SIMULATED EFFECTS OF BEETLE ATTACKS AND SALVAGE ON WATER YIELD AND PEAK FLOWS

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ABSTRACT

The purpose of this paper is to estimate plausible hydrologic effects of mountain pine beetle attacks and subsequent salvage efforts on annual water yield and peak flows from affected watersheds. I use the WinWrnsHyd program, based on the WRENNS (USEPA 1980) procedure to estimate annual water yield and peak flow changes. The WinWrnsHyd program is used to simulate attack by mountain pine beetles under four scenarios: a) No salvage, b) immediate salvage of all merchantable timber, and c) 1-5 year delay of salvage. In each case I impose two wind regimes, 1) winter wind speeds 15-20 km/h and 2) winter wind speeds less than 4-7 km/h. Salvage clear-cuts are 20 ha blocks.

The 'no salvage' and 5-year delayed salvage scenarios produce the greatest increase in water yield and peak flows. Both results are attributed to the standing dead trees which form a barrier to wind penetration to the snow surface to minimize the effect of wind on winter snow loss.

The 'immediate salvage' scenario produces varying results depending upon winter wind speeds and the size of salvaged areas. The snow in 20 ha clear-cuts is susceptible to wind-driven erosion and sublimation losses. With 20 km/h winds, the snow pack can be completely depleted until the height of regrowth (about 20 years after initial beetle attack in this case) is sufficiently high to protect the snow surface from erosion and sublimation. As wind speeds are reduced below 5 km/h, the water yield increases approach those of the 'no salvage' scenario. (KEYWORDS: WRENNS, WinWrnsHyd, annual water yield, mountain pine beetle)

INTRODUCTION

Extensive areas of lodgepole pine in Canada and the United States have been affected by the Mountain Pine Beetle (MPB). Approximately 16 million hectares of lodgepole pine dominated forest in the interior of British Columbia (BC Forest Service, 2010) have been affected with lesser areas in Alberta, Colorado, Utah, Wyoming, Idaho and Washington. All of these forests are in some stage (red-attack and grey dead) of the beetle attack. Sapwood of the attacked trees is colonized by blue-stain fungi transmitted by the mountain pine beetle. The result is a cessation of transpiration, and ultimately death. The process is fairly rapid. In a direct inoculation experiment where sap flow was monitored by heat pulse velocities, flow ceased or was seriously reduced in 10 to 13 days after inoculation (Yamoaoka, *et al*. 1990). Ultimately, all attacked trees will experience some degree of transpiration reduction, and in most, a complete cessation and death. Newly attacked trees turn red about one year after infestation. Trees can stay in the red attack stage for two to four years before turning grey as they lose their needles (http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/facts.htm).

Stands of lodgepole pine are generally quite large and even-aged. Complete watersheds, rather than small clumps of trees will often be affected. This limits the type of mitigation measures that can be taken and still enable the utilization the wood from an affected stand. The effect of these attacks on future timber supply is of major concern to the forest industry as are the effects of extensive forest cover loss on water supplies. In some watersheds the main concern is flooding. In other areas, where the current water supply may be inadequate, loss of forest cover is viewed as a potential opportunity for increasing annual runoff. Both industry and government question whether and where salvage logging and planting are the most ecologically appropriate practices or whether leaving the dead trees standing and relying on natural regeneration provides the best hydrologic benefit

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MODEL AND WATERSHED

Model Used to Simulate Water Yield and Peak Flow Increases

Any model used to simulate water yield must consider those processes that will be affected. Forests affect water yield by evapotranspiration and interception by the tree canopy, distribution and/or redistribution of snow after it reaches the ground and evaporation or sublimation from the snowpack or from snow in transport.

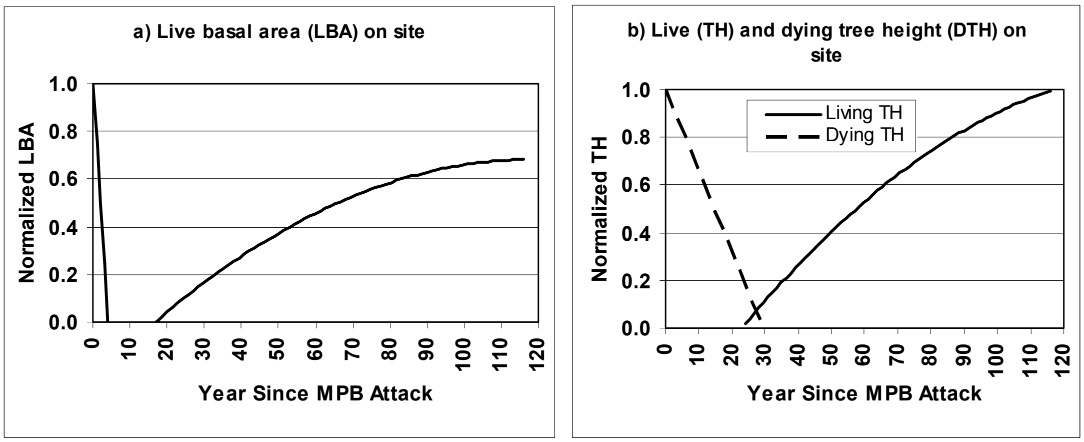

Figure 1. Proposed lodgepole pine regrowth functions to represent a) reduction in live basal area, dead zone, and regrowth of live stand and b) reduction in height of dead stand and subsequent growth of live stand following mountain pine beetle attack.

WinWrnsHyd (Swanson 2004) based on the WRENSS Hydrologic procedure (Troendle and Leaf 1980, USEPA 1980) addresses these processes. Evapotranspiration is a function of cover density and tree form as estimated from tree species and basal area[1]. Snow distribution processes are driven principally by surface wind speed as is vapour exchange with the overlying air mass. Wind speed at the snow surface is affected by the roughness of the surface, i.e. the height of standing live or dead trees in WinWrnsHyd. Monthly precipitation and wind speed for the watershed in question (Table 1) are the only climate data required to use WinWrnsHyd.

Proposed regrowth sequence for water yield

The success or failure of any simulation model to estimate the effects of MPB attacks on water yield is dependent upon correct evaluation of regrowth. There is information available on regrowth after fire (Alberta Forest Service, Phase III inventory tables), but very little on regrowth in managed stands (often proprietary) or from stands after MPB attacks. I relied, in a general way, on a report by the Forest Practices Board (2007) for guidance in defining functions for both basal area and tree height growth after MPB attack. However, the board report does not contain detailed information on either basal area or tree height growth.

I derived a basal area regrowth function for use within the program that estimates the effect of death and subsequent regrowth after attack by mountain pine beetles for the affected stand (Figure 1a). Basal area, in this case living basal area, which indexes evapotranspiration in WinWrnsHyd is assumed to decline linearly to zero during the first three years after MPB attack, and to start new basal area growth approximately 16 years, reaching 30% of pre-MPB attack at 30 to 40 years after attack and 70% at 100 to 120 years, depending upon the quality of the site. Understory evapotranspiration is implicitly defined by evapotranspiration modifier coefficients within each WRENSS hydrologic region as 40 to 80% of potential evapotranspiration.

Clear-cut dimensions, in multiples of surrounding tree height, determine wind effects on snow transport or loss in WinWrnsHyd. Tree height is used in as an indicator of site roughness. Tree height is assumed to decline linearly for about 25 years after MPB attack. The proposed height-growth equation starts new growth at

[1] Basal area is the cross sectional area of the stem or stems of a plant or of all plants in a stand, generally expressed as square units per unit area., i.e., m^2/ha or ft^2/acre.

approximately 10 years after attack although it is overshadowed by the height of the residual stand until about 25 years after attack (Figure 1b). If the residual dead stand is not salvaged, height growth of the regeneration has essentially no affect because the snow surface is protected from wind by the height of the dead trees. If salvage occurs, both basal area and height regrowth proceed as in a normal clear-cut.

Peak flows

WinWrnsHyd estimates changes in peak flows at various recurrence intervals if a peak flow analysis for the area in question has been incorporated into it. Peak flow analyses provide a relationship between the areas of a group of reasonably homogeneous watersheds and their peak daily or instantaneous flow discharges. As such, they are functionally related to the terrain and drainage distribution (physiography) for the watersheds included in that analysis (Linsley *et al*, 1958). The equations obtained from several peak flow analyses from watersheds in British Columbia, Alberta and Colorado have been incorporated into WinWrnsHyd (Table 1). Peak flow analyses within WinWrnsHyd are intended only to alert the user to possible problem watersheds for more detailed study of critical stream reaches.

Table 1. WRENSS regions selected to locate hypothetical watershed for simulation. Selected location within each region in parenthesis: Continental Maritimes (South Okanagan, British Columbia), New England (Boreal, Western Alberta), Rocky Mountains (Alberta Foothills and Colorado watersheds under 2750 m elevation)

Region	Representative Location In Each WRENSS Region			Latitude	Longitude
	Drainage	Precip & Wind	Peak Flow Analysis		
Okanagan, BC	Upper Penticton	Upper Penticton	Penticton Area	49:37:28N	119:22:51W
Boreal, AB	Muskeg River	Grande Cache	Grande Prairie G3 to G7	53:55:32N	118:48:52W
AB Foothills	Nordegg River	Nordegg	Rocky Clearwater R5 to R9	52:49:13N	115:31:10W
Colorado	Fool Creek	Fool Creek	Colorado < 2750 m	39:53:00N	109:53:00W

Hypothetical Watershed

A 100 ha watershed is forested with lodgepole pine (*Pinus contorta* Dougl.) with runoff dominated by snow melt. Ninety percent of the watershed is assumed to have been attacked by MPB in the year 2000. Monthly precipitation, annual water yield and peak flow analyses will be imposed from each of the geographical regions (Table 1). This hypothetical watershed is for illustrative purposes only and should not be construed as a specific watershed in any region.

The WinWrnsHyd model is modified to allow incorporation of the initial changes in live basal area and tree height described by Figure 1. If salvage occurs, regrowth follows the functions shown in Figure 3. All simulations begin with a fully live forest and proceed through time for 100 years. The simulated changes in water yield and peak flows displayed in graphical or tabular form within WinWrnsHyd are changes from the live forest state. Salvage, when simulated, is in 20ha clear-cut blocks.

Scenarios To Be Simulated

The scenarios to be simulated are: a) no salvage, b) immediate salvage of all merchantable timber from 90% of the watershed, and c) a 1 to 5-year delay of salvage. In each case I impose two wind regimes, 1) winter wind speeds 15-20 km/h and 2) winter wind speeds 4-7 km/h.

No salvage

In this scenario the attacked stand is left to regrow. The stand is simulated as clear-cut for live basal area (Figure 1a) and as uncut for the height and density of trees within the affected area (Figure 1b). Snow accumulation under the dead stand is considered to be similar to that under a living stand, as in the initial years after MPB attack there is apparently little difference in snow interception amounts between live and beetle-killed lodgepole pine stands (Beaudry, 2007; Boon, 2008).

Wind penetration to either undergrowth or the snow surface is considered to be the same as in the live forest as the tree height and number of stems will remain the same unless some other factor, such as massive blow-down or fire, intervenes. As the dead stand deteriorates, the height growth of the regenerating stand will gradually replace the standing dead trees to dominate the roughness at the forest floor (Figure 1b).

This scenario results in the greatest increase in annual water yield over the longest period of time (Figure 2). Yields are at maximum until basal area growth begins, in this case at about year 16, and then decline fairly steadily over the next 20 years. Peak flows in the 2 – 20-year recurrence interval range may or may not be increased, depending upon the drainage physiography represented by the peak flow analysis (Tables 2 and 3).

Peak flows were essentially unaffected in Colorado, but would probably be of concern in watersheds in the Boreal Forest and in the Foothills of Alberta's Rocky Mountains, Tables 2 and 3. Although the annual yield increase was great in the Okanagan area of BC, peak flow increases were minimal, about 12% increase at the 2-year recurrence interval, Tables 2 and 3.

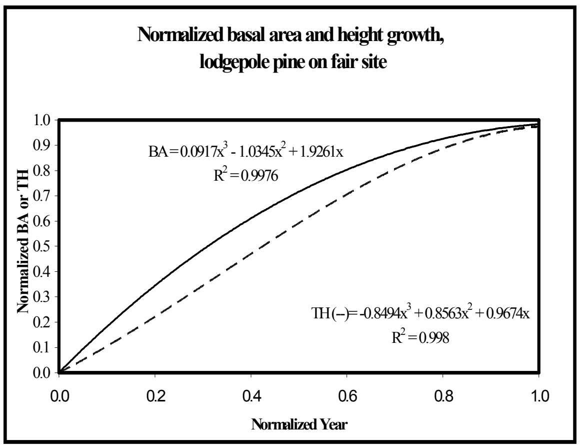

Figure 2. Basal area and tree height growth regrowth curves for clear-cut harvest, normalized to allow for any rotation age (in years) and maximum basal area or tree height (metric or English units).

Immediate salvage of all merchantable timber

In this scenario the stand is harvested at the first sign of MPB attack. Regrowth of both basal area and tree height commences in the year following harvest, and proceeds as in a normal clear-cut (Figure 3). Increases in annual water yield with this scenario are variable and are dependent upon the windiness of the site. For example, in the Okanagan and in Colorado, increases were 16.6 and 24.6% with wind speeds in the 4-7 km/h range, (Table 2). Instantaneous peak flows were constrained to maximum daily potential evapotranspiration as indicated by the flat topping of peak flows (example Colorado, Figure 4, and in all regions at 5-7 km/h wind speeds, Table 2). Instantaneous peak flows were highly variable (example Boreal region Figure 5) or were considerably lower at wind speeds in the 15-20 km/h range, Table 3.

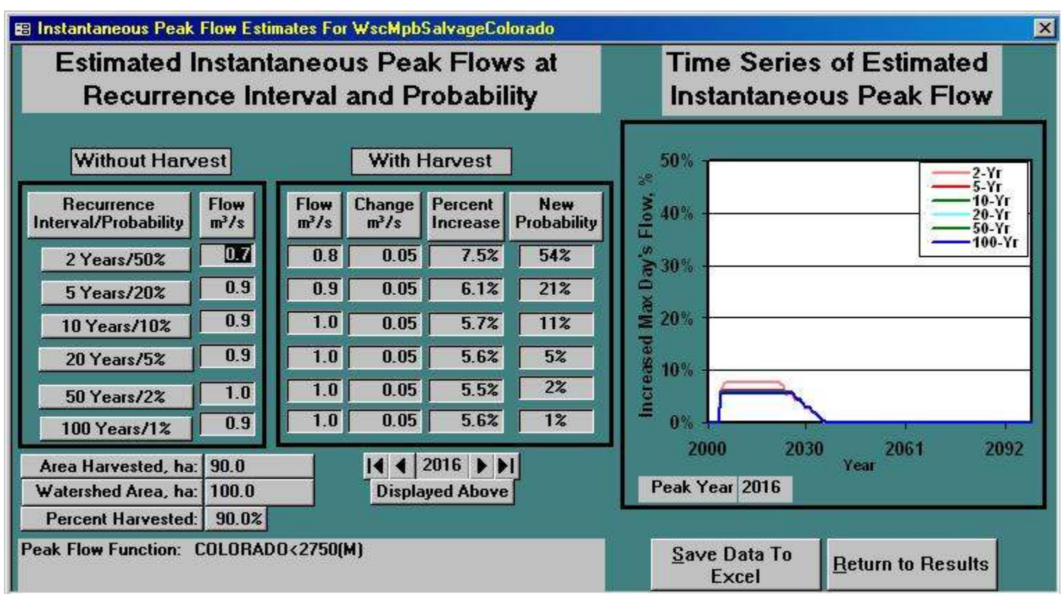

Figure 4. Estimated increases in instantaneous peak flows in Colorado watersheds at less than 2750 m elevation, without salvage.

A 1 to 5 year delay of salvage

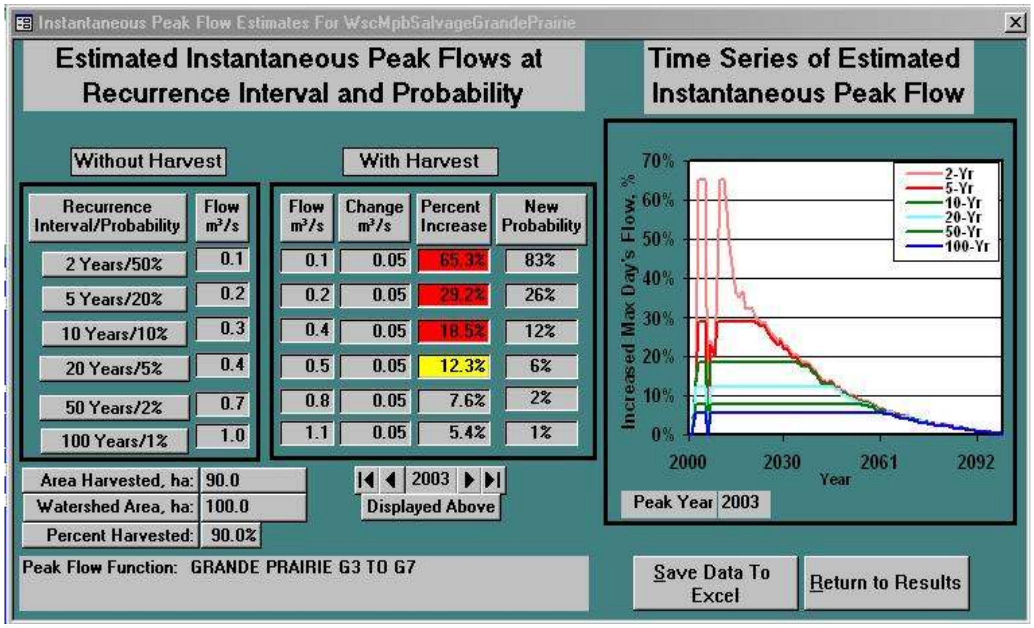

Figure 5. Instantaneous peak flows estimated for the Boreal region without salvage were highly variable with wind speeds of 15-20 km/h)

These scenarios provide some management flexibility. Salvage between the first and third year after MPB attack results in a lower increase in annual yields than "no salvage" (Table 2 and 3). Salvage at year 5 results in the same increase in annual yield as without salvage. The duration of the increase is shorter with all of the salvage options, presumably because of faster regrowth (Figure 7).

Duration of effect

The duration of the effect of MPB attack on increased water yield can be reduced by salvage. The duration of maximum increased water yields with natural regrowth without salvage is about 12 years (Figure 6). With salvage at 5 years, the duration of maximum water yield increase is about 3 years (Figure 7). Similar results were simulated in all regions.

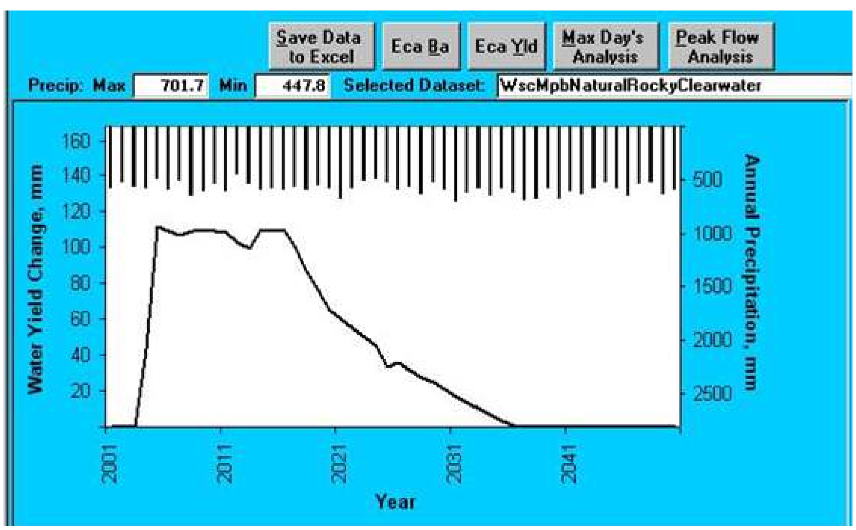

Figure 6. Duration of increased water yield after MPB attack without salvage (Alberta Foothills).

DISCUSSION

The decision as to whether or not to salvage after MPB attack should not be made without regard to the hydrologic consequences. Where water is in short supply, and the topography is favorable to allow substantial increases in annual yield without significant increases in instantaneous peak flow (examples Colorado, Figure 4, and Okanagan regions, not shown), delaying or not salvaging at all may be the best option.

Contrarily, where the terrain is not favorable, and there are downstream or instream water users that may be negatively impacted by substantial increases in instantaneous peak flows (examples Boreal, Figure 5, and Alberta Foothills, not shown), then immediate salvage may be the best option. Neither of these decisions should be made without consideration of the effects on downstream or instream water users.

These simulations indicate substantial increases in instantaneous peak flows at several recurrence intervals (Figure 5, Table 2 and 3). As stated earlier, these estimated increases in peak magnitude are intended as guidelines. Whether or not they would occur in any specific stream reach is beyond the capability of the WinWrnsHyd model. The user would have to examine the channel configuration and gradient tin reaches of interest to see what magnitude of increase in peak flows that could be accommodated.

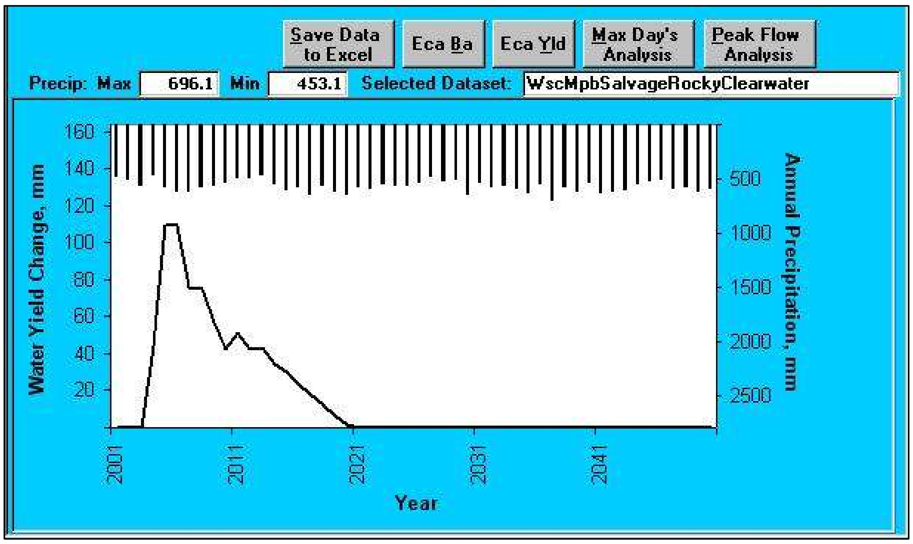

Figure7. Duration of effect with salvage at 5 years after MPB attack (Alberta Foothills).

The frequency of peak events as well as the magnitude may also be increased. In the Boreal region, Figure 5, the magnitude of the 20-year event before harvest, 0.04 m^3/s, is the same magnitude as the 10-year event after harvest, i.e., the magnitude of the 20-year event has become the magnitude of the after salvage 10-year event. Changes in either the magnitude or frequency of events beyond the 20-year event were generally minimal (Figure 5).

CONCLUSIONS

MPB Attacks Without Salvage

Annual water yield

The increase in annual water yield was greatest in the without salvage scenarios, ranging from 109 to 169 mm, Tables 2 and 3, and was consistently high in all regions. Wind speeds had no affect on annual water yield increases in these natural regrowth scenarios. If the management objective was to increase water supply, then this might be the best scenario to use. The treatment is free – the mountain pine beetles do it for nothing! However, the impact on future timber supply would have to be considered. Under the basal area regrowth function used in these simulations, basal area only returns to about 70% of pre-MPB attack levels (Figure 1a).

Instantaneous peak flows

Estimated peak flows are increased at the 2-year recurrence interval in all regions (Tables 2 and 3). However, in the Colorado and Okanagan regions, the estimated increases were minimal. The peak flow analysis for the Okanagan region was from seven watersheds in the Penticton area. Peak flow analyses for a wider range of watersheds should be conducted and used to verify the results for this region.

In the low gradient streams of the Boreal and Alberta Foothills regions, the estimated increases are substantial at all recurrence intervals (Tables 2 and 3).

MPB Attacks With Salvage

Annual water yield

Annual water yield increases with salvage are highly dependent upon the time after attack that the salvage occurs. Salvage at any time during the first 4-years while the basal area of the MPB attacked stand is approaching zero reduces the increase under both of the simulated wind regimes (Tables 2 and 3). Salvage after the basal area of the MPB attacked stand has reached zero has no effect on the first year's water yield increase, but does affect that of subsequent years.

Instantaneous peak flows

Initially, salvage has the same effect on instantaneous peak flows (Tables 2 and 3) as on stands not salvaged. However, salvage that occurs after the increased water yield from an unsalvaged stand has begun to decline may produce secondary instantaneous peaks equal to those from stands not salvaged.

Duration of effects

The duration of annual water yield increases was longest in unsalvaged MPB attacked stands, Figure 6. The light conditions under the dead canopy of an attacked stand are not conducive to lodgepole pine reproduction. Regrowth of basal area does not start immediately as it would in a salvaged and planted or even naturally reproduced stand. And, the snowpack is protected from wind erosion or sublimation by the standing dead trees for quite a few years. These two factors, slow basal area regrowth and snow pack protection, combine to provide almost optimum conditions for increased annual water yield. Salvage at any time before basal area regrowth begins can reduce the duration of the effects, Figure 7.

Table 2. Results all scenarios with wind speeds 4-7 km/h Instantaneous peak increases are constrained to the magnitude of daily potential evapotranspiration.

			MaximumYield Increase			Max Instantaneous Peak Increase, % *			
Location	**Annual**	**Scenario**	**Year**	**mm**	**%**	**2-Yr**	**5-Yr**	**10-Yr**	**20-Yr**
Okanagan, BC	**mm**	Natural	2005	117.4	27.2%	11.7%	9.9%	9.3%	8.9%
Precipitation	679	Salvage 2000	2002	71.6	16.6%	11.7%	9.9%	9.3%	8.9%
Water Yield	431	Salvage 2001	2003	69.2	16.1%	11.7%	9.9%	9.3%	8.9%
		Salvage 2003	2005	82.6	19.2%	11.7%	9.9%	9.3%	8.9%
		Salvage 2005	2005	117.4	27.2%	11.7%	9.9%	9.3%	8.9%
Boreal, AB		Natural	2007	169.1	74.8%	65.3%	29.2%	18.5%	12.3%
Precipitation	590	Salvage 2000	2002	133.3	59.0%	65.3%	29.2%	18.5%	12.3%
Water Yield	226	Salvage 2001	2003	139.3	61.6%	65.3%	29.2%	18.5%	12.3%
		Salvage 2003	2005	136.5	60.4%	65.3%	29.2%	18.5%	12.3%
		Salvage 2005	2006	167.9	74.3%	65.3%	29.2%	18.5%	12.3%
Alberta Foothills		Natural	2007	109	61.6%	30.6%	18.3%	13.6%	10.8%
Precipitation	539	Salvage 2000	2002	73.5	41.5%	28.8%	17.4%	13.0%	10.3%
Water Yield	177	Salvage 2001	2004	70.7	39.9%	28.2%	17.4%	13.0%	10.3%
		Salvage 2003	2006	74.7	42.2%	29.0%	17.4%	13.0%	10.3%
		Salvage 2005	2006	104.9	59.3%	30.6%	17.4%	13.0%	10.3%
Colorado		Natural	2016	104.9	31.1%	7.5%	6.1%	5.7%	5.6%
Precipitation	572	Salvage 2000	2002	72.2	21.4%	7.5%	6.1%	5.7%	5.6%
Water Yield	337	Salvage 2001	2004	69.4	20.6%	7.5%	6.1%	5.7%	5.6%
		Salvage 2003	2006	73.4	21.8%	7.5%	6.1%	5.7%	5.6%
		Salvage 2005	2006	104.9	31.1%	7.5%	6.1%	5.7%	5.6%

* Instantaneous peak increases are constrained in magnitude to less than or equal to daily potential evapotranspiration during the growing season

Table 3. Results all scenarios with wind speeds 15-20 km/h. Instantaneous peak increases are constrained to the magnitude of daily potential evapotranspiration.

Location	Annual	Scenario	MaxYield Increase			Max Instantaneous Peak Increase, % *			
			Year	mm	%	2-Yr	5-Yr	10-Yr	20-Yr
Okanagan, BC	mm	Natural	2005	117.4	27.2%	11.7%	9.9%	9.3%	8.9%
Precipitation	679	Salvage 2000	2013	14.2	3.3%	2.4%	2.7%	3.0%	3.2%
Water Yield	431	Salvage 2001	2004	19.5	4.5%	3.2%	3.7%	4.0%	4.4%
		Salvage 2003	2004	31.8	7.4%	5.2%	6.0%	6.5%	7.1%
		Salvage 2005	2005	117.4	27.2%	11.7%	9.9%	9.3%	8.9%
Boreal, AB		Natural	2007	169.1	74.8%	65.3%	29.2%	18.5%	12.3%
Precipitation	590	Salvage 2000	2003	69.5	16.1%	58.1%	26.0%	16.4%	10.9%
Water Yield	226	Salvage 2001	2004	108.8	48.1%	58.1%	26.0%	16.4%	10.9%
		Salvage 2003	2005	77.3	34.2%	58.1%	26.0%	16.4%	10.9%
		Salvage 2005	2006	159.2	70.4%	58.1%	26.0%	16.4%	10.9%
Alberta Foothills		Natural	2005	112.0	63.3%	32.0%	18.3%	13.6%	10.8%
Precipitation	539	Salvage 2000	2009	37.1	8.6%	14.5%	16.5%	13.6%	10.8%
Water Yield	177	Salvage 2001	2010	37.0	20.9%	15.6%	18.3%	13.6%	10.8%
		Salvage 2003	2004	43.6	24.6%	17.6%	18.3%	13.6%	10.8%
		Salvage 2005	2005	112.0	63.3%	32.0%	18.3%	13.6%	10.8%
Colorado		Natural	2016	109.4	32.5%	7.5%	6.1%	5.7%	5.6%
Precipitation	572	Salvage 2000	2010	26.4	6.1%	4.1%	4.3%	4.4%	4.4%
Water Yield	337	Salvage 2001	2004	40.6	12.0%	6.6%	6.1%	5.7%	5.6%
		Salvage 2003	2004	42.5	12.6%	6.9%	6.1%	5.7%	5.6%
		Salvage 2005	2006	109.4	32.5%	7.5%	6.1%	5.7%	5.6%

* Instantaneous peak increases are constrained in magnitude to less than or equal to daily potential evapotranspiration during the growing season

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REFERENCES

BC Forest Service. 2010. Facts about B.C.'s Mountain Pine Beetle, http://www.for.gov.bc.ca/HFP/mountain_pine_beetle/Updated-Beetle-Facts_Mar2010.pdf.

Beaudry, Pierre G. 2007. P. Beaudry and Associates Ltd., Integrated Watershed Management, 2274 S. Nicholson Street, Prince George, BC. 57 p.

Boon, Sarah. 2008. Snowpack structure in a beetle-killed stand compared with live and logged stands. In: 65th Proceedings of the Eastern Snow Conference, Fairlee (Lake Morey), Vermont. pp. 367-375.

Forest Practices Board. 2007. Lodgepole pine stand structure 25 years after mountain pine beetle attack. Government of British Columbia, FPB/SR/32. 18 p.

Linsley, Ray K., M.A. Kohler, and J.H. Paulhus. 1958. Hydrology for Engineers. McGraw Hill, New York. 340 p.

Swanson, Robert H. 2004. The complete WRENSS hydrologic model. In: 72nd Proceedings of the Western Snow Conference, April 19-22, 2004, Richmond, British Columbia. pp. 99-103.

Troendle, C.A. and C.F. Leaf. 1980. Hydrology, Chapter III, In: An approach to Water Resources Evaluation of Non-Point Silvicultural Sources WRENSS (a procedural handbook). U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

USEPA. 1980. An approach to water resources evaluation on non-point silvicultural sources (a procedural handbook). United States Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia, EPA-600/8-80-012. 861 p.

Yamaoka, Y., R.H. Swanson, and Y. Hiratsuka. 1990. Inoculation of lodgepole pine with four blue-stain fungi associated with mountain pine beetle, monitored by a heat pulse velocity (HPV) instrument. Canadian Journal of Forest Research, 20(1):31-36.