Towards an Understanding of the Potential Hydrologic Impacts of Mountain Pine Beetle in Interior British Columbia

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The magnitude of the current mountain pine beetle (MPB) outbreak in British Columbia's interior pine forests is the largest on record in North America. Between 1999 and 2005 MPB affected 10 million ha and killed roughly 411 million m^3 or about 35% of the 1.2 billion m^3 of mature pine volume in the province. By 2013, total cumulative pine mortality is projected to peak at about 80%. In many interior watersheds, beetle-killed pine covers well over 50% of their drainage areas; in some cases this figure approaches 100%. Such large-scale disturbance has the potential to affect the hydrologic regime of a watershed, including both surface water and groundwater resources. Until recently, however, research on this topic has been limited, so a considerable knowledge gap exists. Although this gap will likely be filled over time through existing initiatives, our limited understanding of the topic represents a significant hurdle to present-day forest managers, who are responsible for balancing the pressures for expedited salvage harvesting of beetle-killed trees with the need to protect watershed values.

The purpose of this paper is to review the nature and scope of the MPB disturbance in British Columbia, list some of the current forest management questions, identify relevant research on the topic, and discuss the potential hydrologic effects of MPB (both with and without salvage harvesting). The discussion of hydrologic effects is based on a combination of the limited hydrologic literature on insect infestation, the considerable knowledge base on the hydrologic effects of conventional forest removal, recent accounts by stakeholders and forest professionals in beetle-affected areas, and our own observations from a recent study conducted near Quesnel, British Columbia, where cumulative pine mortality has already reached 80%.

Keywords: Mountain Pine Beetle, salvage harvesting, hydrology

Introduction

The mountain pine beetle (MPB; *Dendroctonus ponderosae Hopkins*) is the most damaging insect that affects lodgepole pine in western Canada. While not unprecedented as a natural phenomena (Burton, 2006), the current mountain pine beetle outbreak in British Columbia's interior pine forests (that can be traced back to about 1993) is the largest on record in North America (BC Ministry of Finance, 2005). The outbreak started in both the southern and northern portions of British Columbia and has since affected pine species throughout the interior of the province. Pine forests (i.e., lodgepole pine, ponderosa pine, and western white pine) account for approximately 1.2 billion m^3 of the provincial timber volume (Dobbin, pers. comm., 2006) and cover roughly 1/3 of British Columbia's 60 million hectare forest base (Eng, 2005). Of the 20 million ha of forests containing pine in the province, roughly 22% is classified as pure pine (Eng, 2005). The remaining 78% is mixed with other species.

By 2005, approximately 411 million m^3 or 35% of British Columbia's mature pine volume were affected by MPB (Dobbin, pers. comm., 2006). Current Ministry of Forests and Range predictions suggest the cumulative volume of beetle-killed timber will continue to increase provincially until about 2013. At that time, the volume of beetle-killed timber is projected to peak at 80% of the provincial volume of mature pine. Within many interior watersheds, particularly those near the origin of the outbreak (near Vanderhoof), beetle-kill has already peaked, leaving many watersheds between 50 % and 100% of their drainage areas affected.

Such a large scale disturbance could have a dramatic impact on forest hydrology (Alila, 2005a and 2005b). While some research on this topic is available, there is generally a dearth of information available to help forest managers predict the hydrologic impacts at such a large scale. Much of the research available is based on beetle epidemics outside of British Columbia and at considerably smaller scales, so that direct application of these findings to the current problem may not be possible (Alila, 2005b). Several studies have been initiated in British Columbia, many of which are currently in progress. Therefore, in the interim, the potential hydrologic impacts of beetle-kill and salvage harvesting must be hypothesized based on the results of the few relevant studies on hydrologic effects of beetle-killed stands, reference to relevant forest hydrology studies and consideration of stakeholders and forest professionals observations in beetle-affected areas.

In addition to the hydrologic regime, beetle-kill and salvage logging may affect sediment transport (including hillslope and channel processes), riparian function, and water quality (including stream temperature). The focus of this paper however is specifically on changes in water quantity and timing as a result of beetle-kill and salvage logging.

This paper briefly outlines the nature of the forest disturbance caused by mountain pine beetle, some of the current management questions, and the previous hydrologic research on beetle infestation. This is followed by discussion of the potential hydrologic effects of mountain pine beetle with and without salvage logging.

Characteristics of the Mountain Pine Beetle Disturbance in British Columbia

Insects, fire, windthrow, and drought play important and often interconnected roles in the natural disturbance and replacement of pine forests. Since fire control measures have been implemented in B.C. there is roughly three times more mature (i.e., greater than 80 years old) pine now than there was in 1910 (Taylor and Carroll, 2003). The relatively high proportion of mature pine currently in British Columbia is considered to be one of the most important controlling factors in the susceptibility of pine stands to beetle attack and ultimately the magnitude of the current beetle epidemic (BC MOF, 2003). Another important factor in the current epidemic is favourable weather in recent years that supports the survival and growth of beetle populations (i.e., warm summers and mild winters).

At endemic levels, mountain pine beetles infest weakened trees and may attack only a portion of the circumference of the tree (i.e., “strip attack”). The trees will continue to live and therefore there is little evidence of beetle attack. When climatic conditions are favourable and host trees are highly susceptible (i.e., old and/or stressed), the incipient stages of an outbreak may occur. At this stage, small groups of trees are typically attacked. Once incipient populations are established, the beetles expand and disperse to the surrounding pine forest, travelling up to 30 kilometres or more under favourable wind conditions and colonizing up to 30 hectares at a time (COFI, 2004). The rate and pattern of attack varies depending on prevailing wind conditions during late summer when adult beetles usually take flight.

Mountain pine beetles kill mature trees by boring through the bark and mining the phloem – the layer between the bark and the wood of a tree. This effectively “girdles” the tree and prevents the upward flow of nutrients in the tree. In addition, beetles carry a blue staining fungus that causes dehydration and inhibits a tree’s natural defences against beetle attacks (BC MOF, 2004). Both the “girdling” and the fungus kill the tree. This process takes about one year from initial attack, during which time the tree’s foliage changes from green to red and trees begin to shed their needles. By the time the trees turn red, the beetles have moved on to colonize another tree or area. Approximately two years after initial attack, pine needles turn dull red to grey. The needles continue to fall for up to five years or more (Maloney, 2006). Trees at this stage are referred to as “grey attack”. In this stage, trees begin to take on a ghost-like appearance, and unless salvaged will remain standing for some time. The timing and rate of tree fall following beetle-kill varies from stand to stand. Research suggests that most trees begin to fall 3 to 5 years after death, and that the majority of trees fall down within about 15 to 20 years, although resistant snags may stand for much longer (Lewis and Hartley, 2006).

Current Forest Management Questions

There are many unknowns on how MPB affects the hydrologic processes in watersheds. Common questions include:

- Will peak flows increase due to altered snow accumulation and melt processes?
- Will there be more water or less water flowing in the summer?
- Will water tables rise?
- Will stream temperatures increase?
- Will there be increased sediment inputs to streams or changes to large wood recruitment?
- Will stream channels become destabilized or will there be an increase in the rate of destabilization?
- Will riparian function and/or fish habitat be affected?
- How long will projected effects on hydrology last?

These questions in turn create many management questions for MPB affected areas. Uunila et al. (2006) presented a list of nine key management questions:

- Is there a threshold at which the hydrologic effects of MPB are measurable?
- How do small group infestations compare in their hydrologic impact with larger infestations?
- How do location, elevation, aspect, physiography, and weather control the hydrologic impacts of MPB?
- How do the density, type, and extent of the forest understory affect hydrologic response and subsequently forest management?
- How do the hydrologic impacts of MPB vary with time?
- What is the impact of standing dead timber on key hydrologic processes? How does this compare with hydrologic impacts after salvage logging?
- How long will it take for non-salvaged beetle-kill stands to regenerate and hydrologically recover? Is regeneration faster or slower if salvage logging occurs in beetle-killed stands?
- Should forest managers approach salvage harvesting in the same manner as conventional harvesting?
- Will alternative silvicultural systems be required in non-salvaged MPB-affected stands to minimize impacts?

Research Studies

Relatively little research has been conducted on the effects of insect infestations in general, and mountain pine beetle infestations in particular, on forest hydrology. The research outlined below and summarized in Table 1 has traditionally involved paired-watershed or stand-scale studies. More recently, hydrologic modeling has become a focus given the urgency of the problem and the challenges in developing controlled watershed experiments.

One of the earliest relevant studies is that by Love (1955). Love (1955) described an Engelmann spruce beetle epidemic in the White River watershed in Colorado that began in 1939 (following a severe windthrow event) and lasted seven years, ultimately covering 30% of the study watersheds and killing up to 80% of the trees. Based on a review of streamflow and snowpack data, Love (1955) concluded that annual water yield increased by about 19% above pre-epidemic values. Love’s study design was criticized by Bue et al. (1955) as being poorly controlled. Bue et al. (1955) claimed that it was not possible to conclude if streamflows increased in the infested watershed or decreased in the uninfested control watershed. However, a re-analysis of the White River data by Mitchell and Love (1973) indicated water yield increase of 15% to 18%, which supported Love’s (1955) conclusion.

The White River infestation was further investigated by Bethlahmy (1974) using additional data and another watershed (Yampa River). Based on an analysis of covariance on pre- and post-infestation data, Bethlahmy (1974) found that annual water yield increased on average about 12% over a 25 year period following infestation. While the data indicated that increases varied considerably from year to year, based on weather conditions, the maximum increase occurred 15-20 years post-infestation, after which time the process of forest regeneration tends to mitigate impacts. Further work by Bethlahmy (1975) was consistent with the earlier research indicating that average increases in annual water yield post-infestation are about 15% and that the maximum increase (of up to 28%) occurred 15-20 years following infestation. The impacts were evident even 25 years after infestation - annual water yields were still 10% above pre-infestation levels. Bethlahmy (1975) also noted that monthly low flows increased 10-31% and monthly peak flows increased 14-22%. However, changes in instantaneous peak flows were variable; from no change to 27% increase.

A mountain pine beetle epidemic in southwestern Montana in the mid-1970's resulted in a 15% increase in annual water yield, a 10% increase in low flows, and a two-week advancement in the timing of spring runoff, but little change in peak flows (Potts, 1984). These changes were associated with a watershed having 35% of the total timber killed by beetle. The observed changes resulted from reduced evapotranspiration losses, as well as alteration of winter snow accumulation and melt processes in winter and spring. However, the method used by Potts (1984) to infer the treatment effect (i.e., double mass curve) is criticized by Hewlett (1982). Uunila et al. (2006) reanalyzed the Potts (1984) data and confirmed the validity of Hewlett's (1982) suspicion. Due to the small sample size (i.e., 4 years pre- and post-treatment), there was no statistically significant effect. Therefore, the results presented by Potts (1984) should be interpreted with caution.

Schmid et al. (1991) conducted a stand-scale investigation in Colorado and identified a complexity in beetle-infested forests that had not been widely considered. These authors identified the live understory (and needle retention to a lesser extent) in a beetle-killed stand as potentially important factors that mitigate the effects of beetle infestation on snowfall accumulation and rainfall interception. This finding is significant since understory vegetation, including well established conifers (e.g., spruce, subalpine fir, and Douglas fir), is common in many beetle-killed stands in British Columbia. According to Eng (2005), pure pine stands account for only 22% of the forests containing pine the province. Furthermore, over 40% of the stands dominated by pine within the north-central interior of the province have adequately stocked (600 stems/ha) understories (Burton, 2006).

Troendle and Nankervis (2000) modelled a spruce bark beetle epidemic on spruce forests in Colorado and Wyoming assuming between 30% and 50% mortality over a 10-year period. Their results indicated an average water yield increase of 56 mm by the tenth year [comparable to Love's (1955) results] followed by a decrease to pre-infestation yields over the next 60 to 70 years.

Research at the University of British Columbia is currently investigating MPB effects and salvage harvesting on streamflow characteristics in selected watersheds in B.C. (Alila, 2005a and 2005b). Both the Distributed Hydrology Soil Vegetation Model (DHSVM) and UBC Watershed Model (UBCWM) are being utilized in this research. Stand-scale and watershed-scale studies throughout the British Columbia interior are being conducted by government agencies and academic institutions (e.g., Dubé et al., 2005). These studies are investigating the role of standing dead trees, partial retention, retention of advanced regeneration, recovery, and extensive forest cover loss on hydrologic processes (Winkler, 2006).

Table 1. Summary of previous hydrologic research on effects of beetle infestation

Location	**Drainage area (km^2)**	**Dominant forest cover**	**% of watershed infested**	**Average change in annual water yield**	**Change in monthly low flow (late summer-fall)**	**Change in monthly high flow (spring)**	**Change in instant. peak flow**	**Expected time for hydrologic recovery to pre-disturbance conditions**	**References**
White River, Colorado	1974	Engelmann spruce	80% of trees covering 30% of watershed	+50 mm (19%)	-	-	-	-	Love (1955)
				+40–48 mm (15–18%)	-	-	-	-	Mitchell and Love (1973)
				+31.8 mm (12%)	-	-	-	-	Bethlahmy (1974)
				+37.9 mm (15%)	+1.6 mm (31.4%)	+14.9 mm (22%)	+20.2 m^3/s (27%)	>25 years	Bethlahmy (1975)
Yampa River, Colorado	1564	Engelmann spruce	80% of trees covering 30% of watershed	+23.6 mm (11%)	-	-	-	>25 years	Bethlahmy (1974)
				+35.2 mm (16%)	+1.2 mm (9.6%)	+12.0 mm (14%)	no significant change	>25 years	Bethlahmy (1975)
Jack Creek, Montana	133	Lodgepole pine	35% of trees (50–60% of trees > 18 cm diameter at breast height	+45 mm (15%)	+2 mm (10%)	+26 mm (52%)	no significant change to magnitude; peak 2 weeks earlier	>5 years	Potts (1984)
North Platte River, Wyoming & Colorado	1978	Engelmann spruce	Assumed 30–50% tree mortality	+56 mm	-	-	-	60–70 years	Troendle and Nankervis (2000)

Adapted from Uunila et al. (2006).

Overall, the available research suggests that the effects of MPB on forest hydrology may be similar to the effects of forest harvesting. Within even-aged stands the effects include:

- increased annual water yield;
- increased summer low flow;
- variable changes to peak flow magnitude; and
- possibly earlier peak flows.

These effects, which may last upwards of 70 years, would likely be mitigated in uneven-aged stands containing live trees and understory vegetation.

Potential Hydrologic Effects of Mountain Pine Beetle and Salvage Logging in B.C.

The lack of controlled experiments and a paucity of data preclude a quantitative assessment of the hydrologic impacts of MPB and the effects of salvage logging a MPB affected stand. This section therefore outlines an initial hypothesis on the hydrologic effects of beetle-kill and salvage logging in interior B.C. Throughout this discussion, the effects of salvage logging are assumed analogous to those typically associated with forest harvesting. The discussion assumes beetle-kill of comparable scale to traditional forest harvesting. It should be kept in mind that in many cases, the scale of beetle-kill far exceeds the traditional scale of forest harvesting, so the potential impacts discussed below are only initial approximations.

Within each of key hydrologic processes discussed below, forest harvest (i.e., salvage-logging) effects are introduced first. This is followed by discussion of the likely hydrologic effects of MPB assuming no salvage logging occurs.

Snow accumulation / interception

Many authors have documented an increase in snow accumulation in cutblocks compared with adjacent forest. Winkler (1999) summarized 16 previous studies of snow accumulation and melt in areas with a similar climate to the interior of B.C. These previous studies reported a range of from 0% to 67% (average 43%) more snow in cutblocks, compared with the adjacent forest, at the time of maximum snow accumulation. This phenomenon occurs for two reasons:

- Snow falls directly onto the ground, rather than being partially intercepted by a forest canopy - subsequent losses to the atmosphere by the process of sublimation are much smaller in the opening than in the adjacent forest; and
- Wind that occurs during snowfall favours deposition in cutblocks, and may also blow snow from the forest canopy into the openings near the stand edge.

Several factors govern the extent of the increase in snow accumulation in cutblocks, including the tree species, characteristics of the ground surface, wind characteristics, and cutblock characteristics.

Snow accumulation in a beetle-killed stand would likely be greater than in the surrounding live forest and approach that of a cutblock, since interception would be reduced (as crown cover is reduced once the foliage falls off). In the Vanderhoof area, Boon (2006) identified that peak snow water equivalent (SWE) in a dead stand was twice that of a comparable live stand and half that of a cutblock. Boon (2006) suggested that the presence of understorey vegetation would play a mitigating role – in its absence, accumulation under dead stands would be comparable to cutblocks. Standing dead timber would tend to protect the snowpack from the effects of wind (i.e., scour and sublimation). Within the first year of infestation (green stage), interception likely reflects natural conditions. One to two years following infestation (red stage) foliage largely remains, and trees still intercept precipitation similar to surrounding live trees (Schmid et al., 1991). Roughly two to four years after infestation (grey stage), most foliage is lost and interception is likely reduced to near zero (i.e., similar to a cutblock) until new trees become established.

Snowmelt

The general consensus in the research literature is that snow located in open cutblocks melts at a faster rate than snow in the forest. The reason for this difference is that solar energy is the dominant driver of melt, and snow in the openings is much more exposed to solar radiation than snow in the more shaded forest. In 16 studies reviewed by Winkler (1999), snowmelt rates ranged from 0% to 250% faster in the openings compared with the forest, with an average of 43% faster. The wide range of snowmelt rates reflects complex processes and several factors, including the tree species, the slope angle, the slope aspect, and the size, shape, and orientation of the cutblocks.

Preliminary study results in the Vanderhoof area based on one year of data suggest that the energy balance and melt rates in a beetle-killed stand may be comparable to those in a live stand. Considering the processes, snowmelt rate in a beetle-killed stand is still likely to be transitional between the melt rate in a cutblock and the melt rate in the surrounding forest, given some shading afforded by the stand and reduced wind action (i.e., turbulent heat flux). Although standing dead trees emit long-wave radiation (leading to snowmelt), the increased long-wave radiation is likely outweighed by reduced solar radiation (due to shading).

Peak flows

In snowmelt-dominated hydrologic regimes, many research studies have documented increases in total spring snowmelt runoff and increases in peak flow rates. Several (but not all studies) [Troendle and King (1985, 1987), Troendle and Stednick (1999), Troendle et al. (2001) and Van Haveren (1988)], have identified an advancement in the timing of peak flow following forest harvesting. These changes are attributable to an increase in snow accumulation in the cutblocks compared with the uncut forest and faster melt rates in the cutblocks. In a review of 40 studies by Scherer (2001), peak flows either increased or did not change following forest harvesting and the relations between the magnitude of change and peak flow following harvesting varied widely with the level of harvest.

Increased snow accumulation and more rapid melt rates in beetle-killed stands will likely result in higher and earlier peak flows than in the surrounding forest. However, due to mitigating effects of standing dead timber on snow accumulation and melt processes, and more importantly the lack of road development and soil compaction by heavy equipment in the beetle-killed area, the effects on peak flows associated with beetle kill should be considerably less than the effects associated with cutblocks.

Evapotranspiration

Evapotranspiration rates are reduced following forest harvesting and research in northern forests suggest this reduction ranges from 85 mm to 318 mm (Dubé et al., 2005). This leads to an increase in annual water yield, possibly increasing late summer streamflow and/or groundwater levels. Following the establishment of vegetation, however, evapotranspiration rates increase towards pre-harvest levels.

A substantial reduction in evapotranspiration also occurs following beetle-kill in even-aged stands with minimal understory vegetation (similar to clearcuts). The presence of mixed species and understory vegetation in the beetle-killed stand will however have a mitigating effect. The duration of the reduction will depend on the time it takes for vegetation and a new forest stand to establish and mature. We speculate that reduced evapotranspiration rates will continue over a longer time span than for cutblocks, as it will likely take longer for a new stand to establish, unless trees are planted to promote regeneration of beetle-killed stands.

Annual Water Yield

In addition to many reports on the effects of forest harvesting on annual water yield, several comprehensive literature reviews on this subject have been conducted, including Hibbert (1967), Bosch and Hewlett (1982), and Stednick (1996). On the basis of these reviews, the following conclusions can be drawn:

- Forest harvesting increases the total annual water yield from a watershed;
- Re-establishment of forest cover decreases water yield; and
- The specific magnitude of the response to forest harvesting is difficult to predict.

None of the studies reported by Bosch and Hewlett (1982) demonstrated a decrease in yield following harvesting. Based on the work summarized in the above-noted studies, it is generally accepted that 15% to 20% of a watershed must be harvested before an increase in water yield can be noticed, although there is a wide range in this threshold. Once an effect is apparent, the increase in water yield is related to the percent of the watershed harvested. Bosch and Hewlett (1982) reported that in general, coniferous forests cause about a 40 mm increase in annual water yield for every 10% decrease in forest cover. However, the nature of the relation between forest harvest and annual yield increase that has been reported in research studies varies widely.

An average increase in annual water yield of about 12-15% has been reported in beetle-infested watersheds where a varying proportion of the forest was affected (Table 1). In general, the increase in annual yield is expected to be slightly less than in cutblocks due to mitigating effects of the standing dead timber on interception, snow accumulation, sublimation, and melt.

Groundwater and summer low flow

Most of the available research indicates that late summer streamflows are increased or not changed following forest harvesting (Scherer, 2001). The reason for this effect is that both rainfall interception by the forest canopy and summer evapotranspiration are reduced after trees have been removed and this volume of water is available to recharge groundwater as well as become runoff. Scherer and Pike (2003) summarized several studies on this topic that indicated transpiration rates from lodgepole pine, spruce, and fir stands can reach 3.3 mm per day during the growing season.

It is speculated that the effects of beetle-kill on low flows are similar to the effects of cutblocks, and involve a modest increase. Although unsupported statistically, Potts (1984) study suggests that beetle-kill could result in increased low flows (by about 10%).

Recent observations in the Vanderhoof area suggest that reduced evapotranspiration has been responsible for elevated groundwater levels, which have affected forestry operations (BC MOF, 2005; Dubé et al., 2005). In the Quesnel area, the authors have noted that following extensive beetle-kill (roughly 80% of the forest) lowland areas are susceptible to increased groundwater levels and conversion of subsurface flow to surface flow. As a consequence, the magnitude and frequency of flooding (throughout the year) have increased making conditions unfavourable for agricultural activities.

Soil compaction

Soils are generally subject to compaction during forest harvesting and road construction. Soil compaction tends to reduce infiltration rates, increase bulk density, convert soil macro-pores to micro pores, alter overall drainage patterns, and promote surface runoff (Keppeler and Ziemer, 1990). Increased surface runoff could result in increased streamflows. The significance of this potential effect depends on how much harvesting actually occurs on soils subject to compaction, and the extent of the surface disturbance that occurs during harvesting.

Assuming no heavy equipment accesses a beetle-kill area, soil compaction and associated hydrologic impacts from beetle-kill will not occur.

Roads

Roads and ditches associated with forest harvesting increase drainage density and create additional paths for the conveyance of surface water to streams, potentially resulting in a faster stream response to rainfall and snowmelt. In addition, cutslopes can intercept groundwater flow and route it to stream channels more quickly than if the water remained as groundwater. Finally, the surface compaction associated with roads and trails reduces infiltration, thus potentially increasing runoff to streams. Each of these factors tends to increase the volume of storm runoff reaching surface streams and the rate at which runoff becomes streamflow. In addition, cutslopes and ditches along roads can alter the natural drainage patterns of the hillslope below the road.

Assuming no roads are developed to access beetle-kill area, the effects of roads on the hydrologic regime will not occur.

Hydrologic Recovery

Hydrologic recovery occurs as the governing hydrologic processes affected by cutblocks and roads return to pre-harvest levels (e.g., interception, evapotranspiration, snow accumulation and melt, soil compaction). Several authors have addressed the longevity of the effects due to timber harvesting. Summit Environmental Consultants Ltd. (2001) summarized previous studies and concluded that the effects of harvesting can last from about 5 years to more than 35 years.

The time for hydrologic recovery is speculated to be greater for beetle-killed stands than for cutblocks that are harvested and planted. A dead pine forest with no live understory may take upwards of 60 years to hydrologically recover (Maloney, 2005), particularly if the stand is not subject to fire. Modeling by Troendle and Nankervis (2000) suggest recovery may take upwards of 70 years. Clearly, the time for hydrologic recovery will depend on stand characteristics (e.g., presence of non-pine species) and the vagaries of nature which control whether a dead stand will be subject to wind throw or fire.

Summary and Conclusions

The current MPB epidemic has the potential to affect forest hydrology in British Columbia. Based on this review, we conclude the following:

- the effects of MPB are similar to conventional forest harvesting;
- the magnitude of MPB effects is expected to be less than or equal to those of conventional forest harvesting; and
- the time for hydrologic recovery is expected to be longer for beetle-killed stands than for conventional cutblocks.

The disturbance caused by MPB in the province varies due to variability in forest type (e.g., pure vs. mixed stands), understory composition, percentage of watershed affected, and other factors. Therefore the severity of hydrologic effects is also expected to vary.

Since existing knowledge of hydrologic impacts of beetle-kill is limited and given the increasing severity of the current infestation in British Columbia, which is predicted to peak in 2013 (Eng, 2005), it is clear that significant opportunities for research on this topic are available. Much of this research will likely involve stand-scale field experiments and modelling work (e.g., Dubé et al., 2005) rather than controlled field experiments at a watershed scale given the challenges in conducting the latter type of research (Winkler, pers. comm., 2005). As presented by Alila (2005a and 2005b), hydrologic modeling will also become a focus of research in the near future since models, once calibrated, can facilitate the rapid assessment of several current and future management scenarios. In the meantime, forest licensees and resource managers who manage BC's beetle infested watersheds must use the knowledge gained from case studies and consider relevant research on the effects of timber harvesting to help guide forestry in beetle-infested areas.

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