Chapter 6

WATERSHED AND STREAM DYNAMICS

Going with the flow

In addition to causing changes in forest structure, large crown fires may produce rapid alterations in the underlying landscape. In a vegetated watershed, trees and other plants help hold the soil in place, absorb rain, and reduce the snowpack that would otherwise accumulate on the ground. When a watershed burns, dramatic changes in streams may result from tree fall, loss of plant cover, the release of nutrients from vegetation into streams and lakes, debris and sediment flows, changes in water temperature, and shifts in the aquatic food web.

- The loss of vegetation reduces the amount of water absorbed by the soil and plants, which in turn increases the portion of precipitation leaving the watershed.
- The increased water flow can increase erosion and mobilize debris, transporting sediment and nutrients downstream, and affecting floodplain species like aspen, willow, and alder. Runoff events can also destroy bird nests and, at least over the short term, decrease biotic diversity and production.[1]
- But debris flows and floods are a major source of spawning gravels, and the addition of sediments and nutrients to aquatic ecosystems and the higher summer water temperatures (because of loss of shading vegetation) may bring about pulses in aquatic productivity for up to six years after a large fire.[2]
- Like the young seedlings that sprout after the fires, the charred trees that tower over them are part of a long-term shift in nutrient cycling and soil processes. Although some of these snags may remain standing for decades, many have already toppled to the ground, creating a coarse woody debris that provides habitat for certain insects, fungi, and nesting birds.

Gibbon River, July 2000.

The 1988 fires have led to ongoing changes in the park's streams, sending gravel and tree trunks into some sections and deepening others. The magnitude of these changes is affected by the geology, topography, and size of the stream; the amount and timing of subsequent precipitation; and the size and severity of the fire.

Runoff and Erosion

In human communities, erosion is generally regarded as a problem that can reduce topsoil and other property value. If the human species had been around at the time, someone would have wanted to do something about the excessive erosion that resulted in Arizona's Grand Canyon. In Yellowstone, fire-related erosion has been a major factor in the export of sediment from tributary basins and has had a substantial impact on the park's landscape. The sedimentation record shows that fire-related debris flows make up about 30% of the deposits in alluvial fans that have been accumulating during the late Holocene.[3]

G. Wayne Minshall and his colleagues at the Stream Ecology Center of Idaho State University have compared "burn streams," where at least 50% of the catchment burned in 1988, to "reference streams" where no more than 5% of the catchment burned. Comparison with an entirely unburned site was not feasible because nearly all of the park's large watersheds burned to some extent. They found that sheet erosion, rill and gully formation, and mass movement of material occurred on burned watersheds in Yellowstone during the summer of 1989, when heavy rains were followed by widespread "black water" conditions and debris torrents.[4] Three major mudslides and a dozen smaller ones caused by a rainstorm in August 1989 carried large volumes of silt, sand, and stones into the Gibbon River a short distance above Gibbon Falls. Suspended sediment increased in streams in burned watersheds throughout the park following runoff from both snowmelt and rain from spring through summer in 1989 and 1990.

When the water rises.

But the extent of channel alterations was substantially larger in 1991, when at least two large runoff events caused major physical changes and declines in the biotic components in all of the study streams located in burned watersheds with moderate to steep gradients. Most high-gradient burn streams underwent major changes in channel morphology. For example, high flows in the catchment of 3rd order Cache Creek caused the channel to shift laterally about 30 meters, while the channel in 1st order Cache Creek, despite significant regrowth of riparian vegetation, was cut down to bedrock in many areas.

Since 1991, the input of fire-related sediment into Yellowstone streams has been greatly reduced by even sparse growth of herbaceous plant cover, and much of the sediment is now being deposited along the sides of valleys and on flood plains, where the organic and nutrient-rich material contribute to the productivity of these environments.[5] Fire-related debris flows and floods have occurred only in limited areas, such as from dry, south-facing slopes that are slower to revegetate. However, some streams in burned watersheds changed more from 1995 to 1997 than in the first six post-fire years, demonstrating the importance of long-term research after a large-scale disturbance.[6]

Conclusions based on only a few years of data can be misleading, "as evidenced by the apparent 'devastation' of stream ecosystems immediately after the 1988 fires, their rapid progress toward 'recovery' in post-fire years 1 to 2, their equally abrupt downturn in post-fire years 3 to 4, and their massive reorganization in years 7 to 9." The initial "recovery trajectory" was much different—faster initially, with more time before major storm impacts were seen—than was expected.

— Minshall et al., 1998

Streams are commonly differentiated by "orders," where the smallest unbranched tributaries are designated 1st order streams, the joining of two or more 1st order streams forms a 2nd order stream, and so on. The park's largest streams are 6th order. The low-order stream watersheds in Yellowstone tended to burn either extensively or not at all, and when they did burn, they underwent more physical and chemical variations than did higher-order streams.[7] For example, low-order streams in burned watersheds were more likely to experience light and temperature increases because the loss of the shade provided by streamside vegetation would have a larger impact on them. The mean catchment burned at the Stream Ecology Center's study sites was 75% for 1st and 2nd order streams and 50% for 3rd and 4th order streams. However, during aerial and ground reconnaissance they observed that the catchments of many fire-affected 3rd and 4th order streams in the park and along its northern boundary were less than 50% burned, and larger streams even less.

When the snow melts.

Snowmelt accounts for 50% to 70% of the total annual runoff in lodgepole pine and spruce/fir stands of the northern Rockies.[7] The forest openings created by fire can increase the amount of snow and rain that reaches the ground, and the loss of vegetation and increased hydrophobicity (water repellency) of soils may cause snowmelt to begin earlier. After the 1988 fires, water users downstream from the park and agencies responsible for disaster actions were concerned about possible changes in streamflow volumes, and the timing and amount of peak flows.

Data on streamflow has been collected at gauging stations maintained by the U.S. Geological Survey on the Yellowstone and Madison rivers since 1911, making it possible to assess the impact of the 1988 fires on runoff in subsequent years. Based on data through 1998 regarding annual fall soil moisture, spring precipitation, and the extent to which the loss of forest canopy had increased snow and rain "throughfall," three researchers from Montana State University in Bozeman estimated that the fires had increased annual runoff for the Yellowstone River at Corwin Springs 4% to 5%, and that the peak runoff was occurring two days earlier than before the fires.[8] Runoff for the Madison River near Grayling Creek was estimated to have increased about 6% to 8% during the same period. They predicted that runoff levels will remain higher as a result of the fires until the forest canopy closes again toward the end of the 21st century.

However, these increases are relatively insignificant compared to the annual fluctuations that result from variations in precipitation amounts. For example, the lowest volume of runoff recorded for the Yellowstone River (59% of the long-term average) occurred in 1934, during an extended period of drought; the highest runoff (161% of average) was recorded in 1997, when the snowpack was 154% of average.

In comparing three burn and two reference 1st order streams that drain into the Lamar and Yellowstone rivers, Wayne Minshall of the Stream Ecology Center and Michael McIntyre of the Idaho Division of Environmental Quality found that during the first two years post-fire, the burn streams had significantly higher flows in summer and fall than did the reference streams, but not during the snowmelt period.[8] This could be at least partly due to the loss of trees which had previously lowered the water table in summer and fall.


Cache Creek, August 1995.

Both Jones Creek and Crow Creek in the North Absaroka Wilderness in the Shoshone National Forest have primarily north and south-facing slopes of similar steepness and elevation zones dominated by subalpine fir. But while the Clover Mist fire burned only 2% percent of the Crow Creek watershed in 1988, leaving 60% forested; it severely burned 50% of the Jones Creek watershed, leaving 15% forested and newly hydrophobic soil 2.5 to 10 cm deep. Because of the comparative data on fire effects that these adjacent watersheds could provide, a post-fire monitoring study was established as an interagency effort (Shoshone National Forest, Rocky Mountain Forest and Range Experiment Station, U.S. Geological Survey, and the Wyoming Department of Environmental

Quality). During the 1989–92 period, which was not particularly wet, the flow from Jones Creek averaged 540 mm per km^2 of watershed area (66.8 km^2 total area) and Crow Creek, 402 mm per km^2 (in a 49.5 km^2 watershed area). The data collected at these sites suggested that the Clover Mist fire had increased both streamflow quantity and sediment export during this period, but had little effect on peak discharge or summer storm response.[9]

The U.S. Fish and Wildlife Service (USFWS), which previously maintained a field station in Yellowstone, selected study sites on six 4th to 6th order streams in watersheds ranging from 9% burn (Soda Butte Creek) to 50% burn (Lamar River). Their data on streamflow also showed no significant post-fire change in peak discharge. The trends in discharge generally paralleled annual precipitation levels from 1985–91; the peak discharge was highest in 1986, the year of greatest precipitation at all sites except the Gibbon River.[10]

Changes in runoff as a result of fire may alter the interacting influences of erosion, stream channel morphology, sediment composition and concentration, and the recruitment and distribution of large woody debris. However, in places where the forest canopy is only scorched, fallen needles may create a mat that checks erosion, and toppled snags can serve as dams on hillsides. Erosion and channel alteration usually peak during the snowmelt period. But when the very cool extended spring resulted in an unusually slow snowmelt in 1989, runoff peaks were much reduced, and erosion and channel alterations were largely determined by summer rainstorms. The drought of 1988 may also have affected runoff; much of the melting snowpack remained stored in the unusually dry soils.

Forest litter prevents soil loss.

Richard Marston and David Haire measured runoff and soil loss in the summer of 1989 through a series of rainfall simulation experiments at 30 sites in the Shoshone National Forest and the John D. Rockefeller Memorial Parkway representing a range of geologic substrates, logging history, and burn intensities.[11] Soil loss was greatest at sites that had been logged, a finding that was attributed to the reduction in litter on the forest floor. Litter density was the key variable controlling both runoff and soil loss. When the timber is harvested, lodgepole forests are typically clear-cut, leaving no source of post-fire needles to replenish litter cover, but even in forests that had not been logged, lodgepole pine needles burned easily in the 1988 fires. Douglas-fir forests that had been selectively logged provided post-fire needles because they are more fire-resistant.

Marston and Haire found that the correlation between runoff and soil loss was poor. For example, silty soils had lower runoff but higher soil loss. Most soil was mobilized by rainsplash, not runoff, as was evident in the greater soil loss in 1989 from summer storms than from snowmelt runoff. Nor was slope gradient a significant factor; its effect was confounded by the high micro-roughness of the soil surface as a result of litter, grass, and downed timber. For this reason, both logging and fire history had a larger impact on soil loss and than on runoff. But erosion effects generally peak within 10 years after a fire event, while road building, log yarding, tree clearing, and slash burning may produce sources of erosion that persist for decades, and the sediment stored behind fallen logs may be remobilized if salvage logging is done.


Lamar River, September 1998.

Most of Yellowstone's trees are evergreen, but the deciduous trees and bushes it does have tend to be concentrated in the damper areas along streams. The leaves from these plants, such as aspen, willow, and alder, provide organic matter that is much more favorable for aquatic life than are pine and spruce needles.[12] In the absence of fire, stands of evergreens eventually replace the deciduous vegetation along streams, further reducing the transfer of nutrients from the land to streams to lakes. Post-fire regrowth in riparian areas depends on the species that were present before the fire and the intensity of burning. Over both the short and long term, changes in riparian vegetation can affect soil stabilization and the insect community.

Riparian vegetation.

During and after the 1988 fires, Deron Lawrence and Wayne Minshall of the Stream Ecology Center photographed vegetation at five locations along each of 18 burn and 4 reference streams in the park.[13] At the burned sites immediately after the fires, the topsoils were charred and most of the organic matter was vaporized, leaving only mineralized products, yet many stems and tree boles were still intact. After one year, the grasses and forbs were still of low stature and did not cover the soil. These plants intercept rainfall and protect soil from minor erosion but not from intense rainstorms or snowmelt, which can move large amounts of sediment to the stream channel.

During the second year post-fire, the grasses and forbs increased in height and coverage, further stabilizing the soil. But a heavy snowpack combined with spring rains the following year to increase peak flows and sediment loading, which led to widespread channel cutting and vegetation suppression. These high flows returned the successional process to a state in which new plants colonize areas of sediment deposition.

The role of woody debris.

Crown fires can create large amounts of coarse woody debris (CWD), some of which may be combusted or converted to charcoal in subsequent fires. Over the short term, the presence of CWD in streams affects channel morphology, retains organic matter and sediment, and provides habitat heterogeneity and stability for fish and insects. To study the effects of various disturbances on soil quantity and quality, in 1995 Daniel Tinker and Dennis Knight began comparing the amount of CWD in burned and unburned Yellowstone forests to that in clear-cut and uncut sites in the Medicine Bow National Forest.[14] Their research has shown that clear-cut stands of lodgepole pine generally contain 50% less CWD than stands of similar pre-disturbance density and age. But the fire-related changes that result from CWD recruitment can last for decades in forested drainages. In extreme cases where fire has consumed much of the vegetation or water yield is substantially increased, debris loading may decline until revegetation can provide new sources of wood.[15]

Compared to their unburned study sites, McIntryre and Minshall found fewer naturally occurring dams in burned watersheds during the first two years post-fire in 1st to 3rd order study streams, perhaps partly because they had been washed out by higher discharge resulting from the fire. The burn streams were still experiencing a net loss of wood through 1991.[16] Although CWD may increase immediately after a fire, it generally bridges the stream, and in the Yellowstone climate it may take at least 10 years for the effects of wind, decay, and channel repositioning to incorporate it into the stream debris.[17]

Minshall noted that many of the conifer seedlings in the Stream Ecology Center's study areas that had germinated after the fires were six feet tall by 1997, and many of the charred tree trunks were still standing.[19] The continuing growth of young trees and falling of dead trees will continue to alter the availability and movement of CWD.

Fires can increase sediment transport in burned watersheds because the loss of tree canopy increases the raindrop impact on the soil and the loss of ground cover increases surface flow. High

Debris in the Fast Lane

Michael Young and Michael Bozek from the University of Wyoming used the heavily burned Jones Creek watershed and the nearly unburned Crow Creek watershed to compare the movement of CWD by attaching aluminium tags to 160 pieces of debris that were at least two meters long.[18] In 1990 and 1991, debris in Jones Creek was three times more likely to move, and moved more than four times as far as debris in Crow Creek. The greater duration of high spring flows after snowmelt or occasional high summer flows after thunderstorms apparently displaced much of the debris in the burned watershed. But in subsequent years as more dead trees fell over, the debris in the Jones Creek watershed was expected to slow down.

sediment loads were observed in some streams draining burned watersheds after the 1988 fires, but usually only during spring runoff or after heavy thunderstorms. The average annual precipitation was greater from 1989–92 than it had been from 1985–87, but the first two post-fire years had relatively cool springs and dry summers, resulting in slower snowmelt and lower streamflows than pre-fire.

Sediment heads downhill.

With three years of data collected prior to the 1988 fires, Roy Ewing on the park staff continued his research to measure the effects of the fire on suspended sediment in two of the park's major rivers, the Yellowstone and its principal tributary, the Lamar.[20] Compared to the long-term average (1961–90) the largest annual snowmelt runoff (116%) and the largest April–September runoff (102%) on the Yellowstone River at Corwin Springs during the first four post-fire years occurred in 1991. However, these levels were lower than they had been in 1986, when snowmelt runoff was 126% and total April–September runoff was 116% of the long-term average.

Ewing also sought to isolate the changes in sediment levels that were due to the fires from those due to changes in precipitation by determining the relationship between streamflow and sediment for the pre-fire period and using it to project sediment loads for the post-fire period. If an actual post-fire load was greater than the predicted load for a given season, then the increase could be fire-related. In this way, Ewing determined that fire-related increases in suspended sediment had occurred on the Yellowstone and Lamar rivers after the 1988 fires, but not consistently throughout the year or throughout the watershed.

Delayed release of sediment.

The portion of the total sediment load that the river carries as bed load (the coarser sediment) is often larger in the mountainous headwaters. During field trips in the Lamar River basin, Ewing located many woody debris jams which were storing coarse bed-load sediment that would be released during the first high-streamflow storm. Summer transport of sediment in the severely burned steep drainages of the Lamar River basin more than tripled after the fires and yet the effects were not experienced downstream, where they were apparently diluted by clear runoff from unburned watersheds or those unaffected by storms.

Cache Creek, July 1998.

Ewing determined that the sediment load in the Yellowstone River was about 60% higher during snowmelt in 1989–1992 because of the fires; increases during the summer were less than half that. But on the Lamar River, sediment transport appeared to have diminished by 1992 to less than what would have been projected under pre-fire conditions.

Although the native soils are prone to erosion and the background sediment concentrations and load are quite high, Charles Troendle and Greg Bevenger of the U.S. Forest Service found that sediment export in the burned Jones Creek watershed was significantly greater in terms of both concentration and total suspended load than it was in the unburned Crow Creek watershed.[21] During the 1989–92 period, Jones Creek yielded an average load of 59 metric tons/km², compared to only 13 metric tons/km² from Crow Creek. On at least one occasion, after an intense rainstorm in August 1990, the suspended sediment apparently caused some trout to suffocate.[22]

However, "the data do not indicate the hill slopes have unraveled and delivered greater amounts of material to the riparian/channel environment." Troendle and Bevenger hypothesized that because the fire removed riparian vegetation in the Jones Creek watershed, including woody debris and root systems, the material already in the stream bed and banks may have become destabilized and more readily available. "The storm response appears to be from near or within channel sources, minimizing the opportunity for off-site delivery." In the absence of extreme rainfall events or severely wet antecedent conditions, "the opportunity for increased erosion and introduction of new sediment to the channel system appears to have been minimal."

Sediment deposits.

Dan Mahony and Robert Gresswell, continuing the USFWS research, monitored annual variations in streamflow, substrate composition, water chemistry, macroinvertebrate communities, fish populations, and recreational fishing at six sites in the park.[23] Annual precipitation after the fires was similar at all sites, and the peak streamflow occurred about two to four weeks earlier than in the three years previous to the fires. Yet despite large variation in substrate, Mahony and Gresswell found that the amount of fine sediment at different sites was not related to either the size or the burned percentage of the watershed. The most prevalent effect of the fires appeared to be that low-gradient 4th to 6th order streams were functioning as depositional areas for sediment and nutrients transported from higher-gradient upstream burned areas. Data collected by Minshall and Robinson also suggested the presence of "a pulse of fine sediments moving from the burned watersheds into the headwater streams and then gradually into larger burn streams over time."[24]

Organic matter.

The detritus that collects in streams from decaying vegetation, fecal matter, and dead algae is a major source of carbon and nutrients in aquatic food webs. Boulders, rocks, debris dams, and riparian vegetation impede the transport of organic detritus, allowing time for it to be transformed into particles through physical and biological processing before moving downstream. When fire converts upland and riparian vegetation to charcoal and ash (which are not food sources), the amount of light and organic matter that enter streams is immediately affected.

Organic matter in streams can be described as either "benthic" (remaining in place on the bottom) or "transported" (in transit), and measured in two size categories: fine particulate organic matter (FPOM) and coarse (larger than 1 mm) particulate organic matter (CPOM). As a result of major runoff events in 1991, both FPOM and CPOM and the percent charcoal increased at all 18 of the Stream Ecology Center's burned study sites that year.[25] Benthic organic matter increased initially in the 1st to 3rd order burn streams (with the largest increase at the 1st order sites); data since 1989 indicate that although reduced in amount, charcoal was still being added to burn streams, which could decrease the quality of organic matter as food for aquatic insects (see page 96).

In their comparison of 1st order streams during the first two years post-fire, McIntyre and Minshall found that the burn streams transported more organic matter in all seasons and that burn stream CPOM was mostly charcoal, where as CPOM in reference streams consisted of dead leaves, needles, and twigs.[26] They suggested that fire reduces the capacity of burn streams to store organic matter by increasing runoff, by altering the types and magnitudes of riparian vegetation and debris dams that serve as retention barriers, and by transforming the CPOM itself.

Aquatic Habitats

Four large lake watersheds and about a third of the park's streams were in drainages that burned to some extent in 1988. Fire-related changes in riparian vegetation, water quantity and quality, the timing and intensity of peak discharges, and the physical characteristics of a stream can affect aquatic biology. In the Yellowstone fires, the degree of alteration of stream habitat was highly correlated with stream size and the percent of catchment burned.[27] The area burned within the affected watersheds ranged from less than 10% to more than 90%. Because of differences in landscape morphology and in the nature of the fires, streams in the Madison, upper Yellowstone River, and Snake River drainages were less likely to be affected by the fires than the other main river systems in greater Yellowstone. As the size of the watershed increases, larger portions remain unburned and the larger volumes of water that feed the watershed's streams and lakes serve to diffuse the fire effects.[28]

Although fire may cause immediate and temporary changes in water chemistry and food resources, the major potential impact on aquatic ecosystems is the physical disturbances resulting from increased runoff; changes in runoff timing and magnitude may diminish species that lack the genetic or reproductive capacity to adjust. There may also be longer-term shifts associated with the removal and eventual replacement of vegetation and the resulting changes in the stream's food resources and retention capacity.[29]

Most of the effects of fire and fire suppression activities observed in Yellowstone's aquatic habitats have been short-term. Although the 10 million gallons of water drawn from ponds and streams and the 1.4 million gallons of fire retardant dropped by aircraft in or near the park may have had little effect on the fires, they also caused little disturbance to aquatic life. About 100 dead fish were seen in Fan Creek and in Little Firehole River after accidental drops of fire retardant, but the ammonium phosphate was quickly diluted and the effects temporary. Changes in some aquatic organisms, such as diatoms and benthic invertebrates, were observed in small streams, but no obvious effects on the organisms of the larger rivers or on fish populations have been detected.

The proximity of fires themselves did not raise water temperatures above the tolerance levels of fish and aquatic invertebrates, nor did the loss of overhead canopy generally result in greater extremes in water temperatures even in smaller streams. Although the minimum temperature increased 3°C from 1988 to 1991 at two of the Stream Ecology Center's Iron Springs Creek sites and the main Blacktail Deer Creek site, it remained "essentially unchanged" at the other 15 burn sites and the four reference sites.[30]

The pulse of minerals that is released from plant matter by fire eventually reaches the park's waters. By mobilizing nutrients in upstream biomass or soils and moving downstream, fires may serve to link the terrestrial and aquatic biogeochemical cycles.[31] The level of post-fire nutrient input to aquatic systems depends on factors such as fire severity and size, weather, and the physical, chemical, and biological characteristics of the watershed.

Water relocation, 1988.

Changes in water chemistry.

Analysis of water samples from six 4th to 6th order streams in the USFWS study showed slight increases in chemical concentrations during the first or second year post-fire, but they remained within the range of pre-fire records, and the similarity between Soda Butte Creek (9% of watershed burned) and heavily burned watersheds suggested that some increases were not fire-related.[32] The only change in water chemistry that the USFWS attributed to the fires was an increase in silica in the Gibbon and Madison rivers in 1989 and 1990. Elevated silica concentrations are not unusual in rhyolitic watersheds such as these, and apparently resulted from post-fire debris torrents that occurred in the drainage. Silica concentrations in the Madison River, which increased nearly eightfold after the fires and were the highest of any found in the park, may have been related to upstream landslides in the Gibbon River during the summer of 1989.

Minshall found that changes in water chemistry varied considerably among streams, but usually occurred in smaller streams during the first few post-fire years, while ash was available to provide the chemicals and before regrowth of streambank vegetation.[33] At the Stream Ecology Center burn stream sites, the concentration of most dissolved constituents increased between October 1988 and August 1989, apparently in response to recent rainstorms. Nitrate levels were as much as 3 to 4 times higher in catchments with moderate to extensive physical change after the fires (e.g., channel morphology), and they remained elevated in most burn streams, suggesting a loss of nitrogen from the catchment even five years post-fire.[34] However, nitrate levels subsequently declined in burned areas as the growing plants sequestered nutrients and delayed or prevented their runoff into streams.

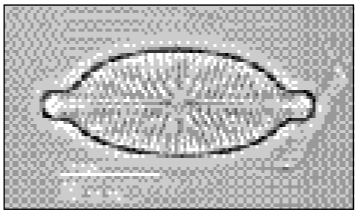
In a project sponsored by the U.S. Forest Service, four scientists from NASA-Ames found that both nitrate and phosphate levels increased significantly in five streams in burned watersheds and were still high five years later.[35] While the levels stayed constant in an unburned reference stream (Amphitheater Creek), nitrate was 2.6 to 33 times higher and phosphate 2 to 29 times higher in burn streams, with concentrations correlated to fire intensity in the watershed and subsequent periods of snowmelt and summer storms.

Efects on groundwater.

To investigate the possibility that the leaching of minerals by ash might affect ground water, for two years after the fires Donald Runnels and Mary Siders of the University of Colorado tested samples at four groundwater wells in watersheds of varying burn intensities for which pre-fire data were available.[36] They found that the changes were minimal and within the known range of pre-fire variation. They suggested that the “assimilative capacities” of the soil and rock substrate were sufficient to attenuate the impact that large quantities of ash-derived solubles could have on the ground water chemistry.

Diatoms

In streams draining montane areas that are low in plant nutrients, diatoms (Bacillariophyta) are often the predominant algae. The Cache Creek catchment, which was 80% burned, underwent substantial shifts in stream morphology after the fires, providing an opportunity to document changes in diatom assemblages along the length of a stream system relative to temporal changes in the physical environment. Researchers from the Stream Ecology Center collected samples at five sites in 1st through 4th order streams in the Cache Creek catchment in September 1988 and August 1989–1992, and compared changes in diatom assemblage structure and stream morphology with those in Rose Creek, a 2nd order stream in an unburned catchment.[37] Both streams drain areas that were primarily vegetated by coniferous forests of lodgepole pine and Engelmann spruce; riparian vegetation consisted of willow, rose, and alder.



Navicula constans (greatly magnified)

Species richness and diversity were reduced in Cache Creek during the study period, especially in 1st and 2nd order streams, but substantial increases were observed in the relative abundance of *Navicula permitus, Cymbella sinuata*, and *Nischia inconspicua* compared to

Rose Creek. The researchers noted that both *N. permitus* and *N. inconspicua* are extremely small diatoms that are probably highly resistant to physical disturbance. They found more pronounced changes in diatom assemblages in 1991, especially in burn streams hit by high flows in late spring and July. As a result of the increase in disturbance magnitude and frequency at the burned sites, disturbance-favored taxa remained dominant there, even after four years.

Lakes

Depending on the amount and timing of precipitation, some of the sediment, debris, and nutrients that move down through the park's watersheds ultimately end up in a lake as their final resting place. As in streams, the increased erosion that may occurr after a fire can increase the sediment load in lakes, and the documented decline in the productivity of Yellowstone Lake during the last century has been attributed to the lack of fire.[38] About a quarter of the Yellowstone Lake and Lewis Lake watersheds and half of the Heart Lake watershed burned to some extent in 1988, but no significant changes have been observed in nutrient enrichment, plankton production, or fish growth as a result. However, these lakes may be large enough in comparison to their watersheds to dilute the effect of any increased runoff. (Yellowstone Lake covers 354 km^2 in an approximately 2,600 km^2 watershed.) Jackson Lake in Grand Teton National Park, which is smaller in relation to its basin and has a different bedrock and more noticeable sediment load, was less able to absorb post-fire sediments without loss of clarity after 26% of its watershed burned in 1988.

Data collected from 1976–91 for Yellowstone's four largest lakes (Yellowstone, Lewis, Heart, and Shoshone) revealed minimal post-fire changes in water quality; Robert Lathrop of Rutgers University believed that the major factor in annual fluctuations of chemical constituents to be precipitation.[39] All of the lakes except Shoshone showed post-fire decreases in sulfate, chlorine, and calcium, and increases in pH, sodium, and potassium, but because of changes in atmospheric chemistry, geothermal influences, and fisheries management, the impact of the fires cannot be isolated. An analysis of Landsat Thematic Mapper (TM) data and Advanced Very High Resolution Radiometer (AVHRR) imagery for Yellowstone Lake from 1987–90 also indicated no changes in water quality. However, because of its large volume and long renewal time (it takes 10 years for the entire lake to be replaced by new water), Lathrop believed the peak effect on Yellowstone Lake may have lagged behind the maximum yield from stream inputs by several years.

A similar analysis by Edward Theriot of the Academy of Natural Sciences in Philadelphia, who looked at data on the same four lakes through 1993, found an increase in total dissolved solids and silica after the fires.[40] Although this could be attributed to increased post-fire erosion from the catchment, Theriot suggested it could also be the result of increased diatom production or a drought-caused productivity decline, which would reduce the biological demand for silica. Other indications of biological activity that he measured, such as underwater visibility, conductivity, and sodium concentration, did not change significantly after 1988.

Beach Lake, September 1994.

Aquatic Insects

Macroinvertebrates, which include all invertebrates large enough to be seen without magnification, are an essential part of the aquatic food chain. Yellowstone's trout fisheries consume aquatic insects such as mayflies, caddis flies, and stone flies that feed on plant matter or by scraping algae off rocks. After riparian vegetation burns, the amount of plant litter falling into streams may decline dramatically, and in once-shaded reaches that are exposed to the sun, algae growth may increase. These shifts can be advantageous to insects that eat food produced in the stream—collectors and scrapers, such as mayflies and riffle beetles—rather than the normally dominant shredders that feed on detritus that falls into streams.

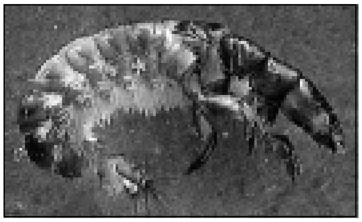
Because little data had been collected on pre-fire macroinvertebrate communities, changes that have been observed in them cannot be definitively attributed to the fires. However, comparisons with sampling done at unburned streams have suggested that the insect communities in burn streams changed dramatically as water conditions and food resources changed, and in some cases, have not returned to their pre-fire composition.

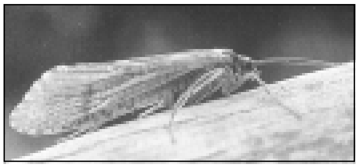
From October 1988 to March 1989, macroinvertebrate abundance and richness decreased in six out of eight burn sites at Cache Creek (while increasing or remaining the same in reference streams), but began to show substantial recovery before the first post-fire year had ended.[41] Changes in species composition, however, were apparent even nine years later, reflecting alterations in food resources and a shift to "trophic generalists"—organisms that can survive in a range of habitats. The Stream Ecology Center researchers attributed these changes at burn sites to high levels of charcoal (more than 40%) in the stream bottom that decreased the palatability and quality of organic matter as food sources. In laboratory experiments to determine the response of benthic macroinvertebrates to different foods, only one of the 11 taxa examined, *Paraleptophlebia heteronea* (a mayfly) could grow on burned detritus, but it didn't increase in post-fire streams because it requires a stable flow and substrate conditions.[42] The only species that increased in abundance at burned sites during the first post-fire year were chironomids (midges) that are believed to have a competitive advantage in streams with heavy sediment deposition because they are sediment burrowers that can produce multiple generations in a single year.

But the abundance and biomass of chironomids dropped steadily after the second year post-fire, and within a decade about half the invertebrates in Cache Creek were feeding on both litter and food produced in the stream; charcoal was still being added to the streams at the burn sites, but at a lower rate. After 1990, most fire-related effects appeared to be the result of higher peaks in runoff that caused physical disturbances in the stream bed, rather than changes in food resources.[43] The real survival test for a species, therefore, appeared to be not its food preferences, but whether it could endure the harsher physical environment of the post-fire stream.

A study from 1988 to 1992 at six burned sites in Cache Creek and four unburned reference sites indicated a correlation between taxa recovery and stream size, probably because of the higher slope and larger burned catchment area of smaller streams.[44] Species that require habitat with stable riffles or slower current velocities declined in abundance and biomass at burned sites during the study period, while generalists such as *Baetis bicaudatus* (a mayfly) and *Zapada columbiana* (a stonefly) were common. They feed on both detritus that falls into the stream and periphyton (attached algae) that grows in it.

Returning in July 1993, the researchers found that the channel morphology at Cache Creek still appeared unstable, and the burned sites there still had different diatom assemblages than the unburned sites at Rose Creek.[45] Periphyton biomass was lower in Cache Creek, suggesting a lack of recovery by primary producers. Chironomids were the most common





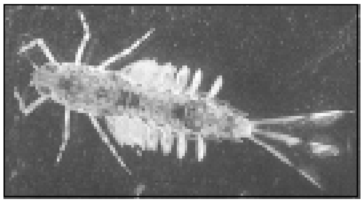
Caddisflies: larva (above) and adult (below) taxon in both burned and unburned sites, but macroinvertebrate richness, density, and biomass were still greater in the unburned sites. Opportunistic species such as chironomids and *B. bicaudatus*, which are well-suited for dispersal through drift (voluntary or accidental dislodgment from the stream bottom into the water column where they move or float with the current) and have relatively short generation times, seemed especially well adapted to post-fire conditions regardless of their trophic niche. The abundance of other species, especially Ephemeroptera (mayflies) such as *Cinygmula, Epeorus,* and *Rhithrogena* decreased soon after the fires and had showed little or no recovery.

While the research done at Cache Creek indicated that post-fire increases in streamflow and the resulting alterations in channel configuration or substrate composition could have reduced macroinvertebrate productivity at low-order streams, the USFWS found that macroinvertebrate abundance and species richness increased between the fall of 1988 and the summer of 1991 in most of its higher-order study streams.[46] Estimated biomass was highly variable among the streams and often highest in the first year post-fire, but no general patterns could be detected. At the three sites that exhibited a substantial decline in macroinvertebrate abundance and a substantial increase in streambank erosion during the first post-fire year (Lamar River, Slough Creek, and Firehole River), the USFWS researchers found no significant correlation between the estimated proportion of silt in the stream substrate and the macroinvertebrate abundance; the estimated erosion was similar at the unburned Soda Butte Creek sites, where macroinvertebrate abundance increased between 1988 and 1989.

The 5th order Gibbon River also showed declining macroinvertebrate abundance, species richness, and biomass during the first three post-fire years, which could have been affected by large fire-related debris flows in 1989 and 1990. The Gibbon River had the lowest post-fire chironomid abundance of any USFWS study site, and it declined as the proportion of post-landslide sand in the stream bottom increased. Sand is an unsuitable substrate for many benthic invertebrates, but the USFWS researchers suggested that the main effect of large sediment inputs from the landslide could be channel scouring, which would reduce the instream vegetation that provides suitable attachment sites for certain taxa.

Many of the invertebrate taxa that USFWS collected from the study streams were classified as moderately to highly tolerant of sediment inputs, suggesting that these streams are adapted to periodic sedimentation episodes. But the most common change in macroinvertebrate communities was in the relative proportion of the various trophic groups. Similar to the trends commonly observed in lower-order streams, macroinvertebrates at the USFWS study sites began to shift from a detritus-based to an autotrophic community (able to produce its own food from inorganic constituents) by the third year post-fire. This was particularly true in the Gibbon River, where a riparian-dependent community (shredders and collectors) was replaced by a community dominated by scrapers. Since scrapers are primarily dependent on food grown within the stream, the increasing abundance in this trophic group indicated an increase in primary production in the study streams.

George Roemhild, an entomologist at Montana State University who began collecting aquatic insects in Yellowstone in 1979, had sampled all of the park's major streams and many small backcountry streams prior to the fires of 1988, and returned to the same sites in 1991 and 1992.[47] Comparing three groups (stoneflies, mayflies, and caddisflies) before and after the fires, he found no large changes in the number or diversity of insect populations over the park as a whole. Noting that samples taken after the fires contained large amounts of charcoal, Roemhild speculated that it may have absorbed noxious gases and chemicals created by the fires, protecting the insects.



Mayflies: nymph (above) and adult (below)

Fish

As with many other kinds of wildlife in the park, fires can have both negative (usually short-term) and positive (generally longer term) effects on fish. An increase in suspended sediment, depending on its concentration and duration, could cause physiological stress, reduced growth, or mortality in fish. But fisheries may benefit from the pulse of nutrients that flows into streams after fires, and fire-killed trees that fall into small to medium size streams can provide cover for fish and slow the current, allowing stressed fish to rest.

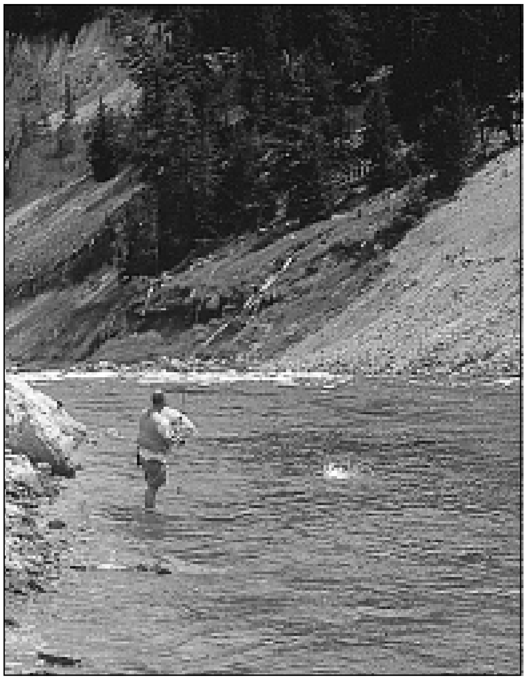
Fire-related mortality.

In addition to the fish that died as a result of an accidental drop of fire retardant in Fan Creek and the Little Firehole River, some mortality was observed during and shortly after the 1988 fires in the streams of a few extensively burned narrow drainages such as Blacktail Deer, Cache, and Hellroaring creeks. Although water temperatures were unlikely to have reached lethal levels in streams of that size, the Stream Ecology Center researchers conjectured that smoke may have caused fatally high ammonia levels in the water.[48] Monitoring by the USFWS indicated that trout populations had reestablished themselves at these locations within one year.

Outside the park, major fish kills occurred in Jones Creek, the North Fork of the Shoshone River, and portions of the Lodgepole and Crandall creeks in the Shoshone National Forest. At Jones Creek in August 1990, suspended sediment concentrations of 9,680 mg/L were recorded after a rainstorm-induced debris torrent, and dead trout displaying symptoms of suffocation were found the next day.[49] Suspended sediment is known to be lethal to salmonids, but usually at higher concentrations or for longer exposures than were found at Jones Creek.

Fish since the fires.

No discernible fire-related effects have been observed in the fish populations or the angling experience in the six rivers that have been monitored regularly since before 1988 (the Firehole, Gardner, Gibbon, Lamar, Madison, and Yellowstone), all of which are 5th or 6th order and therefore less susceptible to substantial alterations in hydrological regime, water chemistry, and vegetation than are smaller streams. Even in the Gibbon River, where landslides in August 1989 brought the most extensive sediment inputs, the spawning and recruitment of young fish appeared unaffected.[50]



Whether the short-term increases in aquatic vegetation and macroinvertebrates in low-gradient 4th to 6th order streams that have functioned as depositional areas for sediment and nutrients from upstream burned areas will ultimately result in greater abundance or biomass of resident fish has not been determined. Post-fire data through 1992 on one to three-year old cutthroat trout showed some of the highest growth rates ever recorded in those streams, but longer-term studies are required to determine if there have been any significant changes across the entire population.[51] Other research priorities have meant that this particular monitoring project has not been continued.

Using a 44-year database, Robert Gresswell's analysis of the Yellowstone cutthroat trout population structure in 1993 did not detect changes that could be attributed to the fires.[52] By the time the fires reached Yellowstone Lake in 1988, the cutthroat trout spawning runs were completed and post-spawners had returned to the lake, where they were unlikely to be affected by any short-term changes in water chemistry.

But because the Yellowstone cutthroat trout is an important grizzly bear food, concern about the possible effect of changes in stream habitat prompted the Interagency Grizzly Bear Study Team to monitor 1989 spawning and related bear activity.[53] Of the 124 tributaries of Yellowstone Lake, 58 had evidence of a spawning run before the fires, of which 34 were located partially or wholly within burned areas. Most of the latter were characterized by open riparian corridors that were not burned intensely and acted as a buffer between the forest crown fire and the stream channel; there was no apparent increase in streambank erosion or change in substrate composition or channel morphology that would affect spawning habitat, nor does there appear to have been a decline in the number of spawning streams. Although the difference in spawner numbers between burned and unburned sites for 1989 in comparison to those recorded for 1985–87 was "marginally significant," the apparent level of bear activity at spawning streams that year did not change.

Compared to that same pre-fire period, five of the streams in the West Thumb area showed a substantial decline in the average peak number of spawners counted in 1997 and 1998.[54] The watershed surrounding the West Thumb of Yellowstone Lake area did burn in 1988, and changes in the timing and magnitude of snowmelt runoff from the loss of vegetation could have affected stream temperatures and flow characteristics. However, other spawning streams in burned watersheds have not shown a similar decline. The more likely cause is the non-native lake trout, which preys upon theYellowstone cutthroat trout and competes with it for other food sources. The lake trout population is believed to have grown steadily since it was illegally introduced sometime before 1988, and is known to be abundant in the West Thumb area.

> "Extensive increases in the rate or amount of fine sediment that enters a stream could affect aquatic macroinvertebrate abundance and diversity or eliminate some spawning areas for fish. Over the long term, however, aquatic organisms in Yellowstone must be able to adapt to fire-related disturbances or they would not have survived to the present."
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> —Minshall and Brock, 1991