resulting in the production of organic matter (Figure 3). This organic matter will eventually fall to the forest floor and accumulate as litter, where it will undergo decomposition in the soil through bacterial consumption and respiration producing CO_2. At that point, soil CO_2 can either diffuse through the soil zone to reach the atmosphere where it can be used by plants, or dissolve in soil water to produce dissolved inorganic carbon (DIC), which is transported with groundwater to streams and lakes. Litter that is only partially decomposed can also eventually enter streams and lakes as particulate and dissolved organic matter (respectively POC and DOC). Marginal amounts of DOC may also enter forest soils via throughfall and direct precipitation. Carbonate rock weathering can also be a component of the carbon cycle of a forest adding DIC through the dissolution carbonate minerals by the weak carbonic acid (H_2CO_3) produced by organic matter degradation.

Figure 3. General forest carbon cycle.



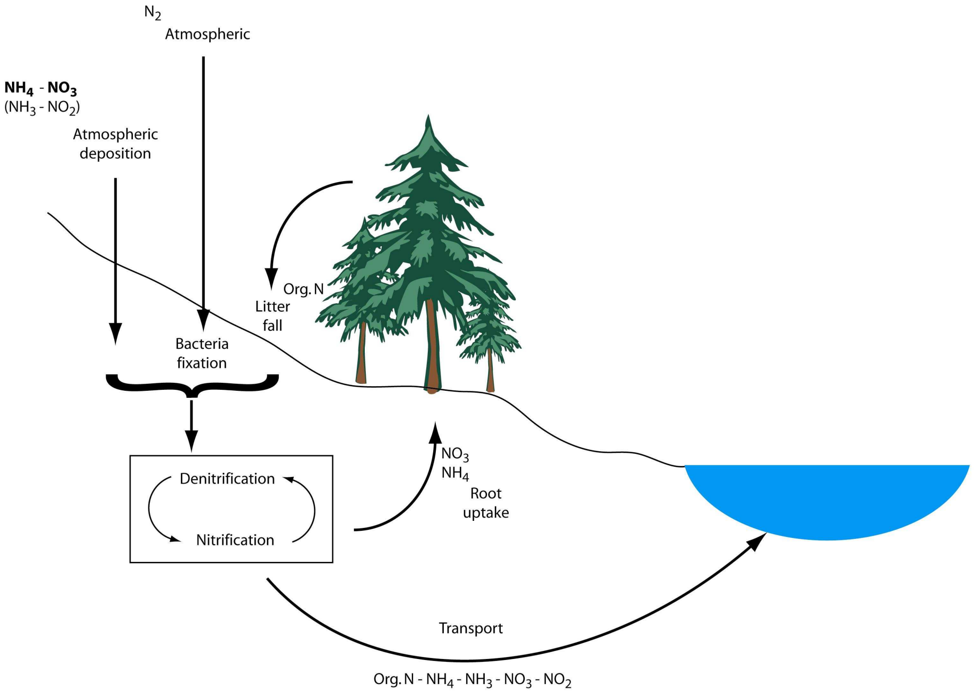
Forests will typically act as a carbon source or sink depending on the age of the trees, the climate, and the time frame considered. The forests in British Columbia have been found to be at equilibrium, meaning that they are currently neither a sink nor a source of carbon to the atmosphere (Chen et al., 2003). This equilibrium between primary production and respiration is due to the relatively old age of natural stands in BC. Thus, any change to the age structure of BC's forests will result in a change in their role in the global carbon cycle.

2.3.2 Forest nitrogen cycle

The atmosphere is the largest reservoir of nitrogen, however most of it is found as molecular nitrogen (N_2). Most living organisms cannot use molecular nitrogen for their metabolic activities. Only N-fixing bacteria in soils (e.g., free-living, *Azotobacter;* or associated leguminous plants, *Rhizobium*) can convert molecular nitrogen (N_2) into ammonia (NH_3). A series of bacterially mediated reactions result in the conversion of ammonia to nitrite (NO_2^-, by *Nitrosomonas*), and nitrite to nitrate (NO_3^-, by *Nitrobacter*). In anoxic environments, the nitrification end products can be denitrified, reduced by other types of bacteria (e.g., *Pseudomonas denitrificans*), resulting in the conversion of nitrate to nitrite which will be reduced to NO. If anaerobic conditions are maintained, physical reactions will turn NO into molecular nitrogen through N_2O. This molecular nitrogen can then be fixed again into ammonia by *Azotobacter* and *Rhizobium*. Therefore, the microbial loop can either nitrify or denitrify nitrogen species depending on redox conditions prevailing in the soil.

Nitrogen can also enter forest soils via wet and dry atmospheric deposition mostly as ammonium (NH_4) and nitrate (NO_3), but also as ammonia (NH_3) and nitrite (NO_2), and via litter fall from the tree canopy (Figure 4). Organic nitrogen from litter fall will undergo ammonification through a process called mineralization, the hydrolysis of proteins and oxidation of amino acids to produce ammonia (NH_3). Rates of nitrogen mineralization differ significantly among forests, with deciduous forests generally much higher than coniferous forests. Vegetation will then use nitrate and/or ammonium to build biomass through root uptake. Most of the inorganic nitrogen available in soils is usually efficiently recycled by vegetation and most of nitrogen in forest soils is "sequestered" in organic matter. Any remaining inorganic nitrogen not recycled by vegetation or sequestered in soils will then be transported with organic nitrogen through the groundwater to streams and lakes. The uptake of nitrogen by vegetation during the growing season results in a seasonal cycle in nitrogen concentrations in forested streams with high concentrations measured in the winter and low concentrations in the summer.

Figure 4. General forest nitrogen cycle



2.4 Effects of Mountain Pine Beetle on forest canopy

The Mountain Pine Beetle (*Dendroctonus ponderosae,* Hopkins) is a bark beetle that attacks and kills lodgepole, ponderosa, sugar and western white pines. It is native to North America and is found from the Pacific Coast to the Black Hills of South Dakota and from northern British Columbia to northwestern Mexico (Amman et al. 1990). Populations of bark beetles follow two modes: endemic and epidemic. Under normal conditions, they are found at endemic levels and cause less than 2% mortality in forest stands (Samman and Logan, 2000). An outbreak will occur when there are sufficient mature or weakened trees available to host the MPB.

An MPB attack begins as they dig through the bark at the base (usually in the lower 4.5 m) of trees in order to dig galleries in which to lay their eggs. During this process they pass through the phloem, the vascular system of the tree that transports water and nutrients to the crown. When MPBs enter the phloem they carry with them spores of the blue staining fungi. Once introduced to the vascular system the fungus can develop and spread through the sapwood, interrupting the flow of water to the crown (Amman et al., 1990). In the summer and early fall the females lay their eggs in the galleries. Once the eggs hatch, ten to fourteen days later, the MPB larvae will feed on the phloem for the next 10 months thus increasing the water and nutrient stress and eventually resulting in death of the tree. As they mature into adults they continue to feed underneath the bark until they eventually emerge to attack another tree. This life cycle usually takes about 1 year to complete, but can be significantly slowed down in cold temperatures. Early fall or mid-spring temperatures below -18 ^{o}C and winter temperature below -37 ^{o}C may affect outbreaks (Amman et al., 1990).

After being infested for about a year the needles of the trees will change from green to yellow, to red and finally grey. Throughout this cycle, the exchange of water and nutrients from the roots to the crown will gradually diminish and will eventually be completely stopped. As the attack on the tree progresses nutrients and water uptake from the surrounding soil will also be gradually reduced and eventually stopped.

3 Review of effects of beetle attacks on forest hydrology and biogeochemistry

3.1 Hydrology

3.1.1 Theory

As will be revealed in the case study review section, there are very few published studies on the effects of beetle attacks on the hydrological cycle of forested watersheds. Conversely, the impacts of forest harvesting on key hydrological parameters are widely documented in the literature and a number of key review papers have recently been published (e.g., MacDonald and Stednick, 2003; Pike and Scherer, 2003; Buttle et al., 2000; Guillemette et al., 2005). These and other studies contribute considerable knowledge on forest hydrology useful for gaining insight into potential impacts of mountain pine beetle infestation on the hydrology of British Columbia watersheds.

An important role of the mountain pine beetle is to open the canopy, thin dense stands of stressed trees, and initiate decomposition (Goyer et al., 1998). A number of hydrological processes depicted in Figure 2 are affected by changes in the forest canopy cover and forest structure.

In British Columbia, snow accumulation and snowmelt dominate the hydrology of most interior watersheds; while rainfall dominates the hydrology of most coastal watersheds. Both the amount and the rate of snowfall/snowmelt and rainfall vary with forest cover, and its removal and regrowth. A direct hydrological impact resulting from the loss of vegetation is an increased amount of net precipitation, either in the form of snow or rain, to the forest floor as a result of a decreased amount of interception by the canopy (Buttle et al., 2005). For instance, Winkler et al. (2005) monitored for 3 years a juvenile and a juvenile-thinned lodgepole pine, a mixed Engelmann spruce, a mature pine stand, and a clearcut to quantify differences in snow water equivalent in south-central British Columbia. Overall, the authors reported a greater peak spring snow water equivalent and greater melt rates in areas of the watershed that were clearcut versus juvenile and mature spruce-fir stands. Similar results were reported in Winkler (2001) and in a review by MacDonald and Stednick (2003) for the Colorado region. Winkler (2001) also mentioned that both snow accumulation and snowmelt rates decrease with forest regrowth. On the other hand, a decrease in net precipitation may occur in coastal regions where fog drip is important and significant vegetation cover is killed by beetle infestation.

A review of paired watershed experiments by Bosch and Hewlett (1982) noted that annual precipitation must exceed 450 mm in order to detect an increase in runoff as a result of removing a larger fraction of the vegetation cover in a watershed. In addition, the timing of a water yield increase depends on the timing of the soil water and groundwater recharge (MacDonald and Stednick, 2003). In spring freshet dominated hydrological regimes, greater snowmelt in beetle-killed stands will likely primarily result in higher and earlier peak flows than previously experienced, with the magnitude of change related to the percentage of the watershed area affected. For example, a review of western Canada studies by Scherer (2001) revealed that changes in peak flow magnitude and timing in snowmelt-dominated watersheds was highly variable, ranging from 0 to 60% higher peaks and 0 to 18 days advancement of the peak.

The removal of the forest canopy will result in less soil water/groundwater depletion during the summer because of a substantial reduction of water loss via evapotranspiration associated with dead trees (MacDonald and Stednick, 2003). There are already signs of greater storage of water occurring in British Columbia watersheds. For example, the Vanderhoof Forest District has reported the occurrence of higher water table levels in MPB affected areas (British Columbia Ministry of Forests, 2005). The greater net precipitation to the forest floor, reduced evapotranspiration during the growing season, and higher water tables will likely lead to increased baseflow or low flows, greater peak flows, and greater annual water yield in MPB affected watersheds. For example, Cheng (1989) utilized a paired watershed technique to show that these changes occurred in an interior British Columbia watershed after clearcut logging occurred over 30% of the 33.9 km^2 area of a watershed infested by MPB. As summarized by Scherer (2001), several studies have shown a general relationship of increased annual discharge or water yield with forest removal (e.g., Bosch and Hewlett, 1982; Stednick, 1996). Another important hydrological parameter likely affected by MPB infestation is low flow. Studies in British

Columbia (Cheng, 1989) and the USA (see MacDonald and Stednick, 2003) generally show that forest harvesting can substantially increase low flows in terms of percentage.

3.1.2 Case studies

A review of the literature revealed that despite the growing importance of beetle kill there is a paucity of research conducted on the impact of MPB on the hydrology of forested watersheds. Note that Cheng (1989) published a paper entitled "Streamflow changes after clearcut logging of a pine beetle-infested watershed in southern British Columbia, Canada", however, the paper is about harvesting in a watershed that happened to have been infested by MPB. In this section, we review the results and conclusions of the available relevant studies.

Western Colorado Forest Studies

To our knowledge, Love (1955) published the earliest hydrological study of the impacts of a bark beetle infestation on streamflow generation. This study took place in the infested White River (1974 km^2) and uninfested Elk River (534 km^2) watersheds located in a plateau of western Colorado. On average, dead trees (Engleman spruce and lodgepole pine > 15 cm) occupied 60% of the White River watershed by 1947. This watershed ranges in elevation from 1981 m to 3658 m, with most of the beetle damage occurring above 3048 m. The average annual streamflow for 1934 to 1951, which includes the pre-and post-epidemic period, was 261 mm The Elk River watershed is located 97 km to the northeast of the White River and covers a similar range in elevation. No information was given on the average annual precipitation.

The author compared streamflow and snowcourse data for the pre-epidemic (1937-40), active beetle outburst (1941-46) and post-epidemic (1947-51) for these two watersheds. After adjustments via regression analysis were made for climatic fluctuations, average annual streamflow was found to increase by 31 mm and 58 mm during (1941-1946) and after (1947-1951) the bark beetle attack, respectively. No information was provided on changes in peak flow. The analyses showed that annual water yield increased after the beetle outbreak, which he reasoned was due to reduced interception of snowfall and decreased evapotranspiration by the dead trees. The author also stated that the beetle-killed areas are not comparable to complete openings in the stand because the dead trees still protect against complete exposure to sun and wind. The work of Love (1955) was contested by Bue et al. (1955) because they questioned whether streamflow increased in the White River or decreased in the Elk River.

Bethlahmy (1974) revisited the study watersheds and offered new data, with the addition of the beetle infested Yampa River (no background information given) and an extended time series, to support the conclusions of Love (1955). Statistical analyses showed that the beetle infested Yampa and White watersheds yielded more water than expected. The smallest discharge increases occurred during the first 5-year period (1941-45) when the beetle population was rising to epidemic levels, with the largest increases occurring 15 years later (1956-60), with no mention as to when the greatest area impacted occurred. The general upward trend in streamflow was not seen in the unaffected Elk River and thus not the result of an increasingly wet climate. The author concluded that the increase in streamflow was a consequence of Engelmann spruce beetle epidemic in the high plateau country of Colorado and stated that a general increase in water supply will persist as long as new trees are killed faster than are replaced by new growth. However, Bethlahmy cautioned that insect epidemics elsewhere may or may not produce similar results because of potential variation of tree species.

Bethlahmy (1975) revisited the high plateau watersheds with the addition of the Plateau River to the analyses, for a total of 2 beetle infested and 2 control watersheds covering the 1946-65 period. The author utilized an "integrating triangle" method to compare annual flows from affected and unaffected watersheds to determine the reliability of relationships between water yield and land use. Standard statistical methods (analysis of covariance) were applied to the datasets to quantify the degree of variability within the control watersheds to validate variability within the treated watersheds.

The analysis showed, while the relationship between the control watersheds remained constant, there was significant variation between the treated watersheds. Based on a comparison of measured post-epidemic water yields and pre-epidemic regression analysis, the author noted that 25 years after the beetle epidemic in the White and Yampa Rivers, annual water yields are 10% greater than expected, maximum monthly flows are 14%-22% higher, and minimum monthly flows are ~15% higher. Her explanation for these changes in hydrological parameters was not changes in climate but in vegetation cover. The presence of defoliated trees, referred to as "ghost forest", would have permitted a greater accumulation of snowfall on the forest floor that would lead to more spring meltwater for runoff production, as well as reduced loss of water back to the atmosphere via evapotranspiration during the summer and fall.

A variable response in peak flow increases following the beetle epidemic was noted amongst the watersheds. Exposure (aspect) of the watershed was considered important when it became clear that the two treated watersheds responded differently to the effects of the beetle epidemic; exposure controls the effects of incoming solar radiation on spring thaw, rate and time of peak flow occurrence. The Yampa River watershed (northerly exposure) is considered a low-energy (LE) watershed, while the White River watershed (westerly exposure) is a high-energy (HE) watershed. For instance, there was an increase discovered in October flows in the LE watershed, resulting from smaller transpiration losses while greater evaporation losses in the HE watershed served to decrease flows. Similarly, high-flows were increased in both watersheds, but more so in the westerly facing (HE) than the northerly (LE) facing.

Southwestern Montana Forest Study

A MPB epidemic in 1975-77 killed an estimated 35% of the total timber in the Jack Creek watershed in southwestern Montana (Potts, 1984). The watershed shows little disturbance by forest management activities. Jack Creek is a third order tributary that drains 133 km^2 of the Madison River. Elevation ranges from <200 m to >3000 m, with high elevations exhibiting true alpine ecosystems. The nearest climate station, 14.2 km away at 1500 m elevation, recorded an average of 374 mm of precipitation for the hydrologic period of study (1974-82). The poor correlation of precipitation and annual water yields limited the use of Ennis data for estimating precipitation in the Jack Creek watershed.

A double mass curve (method used to check consistency of hydroclimatic parameters by comparing data from a single station against composite data from nearby stations) and hydrograph analysis of the data prior to (4 years) and subsequent (5 years) to the tree mortality period, suggested that there was a 15% increase in annual water yield [similarly reported by Love (1955)], a 2–3 week advance in the peak hydrograph, a 10% increase in low flows, and little increase in peak flow. The increase in discharge was attributed to the mortality of the lodgepole pine. According to the author, the desynchronization of the hydrograph was due to changes in the timing of snowmelt runoff because of reduced soil moisture recharge requirements and hydrological changes associated with mortality-induced changes to the forest canopy; no explanations were given with these statements. A noteworthy conclusion was that the observed changes were similar to the pre- and post-logging hydrographs observed during the Fool Creek experiment in Colorado (Troendle, 1983).

Wyoming/Colorado Forest Study

The above studies were conducted on observed hydroclimatic data. Using the WRENSS Hydrological Model, Troendle and Nankervis (2000) simulated the short-term (2001-2010) hydrological consequence of spruce beetle kill on 30% to 50% of the timber in the North Platte River basin (1978 km^2) located in Wyoming/Colorado. Mortality was assumed to have occurred uniformly over the 10 year period.

Modelled water yield increased 2.5 mm (0.6%) in year 1 and 56 mm (13%) by year 10. These results support the findings of Love (1955) and others above. The simulations by Troendle and Nankervis (2000) suggested that increases in discharge could persist, at a decaying rate, for as long as 60-70 years.

Danish Forest Study

The effect of a beetle attack in a Danish inland heath (Hjelm Hede) was examined using a simple water balance model (Ladekarl et al., 2001). The normal annual precipitation (1961-90) is 875 mm and the air temperature ranges from -0.2^{o}C in January to 15^{o}C in July. Detailed measurements of daily precipitation, throughfall, soil moisture, and leaf area index were made and used to validate the soil water balance model.

The effects of beetle attack were estimated by comparing a model run influenced by the change in vegetation due to beetle infestation and a run without changes. To our knowledge this is one of the first studies to demonstrate the change in soil moisture distribution and a decrease in evapotranspiration several years following a severe beetle attack (evapotranspiration estimated to have been reduced 14, 29 and 5% in the 3 years following the 1994 infestation). A change to the water balance was seen as a shift from transpiration to evaporation from bare soil. The following table summarizes the effect of bark beetle infestations on hydrology for the studies reviewed above.

Table 1. Summary of studies reviewed for hydrology impacts

Study	Precipitation (mm)	% basin infested	Annual water yield	Peak flow	Monthly high flow	Monthly low flow
Western Colorado	n/a	60	+10%	delayed	+15-22%	+15%
Southwestern Montanna	374	35	+15%	2-3 weeks early	Ø change	+10%
Wyoming & Colorado	n/a	30-50	+13%	n/a	n/a	n/a
Denmark	875	n/a	- Change in soil moisture distribution - Evapotranspiration reduced by up to 29%			

3.2 Biogeochemistry

3.2.1 Theory

As with hydrological effects, very little published literature exists on the effects of bark beetle attacks on chemistry of either soil, water, or streams in infested forests. However, the impacts of forest harvesting on water chemistry have been widely documented in a variety of environments, and should be a direct analog for evaluating the effects of MPB attacks on water chemistry since both result in the absence of vegetation uptake of nutrients.

In the last 40 years, research on this issue has been stimulated by a controversial experiment in the Hubbard Brook Experimental Forest in central New Hampshire (U.S.A.) carried out in the 1960s (Bormann et al., 1968; Likens et al., 1969; Likens et al., 1970). The experiment consisted of cutting all trees, saplings and shrubs in a 15.6 hectares watershed in winter of 1965. All the cut vegetation remained on the forest floor and regrowth of vegetation was inhibited by the addition of strong herbicides. The study monitored stream water chemistry for a year prior to the disturbance and three years after the cut, as well as in a similar undisturbed watershed in the area. Large increases were observed for every major ion except ammonium, sulfate and bicarbonate after the disturbance. Nitrate concentrations increased 41-fold after the first year, even exceeding toxicity levels. The authors argue that the extraordinary increase in nitrate concentrations played a major role in loss of other nutrients in major ions (Borman et al., 1968, Likens et al., 1969). They explain this phenomenon by the fact that the disturbance increased nitrification in soils (they observed increased numbers of nitrifying bacteria), which resulted in higher concentrations of nitrate but also of hydrogen ions (decreasing pH). With decreasing pH and increasing nitrate, cations are more readily mobilized and leached from the watershed (Likens et al., 1970).

In the 1960s and 1970s, another suite of studies took place in Oregon (U.S.A.). Some were in the H.J. Andrews experimental forest in the Cascade mountain range (Sollins et al., 1981, Sollins and McCorison, 1981, Martin and Harr, 1989) and one in the Coast mountain range in Oregon (Brown et al., 1973), but all producing very different conclusions than for the New Hampshire studies. On the west coast, little impacts on stream water chemistry were observed after disturbance.

Vitousek and Melillo (1979) looked into mechanisms that could explain these divergences. They focused on nitrogen because: i) nitrogen is often a limiting nutrient in ecosystems, ii) nitrate is highly mobile in soils and may enhance mobility of cations, and iii) nitrogen losses have increased more than all other nutrients and elements in most studies. In any disturbed system, nitrogen mineralization (conversion of organic nitrogen into ammonium) will increase. The ammonium may then be nitrified into nitrite and subsequently into nitrate. Finally, nitrates in soils may be leached from soils and flushed to streams. This is the mechanism by which nitrates are lost to streams because of some disturbance in the forest ecosystem. If any of these steps are disturbed or prevented, little or no nitrate is going to be lost to streams. Vitousek and collaborators (1979) have broken these processes into:

1) Processes preventing or delaying ammonium accumulation;
2) Processes preventing or delaying nitrate accumulation;
3) Processes preventing or delaying nitrate mobility.

Four processes could prevent or delay ammonium from accumulating in disturbed forest soils, namely:

a) immobilization or rapid cycling by decomposers,
b) fixation by mineral clays like illite, montmorillonite or vermiculite (only somewhat important in mineral clay rich soils),
c) ammonia volatilization in basic to neutral soils (usually unimportant),
d) uptake by regrowing vegetation.

If ammonium is nitrified to nitrate, three processes could prevent or delay nitrate from accumulating:

a) lag in initiation of nitrification caused by competition between nitrifiers and decomposers for some limiting nutrient, or low initial population of nitrifiers,
b) fast rates of denitrification of produced nitrate into molecular nitrogen or oxides of nitrogen,
c) rapid nonassimilatory reduction of produced nitrate to ammonium.

Finally, if nitrates are allowed to accumulate in disturbed forest soils, three processes could prevent or delay them from being transported into streams:

a) nitrate adsorption on anion exchange site, particularly iron and aluminum oxides,
b) denitrification of nitrates deeper in the soil profile,
c) lack of sufficient percolating water for nitrate transport, which is an important process in dry-summer climate typical of northwestern US and central British Columbia.

Vitousek and collaborators (1979) also categorized responses of forest ecosystems to disturbance into four types:

Type 1: no significant increase of ammonium and nitrate in soil
Type 2: significant increase of ammonium but not in nitrate in soils
Type 3: significant increase of nitrate in soils but not in soils' water
Type 4: significant increase of nitrate in soil water and streams

Consequently, ecosystems will produce different responses ranging from no significant increase in any nitrogen species in soils to large exports of nitrates in streams depending on soil properties, initial communities of bacteria, availability of nutrients, precipitation regime, etc. The fate of other nutrients including cations will likely depend on the type of response the nitrogen cycle produces. If a type 3 response is reached, cations are likely to be leached from soils.

3.2.2 Case studies

To the best of our knowledge, only two studies directly pertaining to bark beetle infestation effects on water chemistry are reported in the literature. One was carried out in the Bavarian forest in Germany (Huber et al., 2004), the other, in the Kiryu experimental basin in Japan (Tokuchi et al., 2004). In this section, we are reviewing in detail the results and conclusions of these two studies. We will also review a study concerning the effects of clearcutting on stream water chemistry and watershed nutrient budgets in southwestern British Columbia (Feller and Kimmins, 1984) because we feel it is relevant to look into the effects of any forest disturbance on water chemistry in our region of interest.

The Bavarian Forest study

The Bavarian Forest National Park, in Germany, consists of 80- to 300-year-old mountain spruce in a cold (yearly average of 3-4.5^{o}C) and wet (1600mm annually) environment. Forest soils are acidic and mineral soils are covered by an organic layer 10 to 18 cm thick. In undisturbed stands, almost all plant available cations are stored in organic matter, whre the recycling of nutrients through microbial decay is functioning well and ammonium is the dominant species of inorganic nitrogen (over nitrate) in the mineral soil. Also, trees in intact stands are not nitrogen limited and yearly uptake of nitrogen is low. Six plots were investigated from 1999 to 2001 in order to understand the changes in seepage water chemistry and nitrogen fluxes after disturbance. One plot was wind thrown in 1983 and four plots were bark beetle (*Ips typographus*) infested, for which dieback of the stands started in 1994, 1996, 1999 and 2000. An undisturbed plot was also studied. In the disturbed stands, more than 85% of the trees died and all of the dead trees were left standing according to the "leaving nature alone" policy. Using the different stands for which dieback started in different years and the 3 years of investigation that took place from 1999 to 2001, the authors have established a chronosequence starting at year 0 (the year the dieback started) to 18 years after the dieback started (plot where the disturbance occurred in 1983 and investigation took place in 2001). At each site, throughfall was sampled as well as soil water in the humus layer and mineral soil (40 cm depth).

Although intuitively one would think that a live pine forest with foliage would have a higher interception capacity than a dead one with no foliage, this study found no difference in the observed interception loss between undisturbed and deadwood stands. In the humus layer, the authors observed significant increases in concentrations of ammonium, nitrate, DOC, Ca^{2+}, Mg^{2+} and K^+ after the dieback. Ammonium is the first tracer to increase in humus after dieback because spruce trees can no longer uptake ammonium (NH_4^+ is taken up preferentially to NO_3^- by spruce) and nitrates only increase 4 years after the beginning of the dieback. Below, in the mineral soil, nitrate levels were higher in beetle attacked plots. Also, higher levels of nitrate were observed in the mineral soil than in the humus layer in disturbed plots. High nitrate levels were correlated very closely to Al^{3+} concentrations. Although concentrations of Ca^{2+}, Mg^{2+} and K^+ were lower in the mineral soil than in the humus layer, increases in these elements were observed in the mineral soil of disturbed plots.

Nevertheless, 543 kg of NO_3^- nitrogen was lost per hectare during the first 7 years after dieback, with a peak of 122kg $N \cdot ha^{-1} \cdot yr^{-1}$ in the 5th year, which is on the high end of nitrate losses for disturbed forests (even for clearcutting). Undisturbed plots lost between 5 and 9 kg $N \cdot ha^{-1} \cdot yr^{-1}$. According to the authors, the source of nitrogen for NO_3^- during these first 7 years (after dieback) was NH_4^+ from the forest floor that was nitrified in the upper mineral soil. The increase in ammonium concentrations in disturbed soils was fed by increased litter fall and accelerated mineralization. In this study, the processes that could delay or prevent nitrate export were either not important enough or inexistent and as result, the system produced a type 4 response. Here, the authors argue that net vegetation uptake of nitrogen by regrowing vegetation was unimportant because decomposition of dead trees dominated. The authors finally suggest that nitrate losses to streams will be compensated by added dead organic matter, but losses in Mg^{2+} and K^+ will likely not be compensated by throughfall inputs, and forest soils will likely present a deficiency in these elements in the future.

The Japan study

The Matsuzawa catchment in the Kiryu experimental basin (Japan) has a surface area of 0.68 ha and is forested by Japanese red pine and Japanese cypress. It receives an average of 1672 mm of precipitation annually and the average air temperature is 12.6°C. Defoliation resulting from pine wilt disease (PWD) started in the late 1980s in this catchment. In 1993, a typhoon struck the region and pines that were affected by PWD were wind thrown and there was no overstory vegetation in the area affected by PWD until 1998. The dead boles were left on the forest floor over the entire watershed. The objectives of this study were to evaluate hydrological processes by which nitrate concentrations increase in stream water and to evaluate the effects of natural disturbances on biogeochemical cycling.

Three plots were investigated within the Matsuzawa watershed. Two were located in the valley where slopes are gentle, one of which is characterized by soils saturated with groundwater, the other by soils unsaturated by groundwater. The third site is located upslope where vegetation was affected by PWD. In 1989, before defoliation started, dead tree biomass was estimated in all three plots; water samples were taken every two weeks until the end of the study from bulk precipitation, saturated groundwater and stream water (pH, major ions and cations); and mineral soils were cored and soil samples were incubated to determine net nitrogen mineralization and net nitrification. In 1991 and 1997, mineral soils were cored and soil samples were incubated again and from 1998 to 2000, litter traps were used to estimate litterfall.

In soils, no difference was observed in nitrogen mineralization rates between the PWD affected site and the unaffected site in 1989 (the year defoliation occurred) and very little nitrification was occurring. Two years later, nitrogen mineralization rates were greatly accelerated at both sites. Eight years after defoliation by PWD, nitrogen mineralization rates remained high at the PWD affected site where more than 90% of the mineralized nitrogen was nitrified, but mineralization rates were back to pre-defoliation levels and nitrification rates were low in the unaffected site down slope from the PWD affected site. The duration of high mineralization rates at the PWD affected site is likely due to decreased vegetation uptake and increased litterfall. In the stream, 5 years (1994) after defoliation started (1989), NO_3^-, Ca^{2+} and Mg^{2+} concentrations increased dramatically while SO_4^- concentrations decreased and outputs of nitrate became larger than inputs.

Pine wilt disease resulted in defoliation, interruption of nutrient uptake and higher litterfall. This in turn induced increases in nitrogen mineralization rates and overall nitrification. Since nitrification produces protons, calcium and magnesium leaching increased from buffering of the produced protons. Losses of inorganic nitrogen in stream water for the three years with the largest nitrate concentrations ranged from 3 to 7kg $N \cdot ha^{-1} \cdot yr^{-1}$, which is quite small compared to losses observed in the Bavarian forest study. The authors suggest that the loss in nitrates was likely due to high annual precipitations and mean annual temperature in the area. Here again, the processes that could have delayed or prevented nitrate export were not important enough to completely prevent nitrate export to the stream and as a result, the system produced a weak type 4 response.

The British Columbia forest harvesting study

The University of British Columbia Research Forest at Haney is located in southwest British Columbia where the mean annual temperature is 9.2°C and the average annual precipitation is 2146 mm (mostly rain). Three small watersheds were selected to study the effects of clearcutting and clearcutting with slash burning on stream water chemistry. Since slash burning produces enhanced loss of nutrients both to the atmosphere and through soil leaching, and have little to do with the effects of bark beetle attacks, we will disregard that portion of the study and only consider the results for the clearcut watershed.

The watershed, forested with western hemlock, western red cedar and Douglas-fir, is an area of 23 ha and was 61% clearcut. Boles were removed from the watershed and great care was taken not do disrupt the forest floor. One year after the clearcut, Douglas-fir seedlings were replanted. A larger watershed, 68 ha of area, served as a control and was not disturbed. Stream water and precipitation were sampled bi-weekly 2 years prior to disturbance and 8 years after. Forest floor and mineral soils were sampled one year prior to disturbance and 7 years after disturbance.

Clearcutting increased concentrations of K, Na, Mg, Cl and NO_3 in stream water for a few years. However, 2 to 3 years after the disturbance, the concentrations of the same elements were lower than in the control watershed for as long as 8 years. The largest increases were observed for potassium and nitrate 3 years after clearcutting. Ammonium concentrations did not change significantly. Stream water export of inorganic nitrogen for the 2 years following clearcutting was 11 $kg \cdot ha^{-1}$ compared to 1 $kg \cdot ha^{-1}$ for the undisturbed watershed. Consequently, nitrogen (and other nutrients) losses were marginal compared to losses observed in the Bavarian forest. Here again, the system produced a weak type 4 response. The authors of this study invite readers to be critical regarding the conclusions of their study for a number of different reasons including the extreme variability that characterizes the ecosystem, which makes it difficult to determine the average concentrations of nutrients in the forest floor and mineral soils. They also point out the fact that they did not look into particulate concentrations of nutrients nor into organic nitrogen concentrations which could be important.

The following table summarizes the effect of disturbance for the three studies reviewed above.

Table 2. Summary of studies reviewed for water chemistry impacts.

Study	Disturbance	Precip. input	Stream output	Net loss	Type of response	Cations lost
		kg of NO_3-$N \cdot ha^{-1} \cdot yr^{-1}$				
Germany	Bark beetle infestation	4.76 to 12.18	~77 with peak at 122	~65 with peak at 116	Type 4	Al, K,Mg
Japan	PWD & wind thrown	1.68 to 4.48	2.86 to 7.28	2.66 to 1.22	Weak type 4	Ca & Mg
BC	Clearcut	~2	~5.5	~3.5	Weak type 4	K

4 Probable impacts of MPB in British Columbia

Since annual precipitation in central British Columbia is generally above the reported 450mm a year threshold necessary to observe increases in water yield after a beetle disturbance, it is expected that MPB infestations will have an impact on hydrology in this province. Although few North American and European studies have been made on the hydrological impacts of bark beetle infestations, all of the reviewed studies report noticeable increases in annual water yield, changes in peak flows and increases in low flows. It is thus highly likely that streams and rivers of interior British Columbia will experience changes in annual water yields, peak flows and low flows following MPB infestations. In light of the present review of the literature, the current MPB infestation in the interior of British Columbia is likely to damage and/or kill enough trees to significantly change interception and transpiration rates in affected watersheds and thus induce changes in annual water yields, peak flows and low flows. As no studies on the hydrological impacts of MPB have been made in British Columbia and given that the province shows wide variations in precipitation regimes, vegetation types and temperatures, it is difficult to predict if those changes will be large or small or even comparable to those reported in the scarce available literature.

Despite the paucity of reported studies directly pertaining to water chemistry effects of MPB infestations, a lot of insight was gained from the many existing published harvesting studies. In the case of water chemistry, it is reasonable to assume that both MPB infestations and harvesting will have similar impacts since the ultimate effect is the same: complete absence of vegetation uptake of nutrients. However, one difference might lie in the fact that during an MPB infestation, the majority of the biomass stays in place and unlike harvesting, nutrients are slowly returned to the soils while the organic matter is degraded.

Another unknown is the effect of forest regeneration on nutrient uptake. Regardless, based on our review of the harvesting and bark beetle infestation literature, it seems reasonable to expect some nutrient losses in central British Columbia forests through streams and rivers following an MPB infestation. The extent of this loss will depend on the type of response for nitrogen and the rate at which the system produces nitrate. If the nitrification rates are high, the system will also produce large amounts of protons that can mobilize cations like calcium, potassium, magnesium and aluminum. The variations in the types of water quality impacts reported for different basins highlights the complexity of biogeochemical cycling within forest catchments. The nitrogen cycle includes many steps, each subject to different controls, so there are many ways in which nutrient loss via the transport of nitrates and cations to soils and rivers could be delayed or prevented.

5 Recommendations and concluding remarks

To improve the understanding of MPB impacts on hydrology and hydrochemistry, we propose a number of research recommendations addressing the broadest knowledge gaps. Short term activities should be two-fold: i) analysis of available climate, hydrologic, and hydrochemical related data ii) hydrological and hydrochemical modelling. Mid- to long-term activities should consist of field data collection which is necessary to refine/verify existing and, if needed, develop new models, as well as to better understand long-term trends/response and reassess/modify forest management strategies.

5.1 Available data analysis

The first proposed short term activity consists of retrieving all available historical climatic (e.g., air temperature, precipitation, etc.) and hydrological (e.g., surface and subsurface water levels, discharge, water temperature, sediment concentration, etc.) related data, as well as water chemistry in MPB affected areas. Ideally, datasets should include several years before a disturbance, during a disturbance, and up to the present. Some hydrological effects have been observed more than 15 years after a bark beetle infestation. As reported in the above literature review, a scientifically accepted approach of assessing hydrological impacts of disturbances (bark beetle or harvesting) is to compare datasets of an unaffected or less affected system to a disturbed watershed for years covering pre- and post infestation. Using data from a nearby and similar watershed that is not disturbed or less disturbed might help to account for regional climatic variations/trends, although such opportunities may be rare in the context of the current outbreak in BC. If such comparative locations can be identified, great care must be taken when comparing the two watersheds. One must account for the morphology (e.g., size, average slope, elevation, etc.), geology (e.g., bedrock and soil properties, etc.), energy balance (e.g., slope orientation, etc.) and vegetation cover (e.g., type, density, structure, etc.) of the study watersheds. A first-order approach could be to construct a relationship between the two datasets before the disturbance to calculate “modelled” undisturbed data after the disturbance for the disturbed watershed. A comparison between the “modelled” data and the measured data in the disturbed watershed should provide reasonable insight into the effects of the disturbance on hydrology and hydrochemistry. This statistical exercise should be repeated in the different eco-climatic zones in British Columbia affected by the MPB. Detailed hydrological analysis of the data is necessary to assess changes in key hydrological variables, such as total annual water yield, peak and low flow timing and magnitude.

5.2 Modelling

A number of hydrological/hydraulic and hydroecological modelling options are available to obtain a first-order estimate of the potential effects of MPB on the hydrology (e.g., discharge, water level, sediment transport, etc.) and hydroecology (nutrients, productivity, etc.) on British Columbia watersheds. First-order modelling attempts should focus on simple and realistic scenarios derived from the literature review, which can be calibrated with existing data. For example, a possible scenario is to examine the effects of MPB infestations on hydrology in the absence of transpiration from a significant portion of the watershed. Another scenario is to examine the effects of MPB infestation on interception and net precipitation reaching the soil, and how this impacts streamflow generation, etc. The first-order modelling scenarios would have to assume that MPB impacted forests regenerate at the same rate as harvested ones since no data is available on that subject.

In addition to the recommended analysis of available data, the first-order modelling attempts should provide reasonable scenarios to define temporary managing strategies in the short-term. However, it is strongly recommended that long-term monitoring of representative watersheds be undertaken to continue existing data collection and collect new data specific to the MPB issue. A more comprehensive data set is essential to develop second-order modelling simulation and to refine the assessment of MPB infestation impacts on the hydrology and hydroecology of British Columbia watersheds in the long-term.

5.3 Monitoring

Large data and knowledge gaps exist in British Columbia that currently inhibit our ability to comprehensively evaluate MPB impacts on various components of the hydrological and hydrochemical cycles. Filling these gaps will require substantial investment in and coordination of short- to long-term field studies addressing the following priority-ranked themes and questions:

Soil and groundwater storage (Priority 1):

- Compared to undisturbed forests (and clearcuts), do MPB impacted areas show distinctly modified infiltration rates, soil moisture regimes, and groundwater table elevations?
- Are the observed changes similar across the watershed or are specific responses observed in mid slope, toe slope, and riparian areas?
- Are such changes associated with distinct changes in streamflow generation mechanisms?

These activities would likely include instrumentation of hillslopes, riparian zones and streams in MPB affected areas to measure changes in moisture status and water tables and to investigate changes in flow pathways associated with MPB impacts.

Water chemistry (Priority 2):

- Does MPB infestation impact nutrient status or water temperature of streams in affected areas?

- Do we see changes in the nitrogen cycle associated with MPB, e.g., higher nitrogen mineralization rates, increased nitrification rates, increased nitrifiying bacteria counts, denitrification rates, and/or increase in cation mobility?
- Is there a significant increase in export of nitrates and cations from soil water to streams and rivers in MPB affected areas?
- Are changes in stream water chemistry and temperature associated with MPB impacts likely to affect aquatic ecosystems?

These activities will likely incorporate monitoring of precipitation, throughfall, stemflow, soil water, groundwater, and streamflow chemistry in undisturbed forests, MPB impacted forests (dead trees) and clearcut forests. Focus should be on the nitrogen cycle as well as calcium, magnesium, aluminum and potassium, as these are most likely to show changes. The above literature review suggests that water chemistry studies should take into account all forms of nitrogen (dissolved and particulate, and organic and inorganic) as well as different soil layers (e.g., humus vs. inorganic soil layers).

Sediment transport and geomorphology (Priority 3):

- Will changes in water table status, magnitude and return period of peak flows, and seasonal modification of streamflow affect sediment transport and controlling processes such as landslides, mass wasting, large woody debris, etc.?
- Will changes in sediment transport and geomorphology affect the health of aquatic ecosystems?

These activities will include monitoring of sediment concentration and stream water turbidity in undisturbed forests, MPB impacted forests (dead trees) and salvaged forests, coupled with geomorphic and aquatic ecosystem surveys.

Precipitation/interception loss (Priority 4):

- How is interception modified by MPB infestation compared to undisturbed forests and salvaged areas?
- How are snow accumulation, albedo and seasonal timing of melt processes affected by forest cover changes associated with MPB outbreak?

These activities should include measurement of seasonal/interannual changes in rain and snow interception and snowmelt between undisturbed forest, MPB impacted forest (dead trees), and clearcut forests.

Evapotranspiration loss (Priority 5):

- To what degree does MPB outbreak affect the evapotranspiration (ET) process, and how do long-term ET rates compare between MPB affected areas, undisturbed forests and salvaged areas?

- To what degree does understory vegetation and direct soil evaporation compensate for ET changes likely to occur in the MPB-impacted canopy?
- How do changes in the ET processes impact soil moisture status, streamflow generation mechanisms and important consequences such as magnitude and return period of peak flows?

These activities should include monitoring of evapotranspiration in undisturbed forest, MPB impacted forest (dead trees), and salvaged (clearcut) forests, as well as study of the partitioning of the relative importance of direct soil evaporation vs. transpiration.

Greenhouse gases (Priority 6):

- How does MPB and related harvesting activities affect the carbon cycle dynamics of BC forests?
- What is the relative importance of carbon dioxide vs. methane emissions (methane is ~21 times more efficient as a greenhouse gas vs carbon dioxide over 100 years) in affected, unaffected and salvaged areas?
- What is the net ecosystem production (NEP) for MPB impacted forests?

These studies will involve monitoring the carbon cycle in undisturbed forests, MPB impacted forests (dead trees) and salvaged (clearcut) forests. MPB impacted forests (not salvaged) will undergo massive organic matter degradation over many years resulting in carbon dioxide and methane (greenhouse gases) emissions. In contrast, forest regeneration contributes to the sequestering of large amounts of carbon through photosynthesis. These two processes will compete to position MPB impacted forests either as carbon sources or sinks. Consequently, quantifying the relative importance of the two processes is an important requirement.

From a priority standpoint (ranked, highest to lowest, Priority 1 to Priority 5) it is recommended that measurement/monitoring of soil moisture and shallow groundwater be given top priority as these activities are straight-forward, tractable, and amenable to regional field monitoring.

Soil/groundwater monitoring also provides a useful measure of the net impact of many other processes affected by MPB infestation (e.g., evapotranspiration, interception, snowmelt, recharge) and in turn fundamentally controls the streamflow generation regime, which affects water quantity, water quality, timing of runoff, peak flow, sediment transport, and health of aquatic ecosystems. Studies in this area should also be aimed at identifying linkages between groundwater and streamflow characteristics.

An important corollary to this response is water chemistry and sediment transport, which are ranked as Priorities 2 & 3. To effectively establish alteration in the streamflow generation processes associated with MPB, studies using naturally-occurring stable isotope tracers would be beneficial if incorporated where possible within the water quality monitoring programs. Gibson et al. (2005) provides a brief overview of recent isotope-based studies of streamflow generation conducted in Canada including British Columbia.

Efforts to study precipitation/interception and evapotranspiration are likely to be of lesser importance (Priority 4 and 5), but are still justified if they support validation/calibration of forest models that predictively link changes in these processes to groundwater/soil water conditions and/or streamflow.

The assessment of carbon cycle impacts and greenhouse gases is also worthy of consideration (Priority 6), although this activity may pertain more directly to carbon budget research than issues considered traditionally as water-budget driven. However, linkages and feedbacks between the water and carbon cycle remain an important frontier research issue.

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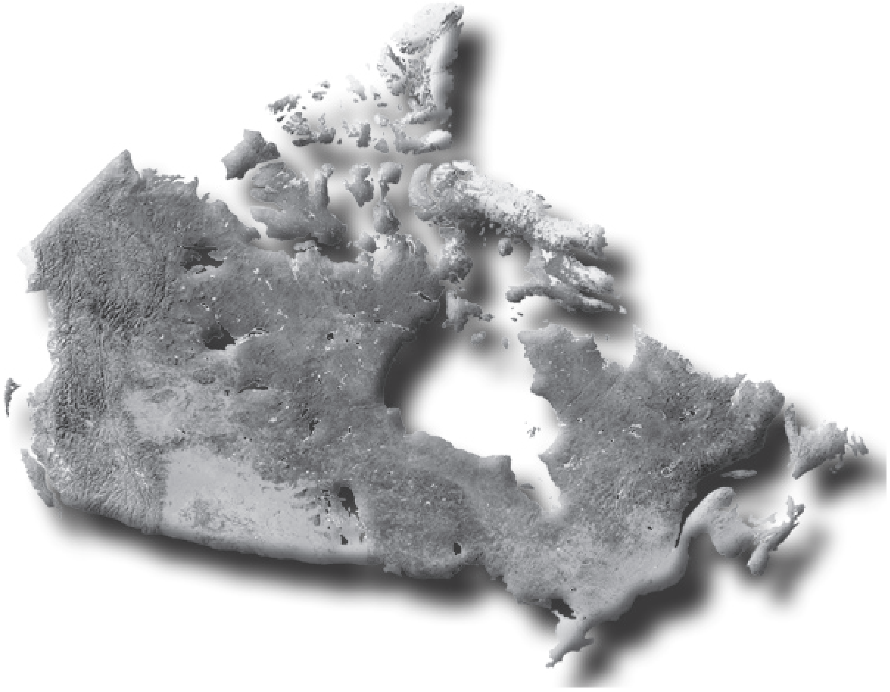

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