Thematic Session Synthesis

Mountain pine beetle and watershed hydrology

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Abstract

Changes to British Columbia's lodgepole pine forests due to the mountain pine beetle (MPB) outbreak will affect stand water balances, hillslope hydrology, and streamflow in many watersheds. The magnitude of this disturbance has prompted a range of research at both stand and watershed scales to address uncertainty about the hydrologic effects of MPB, such as an increased potential for flooding; changes in water yield, peak flows, and low flows; slope and channel changes associated with increased runoff, as well as the effects of hydrologic change on aquatic habitat and drinking water. This paper summarizes the key hydrologic changes expected. It also highlights the results of research currently under way throughout the British Columbia Interior and other regions to quantify changes in hydrologic processes and potential effects at the stand and watershed scales of MPB-related stand mortality and salvage harvesting. General forest planning recommendations and sources of further information are provided.

KEYWORDS: *hydrology, mountain pine beetle, salvage harvesting, streamflow, watershed management.*

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Introduction[1]

The forested watersheds of British Columbia's Interior are a primary water source for aquatic ecosystems and human populations. The current mountain pine beetle (MPB) infestation and associated salvage harvesting have the potential to affect the amount, timing, and quality of water originating from these watersheds. This paper provides a review of research on the effects of the MPB and salvage harvesting on watershed hydrology, and how these activities may affect watershed function.

The current mountain pine beetle infestation and associated salvage harvesting have the potential to affect the amount, timing, and quality of water originating from British Columbia's forested watersheds.

The hydrologic changes resulting from MPB mortality and harvesting are primarily related to the loss of canopy cover. When the forest canopy is reduced through MPB-induced mortality or removed through salvage harvesting, hydrological processes such as interception and transpiration are affected (Figure 1). In general, this results in more water reaching the ground surface and potentially more water available for streamflow. Increased streamflows may have positive (e.g., more water available for human or ecological needs) or negative (e.g., increased flood potential, degraded water quality) effects. Therefore, understanding the magnitude and direction of changes is critical to account for hydrological risks in management and planning for both the forested watersheds and the valley-bottom infrastructure and water-users. Watershed-specific impacts may also be difficult to accurately predict

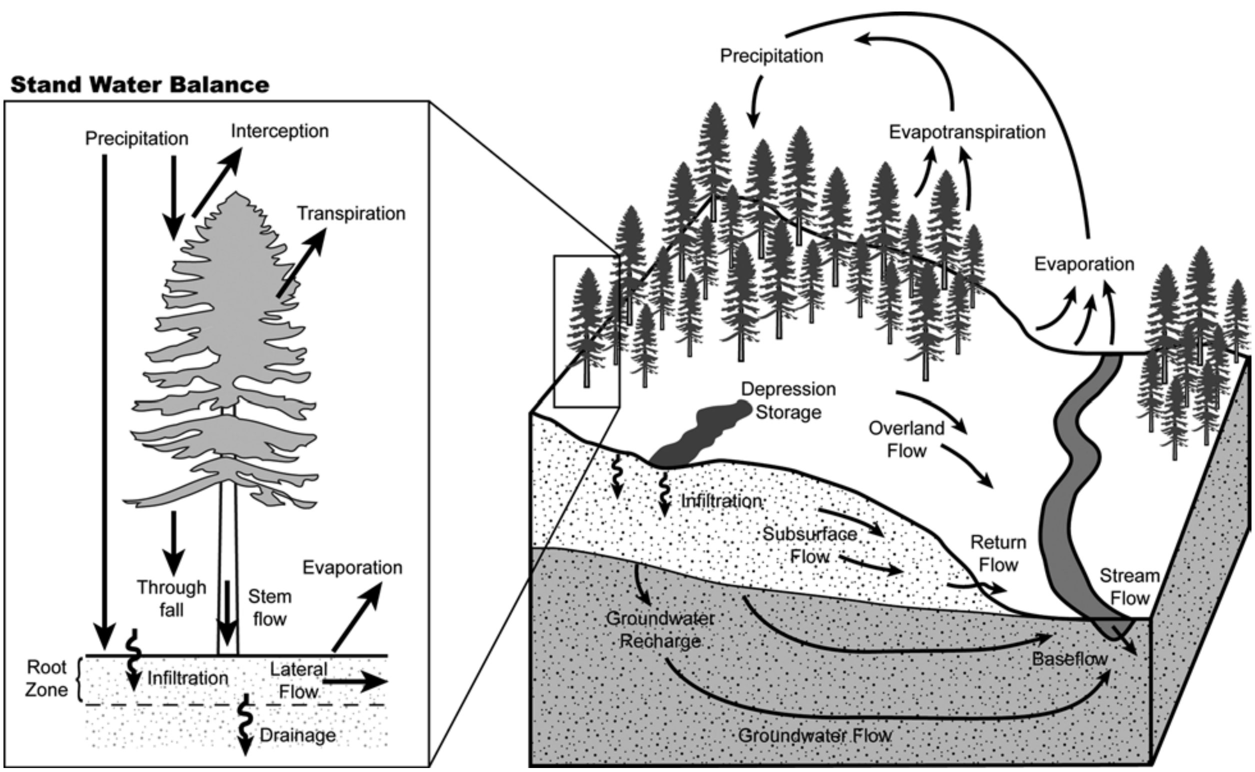

FIGURE 1. Hillslope hydrologic cycle and stand water balance. The loss of forest canopy influences the interception of precipitation and the subsequent loss through evaporation and transpiration (adapted from Winkler *et al.*, forthcoming).

[1] Portions of this document have been reproduced from (with permission): Winkler, R.D., J. Rex, P. Teti, D. Maloney, and T. Redding. 2008. Mountain pine beetle, forest practices, and watershed management. B.C. Ministry of Forests and Range, Research Branch, Victoria, B.C. Extension Note No. 88. URL: *http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En88.pdf*

because of the variable influences of geology, topography, soils, and vegetation on hydrological response.

This paper summarizes the expected changes in water cycling as a result of the MPB infestation and associated salvage harvesting. It is based, in part, on presentations at the Mountain Pine Beetle: From Lessons Learned to Community-based Solutions conference held in Prince George, B.C., June 10–11, 2008. In addition, portions of the paper have been reproduced (with permission) from Winkler *et al.* (2008). Other recent publications on this subject include Uunila *et al.* (2006), Hélie *et al.* (2005), and Environmental Dynamics Inc. (2008). Specifics on other critical areas of consideration when dealing with MPB-affected stands, such as stand dynamics, biodiversity, and forest fire fuel management were outlined by other conference presenters (see, for example, synthesis papers by Swift [page 17], Lewis [page 24], and Hawkes [page 77]).

Effects of Mountain Pine Beetle and Salvage Harvesting on Hydrological Processes and Watershed Response

The effects of forest disturbance (including MPB and salvage harvesting) are typically investigated at the stand and watershed scales. The stand-scale effects investigated include snow accumulation and melt, rainfall interception, stand water balance, stand and hillslope subsurface hydrology, and hydrologic recovery. Watershed-scale effects include effects on streamflow, aquatic ecology, and water quality.

Redding *et al.* (2007b) developed a generalized illustration of the relative changes in hydrologic processes and watershed response to loss of canopy (e.g., through MPB mortality, salvage harvesting, fire, etc.) that shows how hydrologic variables change along a gradient of canopy cover (Figure 2). Although this is a useful tool for understanding the interaction of different processes, it is not meant to provide absolute magnitudes of response or address unique site conditions.

Stand-scale Effects

Snow Accumulation and Melt

A significant portion of total winter precipitation is intercepted by forest canopies and lost through sublimation. The forest canopy not only reduces snow accumulation relative to open areas, it also influences how quickly snow disappears. Snow surveys throughout the Interior show large annual, geographic, and forest-cover-related variability in snow accumulation and ablation, even over distances of only a few kilometres (Winkler *et al.* 2004; Winkler 2007). Storm type also significantly influences canopy interception. This was

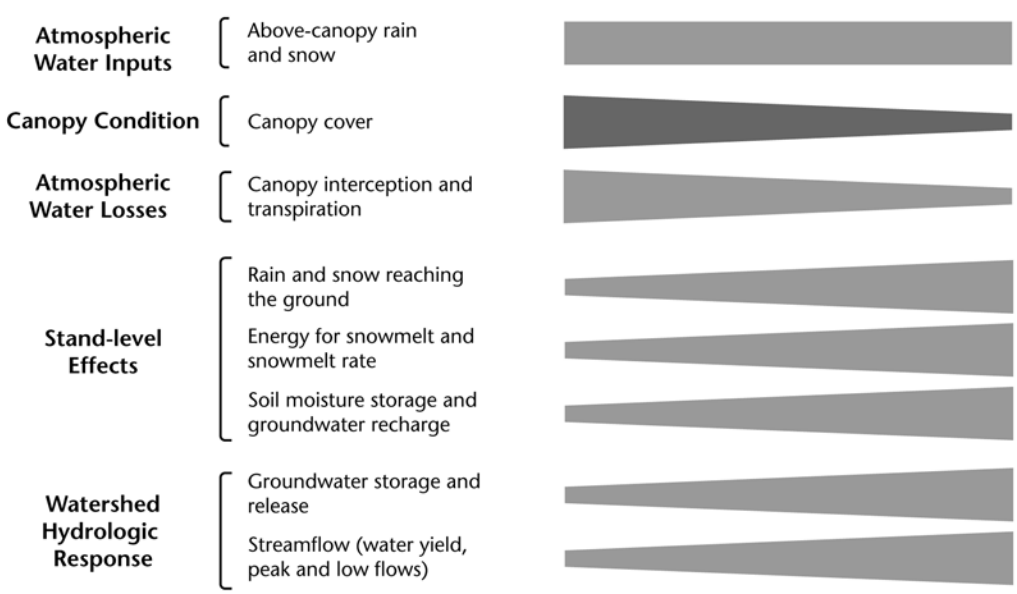

FIGURE 2. The influence of forest canopy alterations on water cycling. The thickness of a wedge represents the trend in a process or effect as the canopy cover (black wedge) is altered; it does not indicate the magnitude of the process or effect. Where the canopy cover is highest (wedge thickest), it is representative of a well-stocked healthy mature stand. Where it is lowest (wedge thinnest), it is indicative of a recent clearcut (adapted from Redding *et al.* 2007b).

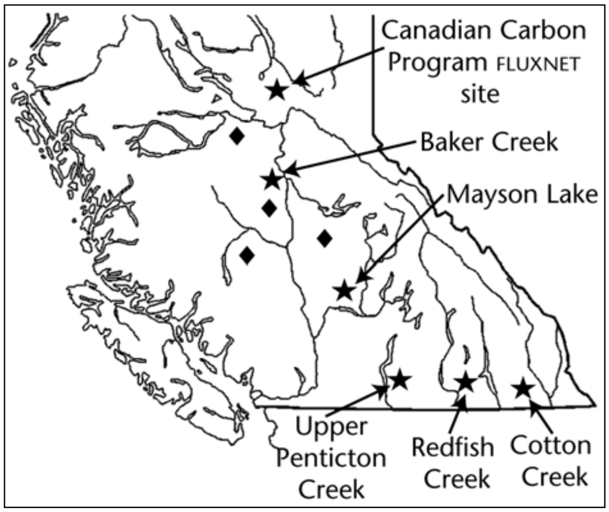

FIGURE 3. Ongoing stand-level research projects examining disturbance effects on hydrological processes. Sites denoted by diamonds are those limited to studies of snow accumulation and melt; at those sites denoted by stars, research covers a range of hydrological processes (including snow accumulation and melt).

evident particularly in dead stands with a coniferous understorey where, during major winter storms, young trees (< 1.3 m tall) were snow-pressed, which limited interception by these canopies (Boon 2007b).

Changes in snow accumulation attributed to changes in canopy cover have been studied at many sites in British Columbia (Figure 3). At long-term research sites on the Thompson-Okanagan Plateau, the maximum snow water equivalent (SWE; liquid water held in the snowpack) in mature lodgepole pine stands averages 11% less than that in recent clearcuts (Winkler 2007). These reductions are smaller than those observed in mixed-species stands at these study sites. Up to 44% less SWE at maximum accumulation has been measured in the mixed-species stands relative to nearby clearcuts. Recently initiated surveys in MPB-attacked stands near Vanderhoof have shown that, at maximum accumulation, SWE in a stand that had lost its needles (grey-attack stage) and in a green mixed-species stand was 53% and 73% less, respectively, than that measured in a clearcut (Boon 2007a). In another study also located in the Central Interior, snow surveys in mixed-species green forest stands near Prince George showed that maximum SWE was 50–60% less than that in nearby clearcuts and that SWE in a grey stand was roughly halfway between; however, little difference was observed in snow accumulation between a green pine stand and a grey pine stand near Prince George during a year of low snowfall (Beaudry 2007).

Snow ablation rates (the loss of snow through both melt and vaporization) are, on average, 15% lower, and snow persists for up to 8 days longer in the forest than in the open (Winkler 2007). In addition, up to 60% slower ablation rates were measured in the mixed-species stands relative to nearby clearcuts (R. Winkler, pers. comm., 2008). Snow ablation rates are decreased by forest canopies partly because of the reduced solar radiation at the snow surface relative to that in the open (Spittlehouse and Winkler 2004). Current research in British Columbia (Teti and Winkler 2008; D. Spittlehouse, pers. comm., 2008) shows that old pine stands which have not been defoliated, and mixed-species, pine-leading stands, transmit 15–30% of solar radiation in early spring depending on the canopy and stand density. This level increases as the stand deteriorates over many years. In a stand attacked in the 1980s, where previous canopy-forming trees had fallen and natural regeneration was well established, transmittance to the snowpack was 57% (P. Teti, pers. comm., 2008). In contrast, salvage harvesting increased radiation transmittance to virtually 100% for at least 10 years (Teti and Winkler 2008). Transmission of radiation to the snowpack decreased rapidly after this time, dropping to approximately 20% within 35 years of logging.

Snow accumulation and ablation recovery (defined as the decrease towards that in the mature forest) were 43% and 29%, respectively, in 20-year-old pine stands. Thinning to remove approximately one-half of the stems did not affect maximum snow accumulation, but reduced snow ablation recovery to 13% (Winkler *et al.* 2005). On the Fraser Plateau, Teti (2007) found that snow ablation rates in young stands are very similar to those in a clearcut for at least 12 years. However, in 35-year-old forests, ablation rates are very similar to those in mature forest. Data from all snow surveys in the Thompson-Okanagan show a 6% reduction in April 1 SWE with every 10% increase in crown closure to a maximum of 55% reduction in SWE (Winkler and Roach 2005).

In large openings at several steeply sloping south-facing study sites in the Okanagan, higher SWE is measured in the forest than in the open at the time of maximum accumulation, indicating that periodic snow disappearance occurs in the open before the main melt season (R. Winkler, pers. comm., 2008). These losses occur due to wind scour, sublimation, and possibly melt during warm periods in mid-winter, and potentially mitigate the effects of increased SWE at other sites across the landscape, resulting in desynchronization of snowmelt and streamflow generation.

Rainfall Interception

Limited research has been conducted on changes in rainfall interception that result from canopy deterioration following MPB attack. In mature mixed pine, spruce, and subalpine fir forests, the canopy intercepts and subsequently evaporates approximately 30% of growing-season precipitation, reducing the amount of water reaching the ground (Spittlehouse 2007). At Mayson Lake north of Kamloops and Penticton Creek in the Okanagan, measurements of rainfall interception indicate approximately 40% of growing-season rainfall is lost in a mature stand (Redding *et al.* 2007c; Winkler *et al.* forthcoming). A well-developed understorey below an old MPB-killed stand intercepted as much rain as live trees (Schmid *et al.* 1991). Storage and subsequent evaporation of rainfall in the litter and moss layers on the forest floor accounts for 20–30% of growing-season precipitation in low rainfall regimes (Carlyle-Moses 2007). In mature lodgepole pine stands in the Rocky Mountain foothills of Alberta, Silins *et al.* (2007) estimated that on average 44% of growing-season precipitation is lost to canopy and forest floor interception in mature stands.

Stand Water Balance

Atmospheric water losses (interception, transpiration, and soil evaporation) in mature pine stands in British Columbia (Spittlehouse 2007) and Alberta (Silins *et al.* 2007) typically account for 60–70% of annual precipitation inputs, with 30–40% of precipitation draining below the rooting zone and available for groundwater recharge and (or) to generate streamflow. Following MPB infestation and salvage harvesting, the proportions of water balance components in an individual stand will change, resulting in an increase in drainage. Water balance modelling carried out for study stands at the Upper Penticton Creek Watershed Experiment indicates that after MPB attack and salvage harvesting more water would be available to recharge groundwater and generate streamflow (Figure 4; Spittlehouse 2007). When compared with mature lodgepole pine forest, red-attack stands show similar amounts of interception loss, while the grey-attack and clearcut stands show reduced interception. Plant transpiration plus soil evaporation are similar between the mature and clearcut stands, and reduced in the red- and grey-attack stands. The most water available for groundwater recharge and streamflow is in the clearcut and grey-attack stands with the red-attack stands intermediate and the mature stand lowest. The modelling indicates that a stand with less than 40% of the trees attacked has a similar hydrological balance to the attacked stand.

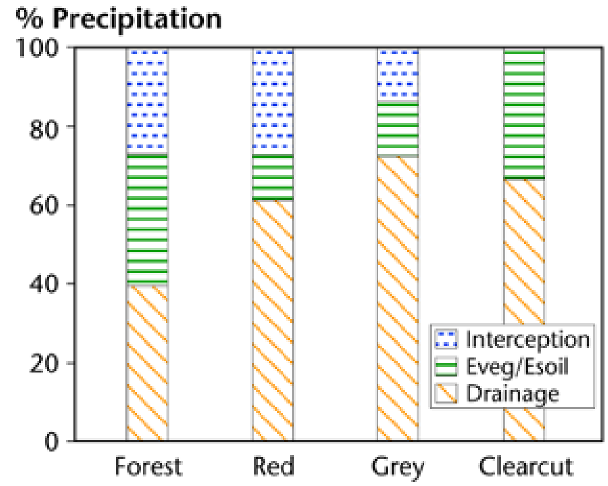

FIGURE 4. Modelled mean annual stand water balance for mature, red, grey, and clearcut lodgepole pine stands at Upper Penticton Creek. Data are results of a process-based stand water balance model run at a daily time step from October 2002 to September 2006. Meteorological inputs (precipitation, temperature, humidity, and above-canopy radiation) and soil properties were held constant for all stands, and only canopy properties were varied (adapted from Spittlehouse 2007). "Interception" represents the amount of precipitation intercepted by the canopy and subsequently evaporated; "Eveg" and "Esoil" represent plant transpiration and evaporation from the soil surface, respectively; "Drainage" represents water that moves vertically below the rooting zone and is potentially available for groundwater recharge and streamflow.

Subsurface Hydrology

With changes in the stand water balance resulting in greater drainage, and hence water available for groundwater recharge, reports of rising water tables affecting trafficability and forest harvesting operations in some areas of heavy infestation and salvage harvesting are not surprising (Rex and Dubé 2006; Dubé and Rex 2008). In the Vanderhoof Forest District in central British Columbia, Rex and Dubé (2006) noted elevated water-table levels in lowland areas (e.g., toe slopes, wetlands, or lowland landscapes) after harvesting. The risk of wet ground increased with:

- decreasing drainage density;
- decreasing understorey vegetation;
- increasing area of sensitive soils (poorly drained or fine texture); and
- increasing pine cover (Dubé and Rex 2008).

Decreased efficiency of surface water drainage and rising water tables can affect the selection of appropriate silvicultural systems (Pothier *et al.* 2003), post-harvest species selection (Landhausser *et al.* 2003), and trafficability (Rex and Dubé 2006).

Little available literature examines changes in hillslope runoff generation before and after harvesting; however, two studies are available with relevance to conditions in British Columbia. In Idaho, Megahan (1983) measured a large post-disturbance (harvest and wildfire) increase in both subsurface stormflow volume (+ 96%) and flow rate (+ 27%) during the snowmelt period. The increase in volume and rate was attributed to a post-disturbance increase in both SWE and melt rates for the study hillslopes. At the Fraser Experimental Forest in Colorado, Troendle and Ruess (1997) measured an increase in annual hillslope outflows from 15% of incoming precipitation under forested conditions to 60% of incoming precipitation for clearcut conditions. The changes were attributed to greater snow accumulation and reduced transpiration for the clearcut plot.

Hydrologic Recovery

For a given set of weather conditions, the magnitude and duration of stand-scale hydrologic change associated with MPB will depend on:

- the percentage of overstorey that has been killed;
- the presence, age, and density of advance regeneration and understorey vegetation; and
- the stand's logging history.

If MPB-attacked stands are left to deteriorate naturally, hydrologic change will be more gradual as trees turn from green to red, drop their needles, turn grey, lose fine branches, and eventually fall to the ground (Huggard and Lewis 2007). At the same time, understorey vegetation may release due to increased light and reduced competition for nutrients and water. In contrast, clearcut salvage harvesting causes a large immediate change to the site water balance through removal of the overstorey. The hydrologic change associated with salvage harvesting will also vary with the amount of ground disturbance, intensity and type of site preparation, degree of drainage disruption, degree of understorey damage, and rate of forest regrowth.

To address uncertainties around MPB impacts on stand-level hydrological recovery, Huggard and Lewis (2007) used models of stand tree growth, field data on understorey composition, and measurements of hydrologic recovery as snow accumulation and melt to generate recovery curves for various forest management options in select Interior Douglas-fir and Montane Spruce biogeoclimatic subzones in the southern interior of British Columbia. The results indicate that clearcut salvage harvesting and planting results in the greatest increase in equivalent clearcut area (ECA) and quickest recovery (see Figure 5 for hypothetical example). Full retention of the dead stand shows the lowest maximum ECA, but the most prolonged full recovery (Figure 5). In selecting a retention or salvage strategy, it will be necessary to balance the risk of a more intensive disturbance with the benefit of a quicker recovery (Huggard and Lewis 2007).

Watershed-scale Effects

Watershed-scale effects of forest disturbance can be difficult to quantify because of large natural variability in climate, geology, and other factors that control streamflow generation and timing. Two main

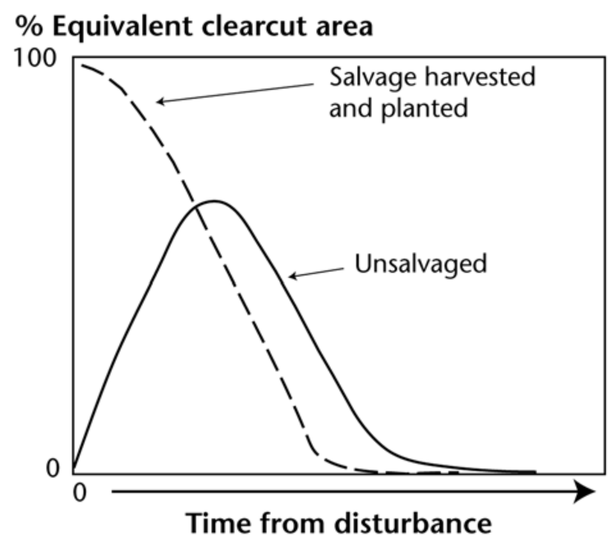

FIGURE 5. Hypothetical hydrological recovery trajectories for salvaged and planted and unsalvaged stands (complete retention). A lower value of equivalent clearcut area indicates greater hydrological recovery (adapted from Huggard and Lewis 2007).

approaches have been used to examine the effects of MPB and salvage harvesting on streamflow: retrospective streamflow analyses and numerical modelling. For retrospective streamflow analyses, long-term streamflow records are analyzed to quantify disturbance effects. The second method is the application of hydrologic simulation models to examine the impacts of various infestation and salvage-harvesting scenarios on streamflow. For further information on the different approaches, see Pike *et al.* (2007).

Retrospective Streamflow Analyses

At Camp Creek in the Okanagan basin, 30% of the watershed was salvage-harvested in 1976–1977 following MPB infestation (Cheng 1989). A paired-watershed analysis showed that annual water yields increased by 21%, peak flows increased by 21%, peak flow timing advanced by 13 days, and April flows also increased (Cheng 1989; Moore and Scott 2005). The duration of peak flow increase lasted approximately 15 years, while elevated April flows persisted for the length of data record. These values generally agree with stand-level measurements of hydrologic recovery of snow accumulation and melt processes (Moore and Scott 2006). No changes in low flows were detected (Moore and Scott 2005).

Extensive forest harvesting has taken place in both the Bowron River and adjacent Willow River watersheds in central British Columbia. Large-scale harvesting occurred in the Bowron River watershed in response to a spruce beetle outbreak in the 1970s. Both watersheds are large (Bowron: 3590 km^2; Willow 3110 km^2) and have long-term streamflow records (Wei and Lin 2007; Lin and Wei 2008). Statistical time series analyses were applied to the data to detect effects related to forest harvesting. No statistically significant effects of salvage harvesting were detected on annual water yields, peak flows, or low flows for the Bowron River watershed (Wei and Lin 2007). In the adjacent Willow River watershed, Lin and Wei (2008) found significant increases in spring and annual peak flows, and an increase in annual water yield that was attributable to harvesting. Neither watershed showed any significant changes in low flows. The reasons given for variable effects of harvesting on these adjacent watersheds included differences in watershed characteristics, climate, and the timing and location of harvesting (Wei and Lin 2007).

The Fishtrap Creek watershed, near Kamloops, B.C., was severely affected by wildfire during the summer of 2003. Since then, an increase in flows occurs during the early stage of the freshet, and high flow periods are lasting longer than before the fire. The earlier and longer period of high flows may be the result of changes in snowmelt dynamics in the basin resulting in a desynchronization of basin melt (Moore *et al.* 2008). The longer duration of high flows appears to be affecting channel processes and sediment movement through the burnt floodplain of the watershed (Moore *et al.* 2008).

Similar increases in peak flow and water yield were found in Montana and Colorado. In Montana, a watershed with 35% defoliation had a 15% increase in annual water yield (Potts 1984). Although no changes were evident in peak flow magnitude, the annual peak occurred 14–21 days earlier and high flow conditions persisted longer with a greater spring monthly water yield. In addition, low flows increased by 10%. In two Colorado watersheds following defoliation of 30% of their area, annual water yield increased 16%. Peak flows occurred 2–11 days earlier and were 4–27% larger following defoliation; low flows also increased 10–31% (Bethlahmy 1975).

Hydrologic Simulation Modelling of Mountain Pine Beetle Infestation and Salvage-harvesting Scenarios

To examine the potential effects of extensive MPB infestation and salvage harvesting on peak flows and water yield, the Distributed Soil-Vegetation-Hydrology Model (DHSVM) was applied to the 1570 km^2 Baker Creek Watershed near Quesnel, B.C. (Forest Practices Board 2007). The model was run with four scenarios:

1. baseline with 13% watershed area harvested and 0% watershed area MPB affected;
2. conventional harvesting with 28% area harvested and a further 2% area MPB affected;
3. MPB epidemic with 34% area harvested and a further 53% area MPB affected; and
4. salvage harvest with 80% watershed area harvested and a further 17% area MPB affected.

The results of scenarios 3 and 4, with the largest amounts of harvesting and MPB-affected area, were striking. For scenario 3, the model predicted a 60% increase in mean annual peak flow and an advance in peak flow timing of 15 days (Forest Practices Board 2007). For scenario 4 with the maximum amount of salvage harvesting, peak flows were predicted to increase by 90% and occur 16 days earlier (Forest Practices Board 2007). The results indicated the potential for a major shift in flood frequency in the watershed; floods with a baseline return period of 20 years may increase to a return period of 3 years under scenario 4. This shift would have major implications for the design of infrastructure on the floodplain and highlights the need to plan the extent of clearcut salvage harvesting in infested watersheds, designate reserve areas, and carefully design stream crossings (Forest Practice Board 2007).

To examine the effects of MPB and salvage harvesting on streamflows, two hydrologic models were applied in the Okanagan basin. The HBV-EC model, which has relatively modest data requirements, was able to reproduce the statistical distributions of post-harvesting streamflow changes (Moore *et al.* 2007). Streamflows in any given year were not always accurately simulated, likely due to an overly simplistic model representation of canopy influences on snow accumulation processes (Moore *et al.* 2007). The University of British Columbia Watershed Model was applied to simulate the effects of complete clearcut harvesting on peak flows and water yield for a number of Okanagan tributary watersheds (Alila and Luo 2007). The results show peak flow increases of 30–100% for 1- and 2-year return period events and freshet water yield increases of 40–75%.

Modelling of streamflow response to MPB and salvage-harvesting scenarios for pine-dominated watersheds of the Alberta Rocky Mountain foothills also predicts the potential for dramatic changes in streamflow (Rothwell and Swanson 2007). The WRENSS model was applied to four watersheds between Grand Prairie and Grand Cache using a scenario of reducing pine cover by 75% within 20 years. Annual water yields were predicted to increase by 9–29%; 2-year return period flows were predicted to increase by 7–53%, and 100-year return period flows to increase by 1–20% (Rothwell and Swanson 2007). The predicted average time to reach pre-MPB conditions was 44 years.

Impacts on Aquatic Ecology

Changes in streamflow regimes following watershed disturbance have the potential to affect aquatic communities and processes (Johannes *et al.* 2007). Large woody debris (LWD) in streams is critical for habitat formation; harvesting in riparian zones can potentially disrupt these inputs. Source-distancing research completed under the Prince George Small Streams Study identified that the majority of active in-stream LWD originated within 10 m of the streambank (Beaudry and Beaudry, forthcoming). In the Okanagan, Wei *et al.* (2007) found similar LWD input rates between MPB-attacked and non-attacked stands; however, the MPB-attacked stands show greater LWD movement distances. In the Bowron River watershed, riparian harvesting in the 1970s continues to affect LWD recruitment and stream recovery (Nordin 2008). In pine-leading stands of the Central Interior, spruce can be the dominant species in riparian zones, indicating that riparian retention is a viable option to maintain aquatic values (Rex 2007). Protecting riparian function and aquatic habitat will have major implications for fish populations, including salmon throughout the Interior of British Columbia (Johannes *et al.* 2007).

Impacts on Water Quality

Little research has been undertaken on the effects of the MPB infestation on water quality; however, based on knowledge from other forest disturbances, some generalizations are possible. Increased road building and stream crossings for salvage harvesting may potentially increase sediment delivery to watercourses. Given the potential for increased flows discussed earlier, it may be necessary to design structures to a higher standard. At Fishtrap Creek in southern British Columbia, mortality of the riparian canopy due to wildfire resulted in a loss of bank strength that caused significant channel change and associated transient increases in suspended sediment concentration (Moore *et al.* 2008). Chemical properties of surface waters may be affected by the MPB infestation and salvage harvesting due to associated changes in water fluxes and biogeochemical cycling. In Colorado, elevated stream water nitrate concentrations were evident after MPB infestation of watersheds and have persisted for a number of years, but remain below drinking water standards (Stednick 2007).

The loss of riparian cover due to canopy mortality or harvesting can lead to increases in stream temperature, which may adversely affect aquatic processes and fish productivity (Moore *et al.* 2005). Although no studies have specifically examined the effects of MPB-related canopy loss on stream temperature, studies that examine harvesting effects in the Central Interior can provide some guidance. For instance, Mellina (2006) found that headwater streams in this area typically feature downstream warming trends, and lake-headed streams feature downstream cooling. The effects of riparian harvesting on stream temperature were greatest for headwater streams compared to lake-headed streams; these disparities may be partially related to differences in groundwater inflows (Mellina 2006). A model is available that can help predict the potential effects of harvesting on stream temperatures (Mellina *et al.* 2002; Mellina 2006). At Fishtrap Creek, the burnt canopy reduced the net radiation reaching the stream surface by about 30% compared to no standing dead vegetation; radiation under the standing dead trees was 50% greater than for pre-fire conditions (Moore *et al.* 2008).

Management Tools

Various tools have been developed, or are currently under development, to assist managers and planners in assessing the potential impacts of the MPB infestation and salvage harvesting on watershed values.

Planning and Operational Tools

Forest and Range Evaluation Program: Fish/Riparian Evaluation Procedure

The goal of monitoring the condition of stream channels and their adjacent riparian management areas is to determine whether *Forest and Range Practices Act* standards and practices governed by regulation are achieving the desired result of protecting fish values by maintaining channel and riparian functions. The specific Forest and Range Evaluation Program (FREP) monitoring question is: "Are riparian forestry and range practices effective in maintaining the structural integrity and functions of stream ecosystems and other aquatic resource features over both short and long terms?" (Tripp *et al.* 2008). Given the linkages between aquatic ecosystems and fish habitats within watersheds, interpretations of effectiveness are relevant not only for site-specific management, but also to determine downstream or downslope effects, and cumulative watershed effects. The main questions addressed by the FREP Fish/Riparian Evaluation Procedure are:

- Are riparian forestry and range practices effective in maintaining the structural integrity and functions of stream ecosystems and other aquatic resource features over both short and long terms?
- Are forest road stream crossings or other forestry practices maintaining connectivity of fish habitats?
- Are forestry practices, including those for road systems, preserving aquatic habitats by maintaining hillslope sediment supply and the sediment regimes of streams and other aquatic ecosystems?

For more information, please visit: ***http://www.for.gov.bc.ca/hfp/frep/values/fish.htm***

FREP: Water Quality Effectiveness Evaluation Procedure

Watershed managers want to determine the effects of forestry and range uses on water quality. When negative impacts caused by fine sediment generation or fecal contamination are confirmed, they need to prioritize actions that will economically mitigate the impacts. The Water Quality Effectiveness Evaluation procedure is a tool that:

- identifies common disturbed forestry and livestock sites that may generate fine sediment (slope failures, road stream crossings, road paralleling streams, windblown riparian leave strips, etc.) and fecal contamination; and
- determines if and how much such sites affect water quality, and provides clear management options to reduce sediment generation at the particular site.

For more information, please visit ***http://www.for.gov.bc.ca/hfp/frep/values/water.htm***

Identifying the Risk of Wet Ground

To address concerns about the limiting effects of rising water tables on forest operations in certain watersheds of the Vanderhoof Forest District, Ministry of Forests and Range researchers developed and tested a tool to identify the risk of wet ground (Dubé and Rex 2008). The method ranks watersheds based on their potential for elevated water tables or drainage problems. The hydrologic risk indicators for potential wet ground are those factors that control the delivery of precipitation to the ground surface (e.g., infestation characteristics) and those that affect the retention of water in the watershed (e.g., watershed characteristics). All of the risk indicators can be quantified on the basis of information available from provincial spatial data resources. The combination of indicators that effectively predict the risk of wet ground are: drainage density, understorey cover, proportion of area with sensitive soils, and proportion of pine cover (Dubé and Rex 2008). The method has been shown to work well for the Vanderhoof Forest District. Some field verification would be required to apply the tool in other areas. For more information, please contact Stephane Dubé (***Stephane.Dube@gov.bc.ca***) or John Rex (***John.Rex@gov.bc.ca***).

B.C. Ministry of Environment: Fisheries Sensitive Watersheds and the Watershed Evaluation Tool

British Columbia's fisheries resources, including the watersheds on which they rely, are an important social, economic, and ecological feature of the province's landscape. Historically, various fisheries management initiatives have been aimed at evaluating watershed sensitivity and protecting fish values. Typically, these were targeted at site-specific stocks or locations, and identified areas in an ad hoc fashion with little consideration for assessing higher fish values at the watershed scale and over the broader landscape. Recognizing the weaknesses of this method, under the *Forest and Range Practices Act*, and using the Government Actions Regulation to legally designate "fisheries sensitive watersheds" (FSW), government has developed a prototype model called the Watershed Evaluation Tool (WET) to comparatively assess watersheds across the larger landscape. A GIS-based (vector) tool, WET has been designed to evaluate and numerically rank third-order (or larger) watersheds at the 1:50 000 scale. Using a consistent methodology, the tool can be applied to various predefined geographic areas ranging in size from the entire province down to a sub-regional scale. The model uses an assortment of consistently available indicators to evaluate each watershed's inherent physical sensitivity and fish values. These indicators are derived from numerous sources including: interpolations of TRIM data, watershed statistics, baseline thematic mapping, modelling, and inventories. The indicators are combined in a series of systematic, normalized, and linear process steps to determine a single relative score or rank for each watershed within a predetermined geographic population of watersheds. Although the tool was designed to help legally designate FSWs, it has other important applications including prioritizing watersheds for restoration, compliance monitoring, and assessing fisheries impacts in watersheds affected by MPB. It was also successfully used to prioritize watersheds for fish passage (culvert) assessment and improvements. For more information, contact Lars Reese-Hansen, B.C. Ministry of Environment (***Lars.ReeseHansen@gov.bc.ca***)

B.C. Ministry of Environment: Risk-based Models

The B.C. Ministry of Environment (Water Stewardship Division) has been developing an office-based assessment framework as a standardized system for hydrologic hazard assessments. The models under development focus on the physical processes important to the assessed hazards and risks. Data is used at a scale appropriate to each process, making the models relevant for a range of applications at the strategic and local planning levels. The assessment process is applied in a GIS environment, with widely available data sets. Basic inputs for the assessment include characterization of the watershed assessment units, identification of threats, and modelling of potential changes to the hydrologic system resulting from interactions within an assessment unit of a watershed's characteristics and associated threat activities. Inherent risks, past impacts, and potential future impacts are all considered separately. One of the component models (peak flow) is introduced below ("Hydrologic Modelling Initiatives"). Hydrologic hazards will be used to help identify values at risk and potential consequences that may result for each value. For further information, contact Martin Carver, B.C. Ministry of Healthy Living and Sport (***Martin.Carver@gov.bc.ca***).

Hydrologic Modelling Initiatives

Predicting the impact of a range of disturbance types on watershed hydrology and then determining the cumulative hydrologic effects is a complicated process. Given the costs and difficulties of conducting watershed-scale field research, hydrologic models will become more widely used to predict the effects of disturbance and climate change on forested watersheds and to test alternative forest management scenarios for their impacts on water resources.

- FORREX is partnering with Alberta Sustainable Resource Development and the B.C. Ministry of Forests and Range to develop a comprehensive synthesis of hydrological models for forest management applications. Forest managers need a method to identify the most appropriate models to answer specific management-related questions under a range of conditions. The project's objective is to describe hydrologic models in terms of their data requirements, assumptions, limitations, and outputs and thereby define their applicability to the forest land base of British Columbia and Alberta. This synthesis will provide a decision-support tool to identify appropriate hydrologic models for a range of circumstances (e.g., landscape characteristics, required outputs, management questions, spatial scale, data availability, etc.). This will ensure that the model outputs (i.e., the information on which management decisions are based) are credible and reliable. The model synthesis results will be published in spring 2009 as a FORREX Series report and a summary article in the Streamline Watershed Management Bulletin.
- The B.C. Ministry of Environment is leading a project to apply a large-scale hydrologic model (VIC model) to investigate the impacts of the MPB

infestation and salvage harvesting on flows in the Fraser River Watershed (Schnorbus 2008). Model calibration and validation are ongoing and results are expected by March 2009. The results of this study will provide guidance around the possible impacts of the MPB disturbance on the potential for flooding in the Fraser River Basin as far downstream as Hope.

Researchers at the University of British Columbia (UBC) are developing and calibrating hydrologic models using field study results from the province's Interior. These models explore changes in streamflow and the potential for flooding that result from extensive MPB-related forest cover loss and salvage harvesting in large watersheds, over long periods of time, and under diverse weather conditions.

- M. Weiler (formerly of UBC, now at the University of Freiburg) is leading a project to predict changes in peak flows resulting from the MPB infestation and salvage harvesting (Weiler *et al.* 2008). The model will avoid the need for complex data inputs and calibration procedures, which is a problem in remote, data-poor regions of the province.
- R.D. Moore (UBC Departments of Geography and Forest Resources Management) is leading a team to develop a new modelling approach for predicting the hydrologic effects of intense forest disturbance. The model structure will be flexible, take advantage of spatial data sets (e.g., digital elevation models and vegetation data) that use readily available meteorological data, and be computationally efficient.
- Y. Alila (UBC Department of Forest Resources Management) is leading a team to apply the physically based, data-intensive research model DHSVM at the Baker Creek watershed. The goal of this research is to integrate stand-level measurements into watershed-scale modelling and to further refine the data inputs and application of the DHSVM model.

Watershed Management Issues and Planning Recommendations

Changes in forest cover related to both the MPB infestation and salvage harvesting can influence stand and watershed hydrology by increasing the amount of water reaching, being stored along, and flowing from hillslopes. Increases in available water, surface runoff, and hillslope flow can:

- elevate water tables;
- stress existing drainage structures;
- increase surface erosion, including damage to forest road surfaces as well as cuts and fills;
- increase landslide activity;
- increase the magnitude and frequency of peak flows; and
- increase channel destabilization, particularly where woody debris recruitment has been reduced.

The consequences of these changes can include:

- loss of soil and site productivity;
- loss of fish habitat;
- reduced water quality;
- damaged property; and
- increased risk to public safety.

Both stand- and watershed-scale changes—immediate or otherwise—may be observed for many years, depending on the watershed and the weather. To mitigate the effects of the MPB infestation on water and watersheds, forest resource planners should consider the following general recommendations.

- Identify watersheds and values at risk.
- Salvage-log in stages using various cutting intensities and retention strategies distributed over the landscape to desynchronize runoff.
- Maintain a diversity of cover types and minimize post-salvage reforestation delays through single-tree or patch retention to protect advance regeneration and through retention of non-pine and broadleaved forest vegetation.
- Delay or interrupt surface runoff by leaving fine and coarse woody debris in openings where possible.
- Avoid sensitive terrain and soil types, and develop erosion control plans.
- Minimize harvesting within riparian areas, particularly in systems that depend on woody debris.
- Construct, inspect, and maintain roads to ensure that natural surface and shallow subsurface drainage remain intact both during and after salvage.
- Upgrade drainage networks on permanent roads before salvage harvesting as necessary to accommodate expected increases in peak flows.

Qualified hydrologists and geomorphologists should undertake watershed-specific assessments, particularly where extensive salvage harvesting is planned, where hydrologic change is expected, or where risks to infrastructure or public safety have been identified. Elevated risks to water values, infrastructure, and public safety as a result of changes in hydrologic and geomorphic processes in watersheds affected by MPB should be clearly communicated to all resource agencies and the public.

Ongoing Research Programs

New and ongoing research projects, both field- and model-based, are under way throughout the British Columbia Interior (Figures 3 and 6). These projects address questions about the effects of MPB-related stand mortality, salvage harvesting, partial retention, and regeneration on:

- snow accumulation and melt,
- stand water balances,
- streamflow,
- channel stability,
- riparian function,
- water quality, and
- aquatic habitat.

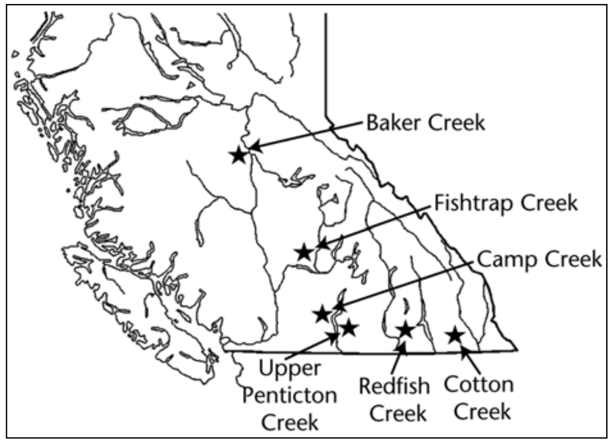

FIGURE 6. Ongoing watershed-scale research projects in the British Columbia Interior that are examining the effects of disturbance on hydrological processes and watershed response.

Research at Mayson Lake is examining mature and young stands as they deteriorate following MPB attack and wildfire. This study focusses on changes in the annual water balance including snow accumulation and melt, rainfall interception, evaporation, and soil moisture. Research into the effects of post–MPB-attacked stand structure on snow accumulation and melt is also being conducted in clearcuts, partially recovered clearcuts, recently attacked pine stands, and pine stands attacked 20 years ago throughout the Cariboo-Chilcotin and on the Nechako Plateau (Teti 2007).

In the Southern Interior, long-term investigations into the hydrologic effects of forest harvesting at Upper Penticton Creek and Redfish Creek, near Penticton and Nelson, respectively, are examining changes in water yield and quality. These long-term projects include stand-scale research focussed on specific hydrologic processes, such as the effects of forest cover on snow accumulation and melt, rainfall interception, evaporation, and soil moisture, as well as on watershed-scale changes in streamflow, channel morphology, water quality, and aquatic habitat. Modelling initiatives are complementing field projects at both locations.

Recently initiated watershed-scale projects include Baker Creek, Cotton Creek, and Fishtrap Creek. At Baker Creek, near Quesnel, monitoring of environmental variables is taking place to quantify hydrologic processes and to model changes in streamflow from heavy MPB attack in this large watershed and its sub-basins. In the Cotton Creek Watershed Experiment, near Cranbrook, hydrologic processes before MPB attacks have been monitored since 2004 and are used to quantify post-attack trends in watershed function (Redding *et al.* 2007a). Research at Fishtrap Creek, near Kamloops, is quantifying the effects of extensive wildfire on in-stream processes, water yield, and aquatic habitat.

Research in the upper Fraser and Nechako watersheds continues to investigate the effect of the MPB infestation and salvage harvesting on riparian zones and stream temperature. This work aims to identify the level of ecological function of small and large streams and their riparian zones over more than 20 years after large-scale harvesting. It is also addressing concerns about rising water tables and the loss of summer ground (i.e., dry soil capable of supporting heavy forest harvesting equipment without becoming excessively disturbed or compacted).

In the sub-boreal spruce forests north of Prince George, a team of researchers from UBC, the University of Northern British Columbia, the Ministry of Forests and Range, and the Canadian Forest Service are measuring water (transpiration and evaporation) and carbon fluxes as part of the Canadian Carbon Program FLUXNET Canada initiative. The stands undergoing measurement include two lodgepole pine stands between 80 and 100 years old that were attacked by MPB in 2004 and 2006, a 7-year-old clearcut with natural regeneration, and a 2-year-old clearcut that was salvage-logged and planted in 2006. More information on this study can be found at: *http://www.fluxnet-canada.ca/*

A UBC research team has initiated a project to evaluate the impact of pine beetle infestation on runoff generation and water quality in a regional context. The emphasis is on evaluating: hydrological changes; sediment generation; carbon, nitrate, and aluminum losses in the water; and differences in the litter composition and hydrophobicity relative to forest management. The monitoring will focus on seasonal effects and storm events (snow melt, storm events, summer low flow), and comparisons will be made within and between regions. The results will be incorporated into a decision-support model that will predict flow-regime changes and the effects on water quality. This model will assist managers in determining mitigation strategies for water supplies and for protecting ecosystem services. For more information, contact Sandra Brown, UBC Institute for Resources and Environment (***sjbrown@interchange.ubc.ca***).

New research results will improve our understanding of hydrologic response to extensive forest cover change and can be used to improve operational guidelines, watershed and risk assessment tools, and flood forecasts. These results will also have relevance in predicting the potential effects of climate change on forests, water supplies, and aquatic habitat. Consult the following websites for additional information about new and ongoing watershed research.

- The Bowron River Watershed Project (***http://www.for.gov.bc.ca/hre/ffip/Bowron.htm***)
- Prince George Small Streams Project (***http://www.for.gov.bc.ca/hre/ffip/PGSSP.htm***)
- Baker Creek Project (***http://www.forestry.ubc.ca/bakercreek***)
- Cariboo-Chilcotin Snow Research (***http://www.for.gov.bc.ca/rsi/research/snow.htm***; ***http://people.uleth.ca/~sarah.boon/forest.html***)
- Upper Penticton Creek Watershed Experiment (***http://www.for.gov.bc.ca/rsi/research/Penticton/index.htm***)
- Fishtrap Creek Project (***http://www.geog.ubc.ca/~beaton/Fishtrap/Overview.html***)
- West Arm Demonstration Forest (Redfish Creek) (***http://www.for.gov.bc.ca/rsi/research/WADF/WADF.htm***)
- Cotton Creek Watershed Experiment (***http://www.forestry.ubc.ca/cottoncreek/***)

Sources of Further Information

In 2006, as part of an interagency flood hazard mitigation initiative, the Provincial Emergency Program produced a series of overview maps. The maps show all third-order and higher watershed boundaries, communities, public infrastructure, forests consisting of more than 40% lodgepole pine, and the area logged during the past 25 years over most of the Interior. Tables summarizing watershed area, the area of pine-dominated forest, and the area logged are also included. These maps and tables provide a useful indication of the extent of both lodgepole pine-leading forest types, where significant stand mortality is expected, and past disturbance. The maps are available at: ***http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/stewardship/***

In 2007, the B.C. Ministry of Forests and Range initiated a project to identify the hydrologic risk of increased peak flow in selected towns and cities in areas affected by MPB. Risk will be assessed using the peak flow impact category of the Interior Watershed Assessment Procedure. The final report will be available in 2008.

Websites summarizing hydrologic processes and management approaches in response to MPB can be found at:

- B.C. Ministry of Forests and Range MPB main site (***http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/***)
- B.C. Ministry of Forests and Range recommended operational procedures to address hydrological concerns (***http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/stewardship/Hydrological%20Recommendations%20Dec%203%202004.pdf***)
- B.C. Ministry of Forests and Range Guidance on Landscape- and Stand-level Structural Retention in Large-Scale Mountain Pine Beetle Salvage Operations (***http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/stewardship/cf_retention_guidance_dec2005.pdf***)
- The Kamloops Forest Hydrology Abstracts Library includes abstracts of papers describing the effects of forest disturbance on water quantity and quality, providing an indication of the potential changes to be expected with MPB (***http://foresthydrology.gov.bc.ca/***)
- Presentations from the July 2007 workshop entitled "Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from

BC, Alberta and Colorado" are summarized by Redding and Pike (2007); the full proceedings are available from: ***http://www.forrex.org/program/water/mpb_hydrology.asp***

- FORREX Forum for Research and Extension in Natural Resources maintains an information portal for information, publications, and events relating to MPB (***http://nrin.forrex.org/servlet/mpb***)
- The Canadian Forest Service's Mountain Pine Beetle Initiative web page includes general overview reports, as well as final project documents (***http://mpb.cfs.nrcan.gc.ca/publications_e.html***)

Conclusions

The potential effects of the MPB infestation and associated salvage harvesting include larger and earlier peak flows and impacts on water quality and aquatic habitat. Changes in flow regimes will be greatest in the short term where extensive salvage harvesting is applied. The changes in flows may have major implications for the design of infrastructure on the floodplain and highlights the need to plan the extent of clearcut salvage harvesting in infested watersheds, designate reserve areas, and carefully design stream crossings (Forest Practice Board 2007). Planning for retention at all scales (stand, watershed, and landscape) will be critical to protect watershed function and maintain flexibility for future management options. In addition, the effects of increased road construction on water quantity and quality are unknown at this time. The effects of roads include both direct effects (e.g., the potential for increased sedimentation) and also indirect effects related to greater human access to previously inaccessible areas.

The magnitude and rate of spread of the MPB infestation highlights the need to maintain long-term watershed research and monitoring capacity and infrastructure. Much of the information synthesized in this paper is based on results of studies that were not originally intended to address questions of MPB infestation impacts. The long-term data sources allow watershed specialists to inform forest management planning in a timely manner, and provide a rich legacy for responding to future disturbances, land use changes, and climate change.

The potential effects of the MPB infestation and associated salvage harvesting include larger and earlier peak flows and impacts on water quality and aquatic habitat.

References

Alila, Y. and C. Luo. 2007. Delineating the limits on peak flow and water yield responses to clearcut salvage logging in large watersheds. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 43–44. URL: ***http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf***

Beaudry, P. 2007. Snow surveys in Supply Block F, Prince George TSA: January to March, 2007. Canadian Forest Products Ltd., Prince George Division, Prince George, B.C. Unpublished report.

Beaudry, P and L. Beaudry. Large woody debris dynamics. *In* Prince George Small Streams Project: A Five-Year Synthesis Report. J. Rex and D.A. Maloney (editors). B.C. Ministry of Forests and Range. Special Report Series. Forthcoming.

Bethlahmy, N. 1975. A Colorado episode: Beetle epidemic, ghost forests, more streamflow. Northwest Science 49(2):95–105.

Boon, S. 2007a. Snow accumulation and ablation in a beetle-killed pine stand in Northern Interior British Columbia. BC Journal of Ecosystems and Management 8(3):1–13. URL: ***http://www.forrex.org/publications/jem/ISS42/vol8_no3_art1.pdf***

_______. 2007b. Impact of MPB infestation and salvage harvesting on seasonal snow melt and runoff. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T.

Redding (editor). Kelowna, B.C. pp. 13–14. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Carlyle-Moses, D. 2007. Preliminary findings on canopy and bryophyte forest floor interception loss of growing-season rainfall at Mayson Lake. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 23–24. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

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

Dubé, S. and J. Rex. 2008. Hydrologic effects of mountain pine beetle infestation and salvage-harvesting operations. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):134. URL: *http://www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf*

Environmental Dynamics Inc. 2008. Mountain pine beetle infestation: Hydrological impacts. B.C. Ministry of Environment, Prince George, B.C. Unpublished report.

Forest Practices Board. 2007. The effect of mountain pine beetle attack and salvage harvesting on streamflows. Victoria, B.C. URL: *http://www.fpb.gov.bc.ca/special/investigations/SIR16/The_Effect_%20of_%20Mountain_%20Pine_%20Beetle_%20Attack_%20and_%20Salvage_%20Harvesting_%20on_%20Streamflows_SIR16.pdf*

Hélie, J.F., D.L. Peters, K.R. Tattrie, and J.J. Gibson. 2005. Review and synthesis of potential hydrologic impacts of mountain pine beetle and related harvesting activities in British Columbia. Natural Resources Canada, Canadian Forest Service, Victoria, B.C. Mountain Pine Beetle Initiative Working Paper 2005–23. URL: *http://warehouse.pfc.forestry.ca/pfc/25684.pdf*

Huggard, D. and D. Lewis. 2007. Summary of ECA effects of options for mountain pine beetle salvage: Stand and watershed level reports. B.C. Ministry of Environment, Kamloops, B.C. Unpublished report.

Johannes, M.R.S., A. Kenney, J. Pouliotte, and D. Steele. 2007. Mountain pine beetle threats to salmon and fisheries resources in BC: Proceedings of the Pacific Salmon Foundation and Fraser Basin Council Workshop. January 30–31, 2007, Prince George, B.C. Golder Associates Ltd., Vancouver, B.C.

Landhausser, S.M., V.J. Lieffers, and U. Silins. 2003. Utilizing pioneer species as a hydrological nurse crop to lower water table for reforestation of poorly drained boreal sites. Annals of Forest Science 60:741–748.

Lin, Y. and X. Wei. 2008. The impact of large-scale forest harvesting on hydrology in the Willow Watershed of Central British Columbia. Journal of Hydrology 359:141–149.

Megahan, W.F. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research 19:811–819.

Mellina, E. 2006. Stream temperature responses to clearcut logging in the central interior of British Columbia: Test of a predictive model developed by Mellina *et al.* (2002). Natural Resources Canada, Canadian Forest Service, Victoria, B.C. Mountain Pine Beetle Initiative Working Paper 2006-08. URL: *http://www.dpp.scf.rncan.gc.ca/archive/projects/3-21_e.html*

Mellina, E., R.D. Moore, S.G. Hinch, J.S. Macdonald, and G. Pearson. 2002. Stream temperature responses to clear-cut logging in British Columbia: The moderating influences of groundwater and headwater lakes. Canadian Journal of Fisheries and Aquatic Science 59:1886–1900.

Moore, D., R. Winkler, D. Carlyle-Moses, D. Spittlehouse, T. Giles, J. Phillips, J. Leach, B. Eaton, P. Owens, E. Petticrew, W. Blake, B. Heise, and T. Redding. 2008. Watershed response to the McLure forest fire: Presentation summaries from the Fishtrap Creek Workshop, March 2008. Streamline Watershed Management Bulletin 12(1):1–11. URL: *http://www.forrex.org/publications/streamline/ISS39/Streamline_Vol12_No1_art1.pd*f

Moore, R.D. and D.F. Scott. 2005. Camp Creek revisited: Streamflow changes following salvage harvesting in a medium-sized, snowmelt-dominated catchment. Canadian Water Resources Journal 30(4):331–344.

_______. 2006. Response to comment by P.F. Doyle on “Camp Creek revisited: Streamflow changes following salvage harvesting in a medium-sized, snowmelt-dominated catchment." Canadian Water Resources Journal 31(2):1–4.

Moore, R.D., D.G. Hutchinson, and M. Weiler. 2007. Predicting the effects of post-MPB salvage harvesting using a conceptual streamflow model (HBV-EC): Initial evaluation using a paired catchment approach. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 41–42. URL: ***http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf***

Moore, R.D., D. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. Journal of the American Water Resources Association 41:813–834.

Nordin, L. 2008. The Bowron River Watershed: A synoptic assessment of stream and riparian condition 20–30 years after salvage logging. B.C. Ministry of Forests, Victoria, B.C. Extension Note No. 86. URL: ***http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En86.htm***

Pike, R.G., T.E. Redding, D. Wilford, R.D. Moore, G. Ice, M. Reiter, and D.A.A. Toews. Detecting and predicting changes in watersheds. *In* Compendium of forest hydrology and geomorphology in British Columbia. R.D. Moore, R.G. Pike, and R.D. Winkler (editors). B.C. Ministry of Forests and Range, Research Branch, Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Forthcoming. URL: ***http://www.forrex.org/program/water/PDFs/Compendium/Compendium_Chapter14.pdf***

Pothier, D., M. Prevost, and I. Auger. 2003. Using the shelterwood method to mitigate water table rise after forest harvesting. Forest Ecology and Management 179:573–583.

Potts, D.F. 1984. Hydrologic impacts of a large-scale mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic. Water Resources Bulletin 20(3):373–377.

Redding, T. and R. Pike. 2007. Mountain pine beetle and watershed hydrology: Workshop summary. Streamline Watershed Management Bulletin 11(1):17–24. URL: ***http://www.forrex.org/publications/streamline/ISS36/streamline_vol11_no1.pdf***

Redding, T., D. Gluns, and D. Moore. 2007a. The Cotton Creek Watershed Experiment: Investigating the effects of forest disturbance on watershed function. LINK 9(2):4–5. URL: ***http://www.forrex.org/publications/link/ISS46/vol9_no2_art2.pdf***

Redding, T., R. Pike, and P. Teti. 2007b. Understanding the effects of mountain pine beetle and salvage harvesting on hydrological processes and watershed response. *In* Overcoming Obstacles to Variable Retention in Forest Management: Science to Management Forum Proceedings, September 25–27, 2007. BC Journal of Ecosystems and Management 8(3):149. URL: ***http://www.forrex.org/publications/jem/ISS42/vol8_no3_scienceforum.pdf***

Redding, T., R. Winkler, D. Carlyle-Moses, and D. Spittlehouse. 2007c. Mayson Lake study examines hydrological processes. LINK 9(2):10–11. URL: ***http://www.forrex.org/publications/link/ISS46/vol9_no2_art4.pdf***

Rex, J. 2007. MPB, riparian retention, and the loss of summer ground: An overview of projects from the Central Interior. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 29–30. URL: ***http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf***

Rex, J. and S. Dubé. 2006. Predicting the risk of wet ground areas in the Vanderhoof Forest District: Project description and progress report. BC Journal of Ecosystems and Management 7(2):57–71. URL: ***http://www.forrex.org/publications/jem/ISS35/vol7_no2_art7.pdf***

Rothwell, R.L. and R.H. Swanson. 2007. Hydrologic effects of mountain pine beetle infestations in western Alberta. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 39–40. URL: ***http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf***

Schmid, J.M., S.A. Mata, M.H. Martinez, and C.A. Troendle. 1991. Net precipitation within small group infestations of the mountain pine beetle. U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Colllins, Colo. Research Note No. RM-508.

Schnorbus, M. 2008. Quantifying the hydrologic impacts of mountain pine beetle and associated salvage operations in the Fraser River watershed. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):135. URL: *http://www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf*

Silins, U., V. Lieffers, D. Reid, B. Brabendar, K. Bladon, and P. Pina. 2007. Stand water balance in absence of mountain pine beetle: Synthesis of several Alberta studies to characterize "reference" water use of lodgepole pine. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 21–22. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Spittlehouse, D. 2007. Influence of the mountain pine beetle on the site water balance of lodgepole pine forests. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. 25–26. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Spittlehouse, D.L. and R.D. Winkler. 2004. Snowmelt in a forest and clearcut. *In* Proceedings 72nd Western Snow Conference, April 19–22, 2004, Richmond, B.C. pp. 33–43.

Stednick, J. 2007. Preliminary assessment of water quantity and quality changes in beetle-killed catchments in north-central Colorado. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 27–28. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Teti, P. 2007. Solar radiation and snow ablation in natural and managed pine stands. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 17–18. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Teti, P. and R. Winkler. 2008. Snow and solar radiation in growing and deteriorating pine stands. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):136–138. URL: *http://www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf*

Tripp, D.B., P.J. Tschaplinski, S.A. Bird, and D.L. Hogan. 2008. Protocol for evaluating the condition of streams and riparian management areas (riparian management routine effectiveness evaluation). Forest and Range Evaluation Program, B.C. Ministry of Forests and Range and B.C. Ministry of Environment, Victoria, B.C. URL: *http://www.for.gov.bc.ca/hfp/frep/site_files/indicators/Indicators-Riparian-Protocol-2008.pdf*

Troendle, C.A. and J.O. Ruess. 1997. Effect of clear cutting on snow accumulation and water outflow at Fraser, Colorado. Hydrology and Earth System Sciences 1:325–332.

Uunila, L., B. Guy, and R. Pike. 2006. Hydrologic effects of mountain pine beetle in the interior pine forests of British Columbia: Key questions and current knowledge. Streamline Watershed Management Bulletin 9(2):1–6. URL: *http://www.forrex.org/publications/streamline/ISS31/streamline_vol9_no2.pdf*

Wei, A. and Y. Lin. 2007. Evaluation of the impacts of large-scale forest disturbance on hydrology in the BC interior. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 33–34. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Wei, A., X. Chen, and R. Scherer. 2007. Assessment of the impacts of wildfire and MPB infestation on in-stream wood recruitment and transportation processes in the BC Interior. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 53–54. URL: *http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf*

Weiler, M., K. Rosin, and C. Scheffler. 2008. Development of a hydrologic process model for mountain pine beetle-affected areas in British Columbia. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and

Management 9(3):139. URL: ***http://www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf***

Winkler, R.D. 2007. Snow accumulation and melt in southern interior lodgepole pine forests. *In* Proceedings, Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC, Alberta and Colorado, July 10, 2007. T. Redding (editor). Kelowna, B.C. pp. 19–20. URL: ***http://www.forrex.org/program/water/PDFs/Workshops/mpb/MPB-Hydrology_Workshop_Handbook.pdf***

Winkler, R. and J. Roach. 2005. Snow accumulation in B.C.'s southern interior forests. Streamline Watershed Management Bulletin 9(1):1–5. URL: ***http://www.forrex.org/publications/streamline/ISS30/streamline_vol9_no1.pdf***

Winkler, R., D. Gluns, and D. Golding. 2004. Identifying snow indices for forest planning in southern British Columbia. *In* Proceedings 72nd Western Snow Conference, April 19–22, 2004, Richmond, B.C. pp. 53–61.

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

Winkler, R.D., R.D. Moore, T.E. Redding, D.L. Spittlehouse, D. Carlyle-Moses, and B. Smerdon. Hydrologic processes and watershed response. *In* Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike, T.E. Redding, R.D. Moore, and R.D. Winkler (editors). B.C. Ministry of Forests and Range, Research Branch, Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Forthcoming.

Winkler, R.D., J. Rex, P. Teti, D. Maloney, and T. Redding. 2008. Mountain pine beetle, forest practices, and watershed management. B.C. Ministry of Forests and Range, Research Branch, Victoria, B.C. Extension Note No. 88. URL: ***http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En88.pdf***