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Techniques for Monitoring Channel Disturbance: A Case Study of Fishtrap Creek, British Columbia

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The effects of wildfires on stream channels are of considerable concern to researchers and resource managers. Fire suppression practices have led to unusually high fuel loads in many forests, making high-intensity crown fires increasingly common (Daigle 1996). Moreover, infestations by pests such as the mountain pine beetle continue to affect an ever-increasing proportion of the forested landscape, contributing to increased fuel loads in many forests, which ultimately may influence the frequency and magnitude of forest fires in these areas (Keane *et al.* 2002). Also, climate change is expected to influence fire frequency (Johnson and Larsen 1991). One of the main conclusions from a recent workshop that discussed fire- and water-related issues for the BC Interior was that quantitative data to describe post-fire response are scarce both locally and in similar environments elsewhere (Pike 2003). These issues highlight the need for detailed, long-term monitoring programs to study the effects of fire on water resources.

Fishtrap Creek was severely burned in the McLure fire of 2003; the burn of the riparian area was extensive, killing virtually all of the vegetation. Studies following other fires have reported damage to fish habitat, water quality, infrastructure, and increased flood hazard. Previous research indicates the probability of hazardous, high magnitude events such as debris flows, floods, or landslides increases following intense wildfires (Benda *et al.* 2003). In particular, 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. Post-fire observations at Fishtrap Creek have not documented any post-fire debris flows, floods, or landslides. Peak discharges (recorded at the Water Survey of Canada gauging station) in the years following the fire have been of average magnitude or smaller, showing no evidence of fire-induced soil hydrophobicity. However, there appears to be a systematic change in channel pattern at Fishtrap Creek related to changes in bank strength following the fire, as vegetation root systems decay and the soil cohesion they provide diminishes. The channel morphology is transitioning from a relatively featureless cascade–pool system to what is best described as a riffle–pool channel (Figures 1A, 1B). Numerous researchers have demonstrated the influence of riparian vegetation on alluvial channel form (Andrews 1984; Hey and Thorne 1986; Millar 2000), but studies of this effect due to forest fire are scarce.

In this article, we present a combination of techniques used for monitoring the initial changes in channel form and sediment transport rates in Fishtrap Creek following fire. The objectives of this paper are to describe specific monitoring techniques and to present the initial results of the monitoring program at Fishtrap Creek to illustrate possible ways in which the data may be used. The complete analysis including methods, initial results, and discussion from the study are not described in detail here but may be found in Phillips (2007). The main

Figure 1. A) Channel morphology before significant channel change; B) Same channel reach following onset of bank erosion in 2006.

objective of the monitoring program at Fishtrap Creek was to document the timing and magnitude of initial changes in channel morphology, sediment sources, and sediment mobility in the aftermath of the McLure fire. Some of the techniques employed to accomplish this objective were (1) surveys of channel cross-sections, longitudinal profile of the channel thalweg, and planimetric mapping of key morphologic elements; (2) launch and recovery of magnetic tracer stones; and (3) estimation of sediment transport rates using the morphologic method. While our study documented changes due to wildfire in an intermediate stream, the methods presented here may be more generally applicable to other channels at various disturbance types.

Channel Surveys

Cross-section and planimetric surveys were used to monitor channel form in Fishtrap Creek. Cross-sections have been resurveyed annually since 2004, allowing us to accurately estimate the net changes in channel morphology via erosion and deposition of bed sediment. Cross-sections are a commonly recognized component of stream channel monitoring programs and the survey methods are widely used; therefore, we will not describe them in detail in this article. In short, a number of permanent cross-sections were established with benchmarks (0.9 m [3 ft.] long sections of ½" rebar driven into the floodplain) installed at both ends of a transect perpendicular to flow direction. The cross-section bed elevation was then surveyed using an automatic level and stadia rod.

Figure 2. A) Bank erosion in the upper reach of the study site. The breakdown of a buried large woody debris jam has apparently amplified bank erosion here. B) Bank erosion in the middle reach of the study site. Dense root systems are exposed where banks have retreated approximately 1 m.

Surveys documented both the timing and magnitude of channel changes following fire indicating little change in channel form during the freshet of the first two post-fire years (2004 and 2005) followed by a much greater magnitude change in the third post-fire year (2006). Lateral bank erosion of up to 1 m was documented in the study area as illustrated by the photos of the exposed root systems (Figures 2A, 2B). The lag time in channel response highlights the importance of establishing a long-term monitoring program to capture a delayed response.

The planimetric mapping provided a generalized map, established a baseline for the detection of significant lateral channel migration in the future, and helped to organize spatial data. Figure 3B contains a section of the longitudinal thalweg profile cross-referenced to cross-sections 1–11 on the planimetric map from the middle reach of the study area (Figure 3A).

To create the map, the bank and bar edges, channel thalweg, and large woody debris (LWD) pieces were surveyed using a laser range finder with an electronic compass attachment mounted on a tripod. A highly reflective target for surveying, such as a bike reflector, and vegetation filter enables the range finder to work more effectively in dense vegetation. Using the known coordinates of benchmarks as control points and the electronic compass to determine the planimetric locations of each survey point, we generated a detailed yet relatively inexpensive planimetric map of the study site. The laser range finder and compass are lightweight, easy to use, and less expensive than a theodolite or total station but are not as accurate. The compass can resolve the bearing to ± 0.5, which results in an error that increases as a function of distance from the target up to ± 0.3 m at a distance of 30 m.

Magnetic Sediment Tracers

Sediment tracers have widely been used to investigate sediment transport patterns in gravel bed rivers (Church and Hassan 1992; Wilcock 1997; Ferguson and Wathen 1998). Sediment tracers provide information about the average distance of movement, sediment sources, and the relationship between grain size and transport distance. However, conventional tracer methods are designed to study the phenomenon of bedload transport for

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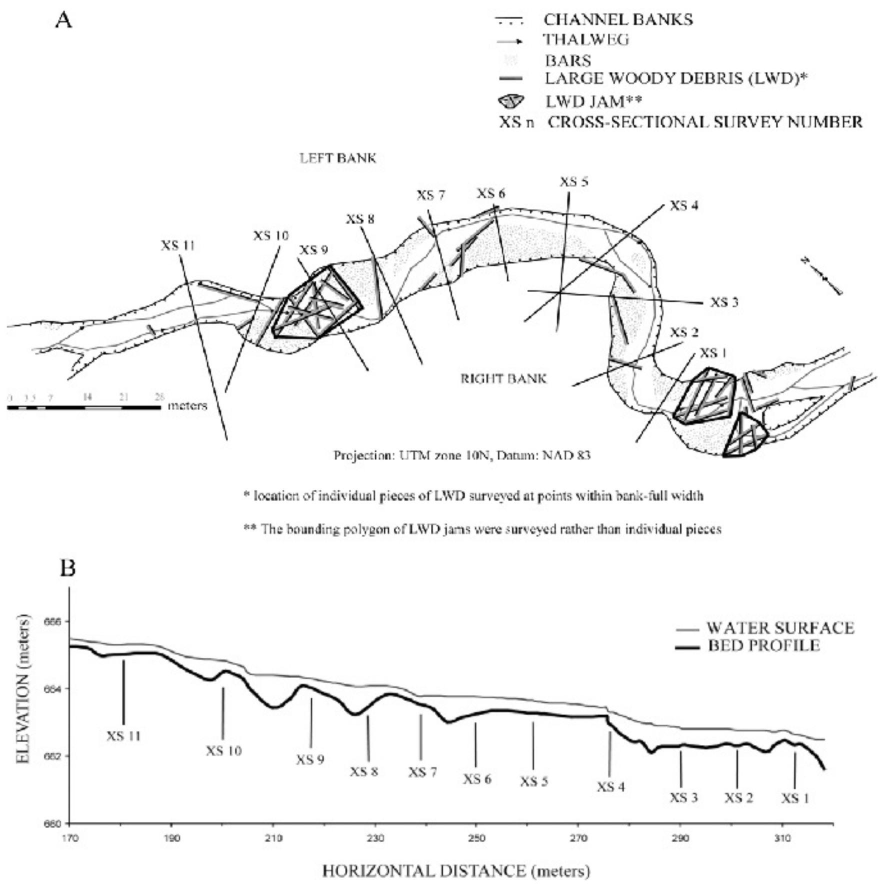

Figure 3. A. Planimetric study area map with the location of cross-sectional bed elevation surveys 1–11 labelled. B. Thalweg longitudinal profile. The location of cross-sectional surveys has been added for reference.

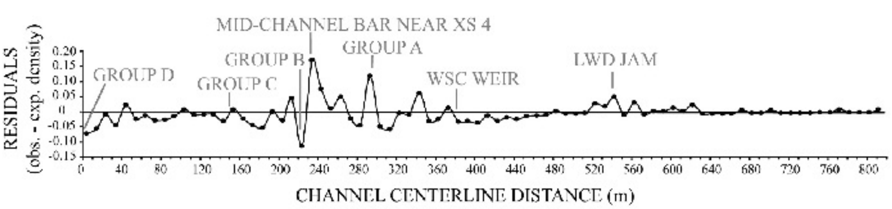

Figure 4. Tracer density residuals along the channel centreline (observed density minus density predicted from gamma model). The distribution highlights the influence of morphological constraints.

research, and thus are very costly as well as difficult to interpret as part of a monitoring program designed to detect changes in the characteristics of the sediment transport regime. One important result from the previous tracer studies is that we can use the behaviour of the mean surface grain size (D_{50}) to accurately represent the average behaviour of entire suite of grains found on the channel bed (see companion article by Eaton, Hassan, and Phillips, this issue).

For monitoring, to generate simple and, above all, repeatable indices of the bedload activity in a stream, we can reduce the cost and complexity of a tracer analysis by using fewer tracer stones, which represent just the D_{50}, rather than the entire bed grain size distribution. This approach documents the effectiveness of a flood event to mobilize and transport particles found on the surface that are the same size as the median grain size, D_{50}.

In April 2006, we launched a total of 400 tracers at Fishtrap Creek. Tracers were deployed at four separate starting points along the channel. At each starting point, 100 tracers (25 from each of the four size classes bracketing the surface D_{50}) were placed on the bed surface. After the spring freshet, the tracers were recovered using a magnetic locator. The work was conducted during the low-flow period in August 2006, when it was easiest to work in the stream channel. The recovery work took two weeks to complete with a recovery rate of about 80%. Nearly all of the tracers moved long distances (some over 500 m) from their starting location. The mean travel distance for all tracers combined was 103 m (~10 times the channel width). Many of the tracers were also deeply buried, indicating substantial scour and subsequent deposition of bed material during a single event.

Previous research has shown the frequency distribution of tracer travel distance to be well represented by a gamma function in many cases (Hassan *et al.* 1991). For comparison, frequency and cumulative frequency distributions of tracer travel distance were generated for each of the Fishtrap Creek tracer groups. Distributions for the normalized travel distances (i.e., the individual travel distance, *L*, divided by the mean group travel distance, L_{MEAN}) were analyzed following the methods described by Hassan *et al.* (1991).

Fishtrap Creek tracer travel distance was strongly influenced by the location of the nearest depositionl area. Tracers were preferentially trapped in morphologic features (i.e., bars, LWD storage deposits). The downstream distribution of tracer deposition was examined by calculating the residuals from the predicted gamma distribution of tracer travel distance. The residuals were calculated as the observed tracer density minus the predicted tracer density. Figure 4 contains the residuals of the density distribution for all groups along the channel. Significant depositional areas correspond with peaks in the residual values indicating a higher than expected number of tracers at that location.

Another useful index of the sediment transport dynamics that can be derived from the tracer data is the typical depth of scour and fill, referred to as the active layer thickness. Since the tracer stones in this study originated on the surface of the bed, their burial depths indicate the depth of deposition occurring after the tracers were deposited. A few of the tracers will have been deposited and buried when local bed scour has reached its maximum, but many will be deposited in the middle of the active layer and some will come to rest on the surface of the stream. The distribution of burial depths for the tracers gives both an indication of the thickness of the active layer (the maximum burial depths) as well as the degree to which particles originating on the bed surface have been mixed into the active layer.

The burial depths (scaled by the characteristic grain size for the bed surface) for Fishtrap Creek do not fit the expected distribution based on previous research (Hassan and Church 1994).[1] Hassan and Church (1994) found that short, single-peaked events produced a negative exponential burial depth distribution while snowmelt and multi-peak events did not. Furthermore, they suggested that armouring of the bed surface (at Harris Creek and Nahal Hebron, for example) prevented substantial vertical mixing and inhibited the likelihood of an exponential decay distribution of burial depths.

The Fishtrap Creek data tend to contradict those conclusions. The data were fitted using an exponential decay function represented by the dark lines in Figure 5(A-I). Goodness-of-fit for the exponential function was assessed using the chi-square ( ) test (Table 1). The 2006 hydrograph for Fishtrap Creek was long and complex with multiple peaks and the bed surface exhibited a high armour ratio, yet the burial depth data fit the exponential decay function remarkably well (Figure 5). We speculate that these differences are due to the lack of well-defined surface structures rather than bed surface armouring or hydraulic conditions. It is likely that the loose, unconsolidated material recently eroded from the banks allowed for thorough mixing and provided little resistance to vertical exchange; however, it is difficult to draw conclusions without further analysis.

Table 1. Chi-square (^{2}) statistics for exponential decay function

Event	^{2}	value for	N
A. Nahal Hebron, Jan. 23, 1983	42.63	16.81	244
B. Nahal Hebron, Oct. 17, 1984	12.23	15.09	141
C. Nahal Hebron, Nov. 8, 1986	35.36	13.28	100
D. Nahal Og, Nov. 8, 1986	18.37	21.67	142
E. Harris Creek, 1990	19.38	13.28	151
F. Carnation Creek, Dec. 3, 1989	14.35	16.81	171
G. Carnation Creek, Feb. 2, 1990 – yellow group	15.95	20.09	96
H. Carnation Creek, Feb. 2, 1990 – orange group	15.90	18.48	104
I. Fishtrap Creek, 2006	8.30	23.21	279

Source A-H: Hassan and Church (1994).

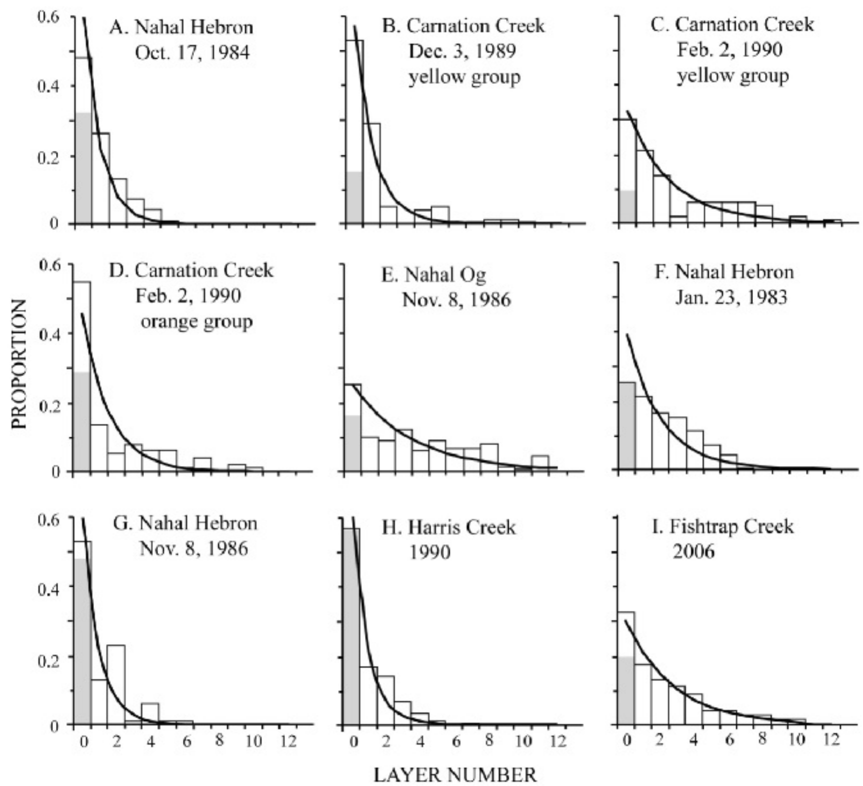

Figure 5. A-H. Depth distribution of all moved particles. Source: Hassan and Church (1994). (I) Fishtrap Creek depth distribution of moved particles from all groups. Layers represent scaled intervals of burial depth equal to the median grain size of the surface for each river. Gray areas represent particles exposed on the surface.

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Sediment Transport

One important aspect of channel adjustment following disturbance is the way in which bed material transport patterns and rates are affected. For a monitoring program, it would be very useful to be able to document changes in the typical volume of sediment transport that occurs each year following a disturbance: bed material transport rates are arguably the best indicators of the magnitude of impact from a disturbance on the physical habitat as well as post-disturbance recovery. Transport rates are notoriously difficult to measure using sediment samplers and are equally difficult to estimate using sediment transport equations based on flow conditions (e.g., Gomez and Church 1989). The morphologic method, which is based on documenting net changes in channel morphology and estimating the typical sediment displacements during a flood event, is an accurate, cost-effective alternative (Ashmore and Church 1998). While the temporal resolution of this technique is limited to the duration of a flood event, it is much more practical for long-term monitoring. The method does not require detailed information of the flow conditions, and thus is ideal for ungauged basins. One way to apply the morphologic method is by assuming a typical path length for the total volume of erosion (or deposition) measured within a reach. To use the morphologic method based on path length, two important data are required:

- the total volume of erosion (or deposition) over the time step of interest; and
- the typical path length of those eroded sediments.

The tracers give reliable and repeatable estimates of the typical sediment transport path lengths, and erosion/deposition volumes can be estimated from surveyed cross-sections. The total volume of erosion/deposition between adjacent cross-sections is estimated by prismatic approximation following the methods of Martin and Church (1995). The equation for the change in volume of erosion is written:

$$V_e = \frac{A_j + A_{(j+1)}}{2} L_{(j,\,j+1)}$$

where V_e is the volume of erosion/deposition (m^3) between adjacent cross-sections j and $j + 1$, A_j is the area of erosion/deposition (m^2) as measured at cross-section j, $A_{(j+1)}$ is the area of erosion/deposition (m^2) measured at cross-section $j + 1$, and L(j, j + 1) is the distance along the channel centreline (m) between the two cross-sections.

The total volumes of erosion and deposition in Fishtrap Creek were calculated from the measured cross-sectional areas surveyed in 2005 and again in 2006. Ten zones were created representing the area between adjacent cross-sections. The distance between adjacent cross-sections (L_r) was taken as the channel centreline distance and the total volume of erosion and deposition for each zone was calculated using the equation above. The total volumes throughout the reach were then calculated as the sum of all 10 zones. Table 2 contains the volume of erosion and deposition for each zone and the total volume and mass of erosion and deposition.

> *When estimates of the net erosion or deposition derived from the cross-sectional surveys were combined with the results of our sediment tracer program, we were able to derive a simple, repeatable index of sediment transport activity.*

Once the total volume of erosion and typical path length are known, the bulk sediment transport rate may be calculated using the equation presented in Eaton and Lapointe (2001):

$$Q_s = \rho_b V_e (L_{MEAN} / L_r) / t$$

where Q_s is the bulk sediment transport rate (kg per event) over time t (event), ρ_b is the bulk sediment density (kg/m^3), V_e is the total volume of erosion (m^3), and L_r is the length of the reach (m) in which V_e was determined. The bulk sediment density was estimated to be 1890 kg/m^3.

The largest source of error in the path length based morphologic method is related to the estimate of erosion and deposition, because the method does not account for scour and subsequent fill occurring during the flood event. However, the level of uncertainty is modest when compared with hydraulic transport equations, which tend to overpredict actual transport rates and have been reported to have errors of an order of magnitude or more. Researchers suggest errors in hydraulic transport equations are possibly due to the failure of equations to account for surface coarsening or variations in the rate of sediment supply (Gomez and Church 1989).

Summary

We have established a long-term monitoring program at Fishtrap Creek by adapting various research methodologies to reduce their cost and complexity and to improve their repeatability. Our approach focusses on generating an index of the sediment transport characteristics and in carefully documenting changes in channel morphology.

Establishing permanent cross-sections allowed us to systematically document the changes in channel morphology over time. Our cross-sections were regularly spaced about one channel width apart, and were resurveyed annually. A planimetric mapping of the channel morphology provided a valuable representation of the channel morphology. The mapping will be repeated only once the cross-sections reveal substantial channel change has occurred.

When estimates of the net erosion or deposition derived from the cross-sectional surveys were combined with the results of our sediment tracer program, we were able to derive a simple, repeatable index of sediment transport activity. The tracer program that we developed involves using only a relatively narrow range of tracers that represent the grains close to the median size of the bed surface: the tracers were placed on the bed surface immediately before the snowmelt freshet and then were recovered after the flood event. Our intention is to repeat the tracer program annually; however, path lengths can also be estimated reasonably well from the flow conditions during the peak flow, once an initial value has been obtained. This can be used to supplement data in years when tracer sampling is not carried out.

By employing this simplified approach, which is designed to maximize the amount of information that can be collected with finite resources, high-quality monitoring programs can be established. The minimum requirement is that the cross-sections be resurveyed annually, with more detailed planimetric mapping conducted only once significant channel change has been detected. The tracer studies must be conducted at least once, and should be repeated when significant changes in channel morphology are detected, since changes in channel morphology presumably occur due to changes in the sediment transport regime.

Table 2. Estimated total volume and mass of erosion and deposition from 2005 to 2006

Cross-section	XS area erosion (m^2)	XS area deposition (m^2)	Zone	DS distance (L_r) (m)	Volume erosion (V_e) (m^3)	Volume deposition (V_d) (m^3)
XS 1	0	1.142	—	—	—	—
XS 2	0.212	0.318	1	11.14	1.18	8.14
XS 3	1.290	1.539	2	12.10	9.11	11.24
XS 4	0.774	1.461	3	11.20	11.58	16.80
XS 5	0.153	0.764	4	10.75	4.98	11.96
XS 6	0.660	0.886	5	11.40	4.63	9.40
XS 7	0.303	1.023	6	11.15	5.37	10.64
XS 8	0.808	0	7	11.85	6.59	6.06
XS 9	1.928	0	8	11.55	15.81	0
XS 10	0.689	0	9	14.50	18.97	0
XS 11	0	0	10	11.75	4.05	0
Total	6.821 m^2	7.133 m^2	—	117.39 m	82.27 m^3	74.24 m^3
					155 tonnes	140 tonnes

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