Abstract

In August 2003, the McLure Fire burned through several watersheds north of Kamloops, including Fishtrap Creek. The burn was extensive, killing almost all the trees in the riparian area. Given our current knowledge, it is not possible to accurately predict channel response to wildfire, the rate of change, or the time scale at which response and recovery may be expected to occur.

The purpose of this study is to document the timing and magnitude of initial changes in channel morphology, hydrology, sediment supply, and sediment mobility in Fishtrap Creek in the aftermath of the McLure Fire. We take an empirical approach that combines stream channel monitoring with physically based data analysis. The results of this study have contributed to our understanding of the response of gravel bed rivers to severe vegetation disturbance and have produced an estimate of the timescale at which significant channel transformations may begin to occur.

During the summer of 2006 (3 years after the fire), we conducted an intensive field study at Fishtrap Creek. Results indicate that Fishtrap Creek is in an active state of transition triggered by the loss of bank strength and subsequent sediment input to the stream channel. Cross-sectional bed elevation surveys conducted annually from 2004 to 2006 have documented changes in channel form. In localized areas, up to 42 cm of aggradation has been observed; aggradation has typically occurred on the channel bars and behind large woody debris. Avulsions and overbank flooding have also occurred as aggradation forced stage height higher. Analysis of the relationship between stage height and discharge at a variety of locations indicate that the vast majority of aggradation occurred during the first peak in the 2006 hydrograph. Magnetic tracer stone analysis indicates that sediment mobility was high during the 2006 freshet. The burial depth distribution of tracers suggests substantial scour and a thorough mixing of the
active layer. The current trend of channel adjustment is expected to continue until the root systems of emerging vegetation begin to stabilize the banks.

**Introduction**

The summer of 2003 in southern British Columbia was an unusually hot and dry summer that followed one of the driest winters on record. Unprecedented low summer flows were recorded for several streams in the Kamloops region (Doyle, 2004). As a result, the 2003 fire season was marked by several large, destructive forest fires. Over 104,000 ha were burned in the Kamloops Fire Region alone (Scott and Pike, 2003).

On July 30, 2003, the McLure fire ignited. High fuel loads, dry initial conditions, and strong winds created a high intensity fire that was exceptionally difficult to contain. The fire’s perimeter quickly grew to hundreds of kilometres over the following days, ultimately destroying the town of Louis Creek and parts of Barriere, B.C. The Tolko sawmill in Barriere was completely destroyed. The regional map of southwestern British Columbia in Figure 1 shows the location of the McLure Fire limits.

![Figure 1. Regional map of Southwestern British Columbia indicating the location of the McLure Fire. Baseline mapping data from ESRI Data and Maps (2002).](image)

The McLure Fire was a high-intensity stand-replacing crown fire. Several watersheds north of Kamloops were severely burned, including Fishtrap Creek. The fire burned an estimated 75% of the watershed with the burn of the riparian area being extensive, killing virtually all the vegetation. The map in Figure 2 identifies the location of Fishtrap Creek Watershed within the McLure Fire limits.
The effects of wildfires on forest ecosystems are of primary concern for researchers and resource managers in North America. There have been numerous studies conducted to analyze the effects of fire on stream channels and aquatic ecosystems. Recently, the research community has reported an increasing number of post-fire analyses, likely because: i) high-intensity crown fires are increasingly common as fire suppression practices have lead to unusually high fuel loads in many forests (Daigle 1996), ii) forest mortality as a result of insect infestation, such as the Mountain Pine Beetle, is contributing to increased fuel loads in many forests (Keane et al., 2002); and iii) climatic change is expected to influence fire frequency (Johnson and Larsen, 1991).

Much of the leading research on landscape response to wildfire has been conducted in southern California (e.g. Rice, 1982; Wells 1987; Florsheim et al., 1991), in the Colorado Front Range (e.g. Moody and Martin, 2001a; Kunze and Stednick, 2005), and in Yellowstone National Park (e.g. Meyer et al., 1995; Legleiter et al., 2003). A large proportion of post-fire studies have been principally concerned with
changes in hydrology, surface erosion, and the effects of mass movements from hillslopes. In fact, surprisingly little research has been conducted to analyze the role of bank erosion on the overall stability of channel morphology following fire. This is likely due to the highly variable nature of channel morphology, the complexity of governing conditions, and the lack of pre-fire data. Currently, no methods for quantifying change or determining the time scale of recovery have been established.

Stream response to wildfire may lead to a number of adverse environmental and socio-economic effects. Research on post-fire ecology indicates that water temperature, water quality, and instream habitat features may be affected by wildfire (Agee, 1993). Increased sedimentation of fine material in riffles may reduce density and diversity of aquatic organisms (Roy et al., 2003). Loss of canopy cover due to fire may also lead to increased summer maximum water temperatures in small streams (Helvey, 1972). Furthermore, there may be significant hazards such as debris flows, floods, and landslides associated with watershed response, which are especially relevant where wildfires occur adjacent to populated areas. The probability of hazardous, high magnitude events has been shown to increase following intense wildfires (Benda et al., 2003; Wondzell and King, 2003). Jordan et al. (2004) observed an unusually large number of debris flows following the 2003 wildfires in southern British Columbia, triggered by high runoff from fire-induced hydrophobic soils.

The response of a given watershed to wildfire is highly variable, both spatially and temporally, depending on several factors including the initial conditions in the watershed as well as the intensity, severity, and extent of fire. Recovery time to pre-fire conditions varies dramatically and is estimated to be 25 to 300 years based on the stability of the system (Debano et al., 1998). Specifically, changes in post-fire channel morphology vary considerably between regions. Wondzell and King (2003) noted that post-fire channel morphology is highly dependent on the regional variations in climate that influence sediment supply mechanisms. Where debris flows and landslides are common such as in the highly active climate of the Pacific Northwest the addition of large quantities of Large Woody Debris (LWD) in combination with coarse sediments can create stable physical structures that dramatically alter channel shape. In contrast, the relatively dry climate of the Rocky Mountain Region is characterized by post-fire input of fine sediments from surface erosion. Fine sediments have less of an impact on channel morphology as finer material is more easily moved through the system (Wondzell and King, 2003). Collins and Ketcham (2001) also documented significant regional variation in California between the dry Chaparral landscape in the south and the moist north coast. They hypothesized that the differences are due to the apparent cohesion provided from vegetation root networks.

Water yield may increase following fire as a result of decreased interception of precipitation and evapotranspiration from the loss of vegetation and litter layer. A literature review by Moody and Martin (2001b) documented significant increases in post-fire peak discharge and annual water yield with a recovery time of 3-10 years. They found that the change in peak discharge is greater than the change in annual water yield and is therefore a more sensitive measure of hydrologic response (Moody and Martin, 2001b). In British Columbia, Cheng (1980) conducted a paired watershed analysis to examine the hydrologic effects of the Eden Forest Fire near Salmon Arm. The study reported higher and earlier peak flows and an increase in total water yield, generally corroborated by post-fire studies in other watersheds (Winkler et al., 2005). In addition, intense ground fires may lead to the formation of hydrophobic soils and other changes in the upper soil horizons. Where clays and organic material are present, the upper soil surface horizons may be altered by high fire temperatures, which may result in decreased total porosity and pore size, thus reducing infiltration rates (Debano et al., 1998).

Changes in snow accumulation and melt in burned and logged watersheds are well documented in the literature. Typically, the loss of forest canopy results in greater snow accumulation and earlier melt (Winkler, 2000). Greater accumulations are largely due to lack of interception and redistribution from altered wind patterns (Scott and Pike, 2003). Snowmelt typically occurs up to two weeks earlier in
clearcut areas compared to forested ones depending on forest type, aspect, and elevation (Winkler, 2000). The same is true following fire. In his study following the wildfire near Salmon Arm, BC, Cheng (1980) documented earlier snowmelt. These findings are also in agreement with the literature on snow accumulation and melt following other vegetation disturbances such as disease (Scott and Pike, 2003).

Where fires cause the mortality of riparian vegetation, stream banks may become vulnerable to erosion. Numerous researchers have demonstrated the influence of riparian vegetation on alluvial channel form (Andrews, 1984; Hey and Thorne, 1986; Millar and Quick, 1993; Millar, 2000; Eaton et al., 2004; Eaton, 2006). Empirical research shows that alluvial channels that support healthy riparian vegetation are deeper, narrower, and migrate more slowly than channels without riparian vegetation (Abernethy and Rutherfurd, 2000).

In forested riparian areas following fire, bank erosion may be responsible for increasing the amount of instream LWD as trees on the banks are recruited into the channel. Early recruitment of LWD occurs as a result of initial tree mortality, while later recruitment of LWD largely depends on bank stability and rates of lateral erosion (Debano et al., 1998). Recruited trees may likewise introduce sediments from their exposed root wads, and often promote further erosion by redirecting flow into the bank or forcing channel avulsions (Hogan, 1986; Bisson et al., 1987; Montgomery et al., 2003; Hassan et al., 2005). Indeed, recruitment of LWD following disturbance has been found to cause significant changes in channel morphology (Collins and Ketcham, 2001; Hogan, 1986; Benda et al., 2003). Increased woody debris loading may lead to channel instability by: i) forcing areas of local scour below LWD obstructions; ii) increasing bank erosion due to flow diversion; iii) promoting deposition of sediments that may form bars, steps, and plunge pools (Montgomery et al., 2003a). LWD jams form at random along the length of the channel and provide structure for sediment storage upstream. The formation and decay of LWD jams over time may influence the sequence of bars and force multiple channels through avulsion (Hogan et al, 1998).

The degree of stabilization provided by bank vegetation depends on the rooting depth of vegetation relative to the maximum channel depth. Bank stabilization is maximized in small and intermediate streams where the rooting depth is equal to or greater than the maximum channel depth (Eaton and Church, 2007). In small- or intermediate-sized watersheds, bank erosion may increase following fire due to the absence of cohesive strength provided from dense root systems of live riparian vegetation (e.g. Collins and Ketcham, 2001). Healthy riparian vegetation has both a mechanical and hydrologic influence on bank stability. The hydrologic influence comes as a result of interception of precipitation that would otherwise have been infiltrated, or by loss of soil moisture through transpiration. Both processes result in increased shear strength due to the creation of negative pore-water pressure, called matric suction (Rinaldi and Casagli, 1999).

The mechanical influence of vegetation arises from greater soil shear strength provided directly from the root structure (Simon and Collison, 2002). In root-permeated soils the shear strength of the soil-root composite increases as a function of tensile strength and spatial distribution of roots (Abernethy and Rutherfurd, 2001). The tensile strength of roots has been measured by many researchers and has been shown to vary with: i) root diameter (Abernethy and Rutherfurd, 2001; Gray and Barker, 2004; Simon and Collison, 2002); ii) species (Gray and Barker, 2004); and iii) growing conditions (Gray and Barker, 2004). While many studies have quantified variation of tensile strength with root size and species, few have documented differences due to growing conditions.

The shape of an alluvial channel has long been recognized to qualitatively represent a response to several factors, or governing conditions (Lane, 1957). The most important governing conditions controlling alluvial channel morphology are: i) the volume and distribution of peak water discharge; ii) the volume and calibre of sediment supplied to the channel; iii) the nature of channel banks (including vegetation); and iv) the landscape history of the drainage in which the river flows (Church, 1992). The landscape
history is important as it generally determines the type and quantity of sediments that are available and controls the valley gradient. The peak water discharge is mainly responsible for channel scale while the nature of sediment supplied to the channel largely controls channel morphology. The balance among the governing conditions determines the level of channel stability (Church, 2006).

An equilibrium channel may be defined as one in which the cross-sectional shape, roughness, and gradient allow transport of the sediment load contributed from upstream (Leopold and Bull, 1979). Sediment can be delivered to the stream channel by landslides, debris flows, surface erosion, in-channel storage sites, bank erosion, tree throw (Dietrich and Dunne, 1978). The quantity and sediment size distribution differs with each sediment delivery process. The channel form at any point in a stream network is the result of a balance between the supplied sediment load and the transport capacity of the channel. A channel that is in a state of quasi-equilibrium (while it may have stage-dependent adjustments to channel form) will return to the same form and surface texture after every flood hydrograph (Lisle et al., 2000). Alluvial channels may adapt to changing water and sediment discharge largely through adjustments in flow resistance. The hypothesis put forward by Eaton et al. (2004) is that equilibrium is achieved when the frictional resistance to flow for the fluvial system is maximized; by maximizing flow resistance, the system’s ability to deform the channel is minimized (see also Davies and Sutherland, 1983).

Maximization of flow resistance in response to sediment supply changes may occur at three scales: grain scale (surface texture); bedform scale (bars, pools); or reach scale (thalweg sinuosity). At the grain scale, the relationship between sediment supply and surface texture is well documented (Dietrich et al., 1989; Church et al., 1998). Experiments by Dietrich et al. (1989) and Lisle et al. (1993) indicate that an increase in sediment supply entering the channel (of the same size distribution as the bed material) will cause the bed surface to become finer and sediment mobility to increase by way of a decrease in the grain-scale flow resistance. At the bedform scale, variations in the spatial distribution of shear stress due to vertical adjustments of bars and pools cause zones of increased sediment transport and an overall increase in transport efficiency (Lisle et al., 2000; Eaton et al., 2006). Montgomery et al. (1999) documented exceptionally high sediment transport rates in high supply conditions. They attributed increased transport rates to changes in grain size and bed roughness that increase transport capacity. And finally at the reach scale, experiments conducted by Eaton and Church (2004) indicate that a system with erodible banks preferentially adjusts flow resistance by varying thalweg sinuosity to account for increased sediment supply.

Field observations and experiments conducted by several researchers indicate that event-scale adjustments in response to increased sediment supply are triggered at threshold conditions (Montgomery et al., 1999; Lisle and Madej, 1992). Although researchers can clearly identify the point at which the threshold is reached in the field, the exact nature of these thresholds is not well understood due to the complexity of the system and measurement difficulties. However, once threshold conditions are reached, the response is generally characterized by short periods of rapid adjustment and intense sediment transport followed by a long period of bed restructuring with only moderate sediment transport rates. Over a longer time scale (on the order of decades), changes in channel morphology may occur as a response-and-recovery sequence characterized by a period of rapid adjustment followed by a long recovery to pre-disturbance state. Or, the result may be a dynamic transition to a disparate state depending on the magnitude of disturbance and subsequent effects on the governing conditions.

Methods

The project involved a number of different researchers, from both academia and from government, but the bulk of fieldwork was be conducted by Jason Leach, Christie Andrews and Jeff Phillips, all of whom are
former (JL & JP) or current (CA) Master’s students at UBC. By combining their thesis work with this project, we were able to conduct high caliber research while at the same time achieving significant cost efficiencies.

Suspended sediment concentrations were monitored at the WSC gauge and just below the confluence with Skull Creek to that we could apply a sediment budget approach to quantify the contributions of fine sediment recruited in the lower reach, largely due to bank collapse, relative to that delivered from upstream sources. In order to study the coarse sediment dynamics, magnetic tracer particles will be installed, and their movement during the spring freshet will be recorded in order to document the sediment transport patterns. The tracers will be a key element of the longer-term study of Fishtrap Creek, wherein changes in channel morphology will probably be associated systematic changes in the mobility of various bed material grain sizes and their typical sediment transport distances.

Twenty survey sections were established in the reach in 2006 and resurveyed in 2007, including 11 that were established in 2004: analysis of the data suggests that nearly all of the changes since the fire occurred during the 2006 and 2007 freshets. We also surveyed of the longitudinal profile (including estimation of the LWD loads) and measured the surface sediment texture of the bed in 2006 and 2007 in order to document any changes.

The flow structure and fluid force distribution within the study reach was documented during the high flow period in 2006 and 2007 using an acoustic doppler current profiler (ADCP) designed for use in small streams, as well as numerous water level loggers placed throughout the study reach in order to document changes in the energy gradient between morphologic units (like riffles, pools, glides and LWD dominated units). This information was used to model the channel stability, and to separate discharge-related changes in channel morphology from riparian vegetation/LWD-related changes.

The stream temperature component involved the installation of temperature loggers along the lower reach, with loggers installed in pools, riffles and side-channel areas to document local-scale thermal heterogeneity. These additional instruments complemented ongoing measurements made at the weir. Micrometeorological measurements (air temperature, humidity, wind speed, solar radiation) were also made over the water surface to provide input data for a heat budget model (Story et al., 2003; Moore et al., 2005b). Solar radiation was measured at a nearby open site to represent above-canopy solar radiation for input to the model. A model based on that developed by Rowland and Moore (1992) for leafless deciduous canopies was applied to simulate the effect of standing dead trees on solar radiation transmission through the canopy. The solar radiation model was be tested directly using measurements of above-stream solar radiation, and also indirectly through comparing observed stream temperatures along the reach with those predicted from the heat budget model. Additional measurements, including streamflow, were be made to quantify the effects of groundwater discharge for inclusion in the heat budget. As a complement to the process-based studies, statistical analysis was be conducted to relate daily stream temperature to stream discharge (measured at the weir) and air temperature measured at a long-term climate station.

**Results and Discussion**

The results of this ongoing research are summarized below, according to the main themes that emerged from the research. For the sake of clarity, we review the key methodologies and we have combined the results and discussion sections under each heading. Many additional details can be found in the MSc thesis by J.C. Phillips, which has been submitted to the MFR library as a deliverable of this project.

*Streamflow patterns at Fishtrap Creek before and after the McLure fire:* Hydrographs of mean daily streamflow following the McLure fire exhibited an earlier rise compared to pre-fire years, sometimes producing flows in early April that exceeded the 1.5-year flood. This pattern is consistent with the hypothesis that snowmelt will begin earlier in burned and salvage-logged portions of the catchment. Peak
flows following the fire had return periods ranging from 1.5 to 2.5 years, based on the pre-fire record. The highest post-fire peak occurred in 2005, when minimal channel change was observed.

In an attempt to detect streamflow changes caused by the McLure fire, regression relations were developed for the pre-fire period for freshet (March-July) runoff and annual peak flow. Because there is no suitable control catchment available, climate data from Kamloops were used to develop predictor variables. For freshet runoff, accumulated winter precipitation and accumulated freshet precipitation were included in the regression model. Post-fire freshet runoff plotted near the pre-fire regression line for 2004 and 2005, but plotted substantially above the regression line for 2006 and 2007. These results suggest that freshet runoff had increased in the latter two years, possibly as a result of salvage logging and continued loss of foliage from dead trees.

For annual peak flow, the only significant variable in the pre-fire regression was accumulated winter precipitation. All post-fire peak flows plotted near or somewhat below the pre-fire regression. This apparent lack of an increase in peak flows, in combination with the indications of higher runoff (at least for 2006 and 2007), may reflect the effects of de-synchronization of melt. However, because the regression relations were relatively weak and there are only four years of post-fire data, these inferences must be taken as tentative and requiring further investigation.

Accumulated streamflow above a threshold of 6 m$^3$ s$^{-1}$, which is approximately the flow at which significant bank erosion occurred, was low in the post-fire period compared to the pre-fire period. For the post-fire period, this index was higher in 2005, when minimal channel change was observed, than in 2006 and 2007, when substantial bank erosion and channel widening occurred. However, the years 2006 and 2007 had relatively high values of accumulated streamflow above thresholds of 4 and 2 m$^3$ s$^{-1}$, the latter being approximately the threshold for bedload movement. These results suggest that streamflow changes associated with the fire were not directly responsible for initiating bank erosion, but could have prolonged the duration of bedload transport.

**Channel morphology:** Stream channels are in constant flux as streamflow, wood inputs and sediment supply vary and channel framework elements develop, erode and migrate downstream. Adjustment of the channel morphology may be a long-term evolutionary process or may be triggered by an event such as a wildfire, a landslide or a flood. Change may occur on one short reach, discontinuously on a longer reach or throughout the watershed. The temporal and spatial pattern of channel morphology alteration makes it very difficult to decide how to study change within a channel.

The surveys show an interesting pattern of bed and bank erosion as well as increasing sediment accumulation in response to the post-wildfire streamflow. The freshet of 2005 had a moderately high peak flow (~9 m$^3$/s), but was of short duration and the channel reacted with minor erosion of the banks and aggradational and degradational adjustments to the bars. The left bank between XS3 and 4 retreated during the peak in late April 2005, but the surveyed cross-section lines did not pick this up as clearly as site photographs do. The greatest surveyed change within the reach occurred at XS9 where logs in a log jam were rearranged and the sediment wedge removed.

The freshet of 2006 saw two moderate peaks (~7.5 and 8 m$^3$/s), but strong flows persisted for a longer time. There was minor bank erosion and bar adjustments in the upper half of the reach (XS5 to 11), but the left bank erosion at XS3 and 4 was quite noticeable. Over 1.5 m of ground surface was removed on the outside of the channel, the slope of the bank was steepened, and the channel base moved approximately 2 metres outwards. Two trees on the margins of the bank were undercut and fell in during May 2006. Sediment accumulation on the inside (right) of the bend created a lateral and point bar between XS3 and 5.
The freshet of 2007 saw three moderate peaks (~6 and 7.5 m$^3$/s), was of long duration, and substantial change was observed along the entire reach. From upstream of XS11 through to XS8 there was major bed aggradation, with up to 2 m of sediment infill at XS9. Channel overflow occurred near XS10 and a secondary channel carried water for up to a month. XS8 had two trees fall in, opening up the bank to erosion during high flows. XS2 through XS4 had continued bank erosion on the outside of the bend and expanded lateral and point bar construction on the inside. The source of the sediment was between XS15 and 19 where the channel had eroded an area approximately 10 by 20 m. XS 14 through XS12 showed significant channel aggradation, channel widening and overflow.

The morphology of the Fishtrap Creek channel post-wildfire appears to be controlled not by the peak flow but by the duration of strong flows. Riparian zone tree roots appear to be a major control on bank strength. Post-wildfire the highest peak flow occurred in 2005, and although this was associated with some bank erosion and bed adjustments, the majority of the changes occurred after long periods of strong flow in 2006 and 2007 after dead tree roots had time to decay.

**Suspended sediment concentrations: four years of post-fire data:** Forest fires often produce an immediate, sizable increase in the volume of fine and coarse sediment supplied to a stream channel network, resulting in dramatically elevated suspended sediment concentrations (often by one or more orders of magnitude) and altered stream channel morphology. Such a response is particularly common where the fire is sufficiently hot to produce soil hydrophobicity. Suspended sediment samples collected from Fishtrap Creek between March and November in 2004, 2005, 2006 and 2007 do not show evidence of this sort of dramatic increase in sediment yield from the surrounding hillslopes, and suspended sediment concentrations (SSC) remained of the same order as monitored in an unburnt reference watershed, Jamieson Creek.

The highest SSC values in the post-fire period were recorded during the 2005 freshet, when streamflow rose to about 9 m$^3$/s, the highest peak flow since the fire. Despite the high peak flow, no significant channel change was observed during the 2005 freshet. The relatively high SSC values that year may represent the flushing of fine sediment that was produced during the fire and the following year, and which was not recruited during the 2004 freshet, when streamflow peaked at only 6.3 m$^3$/s.

In 2006, there were two distinct streamflow peaks, of about 7.5 and 8 m$^3$/s, respectively. During the first peak, the channel morphology remained stable and the relation between total SSC and discharge displayed clockwise hysteresis, typical of supply-limited systems. During the second peak, we observed bank erosion and associated changes in channel morphology; at the same time, the relation between SSC and became noisy. Bank erosion events within the study reach appear to be associated with suspended sediment concentrations of about 100 mg/L. For the second event in 2006, we believe that the chaotic pattern of SSC changes is linked to the random occurrence of channel adjustments and the associated random inputs of sediment to the channel. While discharges above 8 m$^3$/s in 2005 were not sufficient to erode the channel banks, the channel morphology in 2006 was significantly modified during flows above about 5 m$^3$/s, based on our analysis of the SSC data.

In 2007, three distinct peaks occurred, each of which was preceded by a peak in SSC. Channel widening and aggradation also occurred in 2007, primarily during the second peak flow event, producing a similar chaotic relation between SSC and flow for the second and third events of 2007.

The SSC data support the idea that extensive hillslope erosion did not occur at Fishtrap Creek following the 2003 fire, in contrast to the responses encountered in other parts of the southern interior. The patterns of elevated SSC during some flow events are apparently associated with endogenous channel instability driven by loss of bank strength following post-fire decay of riparian tree roots.
**Bedload transport: magnetic tracer stones:** Three years after the McLure fire, Fishtrap Creek is in a state of transition, triggered by the loss of bank strength and subsequent sediment input to the stream channel. Magnetic tracer stones were strategically placed to monitor bedload transport patterns during the 2006 freshet. Data from tracers provided information about the typical path length of mobile sediments, location of aggradational areas, the depth of the active layer, and bedload transport rates.

Tracer data indicates that transport distances were relatively high compared to studies from other creeks. The longest recorded travel distance reached 52 times the channel width. The mean tracer transport distance was more than twice the average pool-to-bar spacing. Such long transport distances were likely related to the long duration of competent flows, high sediment supply, and the lack of well-developed bars before the 2006 freshet. Tracer transport distances appeared to be heavily influenced by the location of bars and other depositional areas. The greatest density of tracers were recovered in one newly formed mid-channel bar.

The burial depth distribution of tracers suggests substantial scour and thorough mixing of the active layer. It is likely that the layer of mobile sediment consisted largely of loose, unconsolidated material recently eroded from the banks; these sediments were likely easily mixed and provided little resistance to vertical exchange. Field observations document the lack of well-developed surface structures on the channel bed.

Data from tracers were also used to calculate sediment transport rates using the morphologic method. The morphologic method is an alternative to standard flow-intensity-based sediment transport equations. Using this method, bedload transport rates are estimated based on changes in channel sediment storage. The method requires the total volume of erosion over a period of time and the typical path length of those eroded sediments. At Fishtrap Creek, the total volume of erosion was estimated from repeated survey cross-sections, while the tracer stones were used to record the path length of eroded sediments. Scour and fill events between channel surveys are not accounted for, which is likely the largest source of error. There is no way in this method to quantify the magnitude of underestimation due to this error. However, the amount of uncertainty is modest when compared with flow-intensity-based transport equations that tend to over-predict actual transport rates and have been reported to have errors of an order of magnitude or greater.

The extent to which current patterns of bedload transport differ from those before the fire is not entirely clear and is confounded by many factors. Continued monitoring at Fishtrap Creek using magnetic tracer stones will provide detailed information about bedload transport patterns during high sediment supply conditions as the channel responds to severe vegetation disturbance and may provide insight into pre-fire conditions as the channel recovers.

**Stream temperature patterns:** Wildfires occasionally burn through riparian zones, resulting in a streamside zone dominated by standing dead defoliated trees. The associated reduction in shade can result in stream warming. As is the case for the effects of streamside forest harvesting, post-fire stream warming raises concerns for the potential impacts on cold-water fish species such as Bull Trout. Because the emulation of natural disturbance is frequently recommended as a paradigm for forest management, there is a need to understand how wildfire influences on hydrology and water quality compare to those of forest harvesting. Unfortunately, quantifying the impacts of riparian wildfire is more difficult than for studies employing a before/after control-impact design, which is the most statistically powerful approach to determining impacts of forest disturbances on hydrology and water quality. Previous studies dominantly compared post-fire temperatures in disturbed streams to those in nearby unburned riparian zones to determine the influence of wildfire disturbance, or compared temperatures upstream and downstream of the disturbed area.
In summer 2004, stream temperatures were monitored at Fishtrap Creek and five other streams in the region, including two others with catchment areas disturbed by the McLure Fire and three that were not affected. There was no systematic difference in temperature between disturbed and undisturbed streams. In fact, one of the undisturbed streams was the warmest. Therefore, it appears that the natural thermal variability between streams may be too great to detect a response to wildfire disturbance using a post-fire treatment-control approach, especially for larger catchments such as Fishtrap Creek.

Stream temperature measured at the Water Survey of Canada weir was moderated by a spring that discharged into the reach several hundred metres upstream of the weir. Daily maximum temperatures measured upstream of the spring were up to 2 °C higher than at the weir. These stream-groundwater interactions can produce substantial thermal heterogeneity along a stream reach and also influence the thermal response to riparian disturbance. Therefore, a single monitoring location may not provide an accurate estimate of disturbance response at the reach scale. In addition, thermal heterogeneity complicates the use of temperature differences above and below a disturbed reach as an estimate of the change due to disturbance.

Water Survey of Canada technicians have made spot temperature measurements during visits to the Fishtrap Creek gauging station, totalling 284 before and 41 after the fire. After accounting for the effects of streamflow and air temperature using regression analysis, a statistically significant increase in post-fire summer water temperatures was detected, averaging about 2 °C. The spot temperatures were made in the late morning, and therefore likely underestimate the increase in daily maximum water temperatures.

**Effects of wildfire on stream temperature processes:** While post-fire stream warming has been reported at a number of sites, including Fishtrap Creek, no studies appear to have addressed the processes controlling the magnitude of warming, particularly the effects of standing dead trees on net radiation at the water surface. The objectives of this study were (1) to quantify the radiation exchanges associated with standing dead defoliated riparian zone trees in comparison to pre-fire forest conditions, as well as a complete removal of riparian vegetation; and (2) to estimate the effects of different canopy conditions on stream warming.

Field studies were conducted in summer 2007 along Fishtrap Creek between the confluence of Skull Creek and the WSC weir. Field measurements included streamflow and stream geometry (width, depth, velocity) at various locations along the reach, as well as microclimatic measurements (air temperature, humidity, wind speed, solar radiation) made at two stations installed over the stream surface and at one site in a clearing. In addition, net radiation was sampled in time and space using a roving net radiometer.

A model of net radiation was developed using digitized canopy photographs to assist in modelling the transmission of solar radiation through the riparian canopy, as well as the emission of longwave radiation by the canopy, atmosphere and surrounding terrain. Over 100 canopy photographs were taken over Fishtrap Creek and processed using Gap Light Analyzer. The model was tested against measured net radiation. To simulate the effects of pre-disturbance vegetation, the model was run using canopy photographs taken at Jamieson Creek, which was not disturbed by fire and which has similar riparian vegetation to pre-disturbance conditions at Fishtrap Creek. To simulate complete loss of vegetation, the canopy photographs were modified to remove the standing dead trees and leave only topography.

A heat budget model was developed to translate the modelled net radiation (and other heat fluxes) into stream temperature changes along the study reach. The model tracks parcels of water leaving the upper end of the reach, and simulates how they change temperature in response to heat inputs and losses as the parcel flows to the lower end.
The net radiation model provided relative accurate simulations of net radiation under current (post-fire) canopy conditions. Comparisons of modelled net radiation for the three canopy scenarios suggest that, on clear sky days, standing dead vegetation reduces net radiation at the stream surface by one-third compared to the topography-only case. In addition, they suggest that the current conditions at Fishtrap Creek provide about 50% more net radiation than would be received at the stream surface under pre-disturbance conditions.

The stream heat budget model produced a close fit between the predicted and observed downstream temperature change. The topography-only scenario resulted in a daily maximum stream temperature increase of ~0.5 °C relative to current conditions. Current conditions produced a daily maximum stream temperature about 1.0 °C higher than under pre-fire canopy conditions. This predicted change likely underestimates the total post-fire warming at the weir, because the model uses post-fire temperatures at the upper end of the reach, which are probably higher than for pre-fire conditions.

This study has demonstrated that standing dead trees do reduce net radiation and stream warming relative to what would occur with a total loss of riparian vegetation. It also highlights the utility of canopy photographs for estimating the effects of forest disturbance on incident radiation, as well as the use of a heat budget model for assessing the resulting stream temperature response.

**UBC Regime Model: predicting the range of potential morphologic changes**: In most of the documented cases of fire-related changes in channel morphology, exogenous (i.e. originating outside the study reach) changes in sediment supply appear to overwhelm any endogenous instabilities. The potential impact of endogenous (i.e. originating within the reach) instability due, for example, to loss of bank strength, is almost never considered. Tools have recently been developed which allow us to predict, even with sparse data, how channels may respond to changes in peak flow, bank strength and LWD loading, among other potentially important variables. The UBC regime model is used here to explore the potential channel response to altered peak flows, loss of vegetation-related bank strength, and to changes in the LWD loading in the stream. Specifically, we have estimated the sensitivity of the channel dimensions and the sediment transport capacity of the channel to changes in peak flow.

It was assumed that increased snow accumulation and rapid melt could increase the peak flows by as much as 50%. Alternatively, desynchronization of melt within the basin could produce a decrease in the average peak flows. The predicted effect of a ± 50% variation in peak flows on channel geometry is modest, and the effect on the transport capacity appears to be of a magnitude that can be accommodated by the fluvial system via changing surface texture for all but the largest decrease in peak flows.

The sensitivity of the stream channel to changes in bank strength due to riparian vegetation was also investigated. Initially, plant mortality is assumed to produce an exponential decline in bank strength. Root regrowth, on the other hand, will allow bank strength to recover to its former values – a process that takes about 3 or 4 decades. Assuming that up to 80% of the total vegetation-related strength could be lost, the model predicts channel widening by over 100% of the original channel dimensions and a possible transition to a multiple thread channel pattern. In this scenario, the predicted transport capacity is reduced, making the system vulnerable to exogenous increases in sediment supply, but the decline is probably not sufficient to induce net aggradation and channel instability.

The largest predicted effect on sediment supply (and the smallest effect on channel dimensions) is associated with changes in the LWD loading within the reach. We assume that the energy gradient dissipated in association with woody debris could vary by ± 0.01 m. This is equivalent to adding or removing five 50 cm tall LWD steps within our 300 m study reach. The predicted effect appears to be sufficient to drive the system into a state of persistent net degradation or net aggradation, even if the exogenous sediment supply remains constant.
The results of the sensitivity analysis suggest that loss of bank strength, leading to channel widening, and thus to LWD recruitment and a reduction in the effective energy gradient, are the most likely causes of the observed changes in channel morphology at Fishtrap Creek. However, as the bank strength recovers and the instream LWD (which is already burned and of questionable mechanical integrity) breaks down, the system is likely to switch from a laterally active, multiple thread system with bars and pools to a laterally stable, degrading system that may ultimately abandon its multiple threads by vertically incising along the main channel. The initial response is expected to lag the watershed disturbance by 3 to 10 years, while the long term response to a decline in the LWD supply is likely to occur only after several decades.

**Rating curves for characterising patterns of channel change:** Rating curves are generally power-law functions that relate river stage and discharge. The stage-discharge relationship is not always static. Changing channel form, flow velocity, or channel roughness over time may lead to a shift in the relationship. Intuitively, aggradation or degradation of the channel bed will result in different stage height values for a given discharge. Therefore, in an unstable channel, if detailed discharge and stage height data are available, breaks in the rating curve may be used to document the timing, and to some extent the magnitude, of channel form adjustments.

In April 2006, nine submersible water level recorders – called divers – were installed in a variety of morphologically distinct sites in Fishtrap Creek. Rating curves generated from diver data illustrate an abrupt change in the stage-discharge relationship at many, but not all, of the sites following the first peak in the hydrograph. Our field observations and cross-sectional surveys also support the site specific changes documented by the divers. At sites where surveyed cross-sections showed significant bed aggradation, an abrupt break in the stage-discharge relationship was recorded. At sites where the channel remained stable, the stage-discharge relationship was relatively uniform.

It was not possible to separate the influence of aggradation, slope, and roughness on stage height in this analysis given the complexity of the system and measurement difficulties. However, it is likely that stage height changes due to slope and roughness, although significant, are relatively small compared to the direct effects of bed aggradation in this case.

The analysis suggests that the majority of channel form adjustments during the 2006 freshet occurred between April 2 and May 2. In fact, at several of the divers, it appears that most of the channel adjustment occurred between the first peak and second peak in the hydrograph (April 9 to April 30). This is an interesting observation since little is known about the timing of channel form adjustments in snowmelt-dominated systems and there are little data available largely because it is difficult to measure channel form directly at flood stages.

**Management Implications**

For intermediate streams, riparian vegetation can dominate bank strength to such a degree that the channel becomes incapable of migrating laterally. The channel morphologies of these streams tend to be structurally very simple, with poorly developed pools and bars and with coarse beds. When the riparian vegetation is disturbed by fire, pest infestation or by anthropogenic activities, the vegetation-related bank strength is quickly lost, and the affected channels become capable of migrating laterally. The channel may become more complex, with moderately well developed pools and bars and with elevated large woody debris (LWD) loads due to lateral channel migration. In extreme cases, such as following forest fires, the channel may become highly unstable, developing a braided channel pattern. As the vegetation recovers, the rates of lateral migration decline and the channel becomes locked within a single, stable channel once again. The morphology of such streams likely follows a cycle related to the disturbance regime for the
riparian forest upon the floodplain, shifting from one morphology to another and then back again as bank strength and LWD load varies over time.

As for forest ecosystems, the riverine habitat is intimately linked with the disturbance history. The habitat characteristics depend on both the processes acting within the channel at the present time, as well as those processes that have been active in the past. In particular, both the physical complexity and the LWD volume for a stream depend on the timing and severity of the last major disturbance to the riparian forest. Off-channel habitat is likely constructed only during the brief period of accelerated lateral activity and morphologic instability that occurs following disturbance. Similarly, inputs of LWD may be dominated by windthrow and lateral erosion immediately after forest fires, particularly in environments like the interior of BC. Thus, while the unstable channel state may be undesirable, from a habitat point of view, the features that develop on the floodplain and in the channel during this phase may determine the value of the aquatic habitat in the future.

Channel disturbance, then, is probably an integral component of maintaining the overall quality of aquatic habitat for a channel network. So long as disturbances are permitted to occur but do not occur in all reaches at the same time, then the overall health of the stream network (from a physical habitat point of view) will be maintained, since habitat quality will be high in some locations, and low in others. However, if either the disturbance mechanisms are suppressed or if a single disturbance event is so widespread that all of the morphologic life cycles become synchronized, then the overall health of the system may severely compromised. The impact of the current Mountain Pine Beetle infestation may be just such a synchronization, resulting in a reduced overall habitat diversity across the landscape, with potentially disastrous impacts on the channel network as a whole, despite only apparently moderate impacts on any given reach of channel.

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