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Hydrological impacts of mountain pine beetle infestation: potential for river channel changes

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Abstract Tree kill and salvage logging are profoundly changing the hydrology of mountain pine beetle-infested, snowmelt-dominated catchments. Baker Creek, located in the interior plateau of British Columbia, Canada, is in the heart of the infested region. This study relates observed and modelled changes in hydrology to geomorphic controls to predict the potential for channel change. Modelling using the Distributed-Hydrology-Soil-Vegetation-Model indicates that discharge is highly sensitive to tree kill and salvage logging, with increases of 65–100% possible. It was found that low-gradient reaches typical of the interior plateau are likely to be relatively insensitive to channel change, but will become significant sediment stores as sediment is mobilized elsewhere in the catchment. Higher gradient reaches, which typically occur where interior rivers incise to meet the Fraser River, are more susceptible to change. A geomorphic threshold classification was able to identify change channel thresholds. Salvage harvesting scenarios exceeding 40% cause some reaches to cross stability thresholds, with the potential for significant changes in channel morphology.

Key words salvage harvesting; fluvial geomorphology; channel stability; Shields number; British Columbia, Canada

INTRODUCTION

British Columbia, Canada has been experiencing a mountain pine beetle (MPB) epidemic since the late 1990s. The MPB (*Dendoroctonus ponderosae* Hopkins) has a preference for mature (>80-year-old) lodgepole pine trees, and is kept in check by periods of sustained cold weather (–35°C, or below –40°C for several days). Infested trees die within a year. In British Columbia, global warming, combined with increasingly mature forests has resulted in the spread of the MPB to epidemic proportions since the onset of the most recent outbreak in 1993 (Lewis & Hartley, 2006). By 2011, the area of affected trees was estimated as 18 million hectares. For catchments in the Central Interior region, the heart of the infested area, the mortality rate exceeds 80%. As such the scale of the current epidemic is unprecedented, both compared to outbreaks which have been documented in the past, and also in terms of the likely impact on forest cover and land use change in British Columbia.

The hydrological response to MPB infestation has been documented for a number of catchments (Uulila *et al.*, 2006). In general, MPB infestation has led to increases in water yield and peak flow, and earlier occurrence of annual peak flow, due to both tree mortality (Love, 1955; Bethlahmy, 1974, 1975; Potts, 1984) and clear-cutting of infested trees (Cheng, 1989). Increases in annual water yield of 11% to 19%, and increases in monthly high flow during the freshet of 14% to 53% have been reported in the literature (Uulila *et al.*, 2006). Most studies suggest full hydrologic recovery to pre-disturbance conditions will take over 25 years (Uulila *et al.*, 2006). In terms of snow accumulation, stands of dead trees behave in an intermediate manner between alive stands and clear-cut stands (Boon, 2007). Whilst snow accumulation is greater in stands of dead trees, this is offset by increased sublimation and wind-blow in clear-cut areas (Bewley *et al.*, 2010; Pugh & Small, 2012). Melt rates are faster in cleared and dead stands than in living stands (Bewley *et al.*, 2010; Pugh & Small, 2012). Decay of dead trees is generally slow (Lewis & Hartley, 2006), and most trees are likely to blow down before they decay. Thus, the likely hydrological response to MPB infestation will depend on the extent and location of dead stands within the catchment, the rate of decay and blow-down of dead trees, and the rate, location and extent of salvage harvesting.

None of the existing studies of MPB hydrological impacts deal with infestation on the scale of the current epidemic and to date, there are no studies that have considered how the hydrological changes induced by the MPB will affect fluvial geomorphology of impacted catchments. The aim of this paper is to discuss a pilot study, which investigates the potential for channel change in the Baker Creek catchment, located in a MPB impacted region of central British Columbia, Canada.

STUDY AREA

Baker Creek is a 1570 km^2 tributary of the Fraser River, located in the interior plateau region of central British Columbia (Fig. 1(a)) at the heart of the MPB infestation area. Clear-cutting of dead trees is ongoing across the catchment. Elevations within the catchment range from 470 m to 1530 m.a.s.l. The catchment is located in the Fraser Plateau physiographic region (Lord & Mackintosh, 1982), which lies primarily at an elevation of 900 to 1000 m.a.s.l, with rounded ridges and summits of 1200 to 1500 m elevation forming the boundaries of the catchment. The bedrock geology of the region is dominated by volcanic material, usually covered by unconsolidated Quaternary age till, alluvium, lacustrine or colluvial deposits. Where Baker Creek passes from the Fraser Plateau physiographic region to the Fraser River Basin physiographic region, it is incised into the underlying bedrock, and lower Baker Creek is confined within a steep-sided valley.

The catchment topography exerts a strong control on the river long-profiles (Fig. 1(b)), with steep headwater reaches, low-gradient reaches in the middle of the catchment, and a steep reach between the junction of Baker and Merston Creeks and the junction with the Fraser River. Headwater reaches consist of low sinuosity gravel bed pool-riffle channels. The low-gradient mid catchment has well developed flood plains and a single, sinuous meandering channel. Rivers are fully alluvial throughout this zone, with a fine to medium gravel bed, and fine-grained alluvial banks and floodplain. There are numerous oxbows and chute cutoffs, indicating that the channel is relatively active. These reaches are generally already cleared of flood plain vegetation for grazing purposes. Lower Baker Creek is a coarse gravel bed river. Where it is confined, it is relatively straight, but gravel point bars develop in the more sinuous unconfined reaches.

There are two Environment Canada climate stations within or close to the catchment, one in Quesnel, at an altitude of 545 m, and one at Punchesakut Lake, in the centre of the catchment, at an elevation of 915 m. Long-term (1971–2000) climate records indicate a mean annual precipitation at Quesnel of 540.3 mm (of which 71.6% is rainfall), and 511.4 mm at Punchesakut Lake (66.4% from rainfall). Within the catchment, precipitation falls largely as snow during the

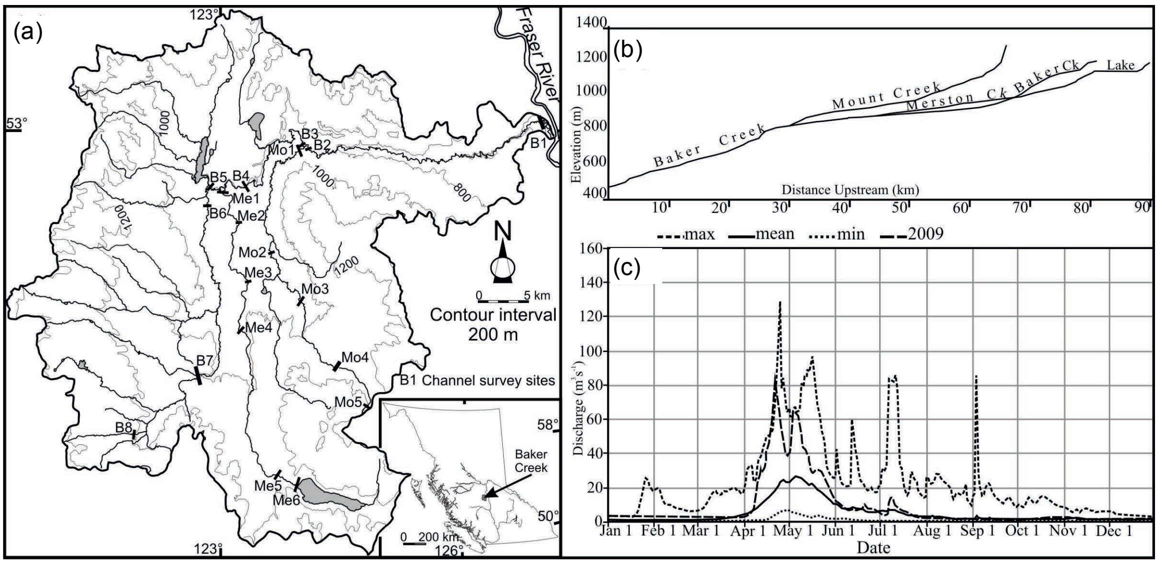

Fig. 1 (a) Location map of the Baker Creek Catchment, (b) Long profile of Baker Creek and its major tributaries, (c) representative hydrographs of Baker Creek (data from the Water Survey of Canada gauging station in Quesnel, at the confluence of Baker Creek with the Fraser River). Discharges are the long-term (1963–2010) average, maximum and minimum daily flow, and the 2009 hydrograph.

months of November to March and as rainfall from April to October, with most rain falling in June and July. Average January temperature is –9.3ºC and the July average is 14.4°C. Long-term analysis of climate and hydrological data by Zhang & Wei (2012) show that the catchment has become drier over the past 30 years, but that forest cover changes due to the MPB have resulted in an increase in runoff which exceeds the reduction due to precipitation reduction.

The hydrology of Baker Creek is nival and strongly reflects the high seasonality of both temperature and precipitation. Low flow occurs during winter and autumn, with seasonal high flows caused by the spring freshet, and summer rainfall causing additional high flows. The onset of snowmelt occurs in late March and early April, and peak flows from snowmelt and rain-on-snow events typically occur in late April and early May. Floods from storm events can cause sharp rises in peak flow throughout the summer months. These floods are easily recognized in Fig. 1(c) as the large discharge peaks in the maximum flow series. Based on this data, the mean annual flood of Baker Creek is 43 $m^3 s^{-1}$.

METHODS

The Distributed-Hydrology-Soil-Vegetation-Model (DHSVM) has been used successfully at Baker Creek to model catchment-scale changes in snow accumulation, snow melt, and discharge (Alila *et al.*, 2009a; Bewley *et al.*, 2010). DHSVM is a physically-based hydraulic model that explicitly solves the water and energy balance for each model grid-cell (Wigmosta *et al.*, 1994). DHSVM accounts for canopy evapotranspiration, snow accumulation and melt, saturated and unsaturated soil flow. Physical variables modelled include topography, streams, soil type, forest cover, cutblocks and roads. Long-term meteorological data from weather stations in, or close to the catchment were used as input variables and for calibration and scenario testing. For the Baker Creek catchment, a 500 m grid was used (total number of grids 6400). When calibrated, modelled hydrographs closely approximated observed hydrographs. The modelled scenarios compared changes in land use and salvage harvest options to a 1970 baseline vegetation condition. The "no salvage" scenario included all non-infested harvesting up to 1995. Full details of the model development and calibration are available in Alila *et al.* (2009a).

This study uses a scenario-based approach to test the sensitivity of the channel to a range of potential discharge increases derived from DHSVM hydraulic modelling. This approach is based on the geomorphic threshold concept (Church, 2002) in that it considers downstream changes in bankfull flow regime, channel geometry and sediment supply in order to define channel reaches that are close to thresholds for geomorphic change, defined using the Shields number (Church, 2002, 2006). The Shields (1936) criterion is a dimensionless expression of the competence of a water flow, defined by the relative lift and drag forces acting on streambed particles, given by:

$$\theta = \frac{\rho_w g R s}{(\rho_s - \rho_w) g D} \tag{1}$$

where ρ_s and ρ_w are the densities of sediment and water, respectively, g is the acceleration due to gravity, R is hydraulic radius, s is slope and D is particle diameter. Although there are theoretical limitations to shear-stress based approaches to channel stability, it is a practical approach which encompasses characteristics of the channel bed and cross-section, the channel components most susceptible to change under changing hydrological conditions. Church (2002, 2006) shows that as Shields number increases, channel characteristics, and channel stability change, with a number of key thresholds evident (Table 1).

Channel characteristics were measured in the field. Channel cross-sections and long profiles were measured at 19 sites within the catchment, on the main stem of Baker Creek, and the Mount Creek and Merston Creek tributaries. Sites were chosen to represent downstream changes in channel geometry. Wolman (1954) pebble counts (100 clasts) were used to obtain grain-size data. This data was used to calculate Shields numbers at the sites, and as a basis for estimating changes in channel geometry under increased flow conditions so that Shields numbers could be recalculated for the discharge increases under the salvage harvesting scenarios.

Table 1 Simplified version of the Church (2002, 2006) classification of alluvial channels.

Shields no.	Sediment type	Channel characteristics
up to 0.04	Cobble-boulder gravel	Steep, step-pool channel, straight and stable
over 0.04	Cobble gravel	Cobble-gravel channel bed, single thread or wandering; relatively steep; low sinuosity; *w/d* >20
up to 0.15	Sand to cobble gravel	Gravel to sandy gravel, single thread to braided; moderately steep; low sinuosity; *w/d* very high
0.15-1.0	Sand to fine gravel	Mainly single-thread, sinuous to meandering; moderate gradient; sinuosity <2; *w/d* <40
1.0-10	Sandy bed, fine sand to silt banks	Single thread, meandered, low gradient; sinuosity >1.5; *w/d* <20.
>10	Silt to fine sand bed, silt to clay-silt banks	Single-thread or anastomosed channels; very low gradient; sinuosity >1.5; *w/d* <15

Table 2 Predicted changes in peak flows and time to peak for a range of salvage harvest scenarios.

Scenario	ΔQ2 (m^3s^{-1})	(%)	ΔQ10 (m^3s^{-1})	(%)	ΔQ20 (m^3s^{-1})	(%)	ΔQ50 (m^3s^{-1})	(%)	ΔTP (days)
Pre-1996	6	14	11	13	13	13	15	12	2
40% cleared	30	66	55	65	65	65	77	64	15
60% cleared	39	88	72	84	84	84	100	83	17
80% cleared	43	95	78	92	91	91	108	90	18
100% cleared	47	104	84	99	99	99	117	98	19

RESULTS

Modelled hydrological changes under a range of salvage harvesting scenarios are presented in Table 2 as increases above the pre-disturbance discharges.

It is assumed in this analysis that because of the easily eroded bedrock and glacial legacy, sediment supply to the catchment is high, and the river system is transport limited (Church & Slaymaker, 1989). Because of this, it is assumed that changes to the sediment load as a consequence of salvage harvesting will mainly consist of an increase in suspended and wash load. In most reaches of Baker Creek, this material will not be deposited, and will not significantly change channel characteristics. Exceptions to this assumption are discussed below.

Downstream changes in the Shields number are shown in Fig. 2. The widespread availability of coarse-grained sediment, from Quaternary terraces and the volcanic bedrock means that relative to channel depth, channel bed material size is coarse, and Shields numbers are relatively low. This is particularly apparent in channels in the high-gradient reaches, where the Shields number averages 0.03 to 0.047, indicating that the channels are below, or just on the threshold of sediment entrainment at bankfull flows. Other high gradient reaches lie in the 0.5 to 0.6 range, above the threshold for bedload transport. Sites in the flatter reaches, where channels tend to be narrow and deep and characterized by finer sediment, have Shields numbers greater than 0.1.

With increasing discharges under the salvage harvesting scenarios, two main responses occur (Fig. 2). Sites with higher Shields numbers (>0.1) show what appear to be marked increases (e.g. site B6). These changes are actually proportionally small (5–20% increases) and do not cross any stability thresholds, indicating a change in sediment regime or morphology. Sites with low Shields numbers (0.03 to 0.04) show proportionally larger increases (20–60%), and almost always cross the stability threshold for bedload transport (e.g. site B3). These changes indicate that the narrow and deep low gradient channels of the central plateau are largely resistant to change, whilst the wide and shallow channels of the higher gradient reaches are more likely to undergo significant changes. These changes are likely to take the form of channel widening, increased sediment accumulation and bar development, and the possible development of braiding in unconfined reaches. In all cases, where stability thresholds are crossed, discharge increases of 66% (40% clearing) are sufficient. In no case do further discharge increases associated with greater clearing levels result in further thresholds being crossed.

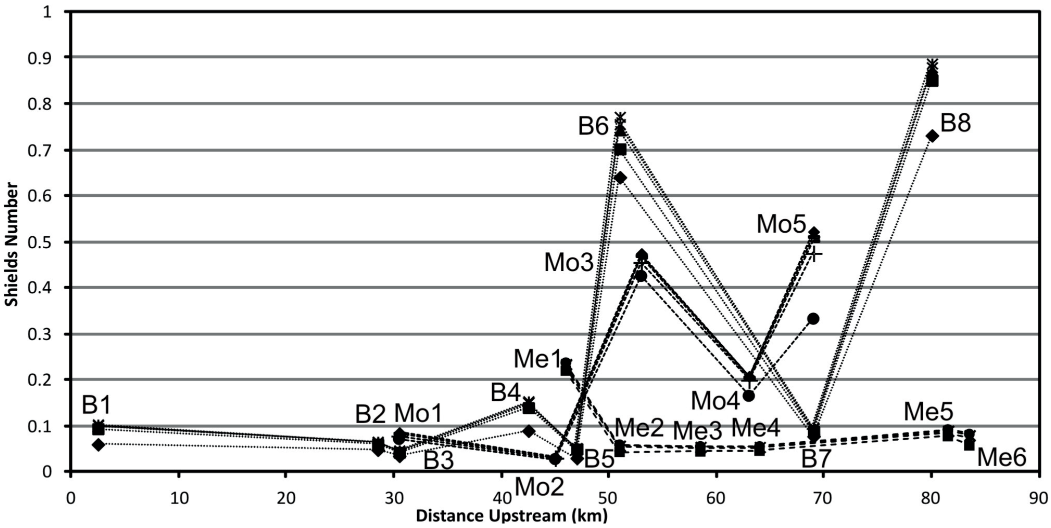

Fig. 2 Downstream changes in Shields number along Baker Creek and its main tributaries. At each site, increases in Shields number under the salvage harvesting scenarios listed in Table 1 are also shown.

DISCUSSION AND CONCLUSIONS

Baker Creek is typical of many rivers in the interior of British Columbia in that much of the catchment consists of a low relief plateau. However, as a tributary of the Fraser River, lower Baker Creek is over-steepened where it enters the Fraser Basin physiographic region. This contrast between a low-gradient main catchment and a higher gradient section above the Fraser River is common throughout the region. Thus, the results from this study have a wide applicability.

The analysis in this study was based on changes to the channel-forming bankfull flow; it is probable that overbank flooding will become far more common than at present, as discharges will increase across the full range of frequencies (Table 1; Alila *et al.*, 2009b; Green & Alila, 2012). In the steeper reaches increased flows across all frequencies will result in further instability as channels are forced to repeatedly adjust to flood-induced changes. In the lower gradient reaches, increased frequency of overbank flooding will be significant in putting large volumes of sediment into storage on the flood plain. Although it is likely that sediment will be mobilized throughout the catchment, the significant sediment storage in the low-gradient flood plain reaches will manifest itself as a reduction in channel width/depth ratio and an increase in within-channel bench deposition (Gomez *et al.*, 1998).

Steeper, gravel-bed channels, common where rivers cut down from the interior plateau to the Fraser River are most susceptible to instability and change. It is likely that there will be significant channel widening, and an increase in width-depth ratios. Sediment mobility will be greatly increased, and will lead to an increase in bar development, primarily on enlarged meander bends and through the development of braiding. Changes in gradient in the mid-catchment can play a large role in altering sediment distribution and channel patterns in alluvial rivers with strong bedrock controls (Marren *et al.*, 2006). The low gradient reaches, which occur in the centre of the Baker Creek catchment, have already been disturbed by flood plain clearing, and are likely to remain relatively stable, even as discharges increase. However, channel dimensions may increase with increasing discharge, and changes such as meander cutoffs may occur during floods.

The MPB is profoundly changing the land cover and hydrology of catchments in the interior of British Columbia. In the Baker Creek catchment, there is a distinction between channels that are likely to remain stable, even with 100% discharge increases, and channels that are likely to cross stability thresholds, becoming unstable and changing character with discharge increases following 40% forest clearing. These threshold discharges can be used to inform hydrological and land use modelling, and produce harvesting scenarios that prevent these thresholds from being crossed.

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