Effects of wildfire on first order stream channel morphology Yellowstone National Park, USA
by Kim J Ernstrom

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:

The wildfires of 1988 in Yellowstone National Park have created a unique opportunity to study the effects of fire in a relatively pristine backcountry setting. These fires affected many watersheds throughout the park raising concern about the short and long-term impacts on stream ecosystems. This study examined the effects of wildfire on first-order stream channel morphology by comparing 20 stream channels located in an unburned watershed to 20 stream channels located in a watershed that experienced high intensity canopy fire. Both of these watersheds were located west of Cooke City, MT in the northeast corner of Yellowstone National Park. Variables measured included watershed area, stream gradient, bank full width, depth, sinuosity, bed material size, stream bank texture, stream bank cover, and amount of large woody debris. Stream morphology was not significantly different between unburned and burned streams nine years following the fires. Reach scale variables such as substrate size and amount of bare ground did differ significantly between the two treatments. These differences in reach scale variables did not appear to be reflected in the morphologic variables. Four possible explanations for the lack of variation between burned and unburned stream morphology are investigated. The most likely explanation is that fire did affect stream morphology initially, but recovery occurred over nine-years. A second possibility is that fire affected reach scale variables, but counter-acting processes involving substrate size and vegetative cover resulted in no net change in morphology. Finally, it is possible that the approach used in this study did not account for other reach scale variations that may influence stream morphology. The possibility that morphology was never affected by fire is discarded based on work by Robinson and Minshall (1996). Methods used in this study allowed collection of a large set of morphologic data in one field season. Techniques are efficient and reproducible by field assistants sampling in remote locations. Further studies incorporating both spatial and temporal approaches are necessary to understand the effects of fire on stream systems in mountainous environments and to make educated decisions about fire management.

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YELLOWSTONE NATIONAL PARK, USA

by

Kim J. Ernstrom

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APPROVAL

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Kim J. Ernstrom

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The wildfires of 1988 in Yellowstone National Park have created a unique opportunity to study the effects of fire in a relatively pristine backcountry setting. These fires affected many watersheds throughout the park raising concern about the short and long-term impacts on stream ecosystems. This study examined the effects of wildfire on first-order stream channel morphology by comparing 20 stream channels located in an unburned watershed to 20 stream channels located in a watershed that experienced high intensity canopy fire. Both of these watersheds were located west of Cooke City, MT in the northeast corner of Yellowstone National Park. Variables measured included watershed area, stream gradient, bank full width, depth, sinuosity, bed material size, stream bank texture, stream bank cover, and amount of large woody debris. Stream morphology was not significantly different between unburned and burned streams nine years following the fires. Reach scale variables such as substrate size and amount of bare ground did differ significantly between the two treatments. These differences in reach scale variables did not appear to be reflected in the morphologic variables. Four possible explanations for the lack of variation between burned and unburned stream morphology are investigated. The most likely explanation is that fire did affect stream morphology initially, but recovery occurred over nine-years. A second possibility is that fire affected reach scale variables, but counter-acting processes involving substrate size and vegetative cover resulted in no net change in morphology. Finally, it is possible that the approach used in this study did not account for other reach scale variations that may influence stream morphology. The possibility that morphology was never affected by fire is discarded based on work by Robinson and Minshall (1996). Methods used in this study allowed collection of a large set of morphologic data in one field season. Techniques are efficient and reproducible by field assistants sampling in remote locations. Further studies incorporating both spatial and temporal approaches are necessary to understand the effects of fire on stream systems in mountainous environments and to make educated decisions about fire management.

CHAPTER 1

INTRODUCTION

In 1988, fires burned over 324,000 hectares (800,000 acres) within Yellowstone National Park. These fires overran natural firebreaks such as ridge tops and river channels and in some cases burned entire watersheds. Fires affected 32 percent of the stream systems in 20 separate drainage basins throughout the park (Minshall et al., 1989). Concern about potential watershed response was raised because fires can alter soil and increase runoff and erosion (Minshall and Robinson, 1992; Ewing, 1996). Resulting changes in hydrologic regime can directly influence the geomorphic processes of stream channels, which in turn can alter fish habitat, riparian vegetation, and overall stream stability (Swanson, 1981).

Many studies have addressed the immediate effects of wildfire on runoff, soil erosion, suspended sediment, and water chemistry, but few have examined the resulting physical characteristics of the stream channel itself. As fire management on public lands changes from a policy of suppression to one in which natural fires are permitted to burn, resource managers need better information about the impacts of fire on stream morphology, critical stream habitat, and channel recovery time. The magnitude and heterogeneity of the Yellowstone fires, along with the many different stream sizes affected, provide an excellent opportunity to document stream response to wildfire after a period of nine years.

The objective of this study was to determine if there are measurable differences in stream channel morphology (bankfull width and depth, width to depth ratio, sinuosity, and substrate size) between first order streams located in a burned watershed when compared to first order channels in a unburned watershed nine years after the fires occurred.

Previous Work

Fire alters watershed processes such as overland flow, erosion, and sedimentation (Swanson, 1981). Changes in these processes can in turn affect stream channel morphologic variables such as width, depth, substrate size, and sinuosity. Most fire effects studies have focused on the short-term impacts of fire on runoff and erosion (Brown, 1972; Ewing, 1996; Rich, 1962; Robichaud and Waldrop, 1994; Tiedmann et al., 1979). Relatively few have examined longer term morphologic response of stream channels to fire.

Fire-Induced Changes in Runoff and Erosion

The most dramatic and obvious influence of fire is the reduction of vegetative cover in the watershed. The extent of the hydrologic responses associated with a loss of vegetation is generally controlled by watershed aspect, slope, soil depth, bedrock geology, fire intensity, and climatic variables such as storm frequency and intensity (Swanson, 1981; Minshall et al., 1989).

Depending on the intensity of the fire and pre-burn soil properites, soil structure can be altered, reducing infiltration and water storage capacities. Hydrophobic conditions, combined with reduced transpiration of plants and diminished rainfall interception by the canopy can dramatically increase overland flow (Robichaud and Waldrop, 1994). Studies in western Montana showed overland flow from spring snowmelt to be eight times greater in burned and logged areas than in unburned plots (Wright and Bailey, 1982). Other studies in arid environments such as New Mexico, California, and New South Wales, Australia showed runoff to be dramatically higher in intensely burned drainages than in less intensely burned and unburned basins (Tiedemann, 1979; White and Wells, 1979; Brown, 1972).

After fire, rill and sheet erosion can increase due to increases in overland flow (Swanson, 1981). Following logging and prescribed burning, erosion rates in western Montana increased from zero in unburned plots to 50 kg/ha the first year post-burn and 150 kg/ha the second year (Tiedemann, 1979). In a controlled experiment in the southern Appalachian Mountains following a prescribed fire, Robichaud and Waldrop (1994) measured soil loss 40 times greater in high intensity burn plots than in low intensity plots one day after the fire. This large difference in erosion was attributed to greater removal of organic material, exposure of soils and lower infiltration rates with high intensity fire.

Suspended sediment load increases as erosion increases (Troendle and Bevenger, 1996). Over a four year period following the 1988 Yellowstone fires, sediment yield averaged 59 metric tons/km^2 in a burned watershed compared to only 13 tons/km^2 from the unburned watershed. This contrast was attributed to removal of riparian vegetation, which destabilized the bed and banks. Ewing (1996) recorded large post-fire suspended sediment increases in the Yellowstone River for the first year following the 1988 Yellowstone fires. Suspended sediment measurements ranged from 156 percent greater than pre-burn averages in April to 42 percent greater in June and 100 percent higher in August. Many of these post-fire watershed responses are controlled by seasonal climate variation, particularly spring snowmelt and intense isolated summer thunderstorms (Swanson, 1981).

Morphologic Responses to Fire

Few studies have quantified the impacts of fires on stream morphology. To the degree that they are documented in studies, changes in morphology usually have been assessed qualitatively with statements such as, "the channel has widened" or "scouring has occurred". The few studies that have quantified morphological response to fire have examined changes in width, depth, substrate size, and movement of woody debris up to five years following fire. Changes in these variables provide evidence of a link between fire and fluvial adjustment.

Increased discharge may scour and enlarge channels within a burned area, then deposit the eroded materials downstream, causing aggradation (Swanson, 1981). White and Wells (1979) reported that in the first year after fires in New Mexico watersheds, low-order channels (first through third) incised as the larger channels (fourth an fifth order) aggraded, sometimes doubling in width. Many of these responses were seasonally driven. For example, spring thaw instigated channel incision in the first and second order streams until mid-summer when water depth decreased and detached bars began to revegetate. During winter, snowpack prevented erosion and deposition, stabilizing the channel (White and Wells, 1979).

Similar responses were recorded over five years following the Yellowstone fires of 1988. In 1991, Blacktail Deer Creek, a burned second order stream, exhibited localized downcutting of up to one meter in some reaches and filling and braiding in others due to debris dams (Minshall and Robinson, 1992). Cache Creek, a burned third order stream, widened and shifted laterally 30 meters during the same time period. However, Rose Creek, an unburned creek in the same region, remained relatively unchanged through the five years of study (Robinson et al., 1996).

Morphologic response to fire on a much smaller temporal and spatial scale was observed in central Arizona. After an intense crown fire burned 60 acres of the Workman Creek drainage, Rich (1962) observed that the amount of deposition and erosion in the stream channel varied with the distance from the burn during the month following the fire. Channel incision occurred immediately below the burned area in the steepest part of the channel, while deposition occurred up to one mile below the burn.

Following the fires of 1988, Minshall and Robinson (1992) documented decreases in median substrate size between 1988 and 1991 in first, second, and third order streams in Yellowstone National Park. Embeddedness, the interstitial filling of coarse bed material by fine particles, increased in first order streams immediately following the fires in 1988, then doubled in third order steams in 1989, after which a decrease was recorded in 1990 and 1991. Embeddedness remained unchanged in fourth order streams until 1991 when a dramatic increase was recorded. This sequence represents a pulse of fine sediment moving through the burned drainage network over time (Minshall and Robinson, 1992).

Florsheim and others (1991) observed a decrease in substrate size in first and second order streams in the months following a wildfire in southern California. During the dry season (May-November) gravel was delivered to the stream channel through dry ravel erosion. Runoff from the first major storm mobilized this material and deposited it in the channel causing an overall decrease in substrate size. The next storm flow scoured 89 percent of the sediment deposited during the first storm. Florsheim and others (1991) concluded that when the average size of bed material is reduced by dry ravel erosion, moderate runoff events are able to move large volumes of sediment, changing stream morphology.

Following fire, spring snow-melt flows and summer storm flows can be abnormally high, mobilizing coarse woody debris and subsequently altering channel morphology. In an area burned by the 1988 Yellowstone fires, Young and Bozek (1996) tagged pieces of woody debris. In following years woody debris moved over four times as far in a burned creek than an unburned creek with comparable geology, gradient, width, drainage area, and pre-fire vegetation.

In another Yellowstone study, Minshall and Robinson (1992) interpreted changes in amount and location of coarse woody debris to be an indicator of channel instability. The number of pieces of woody debris per 50 meter reach in first through third order streams increased during the first year following the fires in 1988. Unburned streams showed no increase. Throughout the remainder of the five year study, first through third order streams located in burned watersheds showed a net loss of woody debris, suggesting that burned streams are much more physically dynamic than streams not exposed to fire.

Summary and Research Expectations

These studies illustrate that fire can alter channel morphology over the short-term depending on the extent and intensity of fire, stream size, watershed slope and variations in seasonal climate (Minshall and Robinson, 1992; Swanson, 1981). Streams in more extensively burned watersheds demonstrate greater channel change than streams draining less extensively burned watersheds (Robinson et al., 1996). Fire effects are more pronounced in headwater streams and diminish with increasing stream order because smaller catchments are often entirely burned, while larger catchments (fourth order and higher) are usually only partially burned (Minshall et al., 1989). Differences in channel morphology are the indirect result of vegetation removal. Reduction in vegetative cover causes increased runoff and erosion and decreased bank stability, which can result in increased sedimentation and mobilization of large woody debris.

Based on this research, I expect first-order streams located in burned watersheds to be wider, shallower, less sinuous, have a smaller median substrate size and have less large woody debris than first-order streams in unburned watersheds. Few studies however, have assessed the mid- to long-term impacts of fires on morphologic variables. None have documented the full range of morphologic variations (width, depth, and sinuosity) among multiple streams of the same order for a period longer than five years after burning. In addition, the time required for watershed and stream channel recovery to pre-burn conditions is not known (if it happens at all). This study is an attempt to document the morphologic response of first-order streams nine years after wildfire.

CHAPTER 2

STUDY AREA

The study area was located in the northeast corner of Yellowstone National Park along the boundary of the Gallatin National Forest in Montana and the Shoshone National Forest in Wyoming (Figure 1). Burned and unburned watersheds were compared to evaluate the morphologic response of streams to wildfire. Twenty first order streams were measured in the burned Cache Creek drainage and in the unburned Pebble Creek drainage (Figure 2). Nine additional streams with check dams installed after the fires were measured in the burned Cache Creek drainage (Figure 2). Locations of the lower end of each reach are specified in Appendix A.

Vegetation, Climate, and the 1988 Fires

Prior to the 1988 Clover-Mist Fire that affected the study area, lodgepole pine (*Pinus contorta*) dominated the forests in the study area catchments, with subalpine fir (*Abies lasiocarpa*) and engelmann spruce (*Picea engelmannii*) occupying the canyon bottoms and whitebark pine (*Pinus albicaulis*) occurring above 2600 meters (Barrett, 1994). The Clover-Mist Fire burned from 39% of the area in the lower reaches of the Cache Creek drainage to 71% in the upper reaches near Republic Pass (Robinson and Minshall, 1996) (Figure 1). High intensity canopy fire consumed the entire canopy surrounding many of the first order streams (Table 1). Trees that were only partially burned in the 1988 fire

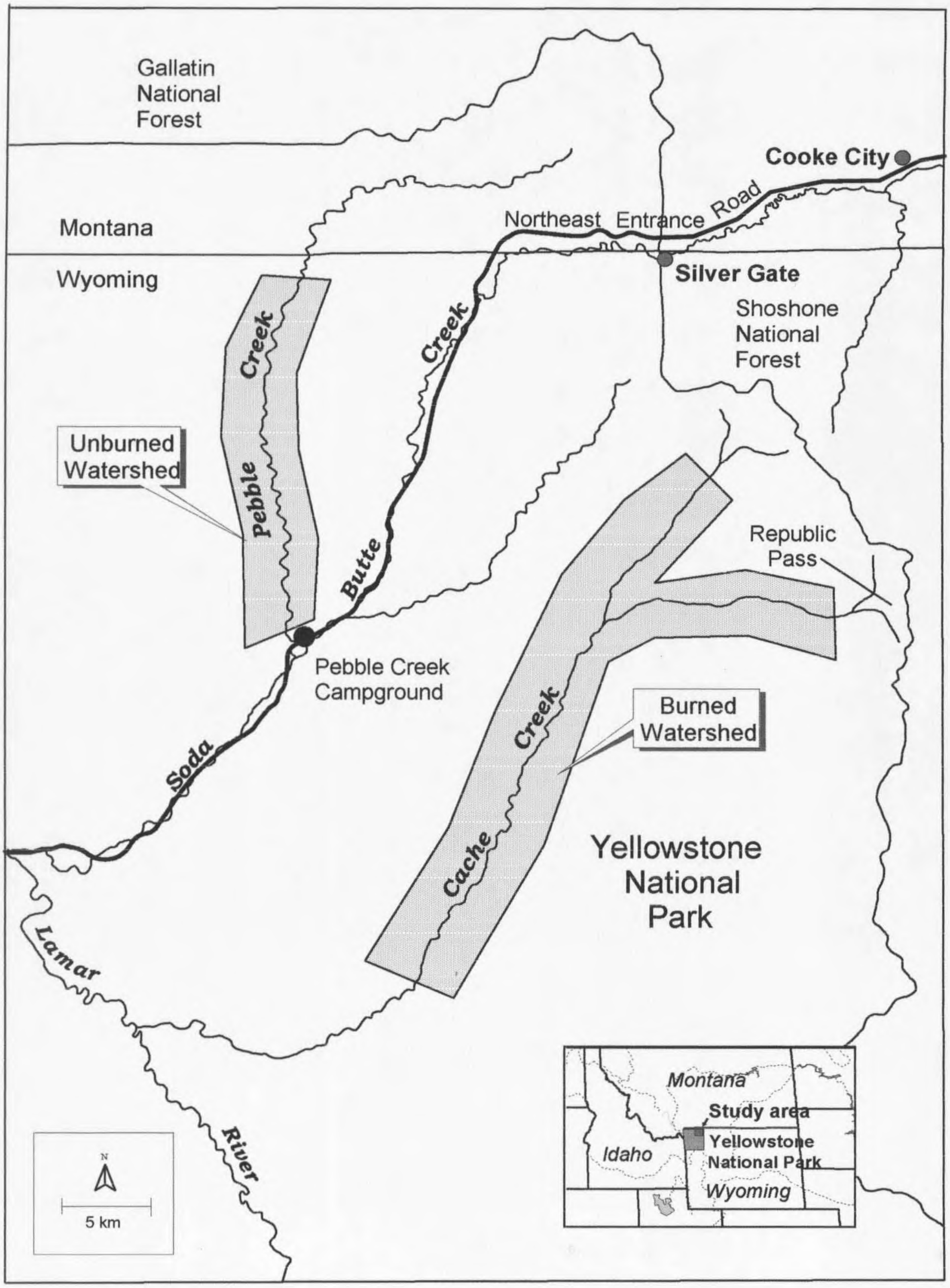

Figure 1. Study area map of Northeast Yellowstone National Park showing the unburned Pebble Creek watershed and the burned Cache Creek watershed

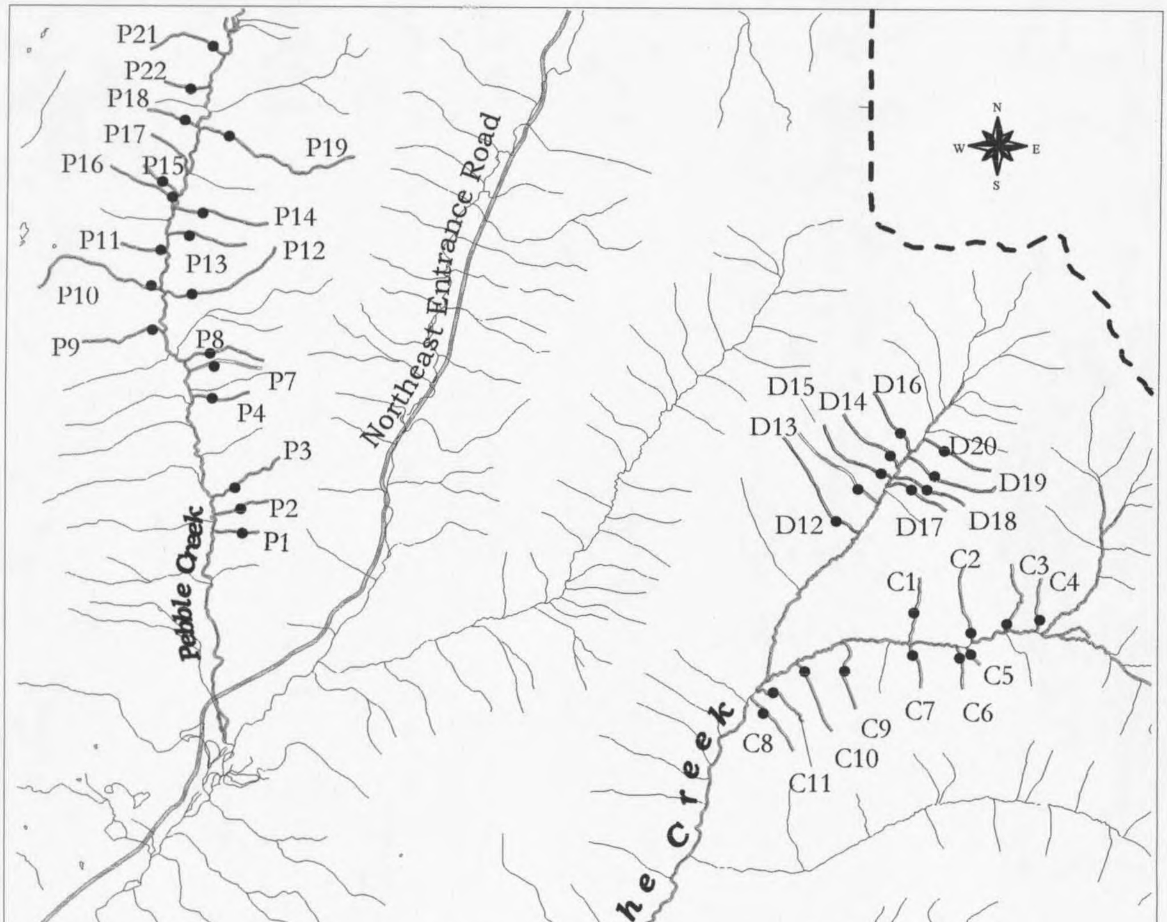

Figure 2. The unburned Pebble Creek and burned Cache Creek watersheds and 49 first-order streams measured in the study. Unburned streams are shown in green, burned streams are shown in red and dammed streams are shown in dark blue. The main stem of Pebble and Cache Creek are indicated by a light blue line. Black dots indicate the downstream end of each study reach.

Table 1. Percent of watershed burned in 1988 fires in first order streams in Cache Creek. Watershed area and percent watershed burned were calculated using a GIS and data layers provided by Yellowstone National Park.

Cache Creek (Burned Watersheds)			**Cache Creek (Dammed Watersheds)**		
Burned Stream #	**Watershed Area (km^2)**	**%Watershed Area Burned**	**Dammed Stream #**	**Watershed Area (km^2)**	**%Watershed Area Burned**
CH1	0.32	98	D12	0.65	88
CH2	0.60	97	D13	0.35	89
CH3	0.63	84	D14	0.26	93
CH4	0.20	100	D15	0.41	93
CH5	0.12	67	D16	0.29	78
CH6	0.50	62	D17	0.17	39
CH7	0.34	67	D18	0.23	48
CH8	0.31	73	D19	0.47	63
CH9	0.49	62	D20	0.37	84
CH10	0.37	79			
CH11	0.36	78			
CH21	1.10	31			
CH22	0.71	66			
CH23	1.00	53			
CH24	1.11	66			
CH25	0.39	47			
CH26	1.14	72			
CH27	0.43	44			
CH28	1.08	26			
CH29	0.94	80			

subsequently died, leaving a watershed that nine years later contains standing dead trees and a ground cover of grasses, forbs, and many lodgepole pine seedlings (Figure 3).

Although 17% of the Pebble Creek drainage was burned, none of the subwatersheds examined in this study were burned. All of the first order streams that were included in this study were completely surrounded by lodgepole pine dominated forests that had not burned for close to 200 years (Barrett, 1994).

Nine streams located in the upper reaches of Cache Creek had check dams installed by the Park Service as erosion control measures following the 1988 fires. Dams were constructed by felling a large tree across the streambed or by building a more elaborate structure with a stack of smaller trees supported by vertical posts (Figure 3).

Climate

In the summer, daytime temperatures in the study area typically range from 2°C to 20°C. Winter temperatures average -11°C with lows near -30°C and highs around -7°C. The thirty year mean annual precipitation in Cooke City, MT (Figure 1) is 65.9 cm (25.54 inches). On average, 509 cm (210 inches) of this precipitation falls as snow during the winter months of October through May. During the summer months convective thunderstorms provide most of the precipitation, averaging 23.6 cm (9.3 in) of rainfall. During the summer of 1994, a relatively dry summer, precipitation was received at the cooperative weather station at the Northeast Entrance of the park on only 19 days. Of these 19 rain events only four of them delivered more that 0.1 inches of rain. In contrast,

Unburned Stream

Burned Stream

Dammed Stream

Figure 3. Photographs of representative streams from the Pebble Creek (unburned), Cache Creek (burned), and upper Cache Creek (dammed) watersheds.

the summer of 1997, a relatively wet summer, produced 29 different rain events and 16 of them were greater that 0.1 inches.

Soda Butte Creek, which is adjacent to Cache and Pebble Creeks (Figure 1) has had a USGS stream gauging station in place since October, 1988. Data from this gauging station indicates that peak flows can occur in May or June depending on the extent of the winter snowpack and timing of spring snow melt. The winter of 1993-1994 was relatively dry and snow water equivalence, measured on April 1, was the lowest (7.1 in) since the 1998 fires. In contrast, the winter of 1995-1996 was one of the wettest on record with a first of April snowpack measurement of 12.8 in. The difference in these snowpack measurements is reflected in the stream discharge record for Soda Butte Creek. In 1994, the second lowest peak flow was recorded (940 cfs), whereas the highest peak flows ever recorded occurred over the next three years including a 50 year flood event in 1995 and a one hundred year flood event in the spring of 1996.

Geology and Topography

Within both the Cache Creek and Pebble Creek study areas the bedrock light to dark andesitic rocks of the Eocene Washburn group (Taylor et al., 1989). Surficial deposits in both study areas are glacial till, kame deposits, and fan gravel alluvial deposits of Pinedale age, with occasional deposits of neoglacial alluvial fan gravels from local floods, mudflows and sheetwash (Pierce, 1974) (Table 2). The till is characterized by a non-sorted, non-stratified mixture of sediment ranging in size from clay to cobbles derived from andesitic volcanic debris. Kame deposits consist of unevenly bedded, moderately to well sorted gravel and gravelly sand with abrupt vertical and lateral changes in grain size. Both the Pinedale and neoglacial alluvial deposits contain poorly to moderately sorted pebble to boulder sized clasts interbedded with sand and silt-clay deposits. Alluvial material is often bordered laterally by kame deposits.

The two main watersheds had similar topography. Stream gradients of the individual unburned and burned first-order streams ranged from 13 to 26 percent and elevations were between 2130 and 2460 meters (Table 3). First-order streams with check dams were slightly higher at 2460 - 2540 meters, but the watershed areas and gradients of dammed streams were comparable to the unburned and burned streams.

Table 2. Stream number and associated surficial material (from Pierce, 1974).

Pebble Creek		**Cache Creek**		**Upper Cache Creek**	
Unburned Stream #	**Material Type**	**Burned Stream #**	**Material Type**	**Dammed Stream #**	**Material Type**
PB1	Till	CH1	Fan Gravel	D12	Fan Gravel
PB2	Till	CH2	Fan Gravel	D13	Fan Gravel
PB3	Fan Gravel	CH3	Fan Gravel	D14	Fan Gravel
PB5	Fan Gravel	CH4	Kame	D15	Fan Gravel
PB7	Kame	CH5	Kame	D16	Fan Gravel
PB8	Kame	CH6	Kame	D17	Fan Gravel
PB9	Kame	CH7	Till	D18	Fan Gravel
PB10	Kame	CH8	Kame	D19	Fan Gravel
PB11	Kame	CH9	Till	D20	Fan Gravel
PB12	Fan Gravel	CH10	Till		
PB13	Kame	CH11	Kame		
PB14	Kame	CH21	Till		
PB15	Kame	CH22	Till		
PB16	Kame	CH23	Fan Gravel		
PB17	Till	CH24	Till		
PB18	Till	CH25	Till		
PB19	Fan Gravel	CH26	Till		
PB20	Fan Gravel	CH27	Kame		
PB21	Fan Gravel	CH28	Fan Gravel		
PB22	Till	CH29	Kame		

Table 3. Topographical summary of stream reaches. Elevations measured at mid-point along each stream reach. Watershed area is calculated for entire first-order stream along which the individual reach was located.

		Pebble Creek	**Cache Creek**	**Upper Cache Creek**
		UNBURNED	**BURNED**	**DAMMED**
Number of Reaches		20	20	9
Reach Elevation (m)	**Mean**	2320	2340	2500
	Min.	2290	2130	2460
	Max.	2360	2460	2540
	S. Dev.	17	105	25
Reach Gradient (%)	**Mean**	13	13	12
	Min.	6	8	9
	Max.	23	26	15
	S. Dev.	4	4	1
Watershed Area of first-order streams (km^2)	**Mean**	0.36	0.61	0.36
	Min.	0.11	0.12	0.17
	Max.	1.7	1.1	0.65
	S. Dev.	0.35	0.34	0.14

CHAPTER 3

METHODS

Data Collection

This study compares 49 first-order watersheds to evaluate fire-induced differences in stream morphology. USGS 7.5-minute topographic maps were used to select Strahler (1952) first order streams as designated by solid blue lines. This group of streams was further narrowed down in the field since some streams were in bedrock channels. When a stream was deemed suitable for measurement, a 100 meter reach was delineated from a random starting point (Figure 2). The choice of 100 meters was based on Rosgen's (1996) recommendation of a study reach 20 times the maximum bankfull width and previous work by Myers (1997). Measured morphologic characteristics included bankfull width, bankfull depth, sinuosity, stream bank cover, and substrate size. A meter tape was laid in the streambed and cross-sections were located every 25 meters for the 100 meter reach. Cross-sections were surveyed using a meter tape, line level, and plumb bob. Bankfull depth was identified using indicators such as breaks in vegetation and changes in bank material as outlined by Harrelson et al. (1994). Average stream depth was calculated from individual depth measurements from each cross-section. The number of depth measurements per cross-section was dependent on the width of the stream.

Cover was estimated at each cross-section using a 1 x 2 meter quadrat adjacent and parallel to each cross-section on the left and right bank. Percent cover was estimated visually for trees, shrubs, forbs, grasses, litter, standing water and bare ground. Values for all quadrats in each reach were averaged. To ensure consistency one person collected cover data for all stream reaches.

Sinuosity was determined in the field with a meter tape. Stream gradient was measured with a stadia rod and hand level. Because of the short range of view of the hand level and visual obstructions along the stream bank, three separate measurements with a 15 meter distance between level and stadia rod were taken along the stream reach. The measurements were taken at the downstream, the middle, and the upstream ends of the stream reach in order to calculate an average gradient for the entire one hundred meter reach.

One pebble count (Wolman, 1954) was performed in a riffle of each stream reach using the U. S. Forest Service step-toe procedure (Harrelson et al., 1994). To avoid user bias (Marcus et al., 1995), only the author selected pebbles to be measured. Soil and sediment samples were taken from the bank and bed at the 50 meter cross-section in each stream reach and analyzed for sand, silt, and clay contents (Klute, 1986).

The amount of large woody debris occurring in each reach was quantified. Only woody material greater than 15 centimeters in diameter that was obstructing the stream channel was counted as large woody debris (Myers, 1997). Large woody debris straddling the stream, but not obstructing bankfull flow, was not included. The number of logjams occurring along each reach was noted, but individual pieces of wood within these aggregates were not counted.

Data Analysis

To simplify and focus on important relationships, variables were grouped into three categories: watershed scale variables, reach scale variables, and morphologic response variables. These variables interact at different temporal and spatial scales to influence stream morphology (Figure 4).

Watershed scale variables, which included watershed area, percent watershed burned, geology and stream gradient, were landscape level variables that had not changed since the 1988 fires. Reach scale variables - percent cover, amount of large woody debris, substrate size (d50 and d90), and silt-clay ratios of bank and bed material can be affected by fire and in turn can influence stream morphology. The morphologic response variables were stream width, depth, cross-sectional area, hydraulic radius, wetted perimeter, and sinuosity. Changes in the watershed and reach scale variables influence these response variables at different spatial and temporal scales.

Box-plots and scatter plots were used to assess the variability within and among the three treatments (unburned, burned and dammed) before statistical testing was performed. These graphs indicated whether or not each variable appeared to differ between the burned and unburned watersheds and were useful in directing subsequent analyses. The data from the unburned, burned and dammed streams used in these analyses are contained in Appendices B, C, and D respectively.

A variety parametric and non-parametric tests, were used to determine if there were significant differences in all variables between unburned, burned, and dammed streams. I first performed a non-parametric Kruskal-Wallis one-way analysis of variance (Shaw and Wheeler, 1985) and an analysis of covariance. The same comparisons were repeated

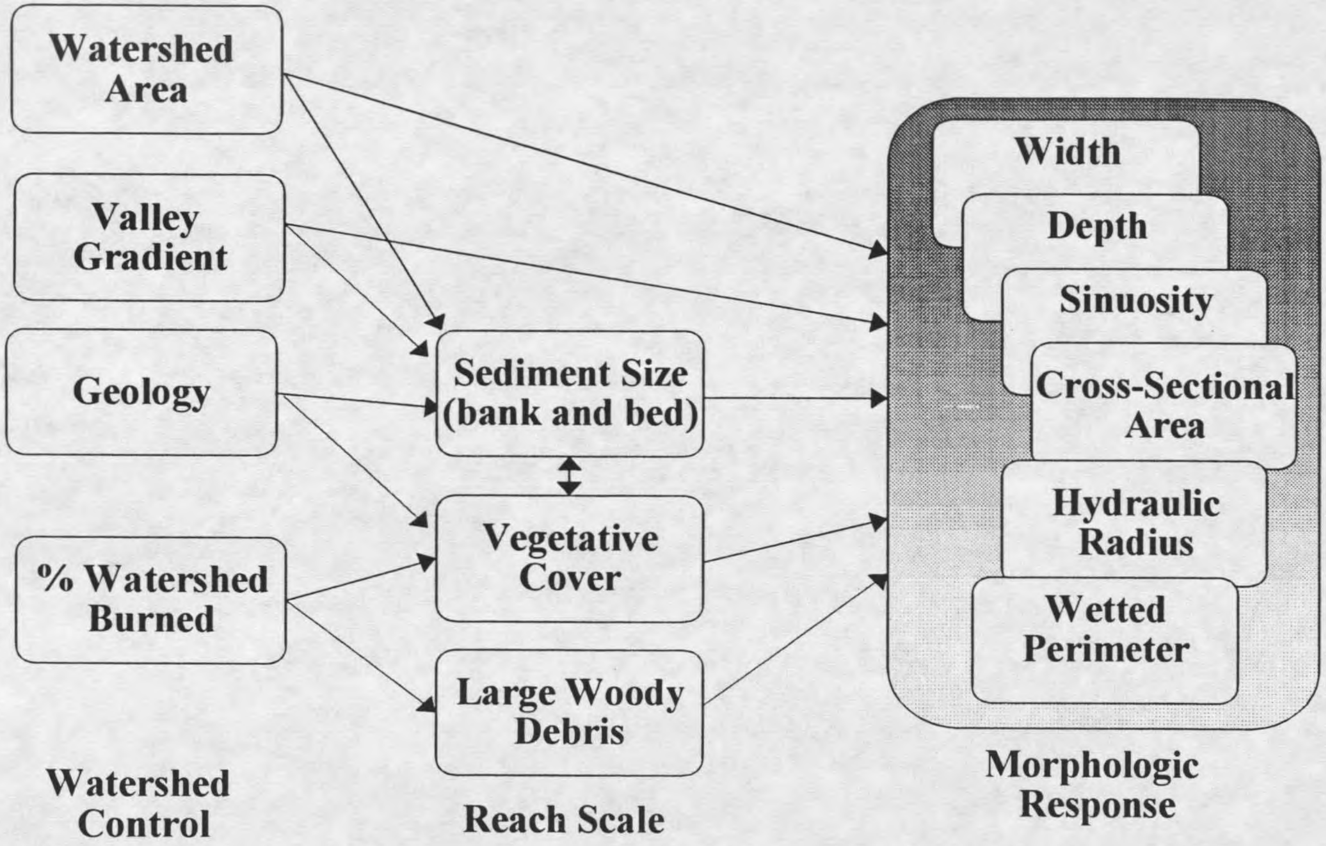

Figure 4. Schematic diagram showing association of watershed controls, reach scale variables and morphologic response variables. Reach scale variables both respond to the watershed controls while also affecting the morphologic response variables. Diagram is specific to spatial scales covered in this study.

using a standard ANOVA. The null hypothesis in all ANOVA comparisons was that there were no differences among treatments at the 0.05 level of significance. The ANOVA was followed by a Mann-Whitney U test of independent means to specify the treatments for which significant differences occurred. I then performed the more conservative post hoc comparisons Least Standard Difference and Newman-Keuls tests to test the strength of the Mann-Whitney U test results.

Pearson correlation (Appendix E) was performed on the combined unburned and burned data sets and scatterplots were examined for linear, non-linear and threshold relationships. The dammed streams were excluded from this analysis because the goal was to isolate the effects of burning disturbance on streams.

Multiple regression analysis, using a backward stepwise approach (Shaw and Wheeler, 1985), was used to evaluate how much of the variance in stream morphology could be accounted for by the watershed and reach scale variables for the undammed streams. Three watershed scale variables (watershed area, gradient and treatment) and four reach scale variables (understory cover, silt/clay in the bank material, d50 and large woody debris) were entered into the analysis at the same time. These variables were selected from the whole group to avoid combining variables that are directly correlated to each other, such as percent bare ground and percent understory cover or d50 and d90. Treatment was entered as a dummy variable, where burned and unburned streams were given values of 1 and 0 respectively. The percentage of watershed burned was also entered.

CHAPTER 4

DATA SUMMARY

Box plots of the watershed, reach scale, and morphologic variables for all three treatments are presented in figures 5 through 8. The boxplots indicated several general relationships among the three treatments. Watershed area for streams located in burned catchments was more variable and appeared to be larger than for the other two treatments (Figure 5). Stream gradient was similar among all stream types. Percent watershed burned was comparable between the burned and dammed streams.

Reach scale variables exhibited some variability among treatments. Burned areas had fewer trees, less litter and had higher percentages of bare ground than the unburned streams (Table 4 and Figure 6). Understory cover (shrubs, forbs and grass) was similar for all treatments, although burned streams had a slightly higher median value than the other two treatments. D50 and d90 indicate the 50th and 90th percentile of substrate size in millimeters and are shown in Figure 6. In general, the channel substrate appears to be smaller for the unburned watershed, with d50 having a greater variability between treatments than d90.

The amount of large woody debris within all three treatments was generally the same (Figure 6). The distribution of sand, silt and clay for both the bed and bank material for all treatments is also generally similar as indicated by the ternary diagram in Figure 7. Compared to the reach scale variables, the morphologic response variables show much

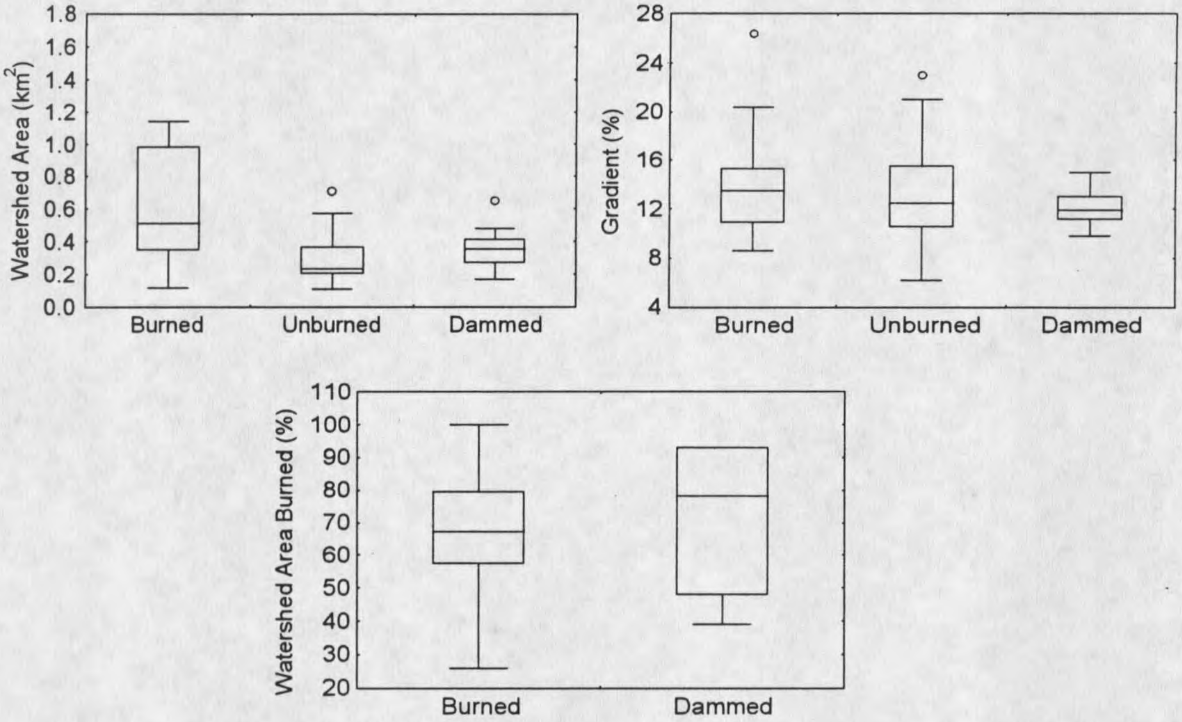

Figure 5. Box-plots of watershed control variables: watershed area, percent watershed burned and stream gradient. The top and the bottom of the box represent the 75th and 25th percentiles, the horizontal line is the median, the whiskers show the data range within 1.5 times the interquartile range, and outliers are represented by circles. All unburned watersheds had zero percent area burned.

Table 4. Summary of percent cover for all stream locations. Minimum and maximum values represent averages of ten plots for each stream reach.

		Pebble Creek	**Cache Creek**	**Upper Cache Creek**
		UNBURNED	**BURNED**	**DAMMED**
% Bare Ground	**Mean**	7.6	16.8	24.5
	Min.	trace	2.0	6.9
	Max.	29.3	36.7	58.2
	S. Dev.	8.4	9.2	15.0
% Grass + Forb	**Mean**	43.5	50.9	47.9
	Min.	15.3	32.5	22.0
	Max.	70.8	72.3	73.2
	S. Dev.	13.9	9.9	16.0
% Tree + Shrub	**Mean**	10.7	6.1	2.3
	Min.	trace	trace	trace
	Max.	24.4	17.0	8.0
	S. Dev.	6.1	4.6	2.3
% Litter	**Mean**	38.1	26.0	25.2
	Min.	14.6	11.7	17.8
	Max.	56.2	42.5	35.7
	S. Dev.	10.8	9.5	6.8
% Tree	**Mean**	7.3	2.4	1.8
	Min.	0	0	0
	Max.	17.2	7.0	6.5
	S. Dev.	4.8	2.3	2.0

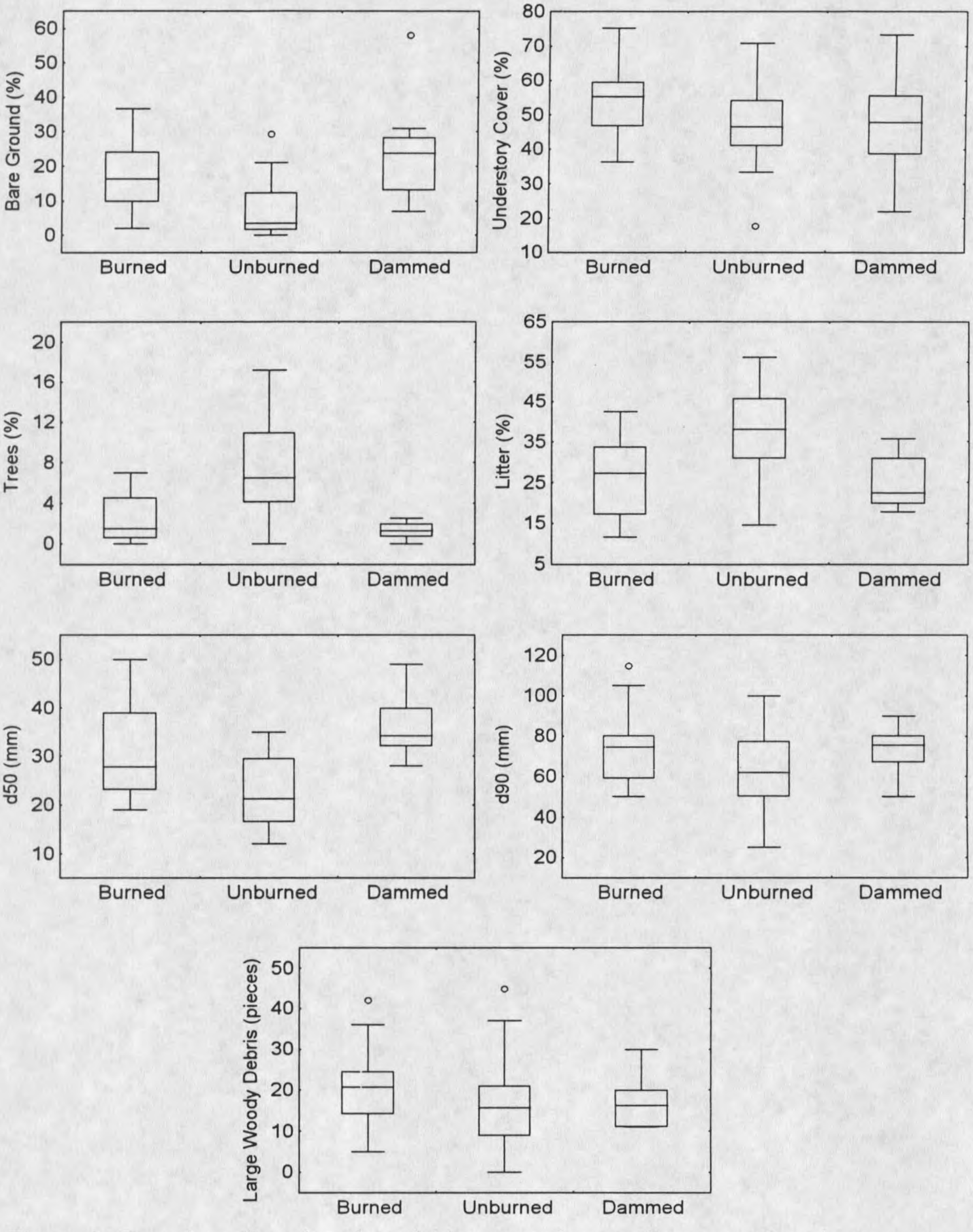

Figure 6. Box-plots of reach scale variables: cover (percent bare ground, understory cover, trees, and litter), substrate size (d50 and d90) and large woody debris.

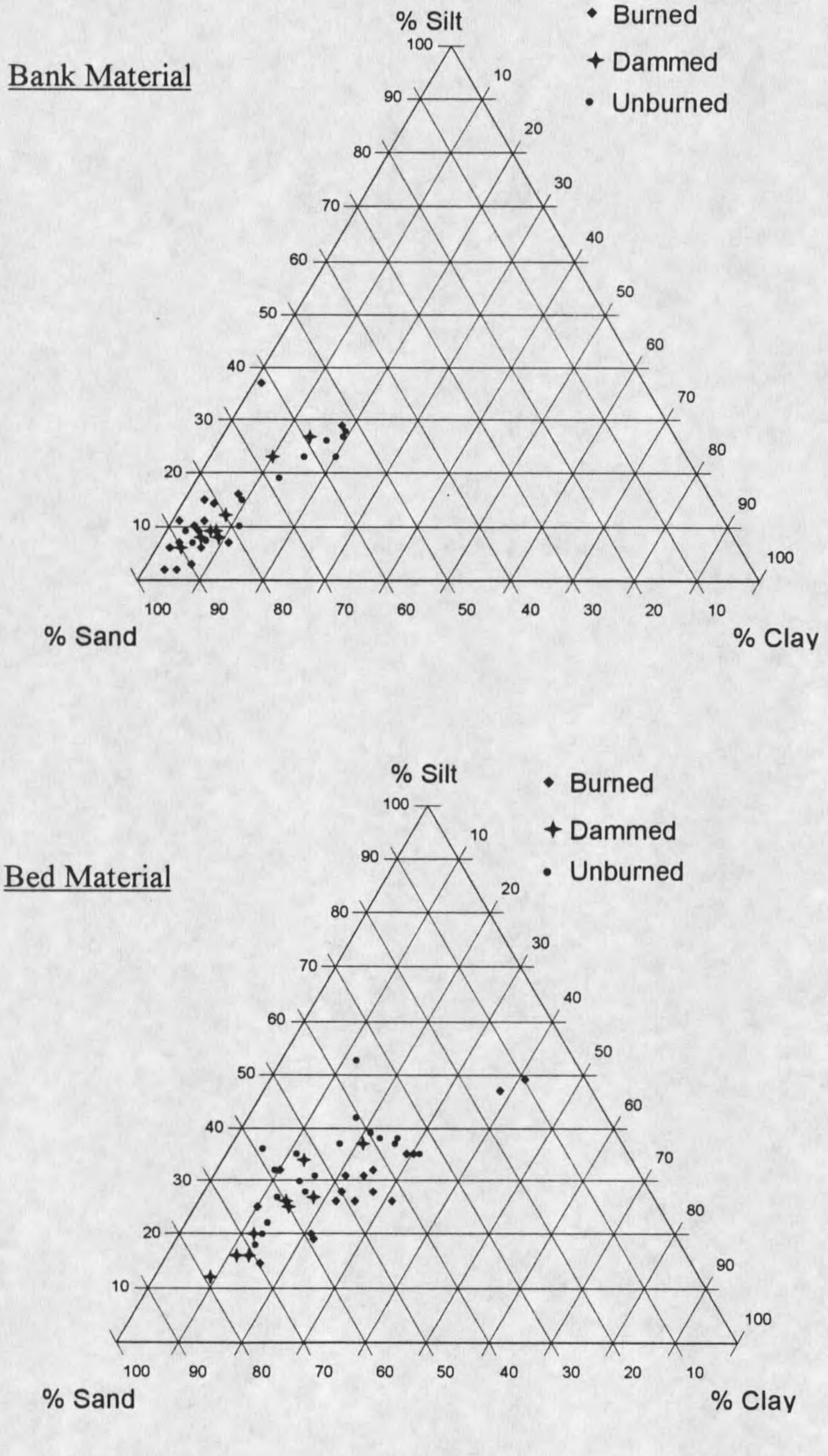

Figure 7. Ternary diagram of percent sand, silt, and clay in the bank and stream bottom material of unburned, burned and dammed streams.

less variability between treatments (Figure 8). Of the six morphologic response variables, only wetted perimeter and cross-sectional area appear to be different among the three treatments.

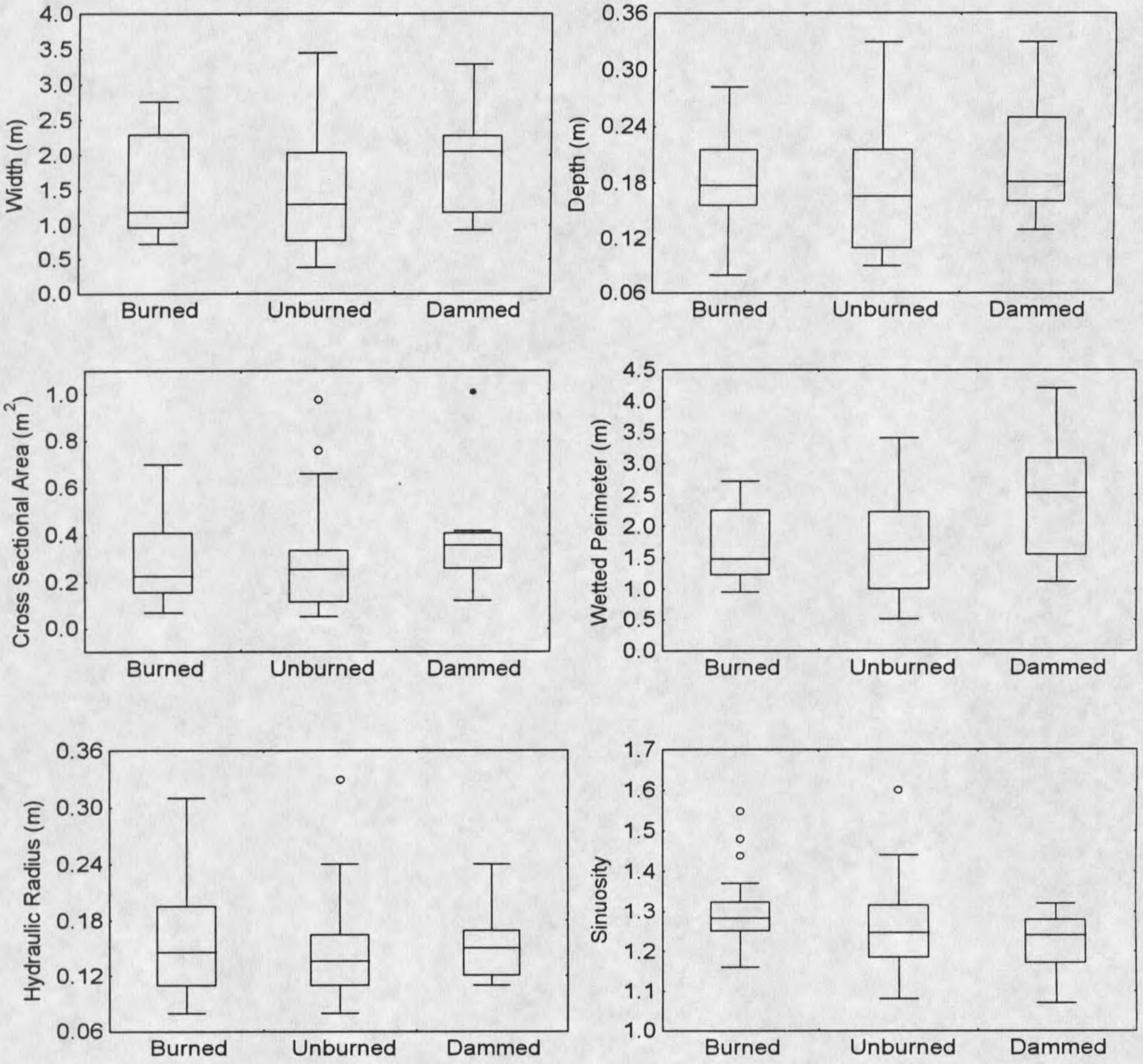

Figure 8. Box-plots of morphologic response variables: width, depth, cross-sectional area, hydraulic radius, wetted perimeter, and sinuosity.

CHAPTER 5

DATA ANALYSIS

Comparison of Burned and Unburned Streams

To infer that differences in channel response variables are related to burning, independent watershed variables should be similar for all treatments. The Kruskal-Wallis test indicates that there were no significant differences in stream gradient between treatments (Table 5). Watershed area for the first order streams in the burned Cache Creek drainage was significantly larger than the streams in the unburned Pebble Creek drainage (Table 6). There were no significant differences in percent understory cover or percentages of silt-clay in the bank material between treatments. There was, however, significantly more bare ground and significantly less litter along the banks of the burned streams (Table 6). The streams within the burned watershed had significantly lower percentages of silt-clay in the bed material and larger d50 substrate sizes when compared to the unburned streams. There were no significant differences in the d90 substrate size or the number of pieces of large woody debris. There were also no significant differences between any of the morphologic response variables between unburned and burned streams (Table 5).

Because watershed area varied significantly between the burned and unburned streams, and stream gradient tended to be greater in the burned streams (although not significantly so), an analysis of covariance (Shaw and Wheeler, 1985) was performed to determine if variations in these variables were contributing to or masking

Table 5. Kruskal -Wallis comparison of burned, unburned and dammed streams. An H value greater than or equal to 6.00 indicates significant variability at the 0.05 level. Significant values at the 0.05 alpha level are shown in bold. The sample size is 20 for the burned and unburned streams and nine for the dammed streams.

Watershed Conrol Variables	**P Value**	**Test Statistic (H)**
Watershed Area (km^2)	**0.01**	**9.9**
Stream Gradient (%)	0.14	1.0
Reach Scale Variables		
Understory Cover (%)	0.10	4.6
Bare Ground (%)	**0.01**	**15.3**
Litter (%)	**0.00**	**12.9**
Bank Silt and Clay (%)	**0.02**	**7.7**
Stream Silt and Clay (%)	**0.01**	**6.4**
d50 (mm)	**0.00**	**15.3**
d90 (mm)	0.31	2.4
Large Woody Debris (pieces)	0.37	2.0
Morphologic Response Variables		
Width (m)	0.36	2.1
Depth (m)	0.37	2.0
Cross-Sectional Area (m^2)	0.25	2.9
Wetted Perimeter (m)	0.09	4.9
Hydraulic Radius (m)	0.65	0.9
Sinuosity	0.16	3.7

Table 6. Pairwise comparison using the Mann-Whitney U test. Significance at the 0.05 level is indicated by bold type and direction shown by "+" or "-" for the first variable in each pair. (e.g. "+" if burned > unburned)

	P-Values		
Watershed Control Variables	**Burned v. Unburned**	**Dammed v. Unburned**	**Burned v. Dammed**
Watershed Area (km^2)	**0.02 +**	0.25	0.05
Stream Gradient (%)	0.76	0.51	0.30
Reach Scale Control Variables			
Understory Cover (%)	0.09	0.72	0.28
Bare Ground (%)	**0.00 +**	**0.00 +**	0.17
Litter (%)	**0.00 -**	**0.00 -**	0.91
Bank Silt and Clay (%)	0.61	**0.01 -**	**0.01 +**
Stream Silt and Clay (%)	**0.00 -**	**0.04 -**	0.27
d50 (mm)	**0.00 +**	**0.00 +**	0.10
d90 (mm)	0.16	0.26	0.10
L W D (pieces)	0.21	0.74	0.29
Morphologic Response Variables			
Width (m)	0.59	0.17	0.28
Depth (m)	0.27	0.23	0.69
Cross-Sectional Area (m^2)	0.54	0.09	0.25
Wetted Perimeter (m)	0.88	0.07	0.07
Hydraulic Radius (m)	0.39	0.57	0.80
Sinuosity	0.10	0.80	0.12

differences among reach scale and morphologic response variables. The results of the analysis of covariance verify that after controlling for watershed area and stream gradient, the dependent variables that were or were not significantly different in the initial Kruskal-Wallis test remained the same (Table 7). These results suggest that factors other than differences in watershed area caused differences in the reach scale variables and that variation in watershed area did not hide differences in the morphologic response variables.

Multiple types of statistical tests were performed yielding the same results. This indicates that the differences seen in the data were actual differences and not artifacts of a particular statistical technique. This conclusion allowed closer examination of fire and whether or not it played a role in reach scale and morphologic response.

Factors Contributing to Morphologic Variations

The only significant correlations between watershed scale variables and morphologic response variables were between watershed area and d50, width, cross-sectional area and wetted perimeter (Figure 9). Stream gradient was not significantly correlated with any variable. Percent watershed burned was not included as a variable because the many zero values in the unburned streams rendered scatterplot correlation analysis useless.

There were four significant correlations between the reach scale variables and the morphologic response variables. Both the d50 and d90 substrate sizes were significantly correlated with stream width, depth, cross-sectional area, and wetted perimeter. Since the d50 and d90 substrate sizes showed the same positive

Table 7. Analysis of Covariance for watershed area and stream gradient. Results significant at the 0.05 level are shown in bold.

Covariate: watershed area

Reach Scale Control Variables	**P Value**	**Test Statistic (F)**
Understory Cover (%)	0.10	2.84
Bare Ground (%)	**0.00**	**11.40**
Litter (%)	**0.00**	**11.00**
Bank Silt and Clay (%)	**0.04**	**3.38**
Stream Silt and Clay (%)	**0.00**	**9.85**
d50 (mm)	**0.02**	**5.66**
d90 (mm)	0.34	0.92
LWD (pieces)	0.31	1.08
Channel Response Variables		
Width (m)	0.29	1.13
Depth (m)	0.96	0.00
Cross-Sectional Area (m^2)	0.51	0.44
Wetted Perimeter (m)	0.22	1.59
Hydraulic Radius (m)	0.89	0.02
Sinuosity	0.24	1.42

Covariate: stream gradient

Reach Scale Control Variables	**P Value**	**Test Statistic (F)**
Understory Cover (%)	0.05	3.99
Bare Ground (%)	**0.00**	**10.85**
Litter (%)	**0.00**	**14.10**
Bank Silt and Clay (%)	**0.01**	**4.91**
Stream Silt and Clay (%)	**0.01**	**9.30**
d50 (mm)	**0.00**	**11.10**
d90 (mm)	0.12	2.54
LWD (pieces)	0.38	0.79
Channel Response Variables		
Width (m)	0.86	0.03
Depth (m)	0.62	0.25
Cross-Sectional Area (m^2)	0.85	0.04
Wetted Perimeter (m)	0.80	0.07
Hydraulic Radius (m)	0.35	0.89
Sinuosity	0.25	1.34

relationship with the cross-sectional measurements only the d50 scatterplots are displayed. The other reach scale variables, percent cover and percent silt/clay were not significantly correlated with any of the morphologic response variables. None of the morphologic response variables that were correlated with the watershed and reach scale variables showed a clear separation between burned and unburned streams (Figures 9 and 10). Extensive graphical exploration did not suggest any significant linear, non-linear or threshold relationships between other pairs of variables.

The multiple regression analysis showed that treatment was only a significant predictor of stream width and only accounted for 10 percent of the variance (Table 8). The effects of treatment did not vary significantly whether entered into other analyses as a binary dummy variable or as a percentage of watershed burned. Understory cover was a significant predictor of width, cross-sectional area and wetted perimeter, accounting for 15 percent of the variance, whereas large woody debris accounted for 21 percent of the variance in sinuosity (Table 8). The d50 substrate size however, was a significant predictor for all morphologic response variables except sinuosity and accounted for 29 percent of the variance. The median substrate size seems to play a much larger role than treatment or any other variable in predicting first-order channel morphology.

Morphologic Response as a Function of Percent Watershed Burned

The previous multiple regression analysis suggests that understory cover and substrate size contribute most to the explanation of morphologic variation between all streams. To evaluate if the percent watershed burned (26 to 100 percent) may

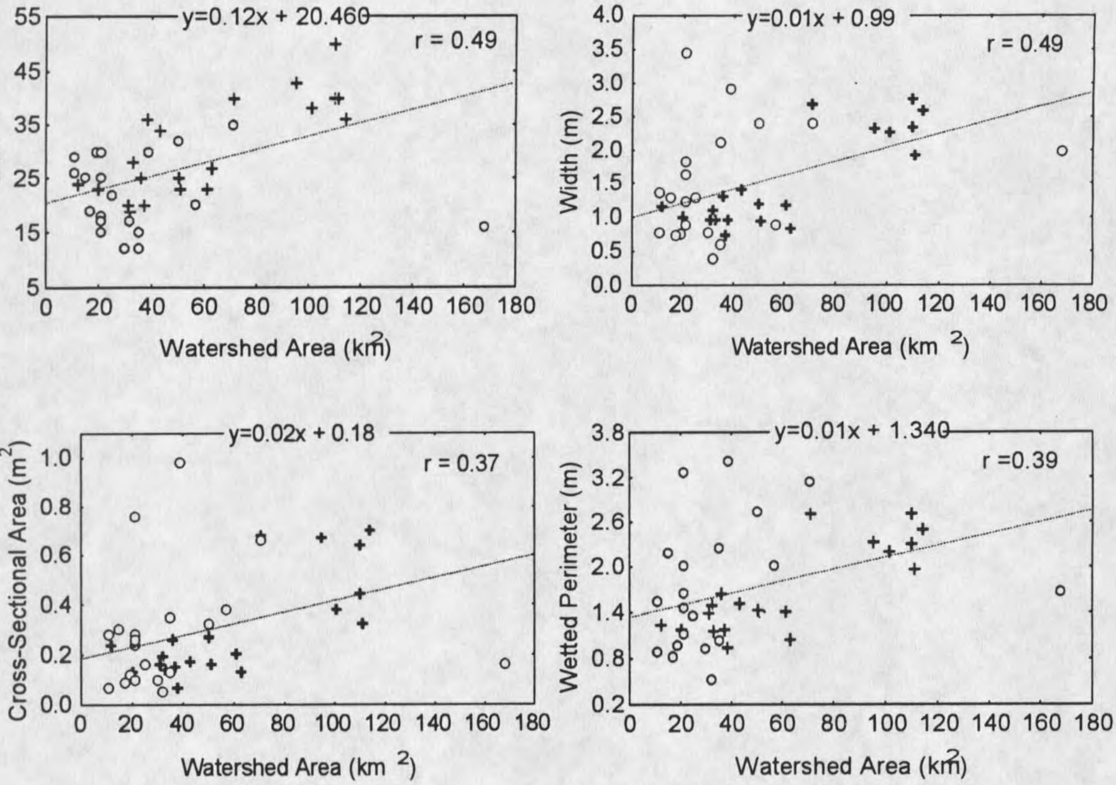

Figure 9. Scatterplots showing significant correlations at the 0.05 level between watershed area and d50, width, cross sectional area and wetted perimeter. Burned streams are indicated by a cross and unburned streams are shown with a circle.

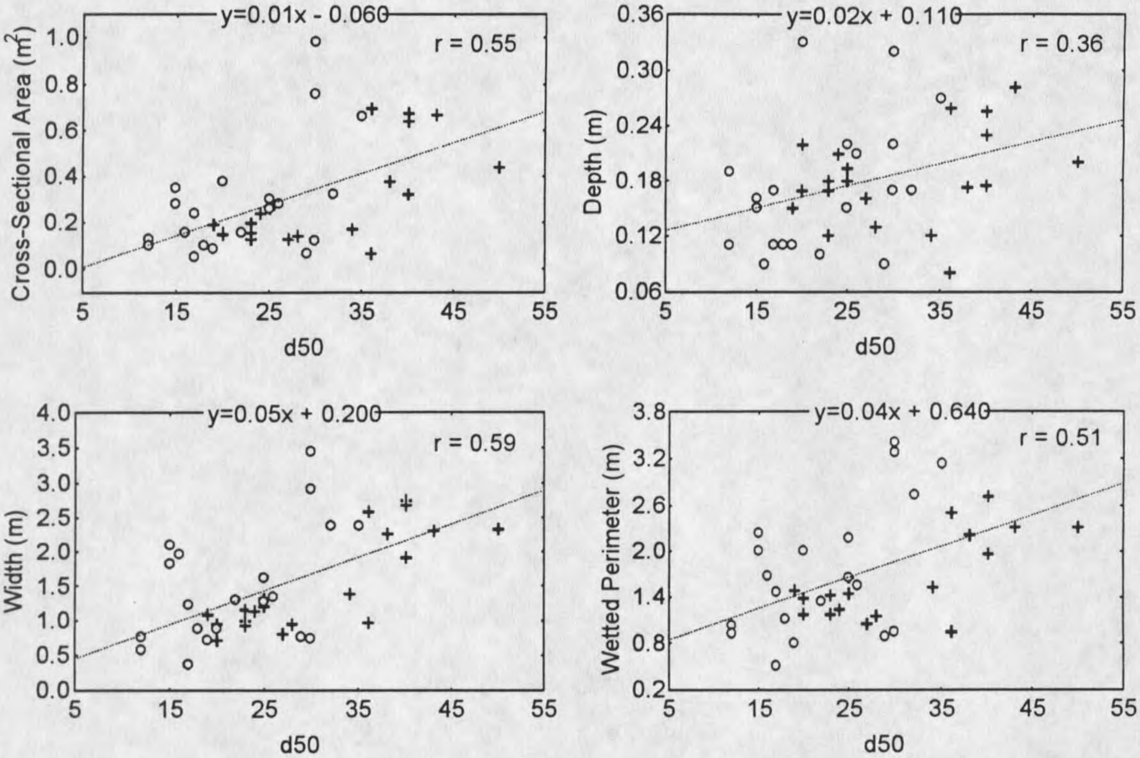

Figure 10. Scatterplots showing significant correlations between d50 and width, depth, cross sectional area and wetted perimeter. Burned streams are indicated by a cross and unburned streams are shown with a circle.

Table 8. R-squared, p, beta and intercept values for multiple regression analysis for combined burned and unburned data sets. Independent variables include watershed area, stream gradient, treatment, percent understory cover, percent silt/clay in bank material, the d50 substrate size and number of pieces of large woody debris. Dependent variables include the morphologic response variables width, depth, cross sectional area, wetted perimeter, hydraulic radius and sinuosity. NS denotes non-significant values.

	Total r^2	Watershed Area (km^2)	Gradient (%)	Treatment	Understory Cover (%)	Silt/Clay in Bank (%)	d50 (mm)	LWD (pieces)
Width	**0.52**							
Partial r^2		NS	NS	**0.10**	**0.15**	NS	**0.29**	NS
p-value		NS	NS	**0.01**	**0.04**	NS	**0.00**	NS
B		NS	NS	**- 0.26**	**- 0.28**	NS	**0.62**	NS
Intercept = 0.38								
Depth	**0.26**							
Partial r^2		NS	NS	NS	NS	NS	**0.29**	NS
p-value		NS	NS	NS	NS	NS	**0.00**	NS
B		NS	NS	NS	NS	NS	**0.45**	NS
Intercept = 0.17								
Cross-Sectional Area	**0.48**							
Partial r^2		NS	NS	NS	**0.15**	NS	**0.29**	NS
p-value		NS	NS	NS	**0.01**	NS	**0.00**	NS
B		NS	NS	NS	**- 0.29**	NS	**0.65**	NS
Intercept = 0.08								
Wetted Perimeter	**0.50**							
Partial r^2		NS	NS	NS	**0.15**	NS	**0.29**	NS
p-value		NS	NS	NS	**0.00**	NS	**0.00**	NS
B		NS	NS	NS	**- 0.34**	NS	**0.60**	NS
Intercept = 0.97								
Hydraulic Radius	**0.45**							
Partial r^2		NS	NS	NS	NS	NS	**0.29**	NS
p-value		NS	NS	NS	NS	NS	**0.00**	NS
B		NS	NS	NS	NS	NS	**0.67**	NS
Intercept = 0.08								
Sinuosity	**0.25**							
Partial r^2		NS	NS	NS	NS	NS	NS	**0.21**
p-value		NS	NS	NS	NS	NS	NS	**0.04**
B		NS	NS	NS	NS	NS	NS	**0.35**
Intercept = 1.01								

indirectly influence morphologic response through the reach scale variables (d50 and understory cover), correlation and multiple regression analyses were performed independently on the twenty burned streams in Cache Creek. Unburned streams were not included because the twenty zero percent watershed burned values bias the regression. As in the earlier analysis, the dammed streams were not included.

A correlation matrix was produced for all combinations of variables for the Cache Creek drainage (Appendix D). Percent watershed burned was correlated with bare ground, understory cover, d50, d90, width, and sinuosity (Figure 11). Percent understory cover is correlated with width and wetted perimeter and d50 is correlated with width, cross-sectional area, wetted perimeter, and hydraulic radius (Figure 12). The above relationships suggest that burning could be influencing reach scale variables (d50 and understory cover), which in turn might be controlling morphologic characteristics.

Multiple regression provides a tool to document the relative contributions of the watershed and reach scale variables on stream morphology. The same variables and methods that were used in the first multiple regression analysis were employed in this analysis. Once again, the results show that when all variables were entered into the regression, burning was only a significant predictor of one variable, in this case stream depth (Table 9). The d50 substrate size coupled with percent silt/clay in the bank material produced the highest r-squared values for width, cross-sectional area and hydraulic radius accounting for 85 and 43 percent of the variance respectively. D50 was also significant in explaining wetted perimeter. The number of pieces of large woody debris contributed significantly to stream depth and sinuosity, but these

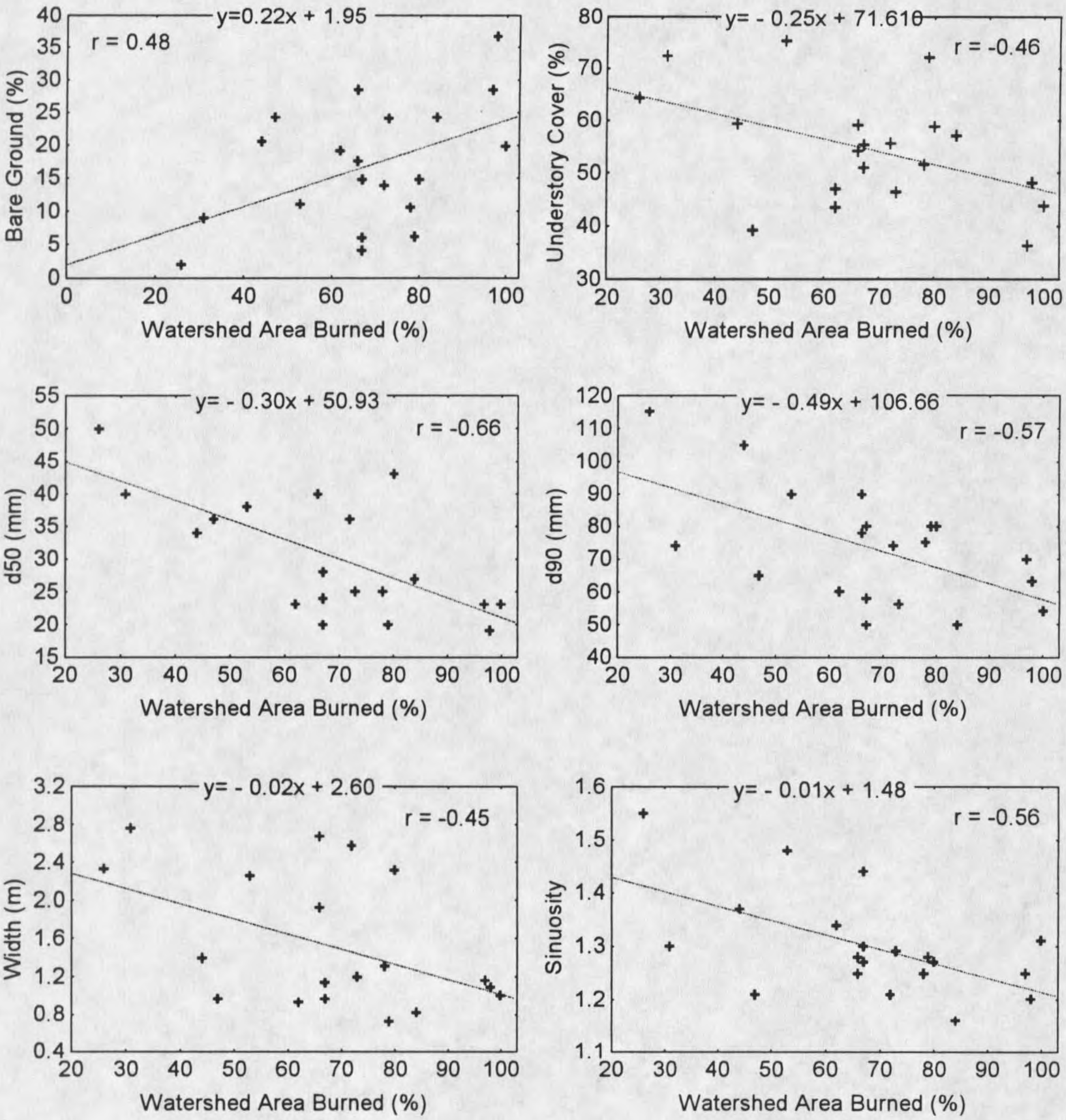

Figure 11. Scatterplots showing significant correlations between percent watershed burned, percent bare ground, understory cover, and d50 and d90, width, and sinuosity for the burned streams only.

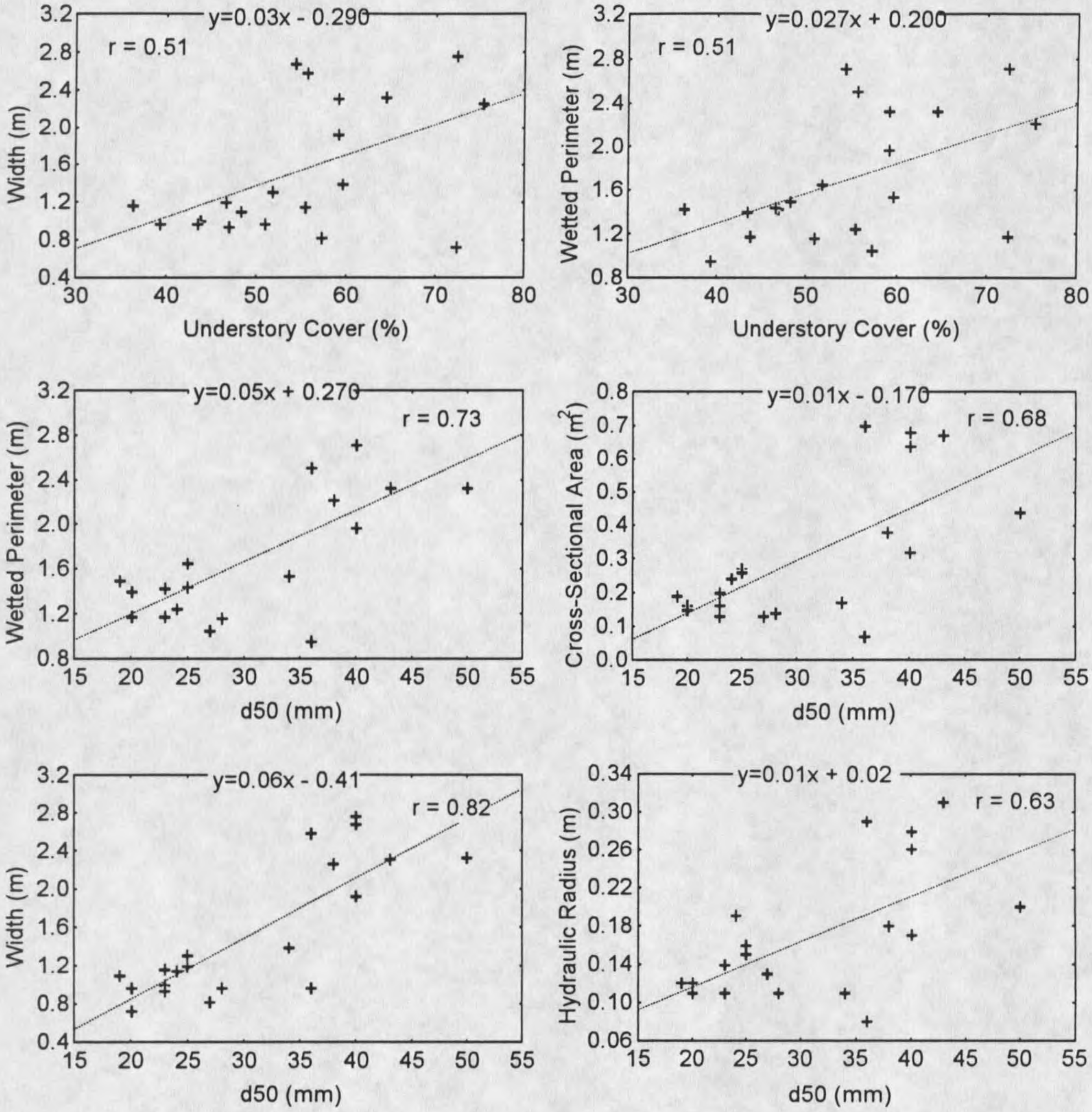

Figure 12. Scatterplots showing significant correlations between percent vegetative cover and width and wetted perimeter and d50 and width, cross sectional area, wetted perimeter and hydraulic radius for the burned streams only.

Table 9. R-squared, p, beta and intercept values for multiple regression analysis for burned streams only. Independent variables include the watershed control variables watershed area, stream gradient, treatment, percent understory cover, percent silt/clay in bank material, d50 and large woody debris. Dependent variables include the morphologic response variables width, depth, cross sectional area, wetted perimeter, hydraulic radius, and sinuosity. NS denotes non-significant values.

	Total r^2	Watershed Area (km^2)	Gradient (%)	Watershed Area Burned (%)	Understory Cover (%)	Silt/Clay in Bank (%)	d50 (mm)	LWD (pieces)
Width	**0.83**							
Partial r^2		NS	NS	NS	NS	**0.31**	**0.67**	NS
p-value		NS	NS	NS	NS	**0.02**	**0.00**	NS
B		NS	NS	NS	NS	**- 0.31**	**0.86**	NS
Intercept = 0.46								
Depth	**0.38**							
Partial r^2		NS	NS	**0.14**	NS	NS	NS	**0.21**
p-value		NS	NS	**0.04**	NS	NS	NS	**0.04**
B		NS	NS	**0.29**	NS	NS	NS	**0.36**
Intercept = 0.07								
Cross Sectional Area	**0.74**							
Partial r^2		NS	NS	NS	NS	**0.39**	**0.65**	NS
p-value		NS	NS	NS	NS	**0.02**	**0.00**	NS
B		NS	NS	NS	NS	**- 0.31**	**0.86**	NS
Intercept = 0.46								
Wetted Perimeter	**0.71**							
Partial r^2		NS	NS	NS	NS	NS	**0.57**	NS
p-value		NS	NS	NS	NS	NS	**0.00**	NS
B		NS	NS	NS	NS	NS	**0.84**	NS
Intercept = 0.25								
Hydraulic Radius	**0.66**							
Partial r^2		NS	NS	NS	NS	**0.30**	**0.66**	NS
p-value		NS	NS	NS	NS	**0.01**	**0.00**	NS
B		NS	NS	NS	NS	**- 0.38**	**0.90**	NS
Intercept = 0.10								
Sinuosity	**0.45**							
Partial r^2		NS	NS	NS	NS	NS	NS	**0.21**
p-value		NS	NS	NS	NS	NS	NS	**0.01**
B		NS	NS	NS	NS	NS	NS	**0.42**
Intercept = 1.42								

r-squared values were the lowest of the group. Overall, the r-squared values in this analysis were higher than those of the previous multiple regression analysis (Table 8), which included both the burned and unburned data sets.

The results from this multivariate analysis indicate that even when the influence of the unburned data set was removed, percent watershed burned was still not a significant contributing factor in explaining morphologic response with the exception of depth. The d50 substrate size was a significant contributing factor in both analyses indicating that this variable was a key factor in explaining variations in the morphologic response variables.

Comparison of Undammed and Dammed Streams

Nine stream reaches located in the upper Cache Creek drainage were measured in addition to the forty natural stream reaches in Pebble and Cache Creek. Since these streams had check dams installed as erosion control measures, they were treated separately from the rest of the data. None of the morphologic response variables in dammed streams differed significantly from the other two treatments (Table 5). There was significantly more silt and clay in the banks of dammed streams than in the burned streams (Table 6). Compared to the unburned streams, the dammed streams had less silt and clay in the bed material and a larger d50 substrate size. As expected, there was significantly more bare ground and less litter along the banks of the dammed channel than along the banks of the unburned streams.

CHAPTER 6

DISCUSSION, SUMMARY AND CONCLUSIONS

It was hypothesized that first order streams located in burned watersheds would have less riparian vegetation, more bare ground, and smaller substrate than streams located in unburned watersheds. These vegetation and particle size differences would in turn cause increases in morphologic variables such as bankfull width, cross-sectional area, wetted perimeter, hydraulic radius, and a decrease in sinuosity and depth. The results of this study suggest that fire has caused differences in understory cover and possibly substrate size between burned and unburned streams, but these differences were not reflected in stream cross-sectional morphology nine years after the fires.

Relationships among Watershed, Reach Scale and Morphologic Variables in Burned and Unburned Streams

Stream gradient and geology were not significantly different between the burned and unburned streams and did not have measurable effects on channel morphology. Although watershed area was significantly larger for the burned streams, an analysis of covariance confirmed the fact that variations in watershed area did not obscure morphologic responses to fire between burned and unburned drainages (Table 7). The only clear watershed scale difference between the drainages was whether or not they were burned in the 1988 fires.

The reach scale variables of d50, percent silt and clay in bed material, percent bare ground, and percent litter were significantly different between burned and unburned streams (Figure 6, Table 6). Correlation and multiple regression in turn suggested that these reach scale variables played a role in controlling stream morphology. As expected (Schumm, 1977), stream width, wetted perimeter and hydraulic radius increased as d50 increased (Figure 10). Less expected was the positive correlation of understory cover with width and wetted perimeter; one typically expects channels to narrow as more vegetative cover increases bank stability (Trimble, 1997).

Treatment was a significant predictor of two of the six morphologic response variables and at most accounted for 14 percent of the variance (Table 8). This suggests that if fire played a role in influencing stream morphology, it was primarily through effects on d50 and to a lesser extent through effects on understory cover. This would make sense since first order streams generally do not have the erosive force to rapidly remove large particles emplaced in their beds by extreme events such as may have been triggered by the immediate effects of fire (Young and Bozek, 1996).

Even though statistical analyses indicated that substrate and vegetation respond to fire and are important in controlling stream morphology, the Kruskal-Wallis analysis indicated that there were no significant differences between cross-sectional morphologic variables in burned and unburned streams at the 0.05 level of significance. It should be noted that the p-value for sinuosity was 0.10 so this variable would have been significantly different between burned and unburned streams at a higher level of significance. The p-values for the other five morphologic response variables ranged from 0.27 to 0.88. There are four possible explanations for the apparent lack of difference in channel morphology. The simplest explanation is that burning did not affect stream morphology. This is unlikely, however, based on results from other studies conducted in the same watershed and region (Minshall et al., 1998; Minshall et al., 1997; Ewing, 1996; Robinson and Minshall, 1996; Troendle and Bevenger, 1996; Young and Bozek, 1996; Minshall and Robinson, 1992).

The second interpretation is that there were morphologic differences in the years prior to this study, but enough time has elapsed to allow for recovery. Minshall and others (1997) observed substantial channel alteration in streams of the Cache Creek watershed up to four years after the fires and predicted stabilization to occur over time as riparian vegetation is reestablished. Swanson (1981) suggested that watershed recovery after fire takes place over a period of eight to ten years, depending on the rate of revegetation and climate variability.

Other evidence for recovery is found in a study of physical characteristics in a smaller number of streams over time in the same Cache Creek watershed. Minshall et al. (1998) suggested that most of the fine sediment had been flushed from the headwater streams by the fifth year post-burn (1993), leaving pebbles, cobbles and boulders to dominate the first order systems. This observation is a reasonable explanation for the larger d50 substrate size and lower silt/clay content in the burned streams of this study (Table 6). At the same time, understory cover of shrubs, forbs and grass was not significantly different between burned and unburned streams (Table 5), suggesting that riparian vegetation had recovered to pre-burn levels, halting or reducing erosional processes. The recovery of stabilizing bank vegetation may have allowed the bank heights and widths to return to pre-burn levels, thus explaining the lack of difference in cross-sectional variables despite the difference in substrate between burned and unburned streams.

A third and related explanation is that counter-acting processes may lead to no net difference in channel cross-sections at this stage of post-burn evolution. As expected from previous studies, percent watershed burned was inversely related to understory cover and substrate size (Figure 11). However, as total understory cover increased, stream width also increased, which is contrary to morphologic theory (Trimble, 1987; Schumm, 1977; Leopold, 1964) (Figure 12). This positive relationship between cover and width may have occurred because the nature of the cover is different in narrow and wide streams. When understory cover was broken down into two components, woody vegetation (shrubs and trees) and non-woody plant material (grass and forbs), the streams with widths greater than 1.5 meters had significantly less grass and forb cover (Figure 13). This suggests that grass and forbs (non-woody vegetation) are more important than woody cover in stabilizing stream banks in this watershed. This observation is supported in recent findings by Trimble (1997) where stream reaches with grass covered banks were significantly narrower than reaches dominated by forest cover.

Another unexpected result was the inverse relationship between percent watershed burned and stream width (Figure 11). This relationship seemed unusual until substrate size was taken into account. Immediately after fire, increased runoff and erosion caused median substrate size to decrease, however, over time this fine material was scoured leaving larger pebbles and cobbles behind (Minshall et al., 1998). As the d50 and d90 substrate size increase, stream width increases (Schumm, 1977; Friedman et al., 1996)

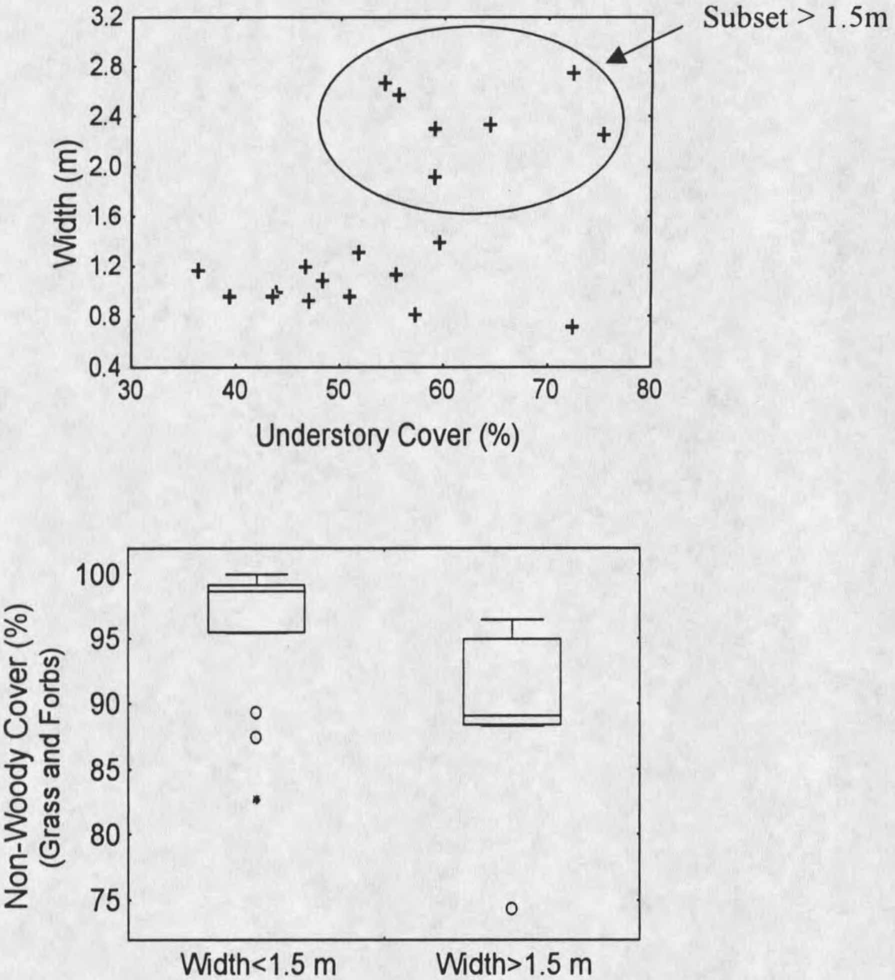

Figure 13. Scatterplot and boxplot of understory cover in streams from the burned Cache Creek watershed. Comparison indicates that non-woody cover (grass/forbs) is significantly less for streams with widths greater than 1.5m. P-value = 0.002, $\alpha = 0.05$

(Figures 10 and 12). Regression analysis supported the importance of substrate size and bank material as significant factors contributing to cross-sectional morphology with silt/clay in bank material and d50 accounting for 72 to 86 percent of the variation in stream width, cross-sectional area and hydraulic radius (Table 9). In addition, the correlation analysis on the twenty burned streams suggested that burning does in fact influence reach scale variables, and these variables in turn can influence cross-sectional morphologic characteristics. For example, percent watershed burned was significantly inversely correlated with understory cover and the median substrate size (Figure 11). These variables were positively correlated with cross-sectional measurements, particularly stream width, wetted perimeter and cross-sectional area (Figures 10 and 12).

Counter-acting processes may explain why no significant differences in stream morphology were detected between burned and unburned streams nine years after the fires (Figure 14). Immediately following the fires, fine-grained sediments enter the streams from burned areas and reduce median substrate size. Over time, this fine-grained material is excavated from the channel bottom leaving larger pebbles and cobbles. This larger substrate tends to promote increases in width, cross-sectional area and wetted perimeter. Initially, woody vegetation (trees and shrubs) are removed, but over time grass and forb cover is reestablished which stabilizes banks and decreases width, cross-sectional area and wetted perimeter. Therefore, larger median substrate sizes tend to promote increases in cross-sectional measurements, while greater amounts of grass and forb cover and less woody vegetation decrease cross-sectional variables. The net effect

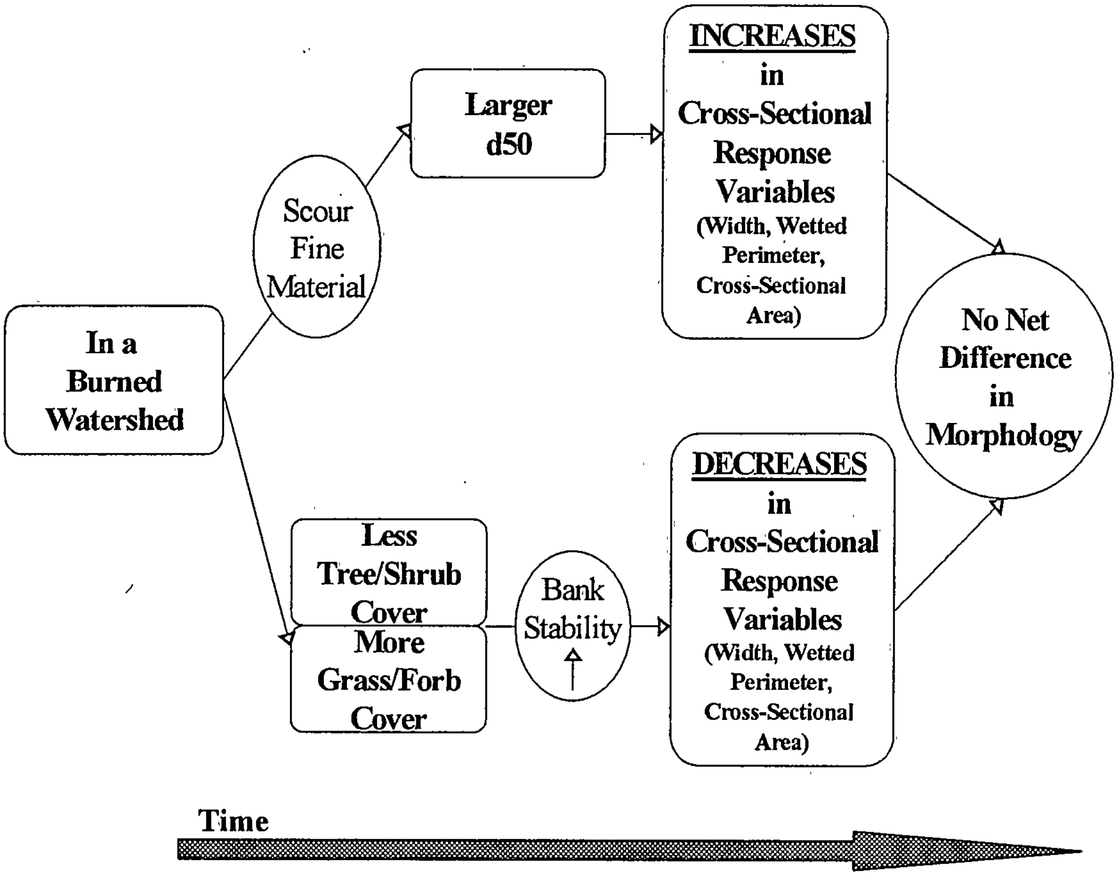

Figure 14. Schematic diagram representing relationships between a burned watershed, d50 and cross-sectional morphologic measurements and the same burned watershed, vegetative cover and cross-sectional morphologic measurements. These relationships operate in a counter-acting manner suggesting a reason that no differences are seen in stream morphology between burned and unburned streams.

of this combination of counter-acting relationships could cause morphologic characteristics of burned and unburned streams to appear similar nine years after the fires.

Finally, it is possible that the approach used in this study was not able to capture differences in morphologic variables between burned and unburned streams because some characteristics of reach scale variables were not quantified. First, geomorphologic factors that were not accounted for in field measurements may be important influences on substrate size, which is in turn an important control on stream morphology. Surficial geology was determined from a map produced by Pierce in 1974. Mass wasting events, such as debris flows, may have occurred since 1974 causing average particle size to increase in some of the burned watersheds relative to the unburned areas. If this is the case, the larger d50 in the burned areas can be attributed to debris flow events, which may or may not be associated with the 1988 fires. Major debris flow activity was not evident from visual inspection of each first-order drainage so it is difficult to say if geomorphologic factors not related to burning have influenced reach scale variables.

Secondly, it was expected that streams in the burned Cache Creek drainage would have greater amounts of woody debris due to the large quantity of snags present in the watershed. However, the majority of the trees burned in Cache Creek in 1988 were dead, but still standing in 1997, which is probably why there were no statistically significant differences in amounts of woody debris between burned and unburned streams. In addition, only material greater than 15 centimeters in diameter was counted as woody debris. Fine woody material (less that 15 centimeters in diameter) could influence the morphology of small, narrow first-order streams to an equal or greater degree than larger pieces of woody debris since large trees may simply straddle the width of the stream and not obstruct stream flow. As rooting strength decreases in the burned areas, riparian snags will begin to fall over, destabilizing banks and increasing quantities of large woody debris within the stream channel. Increases in large woody debris may cause cross-sectional morphology to change in the future as debris dams of fine woody material form behind larger logs (Swanson, 1981; Robinson and Minshall, 1996). This line of evidence suggests that morphologic differences between burned and unburned streams will not become apparent until rooting strength decreases to the point where standing dead trees begin to fall and fine woody material accumulates in stream channels.

Summary

This study documents the similarities and differences in stream channel morphology of forty-nine first-order streams located in burned and unburned watersheds in Yellowstone National Park. It was initially hypothesized that cross-sectional profiles of burned streams would be measurably different than unburned streams, however results suggest that cross-sectional morphologic response variables of streams burned in the 1988 Yellowstone fires are relatively similar to streams that have not been burned for close to 200 years. Time is probably the most important factor in the lack of morphologic difference between the burned and unburned streams in this study.

The reestablishment of non-woody vegetation (grass and forbs) has probably been a key factor in stabilizing stream banks and reducing runoff, which has possibly allowed stream morphology to return to pre-burn conditions. It is also possible that even though streams have recovered from the short-term effects of burning, they have yet to be impacted by longer term processes such as increases in large woody debris caused by decomposition of rooting structures and toppling of dead riparian vegetation.

Reach scale variables such as percentages of bare ground, litter, silt/clay in stream bottom material and substrate size are significantly different between streams in burned and unburned watersheds. Though not conclusive, it appears that fire does indirectly affect these intermediate variables, particularly substrate and percentages of silt and clay. Burned streams have significantly larger substrate and less silt/clay in the stream bottom material. This could be evidence of fine sediment being flushed from the system by high flows prior to the recovery of the understory vegetation. It is not clear however, why differences in these reach scale variables are not reflected in cross-sectional morphologic response variables. It is possible that counter-acting relationships between reach scale variables, vegetative cover and substrate, have caused no net change in stream morphology to be detectable nine years after the fires. It is also possible that as time goes on, woody debris will become available to the stream systems, causing a morphologic response different than that of unburned watersheds.

Management Implications

As more naturally caused wildfires are permitted to burn and more prescribed burn plans are implemented in environments like Yellowstone, land managers must evaluate both the short and long term effects that these fires have on watershed processes. Robinson and Minshalls (1996) work demonstrated that fire impacts on first-order channels can be dramatic in the first post-burn years. This study shows, however, that the natural reestablishment of non-woody riparian vegetation can stabilize stream banks, reduce erosion and return the system to a largely pre-burn morphology within ten years.

Results of this study suggest priorities when extinguishing wildfires. For example, it may be more cost effective to preserve stream habitat by protecting riparian vegetation during burning rather than constructing expensive check dams as restoration measures. Or if short-term effects are not a concern, then it might be appropriate to allow fire to burn first-order systems since recovery appears to occur over relatively short periods of four to ten years. This selective "let-burn" policy would allow more resources to be committed to protecting structures and more sensitive habitats. Such a policy, however, should also take into account potential longer term impacts as inputs from burned first-order streams cascade in higher order streams.

The check dams installed following the 1988 fires appear to have had little or no effect on cross-sectional stream morphology in burned streams (Table 6). The check dams may have been effective in trapping fine sediment along the margins of the streams, as seen in the significantly higher percentages of silt/clay in the bank material when compared to the burned streams. These erosion control structures did not appear to prevent fine sediment from entering the stream channel however, as indicated by the similar silt/clay content and d50 and d90 substrate sizes in the burned and dammed streams. If the management goal was to minimize sedimentation, these results show that post-fire construction of erosion control structures is probably not necessary, at least in the setting of this study. It is difficult to draw further conclusions from this data set since only nine streams were measured. Further research is necessary to evaluate the effectiveness of these dams.

Further Research

Because morphologic response in headwater systems varies with climatic fluctuations and is often influenced by geologic and topographic characteristics, this study needs to be replicated in regions outside of northeast Yellowstone National Park. Because land managers often have a limited amount of time to collect data and make decisions regarding management strategies, methods employed in this study are effective in collecting a reasonably large set of stream data in one field season. Ideally, long-term studies of streams of varying order are necessary to document a full range of morphologic change over time. Spatial studies incorporating pre-burn conditions and post-fire responses over a period of 10-20 years would be most useful in understanding the interactions of variables and changes in stream morphology as a result of wildfire or prescribed burning. A full range of percent watershed burned should be included and it would be ideal to have control streams located in the same watershed as the burned streams. Watershed variables such as watershed area, gradient and surficial geology must be kept as consistent as possible to ensure that only the effects of fire are being examined. Measurements of quantities of both fine and coarse woody debris should be incorporated in any future studies and a consistent method for characterizing this material in relation to stream size should be developed. Studies incorporating these parameters will provide the information necessary to make educated decisions regarding fire management and stream ecosystems.

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APPENDICES

APPENDIX A

INDIVIDUAL REACH LOCATION – ALL STREAMS

Stream #	Location Description
P1	38 meters upstream of trail
P2	26 meters upstream of trail
P3	26 meters upstream of trail
P5	13 meters upstream of trail
P7	38 meters upstream of trail
P8	20 meters upstream of trail
P9	18 meters upstream of trail
P10	32 meters upstream of trail
P11	24 meters upstream of trail
P12	20 meters upstream of trail
P13	15 meters upstream from footbridge
P14	21 meters upstream from confluence of Pebble Creek
P15	23 meters upstream of trail
P16	1 meter upstream from game trail
P17	15 meters upstream of footbridge
P18	25 meters upstream from confluence with Pebble Creek
P19	20 meters upstream from trial
P20	5 meters upstream from confluence with Pebble Creek
P21	50 meters upstream from confluence with Pebble Creek
P22	40 upstream from confluence of Pebble Creek
C1	25 meters upstream from confluence of Cache Creek
C2	20 meters upstream from trail
C3	25 meters upstream from confluence of Cache Creek
C4	75 meters upstream from confluence of Cache Creek
C5	30 meters upstream from confluence of Cache Creek
C6	30 meters upstream from confluence of Cache Creek
C7	45 meters upstream from confluence of Cache Creek
C8	60 meters upstream from confluence of Cache Creek
C9	1 meter upstream from game trail
C10	75 meters upstream from confluence of Cache Creek
C11	65 meters upstream from confluence of Cache Creek
C21	20 meters upstream from fork in stream
C22	50 meters upstream from fork in stream
C23	15 meters upstream from trial
C24	10 meters upstream from trail
C25	3 meters upstream from trail
C26	200 meters upstream from confluence of Cache Creek
C27	2 meters upstream from trail
C28	2 meters upstream from trial
C29	4 meters upstream from game trail
D12	100 meters upstream from confluence of Cache Creek
D13	100 meters upstream from confluence of Cache Creek
D14	25 meters upstream from confluence of Cache Creek
D15	20 meters upstream from confluence of Cache Creek
D16	25 meters upstream from confluence of Cache Creek
D17	75 meters upstream from confluence of Cache Creek
D18	45 meters upstream from confluence of Cache Creek
D19	75 meters upstream from confluence of Cache Creek
D20	4 meters upstream from game trail

APPENDIX B

UNBURNED STREAMS

Burned Streams - Cache Creek

Stream #	Elevation (ft)	Watershed Area (km2)	Watershed Area Burned (%)	Strahler Order	Rosgen Class	Channel Gradient (%)	Channel Slope (deg)	Aspect	Large Woody Debris (pieces)	Sinuosity
C1	8000	0.316	98	1	Aa+3	20.4	11.6	SE	13	1.20
C2	8040	0.601	97	1	Aa+4	13.3	7.6	S	16	1.25
C3	8040	0.627	84	1	A4	10.8	6.2	SW	15	1.16
C4	8080	0.202	100	1	A4	9.7	5.6	SW	13	1.31
C5	8000	0.121	67	1	A4	8.8	5.1	N	17	1.27
C6	8040	0.503	62	1	Aa+3	15.5	8.8	N	42	1.34
C7	7960	0.336	67	1	Aa+3	14.2	8.1	N	36	1.44
C8	7800	0.311	73	1	Aa+4	17.2	9.7	W	20	1.29
C9	7920	0.494	67	1	Aa+3	26.4	14.6	N	23	1.30
C10	7840	0.373	79	1	A4	11.9	6.8	NW	5	1.28
C11	7800	0.36	78	1	A	13.4	7.6	NW	22	1.25
C21	7400	1.1	31	1	A	10.9	6.3	E	21	1.30
C22	7600	0.711	66	1	A3	12.5	7.2	E	8	1.28
C23	7480	0.996	53	1	A4	14.3	8.2	E	26	1.48
C24	7640	1.11	66	1	A4	9.5	5.4	E	22	1.25
C25	7280	0.388	47	1	A4	13.7	7.8	W	36	1.21
C26	7300	1.14	72	1	A3	13.4	7.6	W	16	1.21
C27	7200	0.432	44	1	A3	15.8	9	W	22	1.37
C28	7200	1.08	26	1	A3	8.6	4.9	E	8	1.55
C29	7000	0.945	80	1	Aa+3	15	8.6	NW	26	1.27

APPENDIX C

BURNED STREAMS

Unburned Streams - Pebble Creek

Stream #	D10	D50	D90	Bank %Sand	Bank %Silt	Bank %Clay	Stream Bottom %Sand	Stream Bottom %Silt	Stream Bottom %Clay
P1	**0.2**	15	75	37	37	26	60	25	15
P2	**6**	15	70	48	31	21	53	28	19
P3	**6**	20	95	59	32	9	9999	9999	9999
P5	**10**	30	100	59	36	5	88	9	3
P7	**5**	18	45	61	27	12	54	27	19
P8	**11**	22	52	46	37	17	57	26	17
P9	**9**	30	94	53	31	16	9999	9999	9999
P10	**12**	35	80	67	20	13	86	10	4
P11	**7**	17	50	39	38	23	62	23	15
P12	**11**	32	75	40	39	21	9999	9999	9999
P13	**7**	12	25	34	35	31	68	19	13
P14	**6**	17	37	41	42	17	57	23	20
P15	**6**	19	66	56	28	16	9999	9999	9999
P16	**0.2**	12	29	39	58	13	9999	9999	9999
P17	**10**	25	55	9999	9999	9999	9999	9999	9999
P18	**13**	29	60	69	18	13	9999	9999	9999
P19	**0.2**	16	60	36	38	26	68	19	13
P20	**9**	25	85	56	30	14	88	7	5
P21	**12**	30	63	54	35	11	79	10	11
P22	**9**	26	50	65	22	13	76	15	9

*9999 indicates no data collected