Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: a spatially explicit analysis

Carl J. Legleiter[a], Rick L. Lawrence[b,*], Mark A. Fonstad[c], W. Andrew Marcus[d], Richard Aspinall[e]

[a] *Department of Earth Sciences and Department of Mathematical Sciences, Montana State University, Bozeman, MT 59717, USA*
[b] *Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717-3490, USA*
[c] *Department of Geography, Southwest Texas State University, San Marcos, TX 78666, USA*
[d] *Department of Geography, University of Oregon, Eugene, OR 97403-1251, USA*
[e] *Department of Earth Sciences, Montana State University, Bozeman, MT 59717, USA*

Abstract

Forest fire is a vital ecological process capable of inducing complex fluvial response, but the integration of these effects across entire watersheds remains poorly understood. We collected downstream cross-sectional and geomorphic data, acquired geographic information on land cover and forest fire, and performed spatially explicit statistical analyses to examine fire-related impacts in catchments burned to varying degrees. Generalized least squares (GLS) regression models suggested that channels with a greater percentage of burned drainage area were associated with markedly higher cross-sectional stream power, relatively smaller width/depth ratios, and lower bank failure rates 12 to 13 years after the fires. These results implied that streams became more powerful in the aftermath of forest fire and that net incision had been the primary response in second- to fourth-order channels since the 1988 Yellowstone fires. The extensive geographic coverage of our data, spanning multiple basins with measurements spaced every 100 m, allowed us to hypothesize a process–response model based on these results. We suggest that a wave of fire-related sediment propagates through burned catchments. High runoff events or even moderate flows provide sufficient energy to evacuate the finer-grained material delivered from burned hillslopes to the channel network over a period of 5–10 years. The combination of elevated post-fire discharges and decreased sediment supply then induces an episode of incision. Site-specific channel changes are highly variable because streams can accommodate post-fire increases in energy and sediment supply through multiple modes of adjustment. Characterizing the spatial distribution of stream power would provide a valuable management tool because this variable is strongly associated with percent-burned drainage area and integrates several elements of complex fluvial response. Future research focused on the channel substrate and its evolution through time is needed, but our results indicate a fundamental linkage between fire and fluvial processes.
© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fire; Fluvial geomorphology; Stream power; Watershed; Incision; Bank failure

1. Introduction

Forest fire is an effective geomorphic agent influencing fluvial dynamics and landscape evolution

---

* Corresponding author. Fax: +1-406-994-5122.
E-mail address: rickl@montana.edu (R.L. Lawrence).

(Tiedemann et al., 1979; Swanson, 1981; Morris and Moses, 1987; Meyer et al., 1992, 1995). By modifying hydrologic and erosional processes, periodic burning can induce significant adjustments in stream systems (Florsheim et al., 1991; Moody and Martin, 2001) and corresponding alterations in lotic communities (Mihuc et al., 1996; Robinson et al., 1996; Minshall et al., 1997). Although numerous studies have examined fire's short-term, localized impacts, the integration of these effects across entire basins and over time periods of a decade or more remains poorly understood. Linking fire-related disturbance to observed channel morphology from a synoptic, watershed-scale perspective might help address this void. This study utilized field data from extensive downstream surveys and geographic information on land cover and forest fire to examine a fundamental question: What are the in-channel geomorphic changes associated with fire in the northern Yellowstone ecosystem 12 to 13 years after the burn?

2. Previous research

Previous research has documented increased runoff and sediment production in burned catchments (Helvey, 1980; Morris and Moses, 1987; Ewing, 1996; Inbar et al., 1998). Soil temperatures of 175 to 200 °C during high-intensity fires vaporize organic compounds in forest floor litter, which then condense at depth to form a water-repellent layer (DeBano, 2000; Letey, 2001), resulting in diminished infiltration rates and greater surface runoff (Robichaud, 2001; Martin and Moody, 2001). Reduced ground cover and altered soil properties promote particle detachment and entrainment, facilitate overland flow, and increase erosion (Morris and Moses, 1987; Johansen et al., 2001; Pierson et al., 2001). Comparisons of burned and unburned plots have confirmed elevated post-fire sediment yields (Inbar et al., 1998; Robichaud and Brown, 1999), but these effects are typically short-lived (i.e., 2–4 years) due to vegetative recovery, decreased soil hydrophobicity, and development of a coarse surface lag (Morris and Moses, 1987; Martin and Moody, 2001).

Streamflow also can increase dramatically following a wildfire, and higher discharges have been reported from burned catchments (Helvey, 1980;

Troendle and Bevenger, 1996; Loaiciga et al., 2001). The elimination of plant biomass decreases transpiration and interception losses (Tiedemann et al., 1979; Loaiciga et al., 2001), and reduced storage and infiltration cause a greater proportion of incident precipitation to become overland flow (Morris and Moses, 1987). Peak flow rates also might increase substantially in basins recently devegetated by wildfire. Winter snowpacks might be deeper and melt faster in the aftermath of fire (Tiedemann et al., 1979; Swanson, 1981), and spring runoff exceeded expectations following the 1988 Yellowstone fires (Farnes, 1996). In the summer, burned catchments might be more susceptible to flash flooding and debris flows triggered by convective thunderstorms (Cannon, 2001; Cannon et al., 2001; Moody and Martin, 2001).

Fluvial systems experience a complex response (Schumm and Lichty, 1965) to these fire-related disturbances as width, depth, planimetric geometry, and longitudinal profile adjust to elevated sediment loads and increased flow magnitude/frequency. The relative sizes of these fire-related effects and their temporal persistence as vegetation recovers could affect changes in stream morphology. The extent and severity of burning and position within the catchment also might influence the observed channel response. Headwater tributaries having a greater percentage of burned drainage area might exhibit greater modifications than higher-order streams in which less of the watershed has been affected (Minshall et al., 1989; Minshall and Brock, 1991; Minshall et al., 1998).

Fluvial systems exhibit multiple modes of adjustment (Phillips, 1991) to fire-related disturbance; and reported channel responses range from aggradation and active braiding to entrenchment and narrowing, depending on sediment delivery from low-order tributaries and the timing and intensity of precipitation (Laird and Harvey, 1986; Florsheim et al., 1991; Moody and Martin, 2001). Following the 1988 Yellowstone fires, a 9-year study of Cache Creek documented a series of scour and fill events that caused the stream to wander across the valley floor. Major channel alterations gradually shifted downstream through the watershed over the first 5 years, perhaps in coordination with a pulse of fine sediment (Minshall et al., 1998). On a longer time scale, fire

has been an integral component of Yellowstone's Soda Butte Creek alluvial system throughout the Holocene (Meyer et al., 1992, 1995) and, by acting as a catalyst for sediment transport, might account for a large portion of the long-term sediment yield from Rocky Mountain drainage basins (Morris and Moses, 1987).

An improved understanding of fire's effect on stream systems is essential because of its crucial role in both landscape evolution and modern-day resource management decisions. In this study, we developed statistical models of cross-sectional stream power, width/depth ratio, and bank failure rate in watersheds burned to varying degrees and utilized these results to construct a conceptual framework describing fluvial response to wildfire in the northern Yellowstone ecosystem.

3. Field area

We collected data along eight streams in four watersheds of the upper Yellowstone River basin of Wyoming and Montana, USA. Cache Creek and its tributaries, Soda Butte Creek, and Pebble Creek flow into the Lamar River in NE Yellowstone National Park (YNP); and Tom Miner and Cinnabar Creeks directly enter the Yellowstone River in Montana's Paradise Valley (Fig. 1). The YNP streams occupy glacial trough valleys in a rugged portion of the Absaroka Range underlain by Eocene volcanic and Paleozoic sedimentary rocks. Surficial geology consists of Pinedale-age glacial deposits and Holocene alluvium derived from local floods and debris flows (Meyer et al., 1995; Meyer, 2001). Tom Miner and Cinnabar Creeks lie to the north and are broadly
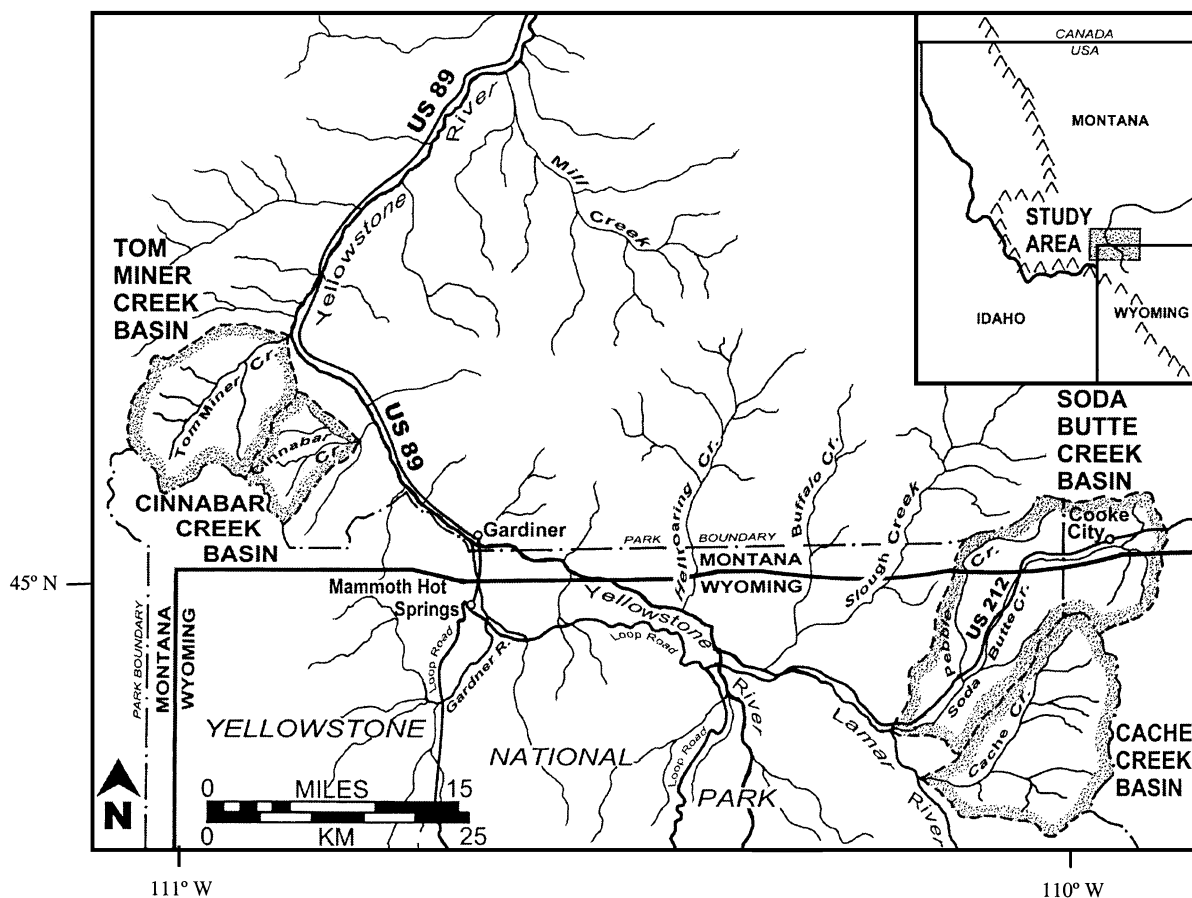

Fig. 1. Map showing the locations of the basins examined in this study. Study basins are shaded. Courtesy of Karen Wynn Fonstad.

Table 1
Physical characteristics and number of downstream survey sites for the eight basins in the study area; total sample size was 886 survey sites, of which 667 were used for model building and 219 reserved for model validation

Basin	Soda Butte Creek	Pebble Creek	Cache Creek	South Cache Creek	South Fork S. Cache	North Fork S. Cache	Tom Miner Creek	Cinnabar Creek
Drainage area at mouth (km^2)	271	65	210	57	23	25	171	36
Estimated $Q_{2.33}$ discharge (m^3/s)[a]	37.1	9.3	28.9	8.2	3.3	3.6	23.7	5.2
Mean basin elevation (m)	2551	2592	2589	2625	2650	2683	2312	2380
Mean basin slope (%)	20.5	20.3	19.1	19.9	18.8	22.5	17.3	22.7
Main stem channel length (km)	36.7	10.8	19.2	4.2	0.4	0.5	16.6	3.5
Average channel gradient (%)	0.8	2.5	1.6	2.6	8.4	3.2	2.8	2.8
Average bankfull width (m)	17.8	9.9	18.5	9.6	4.6	7.7	6.8	4.7
Average thalweg depth (m)	1.0	0.6	1.5	0.6	0.4	0.4	0.6	0.4
Percent-burned drainage area	13	15.4	56.9	38.9	18	47	0	0
Number of survey sites	361	104	192	42	4	5	143	35
Model-building sample size	271	81	144	31	3	4	107	26
Validation data set sample size	90	23	48	11	1	1	36	9

[a] Bankfull discharge at basin mouth estimated from a regional hydrology equation developed from 14 USGS stream gages: $Q_{2.33} = 0.1568 \times (\text{drainage area})^{0.976}$.

similar, with areas of Achaean metamorphic and Paleozoic sedimentary bedrock overlain by Quaternary alluvial, colluvial, and glacial deposits. Runoff is dominated by spring snowmelt (Ewing, 1996), with occasional midsummer peaks triggered by intense, convective thunderstorms (Meyer et al., 1995). Elevations within the catchments range from 1537 m along Tom Miner Creek to 3330 m on the drainage divide separating Soda Butte and Cache Creeks. Channel gradients within the study area average 3.1% and range from 0.1% up to 27%. The four basins we examined varied in size and physical character (Table 1).

Vegetation along our study streams consisted of lodgepole pine and open meadows at lower elevations and mixed spruce and fir in the subalpine zone. The
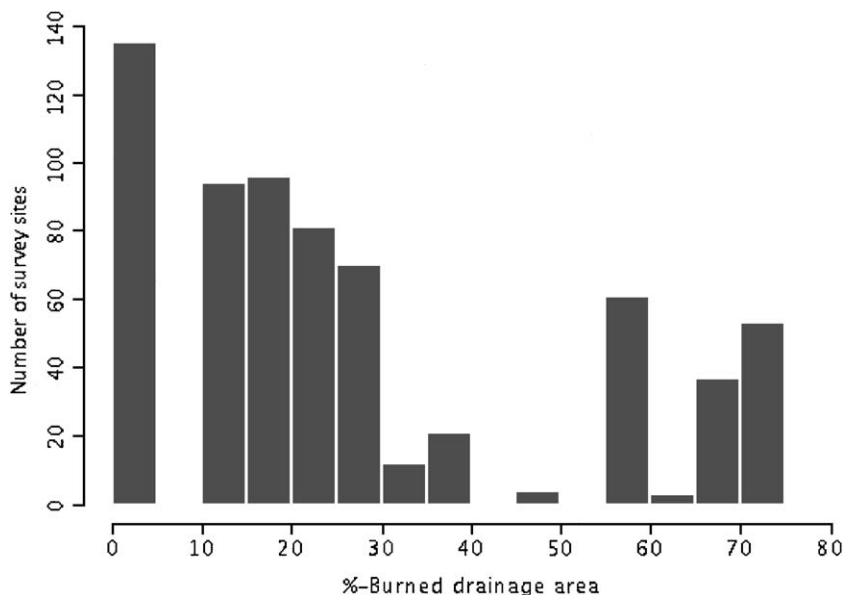

Fig. 2. Distribution of percent-burned drainage area throughout our study basins. The vertical axis represents the number of survey sites within each 5% increment of percent-burned drainage area above each site.

Table 2
Geomorphic factors inventoried at survey sites; for each factor, one level was selected as the base (denoted by *italics*) and indicator variables created for the remaining factor levels; e.g., bedrock-controlled channels were represented by a value of 1 for the "bedrock" indicator variable, whereas colluvial reaches were represented by 0 values for both the "bedrock" and "alluvial" indicator variables

Factor	Levels and base for indicator variable
Channel confinement	confined: valley floor width < 2 channel widths, *semi-confined*: *2 channel widths < valley floor width < 4 channel widths,* unconfined: valley floor width > 4 channel widths
Channel control	alluvial, *colluvial*, bedrock
Channel planform	meandering, *straight*, braided
Channel character	riffle-pool, *run-glide*, step-pool
Channel substrate	boulder, cobble, gravel, *sand*
Valley floor cover	forest, *scrub*, wetland

forest communities are susceptible to intense, stand-replacing fires such as the 1988 conflagration that affected 32% of YNP's fluvial system (Minshall and Brock, 1991). Dendrochronologic reconstructions indicate that these events recur on a 200-year interval (Barrett, 1994), establishing forest fire as a vital ecological process (Romme and Despain, 1989). Per-

cent-burned area in our study basins ranged from 0% in Tom Miner and Cinnabar Creeks, which thus served as "reference" streams, up to 74% in the headwaters of Soda Butte Creek, enabling us to assess the response of channels impacted to varying degrees by wildfire (Fig. 2).

4. Methods

4.1. Field data collection

During the summers of 2000 and 2001, we surveyed 88.6 km of stream length (Table 1). Survey sites were located every 100 m using a laser range-finder accurate to ± 1 m. We estimated the bankfull level using topographic breaks, changes in vegetation and particle size, and undercutting or depositional features (Harrelson et al., 1994). Bankfull width and depth were measured with a tape, lightweight stadia rod, and hand level. In braided reaches, separate bankfull width and depth values were determined for each branch; but subsequent analyses focused on the channel's primary strand because it was generally much larger than any secondary strands. Bed gra-

Fig. 3. Extensive right bank failure on Tom Miner Creek.

dients were derived from 1:24,000 USGS topographic quadrangles. We characterized the local geomorphology by six factors (Table 2) expected to influence channel processes (Knighton, 1998; Wohl, 2000). Between survey sites, we estimated the percentage of active failure along both banks of each 100-m stream segment. Criteria for identifying failure included fresh scarps, devegetated bank surfaces, streamside vegetation submerged within the channel, or any evidence of undercutting features (Fig. 3).

From these field data, we calculated three response variables at each survey site: (i) cross-sectional stream power, defined as the rate of energy expenditure per unit length

$$\Omega = \rho g Q S,$$

where ρ is the density of water (kg/m^3), g is acceleration due to gravity (9.81 m/s^2), Q is discharge (m^3/s), S is the channel gradient (m/m), and Ω has units of W/m (Rhoads, 1987). We used Jarrett's (1984) resistance formula to estimate the value of n in the denominator of Manning's equation and calculated cross-sectional stream power as

$$\Omega = \rho g S w d R^{0.67} S^{0.5} / 0.32 S^{0.38} R^{-0.16},$$

where w represents the bankfull width, d the thalweg depth, and R the hydraulic radius, which is $0.5wd/2(d^2 + 0.5w^2)^{0.5}$ for a triangular channel approximation; (ii) width/depth ratio; and (iii) bank failure rate, the sum of the failure length for both banks along each 100-m channel segment.

4.2. Geographic information on land cover and forest fire

We developed a flow accumulation grid from 30-m digital elevation models (DEMs) and calculated the contributing drainage area above each of our 886 survey sites from this network topology using an Avenue script developed for this purpose in ArcView. Two cloud-free Landsat 7 scenes (path 38, rows 28 and 29) acquired on 13 July 1999 were used to develop a seven-class land cover map based on a supervised maximum likelihood classification. Overall accuracy was 85%, which meets USGS land cover classification criteria (Lillesand and Kiefer, 1999); individual map class accuracies were also calculated

(Table 3). For each survey site, we computed the proportion of the upstream area occupied by each class, and these percent cover estimates were considered as potential covariates affecting channel morphology (Hynes, 1975; Wohl, 2000). The percentage of burned drainage area above each survey site, the explanatory variable of primary interest, was derived in a similar manner. The National Park Service and Gallatin National Forest provided coverages portraying the spatial distribution of forest fire throughout our study area.

4.3. Analysis

The unidirectional flow of water dictates that each point along the channel is influenced by upstream locations so that geomorphic variables are spatially autocorrelated—that is, survey sites situated closer

Table 3
Potential explanatory variables describing land cover conditions and topographic characteristics and position within the catchment for each survey site; the seven land cover variables are percentages of upstream drainage area occupied by each class; map class accuracies computed from 1008 field validation samples are given in parentheses

Variable	Description
Land cover conditions	
Barren	Areas of bare rock or open soil, including those above timberline (82%)
Cropland	Agricultural production lands featuring cultivated fields (78%)
Pasture/grassland	Lands managed as pasture for grazing livestock or open areas devoid of trees and featuring sufficient moisture to support grasses (97%)
Rangeland	Open range used for grazing or natural areas of sparse vegetation (96%)
Forest	Continuous areas of mixed coniferous forest (87%)
Deciduous	Zones of deciduous trees, typically located along riparian corridors (63%)
Water	Lakes, ponds, rivers, and streams (100%)
Diversity	Shannon's diversity index for land cover classes in basin
Topographic indices	
Elevation	Survey site elevation (km)
Distance	Distance downstream from survey origin (km)
Drainage area	Drainage area above survey site (km^2)
Mean elevation	Mean basin elevation above survey site (km)
Mean slope	Mean basin slope above survey site

together tend to be more similar than those separated by a greater distance (Fig. 4; Cliff and Ord, 1973; Griffith, 1987; Vasiliev, 1996). Classical statistical techniques such as ordinary least squares (OLS) regression are of limited value in the analysis of autocorrelated geographically referenced data (Mark, 1984; Griffith, 1996) because spatial autocorrelation implies that several of the assumptions underlying OLS regression will be violated (Legendre, 1993; Nelson, 2001).

In recognition of these issues, we employed a generalized least squares (GLS) regression model that explicitly incorporated the spatial dependence inherent in our data and allowed the assumption of independent errors to be relaxed (Bailey and Gatrell, 1995). To implement this approach, we derived an estimate of the spatial structure represented by the covariance matrix of each response variable. We accomplished this by first developing OLS "trend surface" models using all-subsets regression, added variable plots, and a series of diagnostic procedures (Neter et al., 1996). The residuals from these OLS models were then used to create empirical variograms,
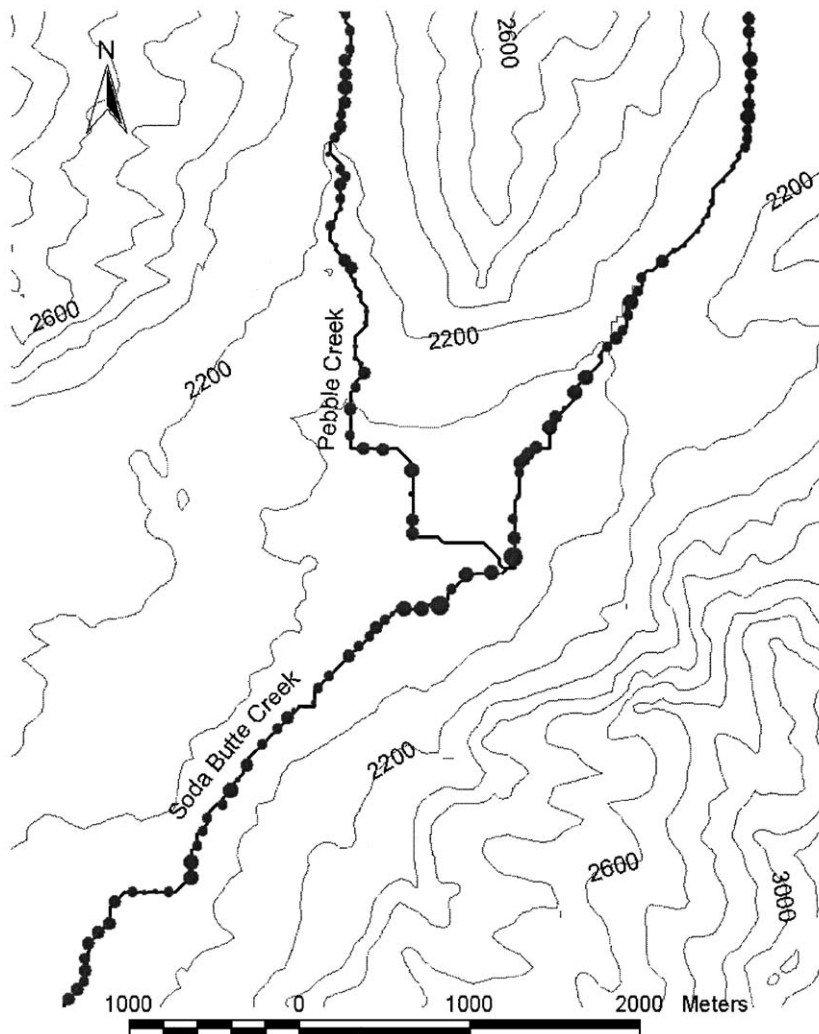

Fig. 4. Width/depth ratios at the Soda Butte–Pebble Creek confluence. Width/depth ratios are proportional to circle size. The similarity of adjacent circles indicates spatial autocorrelation between nearby sites. Contour interval is 100 m.

a graphical portrayal of the degree to which the OLS residuals co-vary as a function of the downstream distance between survey sites (Rossi et al., 1992). We then fit exponential or spherical variogram models using a nonlinear least squares algorithm (Kaluzny et al., 1997) to obtain estimated values of the sill, range, and nugget (Fig. 5), which defined the estimate of the covariance matrix used to create GLS models. This approach provided a means of including both large-scale trends and localized variability in our models while also ensuring that coefficient estimates and standard errors allowed for spatial dependence (Bailey and Gatrell, 1995).

The GLS model coefficients obtained in this manner describe the nature (direct or inverse) and magnitude of the effect of each explanatory variable upon the fluvial response variables in the presence of the other predictors in the model. The fire-related effects we sought to examine, however, might have been confounded with other factors in this multivariate setting. As a confirmation of the effects suggested by the more complex GLS models, we calculated correlations between percent-burned drainage area and each response variable to verify the direction of these relationships in the absence of other covariates.

The accuracy of our models was assessed using independent validation data from our study area. One quarter (25%) of our survey sites were randomly excluded from the initial model building (Table 1) and the GLS models we developed were used to compute predicted values of each response variable at these validation sites. We quantified the magnitude of prediction error at each site by subtracting the predicted from the observed value and taking the absolute value of the difference. Large-sample confidence intervals of 95% (Berry and Lindgren, 1996) were calculated for the absolute deviation prediction errors from each model and compared to the mean value of each response variable.

The percent-burned drainage area coefficient in each GLS model indicated the change in the corresponding response variable expected for a given change in the proportion of the watershed affected by wildfire after accounting for the model's other explanatory variables. We obtained theoretical post-fire values for each response variable by assuming constant values of the other covariates and exponentiating the product of this coefficient and an appropriate increment to percent-burned drainage area. This procedure provided an estimate of the magnitude of
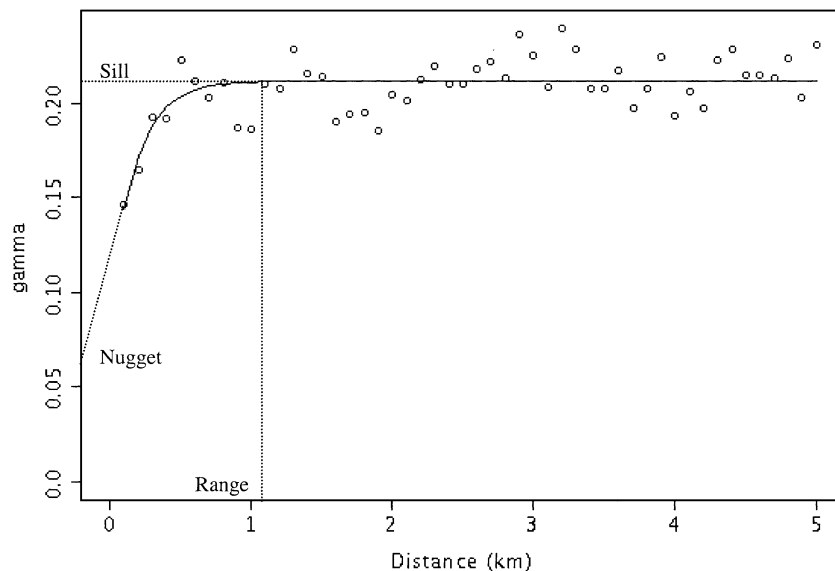

Fig. 5. Exponential model variogram (solid line) fit to the residuals from an OLS regression model for cross-sectional stream power. Gamma is the estimated semivariance calculated for each lag distance, the sill is an upper bound corresponding to the population variance σ^2, the range is the distance at which the sill is reached, and the nugget effect represents sampling errors and small-scale variability.

change and a more interpretable description of fire's predicted effects on fluvial forms and processes.

5. Results

Exploratory analysis of cross-sectional stream power, width/depth ratio, and bank failure rate revealed skewed distributions, so we transformed each response by taking the base 10 logarithm. Explanatory variables describing local geomorphology, land cover, topography, position within the catchment, and percent-burned drainage area were considered during the initial OLS model building (Tables 2 and 3). Simple one-way ANOVAs provided strong evidence (p-value < 0.001) that the three transformed response variables differed across all geomorphic factors. This result justified testing the corresponding indicator variables for inclusion (Table 2). Important differences among basins not captured by the available data might have existed, so we created indicator variables to allow for the possibility that catchments featured unique climate, vegetation, or geology. Added variable plots and partial F tests, however, confirmed that neither the basin indicator variables nor the percentage of the watershed within each of eight aspect classes significantly improved the OLS models, given the other covariates present.

Table 4
Generalized least squares regression model of $\log_{10}$(cross-sectional stream power) developed from $n = 667$ survey sites on second- to fourth-order streams 12–13 years after the 1988 Yellowstone fires (see Tables 2 and 3 for variable descriptions)

Term	Coefficient	p-value
(Intercept)	− 53.60	0.001
%-Burned drainage area	0.022	< 0.001
Mean elevation	8.770	0.001
Forest	0.406	0.002
Drainage area	− 0.002	0.053
Forest valley floor cover	0.281	0.022
Wetland valley floor cover	0.318	0.033
Step-pool channel	0.446	< 0.001
Riffle-pool channel	0.143	0.033
Elevation	− 3.950	< 0.001
Barren	0.470	0.002
Cropland	0.698	0.005
Rangeland	0.269	0.018
Deciduous	0.471	< 0.001

Table 5
Generalized least squares regression model of $\log_{10}$(width/depth) developed from $n = 667$ survey sites on second- to fourth-order streams 12–13 years after the 1988 Yellowstone fires (see Tables 2 and 3 for variable descriptions)

Term	Coefficient	p-value
(Intercept)	1.187	< 0.001
%-Burned drainage area	− 0.0029	0.002
Alluvial channel	0.092	< 0.001
Bedrock channel	− 0.096	0.018
Elevation	0.353	< 0.001
Pasture/grassland	0.115	< 0.001
Rangeland	0.079	< 0.001
Water	0.196	< 0.001
Diversity	1.499	< 0.001

GLS models of the three log-transformed response variables indicated a direct association between cross-sectional stream power and the amount of the watershed affected by fire (Table 4), whereas width/depth ratio (Table 5) and bank failure rate (Table 6) were inversely related to percent-burned drainage area. Explanatory variables describing local geomorphic factors, position within the catchment, and land cover conditions also emerged as significant covariates, but simple correlations between percent-burned drainage area and each response variable confirmed the direction of the fire-related effects suggested by the GLS models. Confidence intervals of 95% for absolute deviation prediction errors were used to assess model accuracy and indicated that predicted and observed values typically differed by 2.23 to 2.64 W/m for cross-sectional stream power, 1.42 to 1.53 for width/depth ratio, and 2.83 to 3.35 m for bank failure rate.

Table 6
Generalized least squares regression model of $\log_{10}$(total bank failure per 100-m reach) developed from $n = 667$ survey sites on second- to fourth-order streams 12–13 years after the 1988 Yellowstone fires (see Tables 2 and 3 for variable descriptions)

Term	Coefficient	p-value
(Intercept)	− 0.371	0.521
%-Burned drainage area	− 0.006	0.003
Confined channel	− 0.205	0.008
Wetland valley floor cover	0.207	0.009
Bedrock channel	− 0.432	< 0.001
Meandering channel	0.143	0.013
Cobble channel substrate	0.194	0.003
Elevation	0.848	0.002
Pasture/grassland	− 0.098	< 0.001

By comparison, the means of these three variables were 758 W/m, 14.6, and 15.4 m, respectively.

6. Discussion

The sample size, geographic extent, and number and diversity of prospective covariates of our data represented an important advance in coverage relative to previous studies; and spatially explicit analyses allowed us to find significant relationships between stream behavior and fire-related disturbance on a watershed scale. In the following discussion, we interpret our GLS results and conclude by proposing a hypothetical process–response model to describe linkages between wildfire and medium-term stream response in the northern Yellowstone ecosystem.

6.1. Cross-sectional stream power

The GLS model provided estimates of the change in stream power expected for a given change in the explanatory variables (Table 4). Interpreting individual coefficients would be spurious because many covariates were correlated with one another, but some general inferences can be drawn.

6.1.1. Non-fire covariates

Cropland, rangeland, and deciduous all had positive coefficients and strong correlations with elevation, implying that these three variables might have indexed position within the watershed in addition to describing land use. Location within the catchment (as indicated by distance, mean basin elevation, drainage area, site elevation, and the land cover variables) was a significant control, consistent with the previous studies of the spatial distribution of stream power (Leece, 1997; Knighton, 1999; Fonstad, 2000). The larger positive coefficient for step-pool channels than for riffle-pool channels is also consistent with the declining rates of energy expenditure associated with the transition from high-gradient step-pool systems to downstream riffle-pool reaches (Chin, 1989; Grant et al., 1990; Wohl et al., 1993). Local vegetation communities were also significantly associated with stream power, and the positive coefficients on the two valley floor cover variables might be partially explained by steeper bed slopes in forested canyons and higher discharges in lower valleys characterized by a greater proportion of open wetlands.

6.1.2. Fire-related effects

Given these covariates, the positive coefficient on percent-burned drainage area provided evidence that cross-sectional stream power was typically higher when the contributing watershed was more extensively burned. A simple OLS regression model confirmed this direct relationship, and the R^2 value of 0.26 (although not reliable due to spatial autocorrelation) indicated that a relatively large proportion of the variation in stream power could be explained solely by the degree to which the catchment had been affected by fire (Fig. 6). Assuming constant values of all other covariates, model-predicted median stream power increased by 66.8% for a 10% increase in percent-burned drainage area. We caution, however, that these are median values and other factors, including both covariates we modeled and other variables, will affect the relation of burned area to stream power at any particular site.

Position within the watershed was a potential confounding factor because some studies have reported that headwater reaches tend to have a greater proportion of burned drainage area (Minshall et al., 1989; Minshall and Brock, 1991; Minshall et al., 1998), as well as steeper channel gradients and thus higher stream power (Knighton, 1999). The weak correlation between percent-burned drainage area and distance downstream (correlation coefficient of -0.196), however, indicated that for our data set, low-order streams were not strongly associated with more extensively burned catchments and implied that the fire-related effects we documented were not an artifact of headwater basins being more severely impacted by wildfire. In addition, the elevation, mean elevation, and drainage area terms in the GLS model (Table 4) accounted to some extent for location in the basin, allowing the percent-burned drainage area coefficient to more effectively summarize the role of wildfire. The pronounced increases in stream power predicted from our GLS model suggested that streams in catchments devegetated by forest fire 12 to 13 years previously had more energy available to modify their channels (Nanson and Hickin, 1986; McEwen, 1994; Huang and Nanson, 2000), erode fire-related sediment (Bagnold, 1977; Bull, 1979), and transport this material through the basin (Graf, 1983; Phillips, 1989).
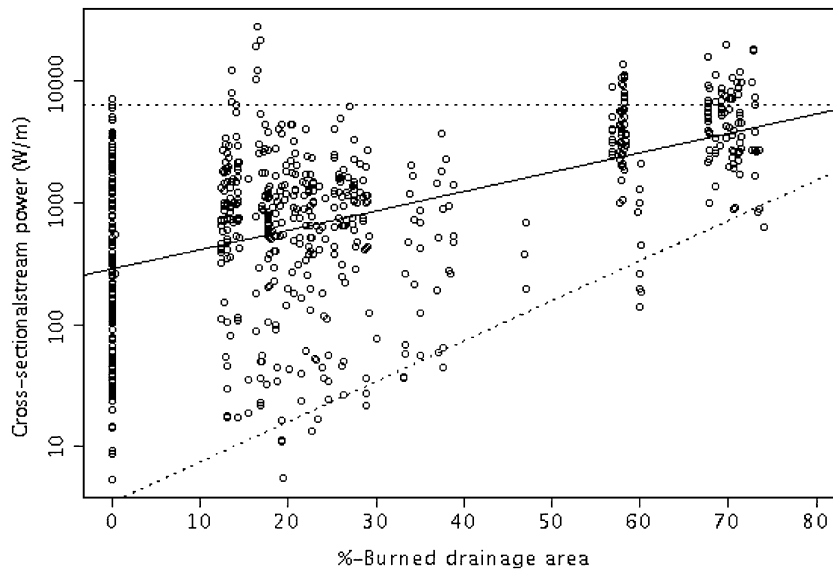
Fig. 6. Relationship between cross-sectional stream power and percent-burned drainage area. The solid line represents the OLS regression model for all survey sites and the dashed lines represent OLS regression models fit to the minimum and maximum cross-sectional stream power values for within each 5% interval of burned area. Note the pronounced increase in minimum stream power for more extensively burned catchments, whereas maximum stream power remains constant.

The effect of fire-related disturbance on stream power relative to other fluvial response variables most likely reflects that this important geomorphic quantity integrates changes in width, depth, hydraulic shape (through Jarrett's equation for roughness), slope, and discharge rather than focusing on only one or two of these factors. Several of these components might be involved in the channel's adjustment to the post-fire regime, and site-specific responses could be highly variable.

6.2. Width/depth ratio

6.2.1. Non-fire covariates

The GLS model coefficients (Table 5) indicated the manner in which channel form, as summarized by the width/depth ratio, was correlated with geomorphic factors and watershed conditions in our study area. Channels were typically wider and shallower in alluvial reaches with less resistant bank materials, whereas bedrock-controlled stream segments featured lower width/depth ratios. The covariates pasture/grassland, range, and water all had positive coefficients and were highly correlated with one another and especially with elevation. In addition to describ-

ing various aspects of land use, these three variables therefore might have acted as an index of position within the watershed, with sites located farther downstream characterized by a greater proportion of open area within their watersheds. The positive coefficients implied that width/depth ratio increased in the lower valleys where discharge was higher and banks tended to be more erodible, consistent with the hydraulic geometry paradigm (Knighton, 1987) and river metamorphosis concept (Schumm, 1969).

6.2.2. Fire-related effects

Given the other covariates in the model, the negative coefficient on percent-burned drainage area quantified fire's association with cross-sectional geometry, and the simple correlation between percent-burned drainage area and width/depth ratio confirmed the inverse nature of this relationship. Assuming constant values of all other covariates, an increase of 10% in percent-burned drainage area would result in a median 6.4% reduction in width/depth ratio. As with the stream power estimates, however, the system's inherent complexity dissuaded us from attaching much practical significance to this exact number. Our results nonetheless indicated that channels were

typically narrower and deeper in more extensively burned watersheds, suggesting that fire-related disturbance in our study area might have induced net incision over the 12 to 13 years following the 1988 fires. Higher discharges from burned catchments, and possibly steeper bed gradients resulting from an initial period of fire-related aggradation, might have caused stream power to exceed an intrinsic threshold (Bull, 1979) and triggered active incision. Net downcutting could occur, for example, if elevated post-fire streamflows counteracted and overwhelmed a shorter-lived increase in sediment load.

Although our model suggested net entrenchment in the more extensively burned watersheds of our study area 12 to 13 years after the fires, repeat surveys would be required to effectively characterize the full spectrum of potential adjustments. Our data described the drainage network at a single point in time, and episodic widening also might have occurred during the system's post-fire evolution. Aggradation could alternate with incision on a local basis as channels undergo a complex response, with the magnitude of change decreasing over time, and disparate behavior might be observed in other environments.

6.3. Bank failure rate

Although the stability of channel margins varied widely across our study area, we attempted to identify factors associated with the collapse and/or retreat of stream banks. GLS model coefficients (Table 6) provided a general indication of the expected change in bank failure rate for a given change in the explanatory variables; and for the most part, the direction of response was consistent with previous studies.

6.3.1. Non-fire covariates

The negative coefficients for confined and bedrock-controlled channels confirmed that these stream reaches exhibited lower bank failure rates, which we attributed to a lack of lateral mobility in narrow canyons and resistant channel boundary materials, respectively. The positive coefficients for wetland valley floor cover and meandering channels, on the other hand, suggested that bank failure occurs more frequently in broad, nonforested, lowland valleys. These results were consistent with the previous studies documenting that vegetative cover influences bank

cohesion (Knighton, 1998) and that erosive forces in meander bends contribute to lateral channel migration (Dietrich, 1987). Our results also implied a direct relationship between cobble substrate and bank failure, perhaps related to the lower cohesion of coarse bank materials (Thorne and Tovey, 1981), which might have been deposited by recent flood events (Meyer, 2001). The elevation and pasture/grassland terms in the model accounted for position within the watershed and perhaps land cover.

6.3.2. Fire-related effects

In the presence of the other covariates, the negative coefficient on percent-burned drainage area implied that bank failure occurs somewhat less frequently in basins more affected by fire. Assuming the covariates are held constant, the GLS model predicted a median 13.3% decrease in bank failure rate for a 10% increase in percent-burned drainage area, but, again, this figure cannot be used to estimate the exact magnitude of fire-related effects due to the importance of local controls on bank stability. The model-predicted reduction in bank failure was inconsistent with the notion that removal of vegetative cover and introduction of fire-related sediment decreases channel boundary resistance and promotes bank instability. A possible explanation is that lateral channel migration was minimal because the predominant channel response 12–13 years after the fire was in the vertical rather than the horizontal dimension. This hypothesis was supported by our models for cross-sectional stream power and width/depth ratio, which suggested that channels draining burned basins experienced degradation and might also imply that erosion occurred primarily on the channel's bed rather than its lateral margins. Sediment data and direct comparison of bank heights in burned and unburned reaches, however, would be required to further substantiate our empirical results.

6.4. Process–response model for fluvial systems in burned catchments of the northern Yellowstone ecosystem

Although short-term, local responses to forest fire have been studied in a variety of environments (e.g., Johansen et al., 2001; Martin and Moody, 2001), the spatial integration of these impacts on a watershed scale remains poorly understood. Here, we combine

our results with those of previous studies to develop a working hypothesis describing fluvial adjustment to fire-related disturbance. Although performing measurements every 100 m across multiple catchments represented an important advance in spatial coverage relative to previous studies, it captured only an instantaneous snapshot of the system's evolution, 12 to 13 years after the 1988 fires. In proposing the following model, we invoke the ergodic hypothesis that "sampling through space can be equivalent to sampling through time" (Chorley and Kennedy, 1971, p. 277) and acknowledge this fundamental limitation to the assumption that our model represents processes over time periods both shorter and longer than a decade.

In the aftermath of a forest fire, removal of vegetation, reduction of ground cover, and alteration of soil properties act in concert to increase overland flow and deliver a greater volume of fine-grained sediment to channels (Morris and Moses, 1987; Moody and Martin, 2001). Following the 1988 Yellowstone fires, the large amounts of silt and sand observed in first-through third-order streams of the Cache Creek watershed were attributed to input from adjacent hillslopes (Minshall et al., 1998). Runoff also might increase due to reduced interception and transpiration losses, hydrophobic soils, and decreased infiltration rates, and flows of sufficient magnitude might remove much of the fire-related sediment (Florsheim et al., 1991). The eventual exhaustion of available fine-grained soils from burned hillsides could both inhibit sediment delivery as a coarse surface lag develops (Morris and Moses, 1987) and exacerbate elevated post-fire discharges as bedrock or low-permeability sub-soils are exposed. Regrowth of terrestrial vegetation, including grasses, shrubs, and tree seedlings and saplings, could cause hillslope erosion to decline to approximately pre-fire levels (Morris and Moses, 1987), and previous research in burned catchments of YNP has suggested relaxation times (the period required for surface erosion and fluvial sediment transport rates to return to pre-disturbance levels) of 5 years (Minshall et al., 1998). Increased streamflows could persist for a greater period of time while a mature forest canopy gradually reestablishes (Tiedemann et al., 1979).

The persistence of elevated sediment flux and increased stream discharge in the aftermath of wildfire controls the nature and extent of fluvial adjustment. The initial pulse of fire-related sediment could induce episodic aggradation, channel expansion, and possibly lateral migration in wider valleys, with the channel system acting as a transport-limited storage reservoir (Moody and Martin, 2001). However, median substrate size decreased following the 1988 Yellowstone fires (Minshall et al., 1998), reducing the critical shear stress necessary to entrain this finer-grained material and implying that the fluvial system might return to a supply-limited state after a brief, fire-related interval of transport-limited conditions. Our results implied that cross-sectional stream power was higher and width/depth ratios lower in more extensively burned catchments, suggesting that the combined effects of elevated discharge and decreased sediment supply might cause a critical degradation threshold (Bull, 1979) to be exceeded in the aftermath of a forest fire (Fig. 7). A wave of cobbles was observed in a fourth-order reach of Cache Creek in 1997 (Minshall et al., 1998), and armoring of the streambed by large clasts immobile under typical flows might impede further downcutting (Bull, 1990, 1991). This hypothetical sequence (Fig. 8) might establish a new set of initial conditions affecting the system's response to subsequent disturbance events (Moody and Martin, 2001).

A previous, long-term study of Cache Creek suggested that a pulse of fine material gradually moved from the headwaters into larger streams during the first 5 year after the 1988 fires. Major channel alterations also appeared to shift downstream over time, from first- and second-order tributaries between 1989 and 1992, to third-order Cache between 1991 and 1997, and finally to fourth-order Cache in 1997 (Minshall et al., 1998). Nine years after the fire, another study in the Cache and Pebble Creek catchments found no significant differences in morphology between burned and unburned first-order channels (Ernstrom, 1999), indicating that these headwater streams had largely recovered by 1997. We examined primarily third- and fourth-order channels, along with a smaller number of second-order streams, 12 to 13 years after the 1988 Yellowstone fires; and at this stage in the system's evolution, net incision appeared to be the dominant fluvial process. These results implied that a wave of fire-related sediment was transported through the system, and the extensive post-1995 braiding on the Lamar River below Cache Creek suggested that fire-related effects were continuing to propagate downstream. Analogous complex responses to increased

Fig. 7. An incised channel in a severely burned portion of the Cache Creek watershed.

sediment loads have been documented in association with agricultural (Knox, 1977) and mining-related disturbance regimes (James, 1991).

Stratigraphic and chronologic evidence from NE YNP has been used to show that periods of fire-related sedimentation on alluvial fans have coincided with episodes of incision on Soda Butte Creek throughout the late Holocene (Meyer et al., 1992, 1995), consistent with our results for cross-sectional stream power, width/depth ratio, and bank failure rate. We hypothesize that increased post-fire stream power provides the requisite energy to remove fire-related sediment and induce net incision of third- to fourth-order channels over the course of a decade or more. Furthermore, because of forest fire's critical role in long-term erosion and sediment yield (Morris and Moses, 1987), we suggest that this process might influence landscape evolution in the northern Yellowstone ecosystem and perhaps other mountainous, fire-prone environments.

6.5. Implications for resource management

Although strong connections between wildfire and stream systems have been illustrated in this study and others, we suggest that the site-specific, short-term channel changes of interest to resource managers could vary widely on a local basis. In this study, cross-sectional stream power was the fluvial response most strongly related to percent-burned area, consistent with the concept that a range of adjustments might occur throughout the drainage network. The elevated energy and sediment supply associated with fire-related disturbance could be accommodated by downcutting and increasing current velocities in some channels while widening to transport more water and sediment in others. Resource managers cannot detect and assess upstream fire effects by examining any single channel feature because multiple modes of adjustment are available (Phillips, 1991). For this reason, cross-section-based monitoring approaches at one, several, or even tens of sites are apt to be inadequate for characterizing basin-wide stream responses. Efforts should instead focus on understanding how individual reaches adapt to the additional energy of the post-fire regime. Detailed knowledge of the local environment is required to make informed management decisions because the nature and extent of these changes will be influenced by a number of variables including substrate characteristics, bank stability, and valley morphology.
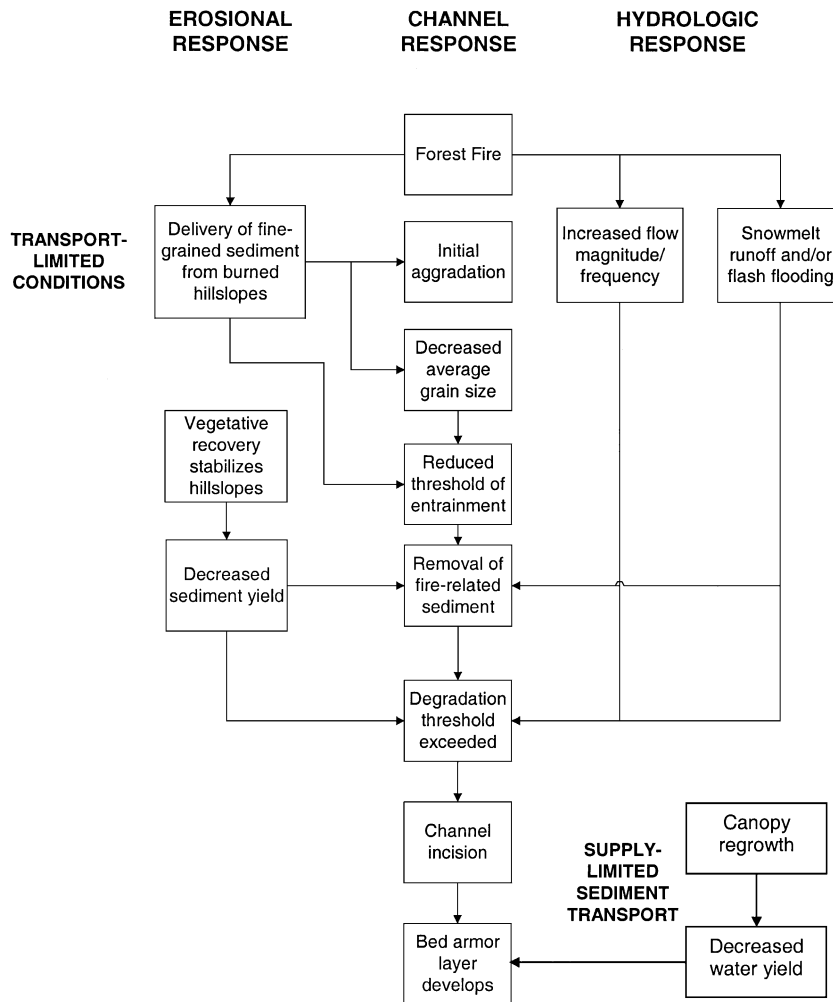
EROSIONAL
RESPONSE

CHANNEL
RESPONSE

HYDROLOGIC
RESPONSE

Forest Fire

TRANSPORT-
LIMITED
CONDITIONS

Delivery of fine-grained sediment from burned hillslopes

Initial aggradation

Increased flow magnitude/frequency

Snowmelt runoff and/or flash flooding

Decreased average grain size

Vegetative recovery stabilizes hillslopes

Reduced threshold of entrainment

Decreased sediment yield

Removal of fire-related sediment

Degradation threshold exceeded

Channel incision

SUPPLY-
LIMITED
SEDIMENT
TRANSPORT

Canopy regrowth

Bed armor layer develops

Decreased water yield

Fig. 8. Conceptual process–response model for fluvial systems in burned catchments of the northern Yellowstone ecosystem. Note that the model presented here might not be applicable in other environments, nor are all possible post-fire responses represented in this diagram.

A potentially effective strategy might be to identify those locations most vulnerable to physical disturbance in the aftermath of wildfire. Previous research in YNP has emphasized the importance of stream discharge and gradient in mediating fire-related effects, noting that, at comparable flows, channel changes were more pronounced in high-gradient streams (Minshall et al., 1998). Given stream power's sensitivity to slope (Knighton, 1999), this was consistent with our finding that streams in more extensively burned catchments tended to be more powerful. Our data also suggested that minimum log stream power values increased in direct proportion to the percentage of burned drainage area, implying that areas having low stream power might be substantially modified as well (Fig. 6). Furthermore, in our study area, the minimum log cross-sectional stream power values for sites of a given percentage of burned drainage area rose sharply above 20%, perhaps reflecting a threshold beyond which changes become more pronounced and/or pervasive. The maximum stream power values for a given percentage of burned drainage area, however, remained constant, possibly indicating that the most energetic, highest-gradient stream reaches were relatively unaffected (Fig. 6). These results suggest that characterizing the spatial distribution of stream power

within mountainous drainage basins could alert resource managers to reaches that are highly sensitive to fire-related impacts.

6.6. Suggestions for future research

The proposed process–response model is a working hypothesis that requires further evaluation. In particular, subsequent efforts should focus upon documenting the production, storage, and removal of sediment in the aftermath of a fire over broader spatial and temporal scales, with special emphasis placed on characterizing the substrate grain size distribution and its evolution through time. An improved understanding of stream power's spatial distribution would also be invaluable because this important variable is strongly associated with fire-related disturbance and integrates several aspects of complex fluvial response. Additional research efforts, we believe, are justified by the intimate connection between fire and fluvial processes.

7. Summary and conclusions

To characterize watershed-scale fluvial response to wildfire, we collected downstream data on channel dimensions and local geomorphology, acquired geographic information on land cover and forest fire, performed spatially explicit analyses, and hypothesized a conceptual framework for fluvial response to forest fire in the northern Yellowstone ecosystem. Our GLS regression models suggested that channels in more extensively burned watersheds tended to have greater cross-sectional stream power, lower width/depth ratios, and less frequent bank failure. Second-to fourth-order streams in the burned catchments of our study area were thus characterized by accelerated energy expenditure, and our results indicated that net downcutting was the primary mode of adjustment 12 to 13 years after the 1988 Yellowstone fires. We suggest that a wave of fire-related sediment propagated through the catchment over 5 to 10 years and that our study occurred during a subsequent incision-dominated phase of the system's evolution.

Channels might accommodate the increased energy and sediment supply associated with the post-fire regime through multiple modes of adjustment (Phil-lips, 1991), with entrenchment occurring in some areas and widening in others. Site-specific responses, therefore, are likely to be highly variable; and traditional cross-section-based approaches to monitoring disturbance impacts might be inadequate. Stream power could provide a more effective summary because this important variable is strongly associated with percent-burned drainage area and integrates changes in width, depth, slope, roughness, and discharge. Characterizing the spatial distribution of stream power within a catchment, therefore, might enable scientists and managers to identify the locations most vulnerable to adverse fire-related effects.

Despite numerous studies of fire's effect on runoff and erosion, the fluvial knowledge base remains meager because previous examinations have for the most part been limited in spatial and temporal scope. Improved understanding of long-term, watershed-scale response to fire-related disturbance will be achieved only through collection of data from catchments burned to varying degrees and thorough documentation of processes occurring throughout the channel network.

References

Bagnold, R.A., 1977. Bed load transport by natural rivers. Water Resources Research 13, 303–312.

Bailey, T.C., Gatrell, A.C., 1995. Interactive Spatial Data Analysis. Longman Group, Essex, UK.

Barrett, S.W., 1994. Fire regimes on andesitic mountain terrain in northeastern Yellowstone National Park, Wyoming. International Journal of Wildland Fire 4, 65–76.

Berry, D.A., Lindgren, B.W., 1996. Statistics: Theory and Methods. Duxbury Press, Belmont, CA.

Bull, W.B., 1979. Threshold of critical power in streams. Geological Society of America Bulletin 90, 453–464.

Bull, W.B., 1990. Stream terrace genesis: implications for terrace genesis. Geomorphology 3, 351–367.

Bull, W.B., 1991. Geomorphic Responses to Climatic Change. Oxford Univ. Press, New York.

Cannon, S.H., 2001. Debris-flow generation from recently burned watersheds. Environmental and Engineering Geoscience 7, 321–341.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39, 171–188.

Chin, A., 1989. Step pools in stream channels. Progress in Physical Geography 13, 391–407.

Chorley, R.J., Kennedy, B.A., 1971. Physical Geography: A Systems Approach. Prentice Hall, London.

Cliff, A.D., Ord, J.K., 1973. Spatial Autocorrelation. Pion, London.

DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 231–232, 195–206.

Dietrich, W.E., 1987. Mechanics of flow and sediment transport in river bends. In: Richards, K.S. (Ed.), River Channels: Environment and Process. Blackwell, Oxford, UK, pp. 179–227.

Ernstrom, K., 1999. Effects of wildfire on first order stream channel morphology, Yellowstone National Park, USA. MS Thesis, Montana State Univ., Bozeman.

Ewing, R., 1996. Postfire suspended sediment from Yellowstone National Park, Wyoming. Water Resources Bulletin 32, 605–627.

Farnes, P.E., 1996. Impact of 1988 Yellowstone fires on snowmelt water yields. In: Greenlee, J.M. (Ed.), The Ecological Implications of Fire in Greater Yellowstone. International Association of Wildland Fire, Fairfield, WA, pp. 39–42.

Florsheim, J.L., Keller, E.A., Best, D.W., 1991. Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, Southern California. Geological Society of America Bulletin 103, 504–511.

Fonstad, M.A., 2000. Spatio-temporal variation in the power of mountain streams. PhD Dissertation, Arizona State University, Tempe.

Graf, W.L., 1983. Variability of sediment removal in a semi-arid watershed. Water Resources Research 19, 643–652.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Bulletin of the Geological Society of America 102, 340–352.

Griffith, D.A., 1987. Spatial Autocorrelation: A Primer Association of American Geographers, Washington, DC.

Griffith, D.A., 1996. Introduction: the need for spatial statistics. In: Arlinghaus, S.L., Griffith, D.A., Arlinghaus, W.C., Drake, W.D., Nystuen, J.D. (Eds.), PhB Practical Handbook of Spatial Statistics. CRC Press, Boca Raton, FL, pp. 1–16.

Harrelson, C.C., Rawlins, C.L., Potyondy, J.P., 1994. Stream channel reference sites: an illustrated guide to field technique. General Technical Report, vol. 245. US Department of Agriculture Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Helvey, J.D., 1980. Effects of a north central Washington wildfire on runoff and sediment production. Water Resources Bulletin 16, 627–634.

Huang, H.Q., Nanson, G.C., 2000. Hydraulic geometry and maximum flow efficiency as products of the principle of least action. Earth Surface Processes and Landforms 25, 1–16.

Hynes, H.B.N., 1975. The stream and its valley. Verhandlungen der Internationalen Vereininung fur Theoretische und Angewandte Limnologie 19, 1–15.

Inbar, M., Tamir, M., Wittenberg, L., 1998. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. Geomorphology 24, 17–33.

James, L.A., 1991. Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. Bulletin of the Geological Society of America 103, 723–736.

Jarrett, R.D., 1984. Hydraulics of high-gradient streams. Journal of Hydraulic Engineering 110, 1519–1539.

Johansen, M.P., Hakonson, T.E., Breshears, D.D., 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. Hydrological Processes 15, 2953–2965.

Kaluzny, S.P., Vega, S.C., Cardoso, T.P., Shelly, A.A., 1997. S+ Spatial Stats User's Manual for Windows and UNIX. Springer, New York.

Knighton, A.D., 1987. River channel adjustment—the downstream dimension. In: Richards, K.S. (Ed.), River Channels: Environment and Process. Blackwell, Oxford, UK, pp. 95–128.

Knighton, A.D., 1998. Fluvial Forms and Processes: A New Perspective. Oxford Univ. Press, New York.

Knighton, A.D., 1999. Downstream variation in stream power. Geomorphology 29, 293–306.

Knox, J.C., 1977. Human impacts on Wisconsin stream channels. Annals of the Association of American Geographers 67, 323–342.

Laird, J.R., Harvey, M.D., 1986. Complex response of a chaparral drainage basin to fire. In: Hadley, R.F. (Ed.), Drainage Basin Sediment Delivery. Publication 159. International Association of Hydrological Sciences, Washington, DC, pp. 165–183.

Leece, S.A., 1997. Nonlinear downstream changes in stream power on Wisconsin's Blue River. Annals of the Association of American Geographers 78, 471–486.

Legendre, P., 1993. Spatial autocorrelation: trouble or new paradigm? Ecology 74, 1659–1673.

Letey, J., 2001. Causes and consequences of fire-induced soil water repellency. Hydrological Processes 15, 2867–2875.

Lillesand, T.M., Kiefer, R.W., 1999. Remote Sensing and Image Interpretation, 4th ed. Wiley, New York.

Loaiciga, H.A., Pedreros, D., Roberts, D., 2001. Wildfire–streamflow interactions in a chaparral watershed. Advances in Environmental Research 5, 295–305.

Mark, D.M., 1984. Some problems with the use of regression analyses in geography. In: Gaile, G.L., Wilmott, C.J. (Eds.), Spatial Statistics and Models. Reidel, Dordrecht, Holland, pp. 191–199.

Martin, D.A., Moody, J.A., 2001. Comparison of soil infiltration rates in burned and unburned mountainous watersheds. Hydrological Processes 15, 2893–2903.

McEwen, L.J., 1994. Channel planform adjustment and stream power variations on the Middle River Coe, western Grampian Highlands, Scotland. Catena 21, 357–374.

Meyer, G.A., 2001. Recent large-magnitude floods and their impact on valley-floor environments of northeastern Yellowstone. Geomorphology 40, 271–290.

Meyer, G.A., Wells, S.G., Balling, R.C., Jull, A.J.T., 1992. Response of alluvial systems to fire and climate change in Yellowstone National Park. Nature 357, 147–151.

Meyer, G.A., Wells, S.G., Jull, A.J.T., 1995. Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. Bulletin of the Geological Society of America 107, 1211–1230.

Mihuc, T.B., Minshall, G.W., Robinson, C.T., 1996. Response of benthic macroinvertebrate populations in Cache Creek, Yellowstone National Park to the 1988 wildfires. In: Greenlee, J.M. (Ed.), The Ecological Implications of Fire in Greater Yellowstone. International Association of Wildland Fire, Fairfield, WA, pp. 83–94.

Minshall, G.W., Brock, J.T., 1991. Observed and anticipated effects of forest fire on Yellowstone stream ecosystems. In: Keiter, R.E., Boyce, M.S. (Eds.), The Greater Yellowstone Ecosystem: Redefining America's Wilderness Heritage. Yale Univ. Press, New Haven, CT, pp. 123–135.

Minshall, G.W., Brock, J.T., Varley, J.D., 1989. Wildfires and Yellowstone's stream ecosystems. Bioscience 39, 176–707.

Minshall, G.W., Robinson, C.T., Lawrence, D.E., 1997. Postfire responses of lotic ecosystems in Yellowstone National Park, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 54, 2509–2525.

Minshall, G.W., Robinson, C.T., Royer, T.V., 1998. Stream ecosystem responses to the 1988 wildfires. Yellowstone Science 6, 15–22.

Moody, J.A., Martin, D.A., 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26, 1049–1070.

Morris, S.E., Moses, T.A., 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. Association of American Geographers 77, 245–254.

Nanson, G.C., Hickin, E.J., 1986. A statistical analysis of bank erosion and channel migration in western Canada. Bulletin of the Geological Society of America 97, 497–504.

Nelson, A., 2001. Analysing data across geographic scales in Honduras: detecting levels of organization within systems. Agriculture, Ecosystems and Environment 85, 107–131.

Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W., 1996. Applied Linear Statistical Models. McGraw-Hill, Boston, MA.

Phillips, J.D., 1989. Fluvial sediment storage in wetlands. Water Resources Bulletin 25, 867–873.

Phillips, J.D., 1991. Multiple modes of adjustment in unstable river channel cross-sections. Journal of Hydrology 213, 39–49.

Pierson, F.B., Robichaud, P.R., Spaeth, K.E., 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. Hydrological Processes 15, 2905–2916.

Rhoads, B.L., 1987. Stream power terminology. The Professional Geographer 39, 189–195.

Robichaud, P.R., 2001. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. Journal of Hydrology 231–232, 220–229.

Robichaud, P.R., Brown, R.E., 1999. What happened after the smoke cleared: onsite erosion rates after a wildfire in eastern Oregon. In: Olsen, D.S., Potyondy, J.P. (Eds.), Wildland Hydrology. American Water Resources Association, Herndon, VA, pp. 419–426.

Robinson, C.T., Rushforth, S.R., Minshall, G.W., 1996. Diatom assemblages in Cache Creek, Yellowstone National Park following the 1988 wildfires. In: Greenlee, J.M. (Ed.), The Ecological Implications of Fire in Greater Yellowstone. International Association of Wildland Fire, Fairfield, WA, pp. 77–82.

Romme, W.H., Despain, D.G., 1989. Historical perspective on the Yellowstone fires of 1988. Bioscience 39, 695–700.

Rossi, R.E., Mulla, D.J., Journel, A.G., Franz, E.H., 1992. Geostatistical tools for modeling and interpreting ecological spatial dependence. Ecological Monographs 62, 277–314.

Schumm, S.A., 1969. River metamorphosis. Journal of the Hydraulics Division American Society of Civil Engineers 95, 255–273.

Schumm, S.A., Lichty, R.W., 1965. Time, space, and causality in geomorphology. American Journal of Science 263, 110–119.

Swanson, F.J., 1981. Fire and geomorphic processes. In: Mooney, H.A., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., Reiners, W.A. (Eds.), Fire and Ecosystem Processes. USDA Forest Service General Technical Report WO-26. US Government Printing Office, Washington, DC, pp. 401–420.

Thorne, C.R., Tovey, N.K., 1981. Stability of composite river banks. Earth Surface Processes and Landforms 6, 469–484.

Tiedemann, A.R., Conrad, C.E., Dieterich, J.H., Hornbeck, J.W., Megahan, W.F., Viereck, L.A., Wade, D.D., 1979. Effects of fire on water: a state-of-knowledge review. USDA Forest Service General Technical Report WO-10 US Government Printing Office, Washington, DC.

Troendle, C.A., Bevenger, G.S., 1996. Effect of fire on streamflow and sediment transport in Shoshone National Forest, Wyoming. In: Greenlee, J.M. (Ed.), The Ecological Implications of Fire in Greater Yellowstone. International Association of Wildland Fire, Fairfield, WA, pp. 43–52.

Vasiliev, I.R., 1996. Visualization of spatial dependence: an elementary view of spatial autocorrelation. In: Arlinghaus, S.L., Griffith, D.A., Arlinghaus, W.C., Drake, W.D., Nystuen, J.D. (Eds.), PhB Practical Handbook of Spatial Statistics. CRC Press, Boca Raton, FL, pp. 17–30.

Wohl, E., 2000. Mountain Rivers American Geophysical Union, Washington, DC.

Wohl, E.E., Vincent, K.R., Merrits, D.J., 1993. Pool and riffle characteristics in relation to channel gradient. Geomorphology 6, 99–110.