Fluvial Geomorphic Response of a Northern California Coastal Stream To Wildfire

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Abstract

The 1995 Vision Fire burned 100% of the 8.3 sq km (3.2 sq mi) Muddy Hollow Watershed at Point Reyes National Seashore. We monitored landscape response for two years in this watershed by measuring rainfall and stream flow, surveying channel change, and quantifying the amount of woody debris supplied to the channel and sediment deposited in a newly formed alluvial fan. Watershed response varied spatially and temporally. With a mean annual rainfall of about 1016 mm/yr (40 in/yr), recovery of fire-adapted vegetation was rapid. The upper and lower watershed sections had the earliest and most rapid geomorphic response. During the first post-fire year in the bishop pine forest of the upper watershed, the combined development of a soil surface crust and hydrophobicity caused excessive runoff.

Channels incised and eroded headward. Permanent drainage density, not including the ephemeral rill network, increased by at least 200%. Sediment was supplied from both hillside rills and channel bed incision. Dry ravelling was negligable. Yet, we expect that the upper section will be first to recover a stable geometry and return to usual rates of runoff and sediment supply. The middle watershed did not significantly change until the second post-fire year when excessive amounts of large woody debris fell into the stream from the riparian alder corridor. Subsequently, sediment supply increased from local bank erosion and sediment transport rates decreased as sediment became trapped and stored in the channel bed. Recovery through the entrenched middle reaches may take years as the large woody debris is redistributed during flood flows and as a mature riparian community develops. The lower watershed responded to high runoff and sediment supply by developing an alluvial fan with a braided distributary system across the valley floor. A minimum estimate of average post-fire sediment load during the first two years was 704 tonnes/sq km/yr (2,626 tons/sq mi/yr). Sediment supply to the alluvial fan was 2.7 times higher during the second post-fire year than the first, due to the changes that occurred in the middle reach. As sediment and water supply diminish, the lower channel will likely return to a single thread channel within a more extensive alder forest. Recovery may occur sooner in the lower watershed than in the middle, since the lower reach channel is not entrenched. High shear stresses during flood flows in the middle reaches will cause continued adjustments in hydraulic geometry. The post-fire channel response for this coastal Northern California stream did not follow the typical Fire/Flood Sequence that is often expected for coastal Southern California watersheds. We hypothesize that differences in watershed response in California's moist north coast environment as opposed to its semi-arid south coast are due to differences in apparent cohesion that is created by the dense root network from vegetation. Within the watershed, response varies spatially along the stream and elevational gradient.

Acknowledgements

We gratefully acknowledge the vision and support of Bill Shook, Chief of Resource Management, Point Reyes National Seashore. For assistance in the field, we thank Paul Amato, Fred Booker, Elise Brewster, Dan Capellini, Susan Canon, Anne Everly, Bret Harvey, Timothy McCrystle, Donna Morton, Yuichi Onda, Ron Stock, and Jeremy Thomas. Tracy Allen of EME Systems went beyond the call of duty to help support and maintain field equipment during adverse conditions. Bill Dietrich provided essential equipment and manuscript review.

Introduction

The fluvial geomorphic response of a stream network in an 8.3 sq km (3.2 sq mi) watershed was monitored for two years to understand the initial influences of wildfire on a coastal Northern California stream. Virtually all of Muddy Hollow Creek Watershed was burned during the October 3rd, 1995 Vision Fire in the Point Reyes National Seashore (PRNS). This report, which was funded by PRNS, focuses primarily on data collected during the second year of monitoring post-fire effects. It draws upon results from first year monitoring (Collins, 1996), a project funded by the Marin Community Foundation for the West Marin Environmental Action Committee. A copy of the first year report is on file in the PRNS Natural Resources Library.

Muddy Hollow Creek was chosen to learn about natural geomorphic and fluvial processes following intense wildfire for three principal reasons. One, most of the watershed was already in a relatively natural condition, except for previous land use impacts from grazing; it therefore allowed monitoring of natural processes without confounding influences of urban runoff. Two, fluvial and geomorphic processes were not influenced by-post fire disturbances such as aerial seeding, application of mulches, or construction of sediment basins because National Park Service policies did not require these post-fire erosion control techniques. Three, while much literature addresses landscape response for streams and watersheds for coastal southern California, and inland coniferous watersheds, yet scant information exists for north coastal watersheds, particularly bishop pine forests, which have very different floristic environments due to their moist coastal climate and greater rainfall regime.

Background Information about Landscape Response to Fire in Southern California

Until recently, much of the post-fire erosion control response to wildfire throughout California has been based upon landscape response of Southern California watersheds, even though climate, vegetation, and geology vary throughout the State. Post fire erosion and runoff monitoring following the 1991 Oakland Hills Tunnel Fire (Booker, 1998; Collins and Johnston, 1995; and Booker et al, 1993) has begun to document wildfire response in northern California that does not typically follow the often-anticipated Southern California model. If we first examine the typical landscape response for Southern California, differences and similarities in response for the MHC Watershed can then be recognized and understood. Such an understanding could lead to improved post-fire management response, cost–effective planning, and necessary future monitoring efforts for other north coast watersheds.

Current literature indicates that many coastal Southern California ecosystems have a fairly predictable response to fire, called the Fire Flood Sequence (Rice 1982; Wells 1981,1987). The scenario for these arid watersheds follows.

In the fire-flood model, the first significant winter storms produce unusually high runoff and sediment loading from burned watersheds. The high runoff is caused by a hydrophobic (water repellent) layer that forms in the shallow subsurface soils during fire. Vaporized organic compounds condense in the soil subsurface at a fairly uniform but relatively shallow depth to create a layer that impedes water infiltration (Debano, 1981). As a result, much of the rainfall that would normally percolate into the soil is shed as surface runoff. This causes a substantial increase in the amount of flow, as well as the height of the peak flood relative to the amount of runoff. Hence, the amount of runoff relative to the size of the drainage becomes uncharacteristically large for non-fire conditions.

Two very different geomorphic processes cause the high sediment load. One is associated with water, the other is not.

In the Fire-Flood scenario, the immediate process associated with sediment supply to the channel network is dry ravelling. It occurs either during or immediately after fire, whereby soil, rock, and debris ravel from steep hillsides directly into dry ephemeral or intermittent channels, filling them with large amounts of loose unconsolidated sediment. When the vegetation burns, its effect of buttressing the soil that has accumulated against the uphill side of the trunk is lost. On steep hillsides, substantial quantities of sediment can be rapidly delivered to the channel through this mechanism, especially if the soils lack cohesion.

Clays generally provide soil cohesion, and root networks provide apparent cohesion. Many of the soils in the Southern California Coast Ranges have granitic soils, which characteristically have very low clay content. For the Southern California arid climate, the fire-adapted vegetation is typically sparse, creating soils that tend to have a low density of root networks, low organic content, poorly developed litter layers, and abundant areas of exposed soil surface. In the absence of fire, the process of dry ravel has been reported to account for as much as 50% of the annual erosion in the steep mountains comprised of granite or coarse-grained sandstone bedrock (Anderson et al, 1959; Krammes, 1965; Rice, 1974). The sediment that accumulates in the stream beds from dry ravelling processes cannot be mobilized until there is sufficient winter runoff contained within the channel.

The second sediment supply process is associated with the hydrophobic layer and requires rainfall and runoff to deliver sediment to the channel system. Overland flow on the hillsides concentrates into rills, causing soil loss and additional sediment and ash supply to the channel network from the hillsides. The coarse-grained characteristics and low clay content increase the probability that hydrophobic conditions will exist, even though pre-fire infiltration rates are usually high. Once a water repellent layer develops, the layer of soil and ash above it is easily removed by surface erosion processes, while the layer below remains dry. If the hydrophobic layer is pervasive, rill networks will develop over much of the landscape (Wells, 1986). If rainfall is intense or prolonged, and the soil deep, the rills will incise into gullies.

Sediment additions from both ravelling and rilling processes cause bulking of the first winter stream flows with loose unconsolidated sediment. These highly bulked flows, in association with increased runoff, can produce downstream mud flows that may have similar effects to debris torrents and debris flows. In particular, alluvial fans at the base of steep hillslopes may aggrade by deposition and spreading of bedload, while large volumes of fine sediments are transported farther downstream within the floodwaters.

The response of MHC was different than the post fire erosion response in the Northern California Oakland Hills Tunnel Fire that was studied by Booker et al (1993). In both cases, dry raveling was not an important process of sediment supply to the streams, yet development of a rill network and subsequent sediment supply was much greater in the MHC watershed than the Oakland Hills. In the Oakland Hills post fire erosion response was insignificant until after the soils were mechanically disturbed during post fire rebuilding efforts and by subsequent fuel management practices (Collins, unpublished data). We believe that the main difference in response of these two northern California environments was due to the different soil types that caused a surface crust and a greater degree of hydrophobicity to develop in the granitic soils of MHC as opposed to the more clay-rich sedimentary soils of the Oakland Hills.

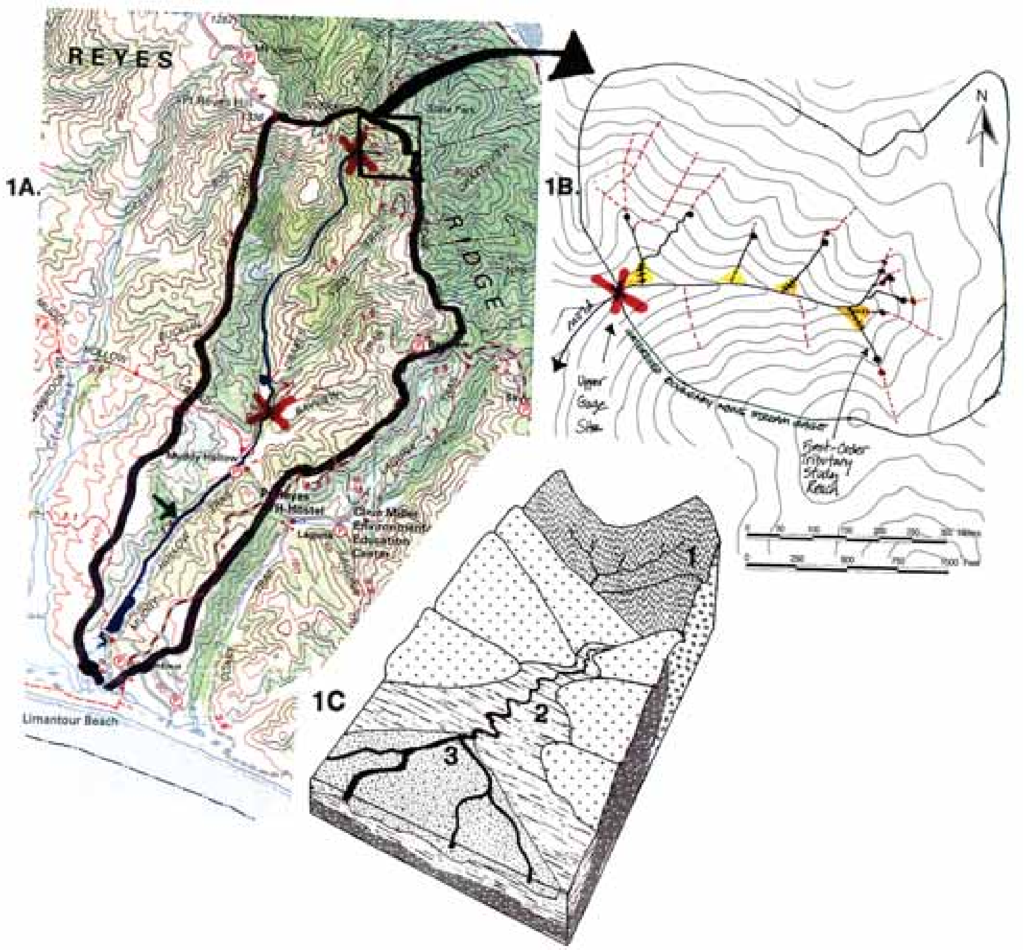


Figure 1

A) The boundary of Muddy Hollow Reservoir is outlined in black. The red X at the top of the watershed shows the Upper Gage Site location. The red X in the middle shows the Lower Gage Site location. The green arrow near the bottom of the watershed shows the location of the apex of the alluvial fan during the spring of 1998

B) A detail of the Upper Watershed Section is shown. Red dashed lines represent rills that developed after the fire along the main axis of zero-order basins. Blue dots show the original location of channel heads, while red dots show their post-fire location. Hatched blue lines show alluvial fans that became channelized after the fire, while dotted blue lines show alluvial fans that did not become channelized. Yellow areas show alluvial fans at the base of steep tributaries.

C) A conceptual diagram of the watershed is shown where point 1 represents the Upper Section which is primarily granitic rocks as shown at depth at point 1b. Point 2a and 2b represent the Middle Section which has both Quaternary sands and gravels (2a), and marine sedimentary rocks (2b) as shown at depth at point 2c. Point 3 represents the Lower Section as indicated by the alluvial fan which has very recently deposited sands and gravels.

Physical Setting of Muddy Hollow Watershed

Topography

The 8.3 sq km (3.2 sq mi) watershed of MHC flows 3.4 mi toward the Pacific Ocean on the southwest side of the PRNS in Marin County, California (Figure 1). Peak elevation is about 328 m (1,076 ft), which also corresponds to total topographic relief. The steepness of the hillsides approaches 60% in several upper headwater drainages, but as MHC flows southwestward, it eventually cuts through consecutively younger marine sedimentary bedrock that has increasingly gentle topography. After MHC reaches half its total distance, it flows into its alluvium-filled valley. At its downstream end, fresh water flows from Muddy Hollow Reservoir into an artificially truncated tidal salt marsh that is part of the southeastern edge of the Estero de Limantour. Limantour Spit blocks the Pacific Ocean from the estuary shoreline of Muddy Hollow.

Climate

The Mediterranean-type climate of the PRNS provides a mean annual rainfall ranging from about 1,000 mm/yr (40 in/yr) at Inverness Ridge to 600 mm/yr (24 in/yr) at the western shoreline (Evans, 1988). Snowfall is extremely rare. Most precipitation occurs between December and February. Figure 2 shows monthly precipitation at the Bear Valley Ranger Station for the 1995 Water Year(WY) preceding the fire and the three years following. Bear Valley Station is 3.2 km (2 mi) southeast of the Muddy Hollow headwaters. 1997 was the only year that did not have greater than average rainfall. Instead, it had nearly normal rainfall of 970 mm (38.2 in). 1998 was an El Nino winter. It had greater than 180% of normal rainfall totaling 1,840 mm (72.7 in). The first winter after the fire (1996) had 115% of normal rainfall. The year preceding the fire (1995) was also a wet year. Rainfall was 159% of normal.

Geology

The geology of Point Reyes has been recently re-described by Clark and Brabb (1997) following earlier mapping and interpretation by Galloway (1977). From the eastern headwaters to the western shoreline, the bedrock units in MHC drainage are as follows: in the Upper Section the mainstem MHC incises into mildly to strongly weathered, Cretaceous-aged granodiorite and granite for a distance of about 2,194 m (7,200 ft) before next flowing 122 m (400 ft) through a short segment of the Laird Sandstone. MHC then flows for about 488 m (1600 ft) through the Middle to Upper Miocene-aged Monterey Formation, which is a thin-bedded and laminated porcelanite and chert with several thin to medium interbeds of arkosic sand. Throughout the Laird sandstone and from this unit downstream, with a few minor exceptions, mainstem MHC flows through its own Quaternary Alluvial Sediments. The subsequent bedrock units from east to west of the watershed that are exposed in some of the adjacent low gradient tributaries include Miocene glauconitic Santa Margarita Sandstone, Upper Miocene Santa Cruz Mudstone, and Upper Miocene to Lower Pliocene–aged

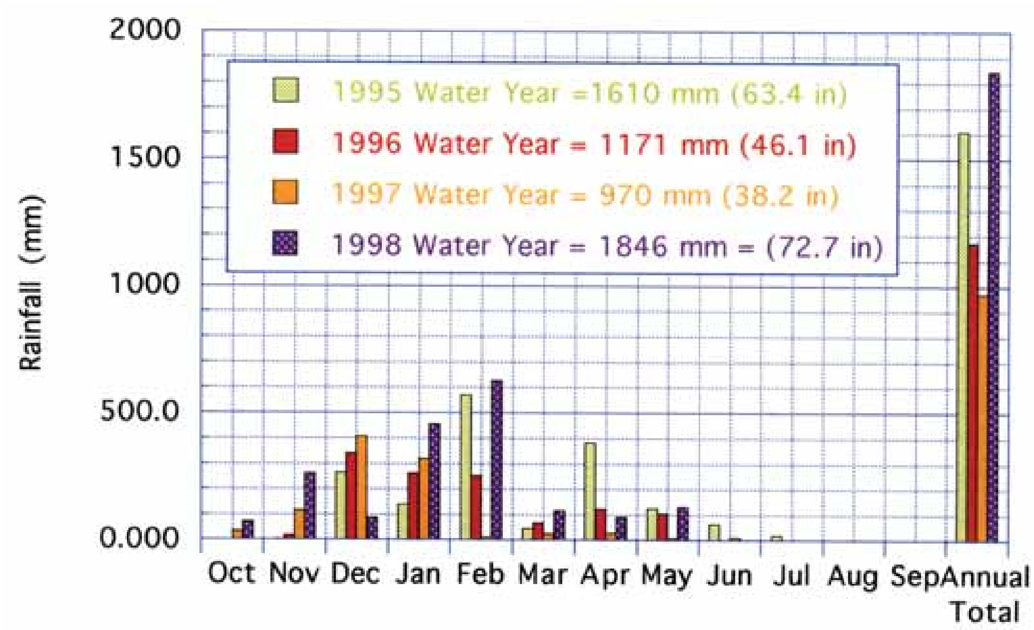


Figure 2

Monthly rainfall totals are shown for the Bear Valley Ranger Station. Water Year 1995 was before the Vision Fire. If the mean annual total for the area is 1,016 mm (40 in), then three of these four years had above average rainfall. The El Nino year of 1998 had 182% of normal rainfall.

diatomaceous mudstone and siltstone beds of the Purisima Formation. This latter unit at the western-most portion of the watershed was formerly referred to as the Drake Bay Formation by Galloway (1977). These geologic units comprise the Middle Section. The Lower Section is comprised entirely of Quaternary Alluvium.

Bedrock throughout MHC and the greater Point Reyes Peninsula has been mechanically weakened, fractured, and sheared by numerous faults that splay from the northwest trending San Andreas Fault. Tomales Bay demarcates the San Andreas Fault. It is located about 1.6 km (1 mi) east of the MHC watershed divide. A major earthquake of magnitude 8.3 on the San Andreas Fault affected this region in 1906. The long-term combined processes of landsliding and fluvial dissection have largely shaped the landscape of MHC. Both seismic shaking and high intensity rainfall have triggered landslides.

Vegetation

The vegetation in MHC watershed varies with geology and elevation. The granitic headwaters above an elevation of 171 m (560 ft) are dominated by bishop pine forest. The predominant understory includes a dense and often impenetrable thicket of huckleberry, manzanita, ceanothus, chinquapin, madrone, salal, coffeeberry, wax myrtle, and sword fern. Between the elevations of 98-171m (320-560 ft), the vegetation varies from bishop pine forest, to oak/bay woodland, or north coastal chaparral that is dominated by coyote brush. Below an elevation of 98 m (320 ft), the hillsides are predominantly north coast chaparral, and grassland to a lesser degree. Along the riparian corridor, downstream of the headwater pine forest, the channel is lined with red alders. They have a dominant understory of blackberry, thimbleberry, and sword ferns. Willow, elderberry, big leaf maple, hazelnut, and buckeye have minor presence. The riparian corridor changes to a wide alder forest at the lower end of the valley at the upstream end of the reservoir. The reservoir was constructed over former tidal marsh. Downstream of the reservoir, the tidal marsh is dominated by pickleweed.

Many of the plant species in Muddy Hollow are adapted to fire. In particular the bishop pines require fire to release seeds from their cones, while other species, such as bay, madrone, manzanita, coyote brush, huckleberry and chinquapin have adapted to fire by crown sprouting. Such fire-adapted vegetation has root networks that remain viable even when the surface biomass has been totally consumed by fire. This is important because the roots continue to add to the apparent cohesion in the soil.

Hydrology

MHC has perennial flow from its headwater first-order streams to its outlet. The lower MHC is a fifth-order channel. It has three major forks. The mainstem channel is the Middle Fork. Stream flow was not gaged prior to this post-fire study. Based upon published Regional Curves of discharge versus drainage area (Leopold, 1994), the predicted bankfull discharges for different segments of MHC are shown in Table 1.

Land Use

Historically, MHC flowed freely to the Estero de Limantour where it transitioned into a tidal slough that invigorated a tidal salt marsh. During the 20th Century, two reservoirs were constructed on the lower and middle sections of the valley. At the lower end of the valley, Muddy Hollow Reservoir was constructed by 1963 for recreational needs of a planned resi-

Table 1. Predicted MHC Bankfull Flow From Regional Curves

Drainage Area Sq KM (Sq MI)	Predicted Bankfull Discharge CMS (CFS)	Length of Channel Upstream KM (MI)	Study Site
0.28 (0.11)	0.18 (6.5)	0.5 (0.3)	Upper Gage Site at Downstream Boundary of Upper Watershed Section
5.07 (1.96)	2.55 (90)	3.2 (2.0)	Lower Gage Site in Middle Watershed Section
7.15 (2.76)	3.54 (125)	5.0 (3.1)	Downstream Boundary of Middle Watershed Section
8.29 (3.20)	4.11 (145)	5.5* (3.4)*	Downstream Boundary of Lower Watershed Section

*Before construction of Muddy Hollow Reservoir, MHC extended 5.9 km (3.7 mi) to the Estero.

dential subdivision. The dam was placed across the tidal marsh, truncating about 457 m (1,500 ft) of the upper salt marsh and its attendant slough that previously conveyed water and sediment to the Estero. Around 1952, prior to dam construction and perhaps in preparation of draining the valley for subdivision, about 701 m (2,300 ft) of the channel upstream of the Estero was ditched, straightened, and moved to the north side of the valley. 1942 photos indicate that much of the lower valley was covered by extensive, but young riparian forest at this time.

The upper reservoir, called Bonelli's Lake, was constructed in the late 1950's. It was located about 2.3 km (1.4 mi) upstream of the Muddy Hollow dam. It was developed for maintaining water supply to a commercial nursery that was located immediately downstream (verbal communication from Dewey Livingston, Historian Point Reyes National Seashore). The dam at Bonelli's Lake breached during a 1982 storm event that caused widespread flooding and landsliding throughout Marin County. The bedload upstream of the lake had been captured for about 32 years behind the dam. Presently, the channel has incised 7.6 m (25 ft) into its previously impounded sediments that now have a young alder forest.

Dairy farming began about 1857 at the Muddy Hollow Dairy. The farm was located in the main valley, 2.4 km (1.5 mi) upstream of the Muddy Hollow Reservoir dam. An 1859 topographic map from the US Coast and Geodetic Survey shows that the valley downstream of the dairy site had four small riparian groves (probably willow) through the lower, mostly grassland valley. According to Livingston, a circa 1900 photograph of the dairy shows that riparian vegetation and the former willow groves were entirely missing along MHC upstream of the dairy to beyond Bonelli's Lake. According to Livingston there was also another smaller, more short-lived dairy, called Sunnyside that was located along the ridge of MHC.

Dairy ranching dominated Muddy Hollow until the 1920's when sheep ranching and truck farming of pea crops took over the general vicinity of the Muddy Hollow Dairy. These latter activities only lasted until the 1940's when the land was sold for subdivision. From the 1950's through the early 1970's cattle herds from nearby beef ranches were allowed to graze the watershed. After the early 1970's the PRNS ceased all grazing activities in MHC watershed.

The influence of road construction in the watershed has been relatively minor. There are no paved roads within the watershed, yet there are a few maintenance trails and abandoned ranch roads. Two significant dirt roads exist. One crosses the creek near the location of the old Muddy Hollow Dairy. It was probably constructed during the truck farming era. When the land was sold for subdivision (around 1950's) its bridge was replaced with a 0.9 m (5 ft) diameter, corrugated metal culvert, which was removed later in 2001. The other dirt road which has been abandoned parallels the mainstem valley from the estuary to the headwaters. The section of road downsteam of Muddy Hollow Dairy was probably constructed between 1960-1963. Within a very small portion of MHC watershed near the top of the Inverness Ridge, there is a gravel road that provides access to several houses along the headwaters of the South Fork. Most of these homes were built during the 1970's and have little influence on MHC.

Fire

The incidence of naturally caused fires, such as those generated by lightening strikes, is probably very low for Point Reyes. Conversely, the incidence of anthropogenic-related fires was fairly high. The frequency of fires however, is probably less now than when the land was occupied by Native Americans that managed patches of their landscape by setting frequent fires. Barbara Moritch, PRNS Vegetation Management Specialist, suggests that fire frequency was about 8-14 years before non-native settlement. Only two fires may have affected the bishop pine forest in MHC during the last 150 years. The more recent fire may have occurred in the lower headwater forest prior to November 1942. This is indicated by examination of historical 1942 stereo photos. Based upon counts of annual growth rings of the oldest bishop pines in the upper northwestern Muddy Hollow ridge, we determined that the last fire in that area might have occurred around 1895.

The high intensity of the 1995 Vision Fire was most likely much higher than historical fires set by native people. In the bishop pine forest, the Vision Fire evolved into a high intensity crown fire, killing all pines in the upper watershed and removing all other vegetative surface cover. Nearly 100% of the watershed burned, except for some wetland areas at the upstream end of Muddy Hollow Reservoir. Fire intensity of the riparian alder corridor ranged from crown fire to understory burn.

Methods

Study Approach and Selection of Study Sites

This study was designed to provide an understanding of the overall landscape response to fire. We developed an approach to provide both extensive reconnaissance of different morphologic sections of the watershed, and detailed monitoring of representative stream reaches. Based upon stream gradient and valley conditions, the watershed along the mainstem MHC was conceptually divided into Upper, Middle, and Lower Sections (Figure 1C).

The Upper Watershed Section consisted of first- to third-order channels within granitic terrain. Average stream gradients are typically greater than 10%. The Upper Section has a drainage area of 0.26 sq km (0.10 sq mi or 68 ac). Following the fire, rainfall and stream flow were gaged at the downstream end of the Upper Section. The length of the upstream channel is about 0.48 km (0.3 mi). Repeated surveys of longitudinal profile and cross section were conducted on first- and third-order sections of the mainstem. Reconnaissance level mapping of the entire channel network was done with a fiberglass tape to measure channel distance. Observations of soil erosion and tests of hydrophobicity were also made over most of the Upper Section. Within it, the mainstem channel flows in a very narrow channel infall that is stepped, probably from former debris flow deposits. The valley fill frequently separates the channel banks from the base of steep hillsides. The pre-fire mainstem channel alternated from being barely incised in the valley fill (about 0.4 m or 1.5 ft), to occasionally deeply incised (up to 1.5 m or 5 ft) in bedrock. Montgomery and Buffington (1997) have described such headwater channels as “sediment source reaches”.

The Middle Watershed Section includes the attendant tributary channels and the mainstem channel, which ranges from third- to fifth-order. It ends at the apex of a newly formed alluvial fan in the lower valley. Total drainage area is 7.15 sq km (2.76 sq mi 1,766 ac) and upstream channel length is 5.0 km (3.1 mi). The mainstem gradient ranges from 1% to 10%. Before the fire, few depositional bars existed within the mainstem channel. According to Montgomery and Buffington classification (1977), this might indicate that the Middle Section functioned as a “transport reach.” Lack of bars might also indicate that sediment supply was low prior to the fire. Most of the channel was incised within its own, older alluvial fill in a narrow to moderate-sized valley that ranged in width from 15-107 m (50-350 ft). A continuous riparian alder corridor existed along the channel on the valley flat. Rainfall and stream flow were gaged at the lower third of the Middle Section. Drainage area above the gage is 5.07 sq km (1.96 sq mi or 254 ac) and channel length is about 3.2 km (2.0 mi). A detailed stream map of the channel reach at the lower gage site was made (Figure 6). A longitudinal profile was surveyed and several cross sections were repeatedly surveyed.

Before the fire, the Lower Watershed Section consisted of the fifth-order mainstem channel in the lower valley. This section now defines the extent of an alluvial fan that is presently defined by numerous distributaries. Its lower boundary is the open water of Muddy Hollow Reservoir. Valley width ranges from 60-150 m (200-500 ft). Stream gradient is generally less than 1%. The total drainage area upstream of the Lower Section is 8.29 sq km (3.20 sq mi or 2,048 ac) and channel length is 5.5 km (3.4 mi). Before the fire, the Lower Section would have been classified as a “response reach” according to Montgomery and Buffington (1997). Within the alluvial fan, soil pits were dug to quantify the amount of sediment deposition that followed the two post-fire winters. After each significant storm, the position of the apex of the alluvial fan in the lower valley was measured to determine changes in stream behavior.

During the first post-fire spring, the entire mainstem channel was walked. It was re-walked the following spring of 1997. Channel conditions were observed, and woody debris and landslides were quantified. Photographs were taken to document channel condition. By the second year, most of the channel was nearly impassable due to the numerous alder trees that fell into or across the channel.

Testing of hydrophobicity

The extent and significance of water repellency was determined by using a standard water drop test used by the Natural Resource Conservation Service. Small soil pits and trenches were dug to test the significance of hydrophobicity throughout the rainy seasons.

Stream Flow and Rainfall Gauging

The upper gage location was used to indicate runoff conditions from a third-order stream that was influenced by significant hydrophobic soils in the burned bishop pine forest. The lower gage location was used to indicate runoff conditions of the fifth-order stream system in a gently sloped alluvial valley that had low to moderate fire intensity in the riparian alder forest. Data on amount and intensity of precipitation were collected at both sites with a continuously recording, tipping bucket gage. Rainfall was measured at both sites at intervals of two minutes at the upper site and 5 minutes at the lower site.

The range of stream discharge was determined by developing a rating curve for stream stage at different discharges. Stage was determined by using a continuously recording capacitive sensor at the Upper Site during the first year after the fire and at both sites during the second year. When it was not raining, stage was automatically recorded every half-hour at the upper site and every hour at the lower site. During precipitation, stage was recorded every 2 minutes and 5 minutes, respectively. For both sites, the gage was placed in a straight reach of channel where velocity measurements were taken by using a combination of orange peel floats and/or a Marsh McBurney current meter. Calibration between the two methods was conducted for low to moderate flow conditions. Velocity measurements from surface floats were multiplied by a correction factor of 0.8 to determine average velocity. Stream discharge was determined by surveying the cross sectional area of flow and multiplying by average velocity.

New rating curves had to be developed several times when the cross sectional area was altered by bank erosion and/or changes in bed elevation. At the lower site, maintenance of the gage site and calibration of a rating curve became increasingly difficult because of the effect of woody debris from alders falling into the channel during the second post-fire year. By the third year, the lower gage was moved downstream, but that site also had to be later abandoned due to large woody debris. At the upper site, the combination of re-growth of understory species and pine seedlings by the third year made access to the stream and the gage site nearly impossible.

Cross Section and Longitudinal Survey

Cross sections for discharge measurements were surveyed by using both standard surveying techniques with a self-leveling level and telescoping rod, and by level line measurement with a tape and rod. Stakes were placed to mark the end points of the survey to permit accurate re-measurement. Longitudinal profiles were surveyed with level and rod. Flagging was placed every 10 m (33 ft) to match the center line tape for re-survey. The long profile was surveyed twice at the Upper Gage Site and once at the Lower Gage Site. All elevations reported are relative. The longitudinal profiles were surveyed over at least 20 bankfull widths to be statistically representative of the channel conditions.

Soil Pits

Along the alluvial fan soil pits were dug at 10 m (32.8 ft) intervals along 6 transects that were spaced about 33 m (100 ft) apart. The pits were dug deep enough to intercept the ash layer that fell during the Vision Fire. It was usually no greater than 0.9 m (3 ft) deep. Stratigraphic changes were described and measured to develop a profile that represented the thickness of overlaying post-fire sediment deposits for both post-fire rainy seasons.

Geomorphic Map

A detailed geomorphic map was made of the stream reach at the Lower Gage Site within the Middle Watershed Section during the summer of 1997. Mapping was performed with a Brunton compass and fiberglass tapes placed along the centerline of the channel and at cross sections spaced about 10 m (33 ft) apart. Sorting patterns of the sediment on the channel bed were mapped as distinct size classes and all large woody debris and standing alders within the active channel and near bank zone were mapped.

Results of Monitoring and Discussion of Watershed Response

Upper Watershed Section

Hillside Soils

The combination of high intensity fire, soil texture, organic compounds in bishop pine

Photo 1 (right)
The Upper Watershed Section is shown for January 16, 1996. Light-colored trails mark areas of rilling where ash has been removed by overland flow.

Photo 2 (left)
The same general vicinity of the Upper Watershed Section is shown for February 11, 1996. An extensive network of rills has formed and much of the ash has been displaced.

litter, and possibly the root mycorrhizae associated with bishop pines caused the soils in the upper drainage of MHC to be intensely and pervasively hydrophobic during the first post-fire winter. These soils are granular and lack clays. A water repellent horizon extended from 5 to 20 cm (2 to 8 in) in depth. At the beginning of the first winter, ash covered the top 2 cm of soil. By mid December, after a cumulative rainfall of 260 mm (10.2 in), small rills defined the removal of the ash layer by surface flow (Photo 1). By mid February, after a cumulative rainfall of 600 mm (23.6 in), most of the ash had been displaced from the surface and an extensive network of rills carved the soil (Photo 2). The exposed soil quickly developed a crust of fine particles that sealed the surface from infiltration. This was also observed by Onda et al (1996). They determined that during the initial storm of the season, the runoff ratio was 10, and about 50% of the runoff was caused by the surface crust, not the hydrophobicity. We observed intense hydrophobicity in the presence of dense bishop pine root network where mychorizzae were present.

By the beginning of the second winter, hydrophobicity was patchy and had mostly disappeared by winter's end. Sprouting vegetation, including moss, had broken up much of the surface crust. Wetting of the subsurface was eventually accomplished by a variety of mechanisms including incision from rills, bioturbation by plants and animals of the surface crust and water repellent layer, flow along surface stems and roots of new plants, development of macro pores by plants, and decay of the organic oils. It may be possible that the condition of the mycorrhizae also contributed to the decline in hydrophobicity. It is worth noting that we determined by similar testing techniques that patchy hydrophobic conditions existed in an adjacent unburned bishop pine forest.

As the second and third winter proceeded, we observed that relatively few pines were uprooted. Instead, many seemed to break at their trunks; thus, soil disturbance was minimized. Prior to this time most of the pine trunks were still upright.

Linkages of Sediment Supply from Hillslopes to Channels

A reconnaissance was performed of the upper basin shortly after the fire to observe whether ravelling processes supplied dry sediment to the channel during the fire. None was observed. This was similar to the 1991 Oakland Hills Fire response (Booker et al, 1993). This is considered a significant difference in response from Southern California watersheds. The only place where sediment had been supplied to the stream, before rainfall, was in two locations where large trees, adjacent to the channel in narrow canyons, had fallen from steep slopes. Their upturned root boles caused soil to fan out into the channel.

Evidence of landslides active within the last 25 years was also sought within the Upper Section. A couple of very small bank slumps, caused by previous undermining by flow, were observed at sites where the channel flowed through narrow colluvial/alluvial deposits. During the second winter, there were some additional small bank slumps caused by bank erosion and bed incision. No new landslides were observed until winter February 1998 when El Nino conditions caused prolonged rainfall with periods of high intensity. At least 5 hillslope-generated landslides were observed from this event in the bishop pine headwaters. It is notable that slides were observed throughout various burned and unburned areas of Point Reyes after the February 1998 storms.

After the rains started sediment and ash from the hillsides were supplied to the channel by overland flow and rilling processes on the surface soils. By mid-winter, rills that became permanent channel extensions eroded as much as 0.3 m (1 ft) in depth along the axis of each small valley upstream of first-order channel heads. A dense network of smaller rills fed into each main axis rill. These previously unchannelized basins have been referred to as zero-order basins. The extent to which channels extended headward of zero-order basins is shown in Figure 1B. These new extensions are shown as red dashed lines. They function as ephemeral channels. Although they persisted during the second winter, they did not appear to change their width or depth after the decline in hydrophobicity.

Physical Changes in First-order Channels

The channel head locations of first-order streams throughout the Upper Section were mapped before the onset of winter rains. These channels were all spring fed by perennial flow. They are shown as blue dots in Figure 1B. Following the first post-fire year, the channel heads were remapped because increased runoff had caused most of them to extend headward. The new locations are shown as red dots. The dashes represent the headward channel extensions that went up the main axis of the hollow. These will most likely be ephemeral features that disappear after vegetation recovers and a litter layer develops.

The downstream extent of the first- and second-order channels was also mapped before the influence of winter rains. Most of these channels were not connected to the mainstem MHC because small unchannelized fans at the base of the slopes separated them. This means that upland sediment supply from these channel and hillside linkages was previously disconnected from mainstem MHC, and stored in deposits from fluvial and debris flow processes. Similarly, perennial flow from upstream channels was previously disconnected from the mainstem MHC because it went subsurface at the apex of the fans, thereby contributing to base flow. By mid January 1996, increased runoff carved permanent channels into three of the five fans (fans are showed with hachured lines in Figure 1B). By the end of the rainy season the depth of incision in the fans was as much as 1 m (3.2 ft). The fans shown with dotted lines did not incise, yet they contributed their post-fire runoff as overland flow to mainstem MHC.

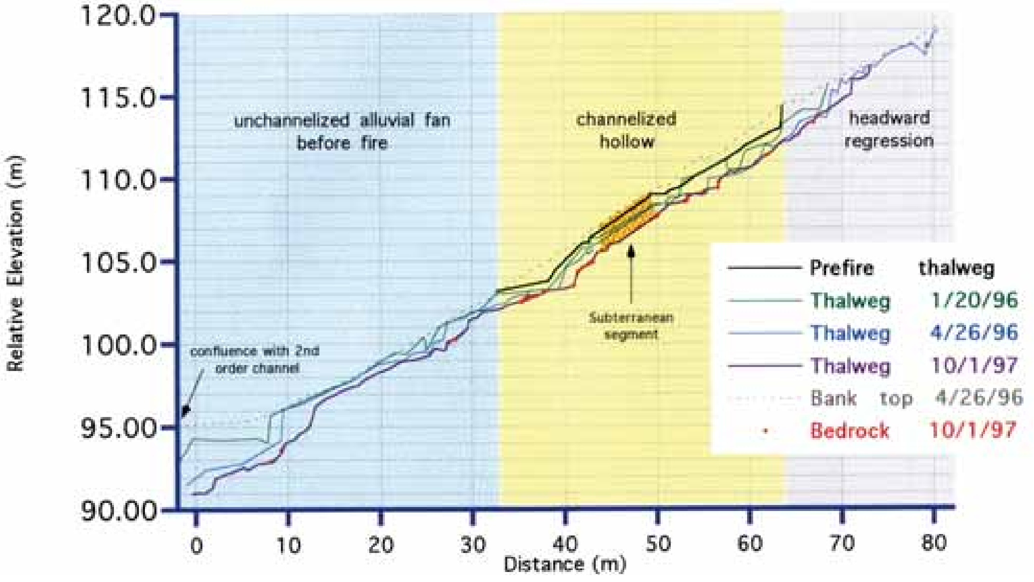
As a result of post-fire headward extension and increased connection of first- and second-order tributaries to the main Muddy hollow channel, the drainage density (which is simply the length of channel divided by unit area) changed from 12 m/ha (17 ft/ac) to 25 m/ha (33 ft/ac). This 200% increase is a conservative estimate for the Upper Section for the first year, because it excludes the extensive shallow rill network that extended beyond the central axis of each zero-order basin. Such an increase may more accurately represent the second or third post-fire years, when the shallow rills began to diasapear because of the loss of the deterioration of the hydrophobic layer in the soil. If the spring heads stabilize at their present locations, the long-term change in drainage density may be about 118% in the Upper Section.

A first-order tributary was selected to monitor in detail. Its location (shown with black arrow in Figure 1B) was near the top the drainage. The channel was initially disconnected from the mainstem by an unchannelized alluvial fan. A portion of its middle reach was actually a short subterranean tunnel. Its changes in gradient are shown in Figure 3 for four different time periods: early November 1995 before rainfall; first post-fire mid winter (1/20/96); end of first post-fire year rainy season (2/26/96); and end of second post-fire year rainy season (10/1/97). Overall, the channel gradient of about 33% remained the same. The profile shows consecutive episodes of relatively parallel downcutting by as much as 2.1 m (7 ft), but averaging about 1 m (3.2 ft). The pre-fire average depth of the channel was about 0.6 m (2 ft) and a thin veneer of alluvium covered the bed. The post-fire channel became deeply entrenched by excessive amounts of runoff carving the slightly to moderately weathered and fractured granitic bedrock. Deposition was insignificant. The channel head has extended upstream about 7 m (22 ft), while the ephemeral, main axis rill extended another 76 m (250 ft). Photos 3 and 4 show the changes near the channel head between pre-runoff conditions and three months later.

The widening of the banks by erosion was not as significant during the first winter as it was during the second winter. However, it was more significant during the first summer than it was during the second summer and winter combined. Additionally, sediment supply from undermining of the banks at low to mid-level height exceeded the supply from widening at the top of the banks during both years. Slumping of the banks from undermining did not occur during the first year. It happened at a few

Figure 3 - Muddy Hollow First-Order Tributary Longitudinal Profile.

Repeated longitudinal surveys are shown for the First-order Tributary that is shown in Figure 1B. Before the fire, transport of water and sediment to the mainstem channel was inhibited by the alluvial fan.



sites during the summer of the second year, and happened pervasively during the third summer and winter. This may have been because of the draw-down effect of the water table, the loss of cohesion in the soil from drying, and the loss of root strength as the fine network of bishop pine roots decayed. The amount of channel widening exceeded 1.5 m (5 ft) in several areas and averaged about 0.7 m (2.3 ft).

As indicated by the mapping and surveying of first-order channels the increased drainage connectivity by incision of unchannelized fans accompanied by headward extension increased the rate and amount of water and sediment delivered downstream.

Physical Changes in Third-order Channel

The longitudinal survey of the third-order channel was conducted along 200 m (656 ft) of channel. The lower half was resurveyed four times, the upper half was surveyed twice. Most the sediment that was mobilized in the headwaters was transported through the entire Upper Section. Through the surveyed longitudinal profile reach, only a minor amount of sediment accumulated on 15% of the channel length. Trapping behind small woody debris was usually the cause. At one short site the maximum depositional thickness was 0.58 m (1.9 ft). The remaining 85% of the channel eroded, leaving 50% of its length as exposed bedrock. Average incision depth was about 0.17 m (0.6 ft), but ranged up to 0.46 m (1.5 ft). Most of the erosion took place during the first rainy season.

The small inset in Figure 4 shows the profile as surveyed after the second rainy season over a 200 m (656 ft) reach. The upper part of the reach has a slope of 15% and the lower part has a slope of 11 %. The position of the Upper Gage is shown. The larger graph in Figure 4 shows net erosion and deposition between 1/96 and 2/97 for a 50 m-long (164 ft) segment of the profile between distance stations 100 m and 150 m.

Hydrologic Conditions in Third-order Channel

The Upper Gage data indicate that the amount of rainfall that is required to produce a given flow decreased substantially for the second rainy season compared to the first. It is also highly probable that the amount of rainfall required to produce a given discharge for the post-fire years is substantially less than required for pre-fire conditions. If we assume that the pre-fire bankfull flow was about 0.18 CMS (6.5 cfs), bankfull flow was exceeded at least 7 times during the first post-fire winter and only once during the second winter. This discharge seemed consistent with geomorphic indicators in the channel before the first post-fire rainfall. During the first winter, only 8 mm (0.3 in) of rainfall was required to cause the bankfull flow to be exceeded.

During the second winter, it required 45 mm (1.7 in). This is at least 5.6 times the amount from the previous year and shows the influence of the loss in hydrophobicity and surface crust of the soil.

Photo 3 (left)
The head of the First-order Tributary that was surveyed in detail is shown for early November 1996, before post-fire rainfall influenced the site. The channel had a trickle of perennial flow. Average depth was about 0.6 m (2 ft) and average width about 0.3 m (1 ft).

Photo 4 (right)
The same site is shown as in Photo 3, but the channel has deepened, widened, and eroded headward by 4.5 m (15 ft). Note the exposed granite of the channel bottom that had been previously covered by a thin veneer of sediment before becoming incised by at least 1.3 m (4 ft).

Table 2 shows a number of characteristics for selected storms that occurred from January 1996 to November 1998 at the Upper Gage Site. The data are derived from the hydrographs that were developed from the site. Table 2 indicates the rainfall total used to determine the runoff coefficient and it shows the number of minutes of lag time from peak rainfall to peak discharge. It shows rainfall intensity for 2-, 20-, and 30-min intervals, runoff coefficients, and peak discharge.

Peak rainfall to peak hydrograph averaged about 9.5 min for WY 1996 and about 34 min for WY 1997. The lag time for the storm of Dec 29 for WY 1997 was considered an outlier. Based upon recurrence intervals for rainfall intensities at Point Reyes Station (BAER Team Report, 1995), none of the 30-min rainfall intensities exceeded a 2-year event, which require 10.4 mm of rainfall. MHC runoff coefficients are highly variable depending upon antecedent soil moisture and time of last rainfall.

The highest runoff coefficient, 42%, was for April 1,1996 where a significant amount of rain had fallen several hours earlier. The next highest runoff coefficient, 38%, was from December 29, 1996, which also had been preceded by intermittent rainfall for the previous two days. Interestingly, the April WY 1996 storm also had the highest peak discharge for the year, 0.41 CMS (14.5 cfs), but the Dec WY 1997 storm had a peak discharge of only 0.12 CMS (4.5 cfs), which was not the highest discharge of the year. The storm that had the highest peak discharge in WY 1997 was January 22. It had the highest 30 min rainfall intensity (9.4 mm or 3.7 in), a runoff coefficient of 28%, and a peak discharge of 0.18 CMS (6.5 cfs). The storm that had the highest 30 min intensity (8.8 mm or 3.5 in) in WY 1996 was three hours earlier than the previously reported April 1 storm. It had a runoff coefficient of 26% and a peak discharge of 0.26 CMS (12.8 cfs).

Autumnal base flow was also determined at the Upper Gage Site. During October 1996, base flow was 0.038 cfs, and for October 1997, it was 0.055 cfs. This difference may be significant because 1997 was a lower rainfall year that was just 96% of normal, while 1996 was 115% of normal rainfall. The greater baseflow during the second year may reflect the greater infiltration that occurred after the hydrophobicity and the surface crust diminished.

Middle Watershed Section

Physical Changes in the Third to Fifth-order Channel

In the Middle Watershed Section of MHC only patchy, non-uniform hydrophobicity was observed in the grassland, North Coastal scrub, and oak/bay woodland soils. Neither post-fire dry ravel processes nor rill development were observed along the mainstem channel or adjacent hillsides. This may be due to the more clay-rich soils developed from sedimentary rocks, more gentle topography, and perhaps, less natural patchy hydrophobic soil development within unburned north coastal scrub

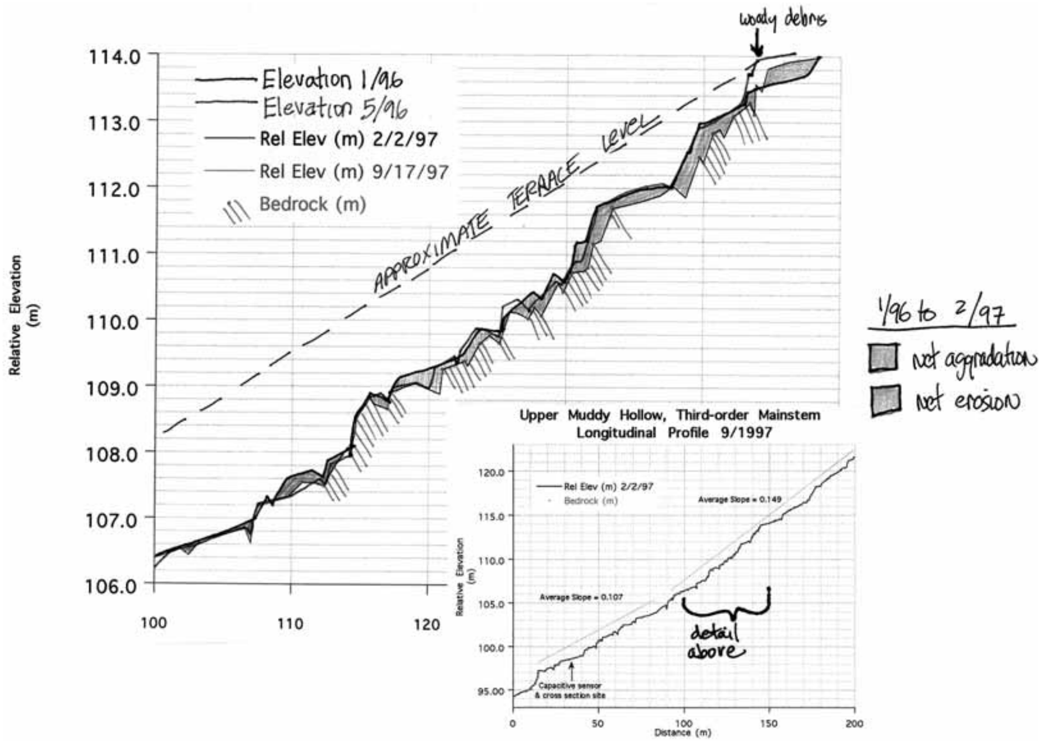


Figure 4
Upper Muddy Hollow Longitudinal Profile, 1996 to 1997.

A detail (large graph) of net erosion and deposition is shown for 50 m (164 ft) of the 200 m-long (656 ft) profile (small graph) of the third-order Muddy Hollow mainstem.

than within bishop pine forests because of different mycorrhizal associations. Rills and gullies were observed on some of the abandoned dirt roads but they had little influence on sediment delivery to the channel.

There were areas where the riparian alders had full crown fire, but more commonly, just the base of their trunks exhibited fire scars. Seared leaves were still visible on most of the alder crowns. Many alders remained viable, although clearly stressed, until the second spring season when they began to fall by either their root boles pulling from the soil or by their trunks snapping well above the ground surface. Subsequently, much more soil disturbance occurred on the valley flats with alder forest than in the steep slopes of the bishop pine forest. This was particularly pertinent along the stream banks where the falling trees literally ripped the banks apart, leaving loose unconsolidated soil in the channel and creating many woody flow obstructions that would initiate channel adjustments and more bank erosion.

During the first 1996 spring reconnaissance of MHC mainstem, we quantified the amount of active landslides and debris jams as we walked down the channel. The number of large woody debris (LWD) that was in the channel prior to the fire was possible to quantify because it did not have burn scars. During the second spring in 1997, landslides and debris jams were recounted. Additionally, the location of LWD was noted as to whether it was in the active channel bed or across the banks. This was important to note because the channel throughout the Middle Section was moderately to deeply entrenched, meaning that only high flood flows would intercept the wood across the banks or it would not be intercepted until it decayed or warped. The results of the reconnaissance are shown in Figure 5A.

The amount of LWD that was in the channel and/or across the banks increased from 260 elements from pre-fire 1995 conditions to 1,043 elements in 1997. The average 1995 wood spacing was 17.3 m (57 ft) over the 4.5 km (2.8 mi) Middle Section. Of the 1997 total of 1,043 wood elements, 86% were alders and most were whole tree trunks. About 10% were elderberries. The remainder included (in order of importance) bay, willow, oak, and juniper. About 56% (580 elements) of the total amount of 1997 LWD were in the active channel bed. This created an average 1997 LWD spacing of 7.7 m (26 ft). The remaining 44% of the total

Table 2. Characteristics of selected storms and flow at the upper gage site

	Rain-fall (mm)	Peak Rainfall to Peak Discharge (min)	RAINFALL INTENSITY TOTAL (mm)			Runoff Coefficient (%)	Peak Discharge (cms/cfs)
			Highest 2 min	Highest 10 min	Highest 30 min		
Water Year 1996							
Jan 20,1996	3.2	9.8	0.8	2.2	3.2	10	0.10 / 3.5
Jan 20,1996	8.0	7.6	1.2	4.2	7.2	19	0.25 / 8.9
Jan 26, 1996	5.6	8.9	1.2	4.2	5.8	17	0.25 / 8.5
Feb 3, 1996	11.0	12	0.6	3.6	3.6	28	0.26 / 9.1
Feb 3, 1996	8.4	7.1	0.6	2.4	3.6	28	0.26 / 9.1
Feb 4, 1996	4.0	11	1.2	2.8	8	22	0.14 / 5.1
Feb 19, 1996	8.8	11	1.0	3.2	3.2	22	0.18 / 6.2
Feb 21, 1996	8.8	13	1.2	3.4	4.4	12	0.25./ 8.8
Apr 1, 1996	3.6	12	0.6	2.2	4.8	10	0.12 / 4.3
Apr 1, 1996	3.6	10	1.6	3.4	4.2	11	0.13 / 4.5
Apr 1, 1996	8.4	11	1.2	5.2	8.8	26	0.26 / 12.8
Apr 1, 1996	8.0	8	2.0	5.6	6.2	42	0.41 / 14.5
Water Year 1997							
Oct , 29,1996	23.4	17	1.4	2.0	3.4	5	0.03 / 1.0
Nov 16, 1996	30.6	19	2.6	4.6	5.8	6	0.03 / 1.1
Dec 5, 1996	59.4	86	1.6	3.2	6.2	10	0.05 / 1.6
Dec 10, 1996	36.6	16	1.4	2.6	6.0	16	0.05 / 1.8
Dec 11, 1996	18.0	30	1.4	1.6	2.2	35	0.04 / 1.5
Dec 26, 1996	40.8	10	1.4	4.6	7.4	13	0.05 / 1.9
Dec 29 - Jan 1	182.2	109	1.6	3.6	6.8	38	0.12 / 4.4
Jan 22,1996	45.8	20	2.2	3.8	9.4	28	0.18 / 6.5
Apr 18, 1997	14	16	1.8	2.0	2.8	17	0.03 / 1.0
Water Year 1998							
Nov 10, 1997	5.0	86	0.6	1.8	3.8	8	0.05 / 1.7
Nov 26, 1997	21.8	28	1.4	3.8	7.6	32	0.04 / 1.4
Nov 29, 1997	20.4	16	1.4	4.4	6.4	19	0.04 / 1.4

Figure 5A
Pre- and Post-fire Woody Debris, Slides and Debris Jams along MHC Middle Watershed Section.

The amound of woody debris before and after the fire is shown. Of the 1,043 woody debris elements influencing the channel, 86% are alders. The amount of slumps and debris jams are also shown for the second two years.

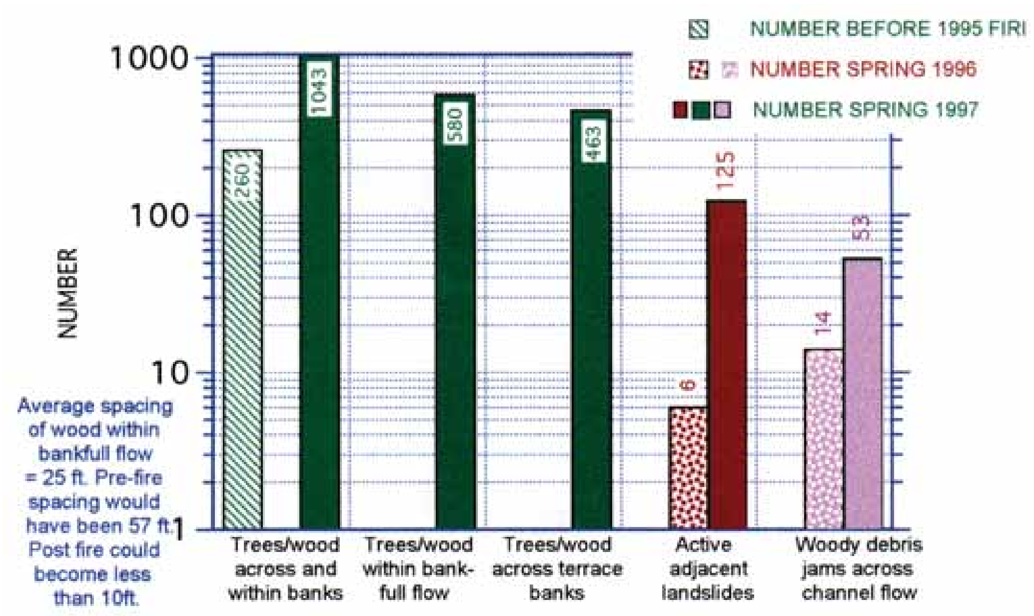
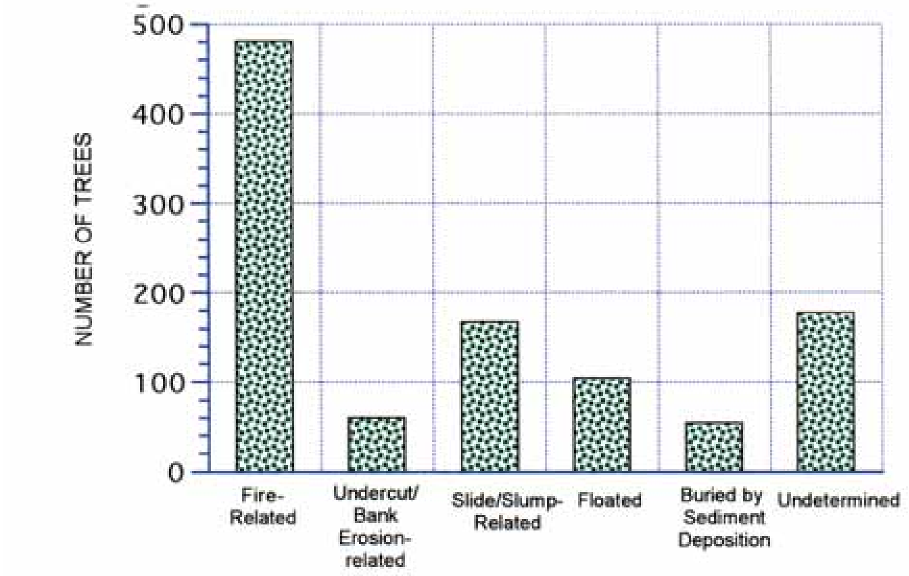


Figure 5B
Recruitment Processes of Woody Debris along the Middle Section of Muddy Hollow Creek, 1997.

The way that woody debris is recruited to the channel is shown. For wood listed as floated, its method of recruitment could not be determined.



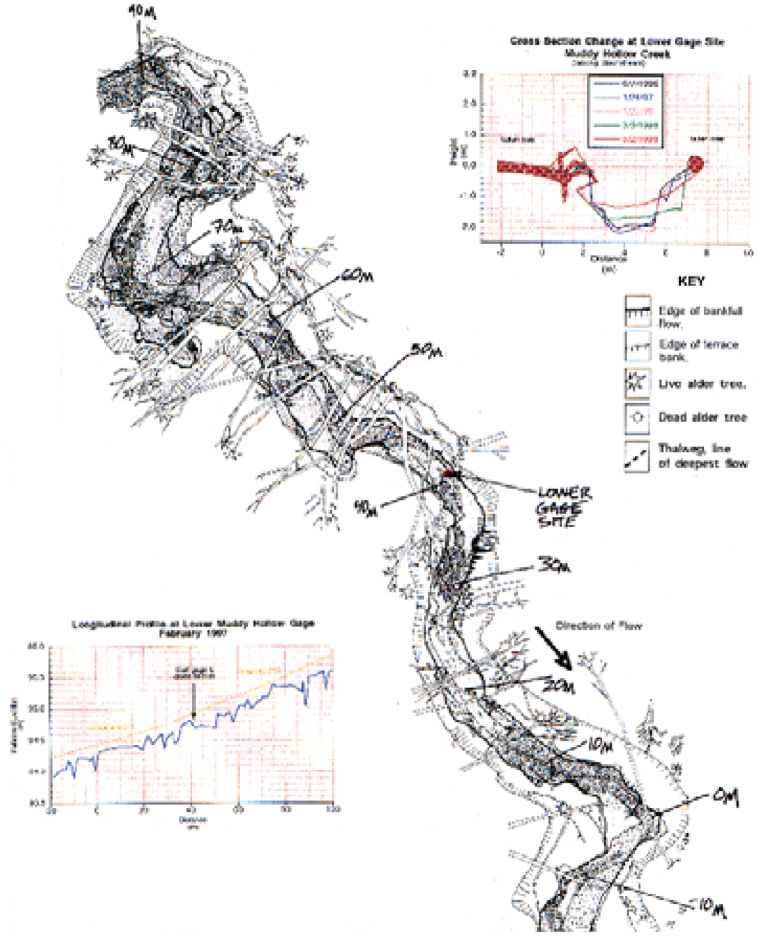
number of LWD had fallen across the channel banks. By the third 1998 spring, many of the alders that were across the banks started to bend into the channel or broke apart and fell into the active bed. Thus, a conservative estimate of LWD spacing by 1998 or 1999 is about 3 m (10 ft). Between 1996 and 1997 the number of woody debris jams also increased from 14 to 53. There was no indication that there were existing debris jams before the fire. This number, in the short-term, will likely increase as large alders continue to break into transportable sizes. However, the number will eventually diminish as wood is redistributed during floods and as it continues to decay. Hence, some debris jams will increase in size and could cause channel avulsions.

The number of active slides and slumps along the channel increased from 6 in 1996 to 125 in 1997. This represented an increase in local sediment supply during the second year, not just an increase in sediment supplied from the headwaters. The channel, prior to adjustments caused by the fire, appeared to have become quite stable after it had adjusted to earlier land use impacts of grazing and reservoir construction, which likely contributed to its entrenchment.

The process of LWD recruitment to the channel was also quantified during the 1997 reconnaissance. Figure 5B shows that in 1997, 46% of the LWD elements were directly supplied by the effects of fire, 16% were supplied by landsliding, 10% had already floated downstream

Figure 6
A map of the Lower Gage Site in the Middle Watershed Section is shown for summer conditions of 1996.

Distance stations on the map match the distances shown on the longitudinal profile.



(input mechanisms could therefore not be determined), 6% were supplied by stream flow eroding or undermining the banks, and 5% were supplied by sediment building up on the bed, thereby incorporating LWD by elevating the bed level. Recruitment processes for about 17% of the LWD was not determined.

Figure 6 shows a 1996 map of a 100 m-long (328 ft) reach at the gage location. It depicts the large quantity of LWD that accumulated in the channel bed and across its banks. It is representative of much of the channel throughout the Middle Section. The longitudinal profile in Figure 6 indicates that the stream gradient was about 1.4%. The deepest pool was 0.4 m (1.3 ft) and the other pools were less than 0.3 m (1 ft) deep.

Pre-fire bankfull width was about 2.7 m (9 ft). Based upon a general finding that there should be a pool for every 5-7 bankfull widths (Leopold, 1994), the spacing of pools deeper than 0.3 m at 13.3 bankfull widths fails to meet this criterion. We expect that before the fire, pool spacing may have been greater than the immediate post-fire condition because sediment supply was lower (thus pools would not have been filled). Pre-fire wood spacing was about 6.3 bankfull widths.

The cross section at the upper right corner of Figure 6 shows the changes in width and depth that occurred near the gage site between June 1996 and May 1998. The cross section existing before fire was not expected to be much different from that shown for 1996 because no significant erosion was observed at the site at the time of the survey. The amount of cross sectional change prior to the 1998 February flood flow of the El Nino year was about 0.2 m (0.7 ft) of incision followed by the same amount of deposition. During the February flood, when high flows started to intersect much of the LWD, the banks widened by nearly 1.5 m (5 ft). The bed elevation increased in height by another 0.3 m. At the end of the rainy season the bed averaged about 0.7 m (2.3 ft) higher than its 1996 elevation. These changes were due to wood slowing the water velocity, trapping the sediment, reducing the channel gradient, and creating obstructions to flow that increased local sediment supply.

Hydrologic Conditions in Third- to Fifith-order Channel

During WY 1996, the amount of precipitation at the Lower Gage was about 60% of the amount at the Upper Gage. This corresponds with the expected rainfall gradient from the Pacific Ocean to the Inverness Ridge. Based upon the flow records and bankfull indicators at the site, we expect that bankfull flow at the lower gage might be slightly less than the 2.6 cms (90 cfs) predicted by statistical tendency from Regional Curves (Leopold, 1994). Tentatively, the data suggests 2.0 cms (70 cfs). This might be due to the much lower amount of rainfall in the Middle rather than the Upper Section. It might also be due to recharge of the alluvial valley.

During WY 1997, the Lower Gage may have exceeded bankfull flow only once during January 22 where peak flow was estimated as 2.0 cms (70 cfs). In 1998, it was exceeded at least once on February 9 when discharge was estimated at about 3.3 cms (116 cfs). To determine discharge for WY 1996, we used 29 storms during our period of record to develop a linear regression between discharge at the Upper Gage and the Lower Gage (R=0.91) The maximum discharge during WY 1996 may have been about 4.5 cms (160 cfs) during the first of January.

Lag times from peak rainfall to peak flow, and runoff coefficients were not determined for the Lower Gage because we were not confident that the data logger recorded the highest peaks of all storms. This is because measurements were set to be recorded every 5 minutes at the Lower Gage Site, but some of the flashier storms may have produced floods that peaked between the recording interval.

Base flow at the Lower Gage Site during 1 October 1996 was 0.014 cms (0.51 cfs). During 1 September 1997, it was 0.0102 cms (0.36 cfs), and 1 September 1998 it was 0.0136 cms (0.48 cfs). Unlike the Upper Gage Site, the lowest base flow coincided with lowest mean annual precipitation. The highest baseflow at the Lower Gage occurred during the first year after fire, although the third year after fire had 1.6 times more rainfall. We speculate that baseflow was highest the first year at the Lower Site because there was reduced evapotranspiration by plants during the growing season. Unlike the small percentage of area represented by hydrophobic soils in the bishop pine forest that did not have shallow surface saturation, the larger proportion of the watershed had soils that did saturate during winter. Therefore, soils throughout the Middle section maintained a slightly elevated base flow for the first post-fire year compared to the following years when vegetation was rapidly growing. Recall that the Upper Gage Site had less baseflow during the first year after fire due to hydrophobic soils that also developed a surface crust. The amount of change in base flow from pre-fire conditions is not known since stream gaging had not been previously conducted.

Lower Watershed Section

Changes in the Location of the Apex of the Alluvial Fan

Shortly after the first post-fire rainfall, an alluvial fan developed near the downstream end of the valley, about 960 m (3,150 ft) upstream of the Muddy Hollow dam. The lower channel that flowed within an alder forest that developed after the 1982 flood, filled with sediment. By the end of the rainy season, the apex of an alluvial fan was positioned at about 1,010 m (3,314 ft) upstream of the dam. The channel across the fan became braided and split into several distributaries. It had been a single thread channel prior to the fire. During the 1996 high flows, the full width of the lower valley was submerged. This caused sand to coarse-sized gravel to splay over the charred soils. In some areas the entire width of the valley, which was as much as 150 m (500 ft) wide, was covered with post-fire-related sediment. Most sediment was sand-sized and granitic in origin. Very little silt was observed. If it was present, it probably did not represent much of the total sediment load. The fine suspended load may have been deposited in Muddy Hollow Reservoir.

During the second winter, there were two additional upstream breaches of the mainstem channel upstream of the 1996 fan apex. The first breach caused the fan head to move upstream by 15 m (50 ft). The fan head was now out of the alder forest and into open meadowlands. The second channel breach, which occurred in later January moved the fan head another 16 m (52 ft) upstream. During the entire rainy season, the channel continued to braid and separate into distributaries. In total, the fan apex moved 1,041 m (3416 ft) upstream of the dam, representing complete burial of the previous channel (Figure 7).

During the early 1998 winter, the channel did not breach its banks. In fact, flow and sediment supply was diminished enough that the channel formed into a single thread channel across its entire alluvial fan. As the channel increased its depth, it transported sediment that had been stored in the fan to points downstream of the toe of the fan. In this way, an extension of the fan was built by deposition occurring downstream of the fan instead of upstream. This occurred until the February flooding, which was associated with El Nino conditions. During the flood event, the apex of the 1997 fan moved upstream by an additional 69 m (227 ft) and the channel began to braid again across the fan. By the middle of the 1998 rainy season the fan head moved another 95 m (312 ft) upstream. By the end of the season it had moved another 168 m (533 ft) upstream. Thus, by the end of spring the fan head was 1,414 m (4,641 ft) upstream of the dam (Figure 7).

During the growing season, even on the fan, vegetation recovery was rapid, even though several feet or more of sediment had been deposited onto the valley floor. A new alder forest began to expand in aerial extent. The open meadow section had lush growth of annuals and perennials including grasses, sedges, bulbs, and herbaceous plants.

Volume of Sediment Deposited in the Fan
Stratigraphic relationships were developed between the sediment exposed in each of the soil pits that were dug across the alluvial fan. In this way, the volume of sediment deposited in the alluvial fan could be estimated. Conservative estimates of first and second year post-fire sediment yield could be made with the qualification that the amount reported does not represent the total annual sediment load, which would include both the bedload and suspended load. The amount of sediment deposited on the alluvial fan represents only a portion of the total post-fire volume. It does not include suspended load carried downstream of the fan, and it does not include the amount stored in the channel bed upstream of the fan.

To facilitate comparisons of sediment yield with other streams, we converted sediment volume into a weight by using a bulk density value of 1.63 for gravel and sand (recommended by William Dietrich, UC Berkeley Department of Geology and Geophysics) to convert cubic yards into tons (Table 3).

The total volume of sediment deposited on the alluvial fan during the first post-fire year was 1,833 cu m (2,398 cu yd). During the second, it was 4,970 cu m (6,500 cu ft), which represents about 73% of the total. For both years the combined total volume was 6,802 cu m (8,897 cu ft), meaning that the minimum post-fire sediment yield over two years was 1,407 tonnes/sq km (5,252 ton/sq mi). This is probably much higher than the average annual load. It is notable that rainfall during the second post-fire year was 0.8 times less than the first year, hydrophobicity was prevalent in the upper watershed during the first year not the second, and yet 2.7 times more sediment was supplied to the fan during the second year. This was because the channel through the middle section started becoming a sediment source as its banks responded to the disturbance caused by falling alder trees that ripped the banks apart and provided large woody debris that created flow obstructions throughout the Middle Section.

Synopsis of Temporal and Spatial Watershed Response

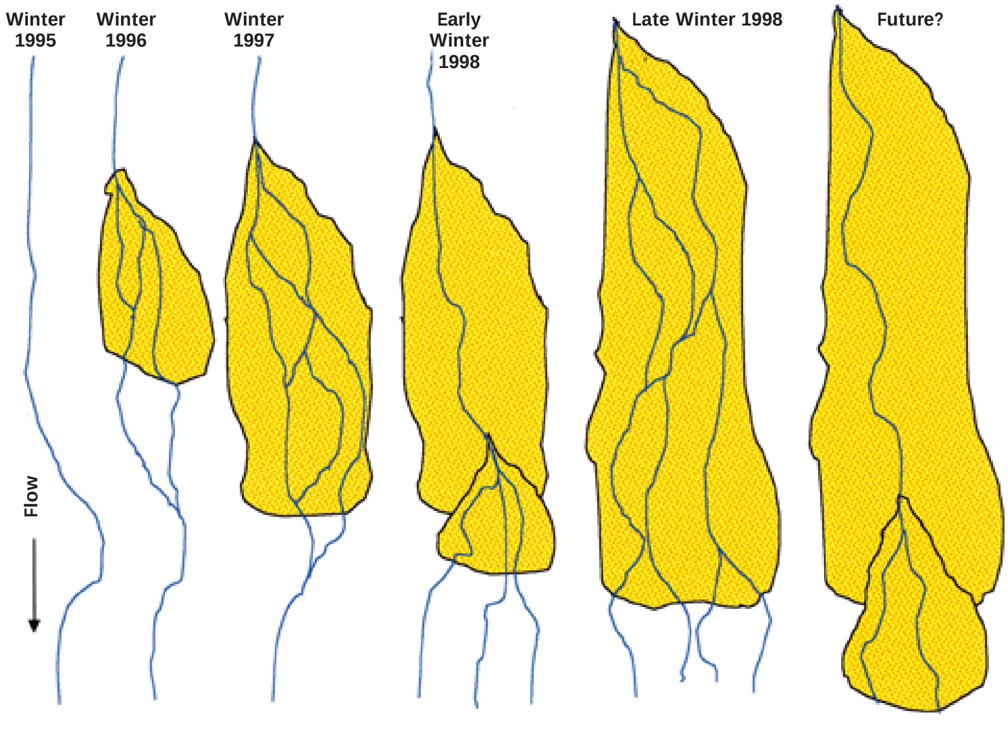
Before the fire, the Upper Section of MHC watershed functioned as a source and storage reach. It had part of its channel network disconnected by alluvial fans and historically it had punctuated sediment supply from mass wasting processes during landslide producing storms. Otherwise, sediment supply may have been fairly gradual from soil creep along the steep hillsides. After the fire it changed to a source and transport reach dominated by surface erosion processes that develop from particularly intense wildfire. Sediment storage was virtually eliminated and drainage density increased. During the first few storms following fire, the channels adjusted to the increased runoff by eroding their beds and banks and increasing the drainage density to accommodate the increased supply of water and sediment. As the drainage density increased the channel adjusted its geometry by eroding more to accommodate more flow, which then generated more sediment. Runoff from the hillsides diminished during the second year. It was caused by the reduction of hydrophobicity and breaking up of the surface crust on the soils by plants and bioturbation. During the third post-fire year the soils were saturated enough to respond again to landslide processes while the importance of surface erosion began to diminish. As recovery proceeds in the headwaters, sediment supply will again be punctuated by landslide producing storms. The importance of the headwaters, as a source reach from surface erosion processes should rapidly declined following the first few years. Potential for increased frequency of landslides may stay higher until a dense root network develops from mature bishop pines.

The Middle Section of MHC watershed has functioned, at least over the last few hundred years, as a transport reach. This changed for a short period during the latter half of the 20th Century following the construction of Bonelli's Lake. While the dam was in place, it stored sediment upstream of the dam and cut-off the sediment supply downstream. This probably initiated a period of incision and subsequent entrenchment of the channel below the dam that subsequently became a local, but short-term sediment source as the bed incised. After the dam was breached during the 1982 storm, most of the sediment supplied to the system was again transported through it. The channel functioned this way through the first year after fire as indicated by minimal sediment storage in the channel bed, but by the second post-fire winter, it changed from a transport reach to a combined source and response reach. This was primarily due to the largest amount of LWD supplied to the channel, not due to hydrophobicity through the Middle Section, or necessarily from increased peak flows. We expect that the channel through the middle section will continue to function in both these ways for a number of years for several reasons including: 1) water and sediment transport rates will decrease because of reduced gradient caused by the higher base level from deposition of sediments on the downstream fan and from local entrapment of sediment behind LWD; 2) the local banks will generate more sediment as LWD continues to fall into the channel and is remobilized; and 3) during large floods high shear stresses will initiate erosion on the bed and banks because the channel is entrenched and does not develop a functional 'inner" floodplain.

The lower watershed above Muddy Hollow Reservoir has periodically functioned as a response reach ever since the reservoir was constructed. Prior to its construction and to land use activities, we expect that the entire channel and tidal slough system functioned to transport a fairly low sediment load out of the watershed and into the estuary. After cattle grazing affected the watershed, we expect that an alder forest began to invade the meadow of the lower valley floor because of increased sediment deposited on the floodplain and from draining of the valley by ditch construction. After construction of Muddy Hollow Reservoir, the base level of MHC was elevated. This caused deposition at the upstream portion of the reservoir and the valley upstream of its open water. A newer alder forest began to invade the valley floor. For a short time following the breach of Bonelli's Lake during the 1982 flood, the valley upstream of the Muddy Hollow Reservoir developed a new alluvial fan that supported yet another new alder forest. Following the fire, the lower reach functioned as a response reach by building another alluvial fan upstream and on top of the 1882 fan. For a short time during the early 1998 winter, when both sediment and water supply were relatively low, the channel on the fan also became a source reach. This was because sediment was supplied during the reformation of a single thread channel that incised into the fan and redistributed its bed sediments downstream of the toe of the post-fire fan. When flood flows occurred during the middle of the 1998 winter, the lower reach again functioned as a response reach. It began to develop distributaries and braided channels. In the future, as sediment supply shuts down, the channel in the Lower Reach may develop enough sinuosity to primarily function as a transport reach except during extreme storm events.

Figure 7
Conceptual sketch of the sequential growth of the post-fire alluvial fan upstream of Muddy Hollow Reservoir.

When the sediment supply is high, the alluvial fan grows as the channel braids and separates into distributaries. When the sediment supply from upstream fluvial transport decreases, a single thread channel incises and reworks sediment in the fan and deposits a new fan downstream.



The spatial and temporal effects of fire on baseflow appear to be dependent upon position in watershed and distribution of hydrophobic soils. If extensive hydrophobic conditions exist, baseflow may be diminished due to lack of infiltration. If these conditions do not exist and the watershed was previously densely vegetated, then baseflow may be increased due to the lack of evapotranspiration effects of vegetation.

Initial Hypotheses

A number of preliminary hypotheses were developed from this study. They are enumerated below.

1. Landscapes in coastal Northern California with similar geology to landscapes in coastal Southern California that both develop post fire hydrophobic conditions, have different geomorphic responses to erosion processes. These differences may be due to greater root density and their influence on apparent soil cohesion of plant assemblages that are adapted to Mediterranean-type climates compared to arid climates. As a result, post-fire sediment ravelling and bulking of flows was not an important process in Muddy Hollow watershed.
2. Large woody debris supplied from fire damaged riparian corridors can plays a critical role in altering transport reaches into source and response reaches for years after the event of fire.
3. Spatial and temporal effects of wildfire on peak and base flows depend upon position and distribution of hydrophobic soils in a watershed.
4. Amount of post-fire sediment supplied to a channel also depends upon position and distribution of hydrophobic soils, and upon the supply of LWD to the channel system.
5. Alder forests on the valley floor are a modern feature caused by increased sediment supply onto the valley floor. This hypothesis was developed by comparing historical circa 1860 maps to aerial photos dating back to 1942. The historical maps show minimal riparian vegetation on the lower valley floor. We suggest that as grazing and agricultural practices increased, sediment supply also increased, effectively elevating the valley floor enough to reduce seasonal saturation in meadowlands upstream of the tidal marsh. The water table began to fluctuate enough that alders could be supported in an environment that was not saturated for extended time and that was not stagnant.
6. In areas where surface crusts develop on hydrophobic soils, the first post-fire year base flow may be decreased below natural background rates because of the lack of saturation. In areas not dominated by hydrophobic soils base flow may be increased above natural background rates because of the loss of evapotranspiration.
7. Mycorrhizae in association with certain vegetation species may play an important role in development of hydrophobic soils.

Recommendations for Continued Monitoring by PRNS

The best way to determine change from catastrophic events is to have pre-existing data. The value of long-term background data far exceeds the value of short-term monitoring, such as this study that cannot definitively establish magnitude of response compared to background rates, and length of time required for recovery. Establishing baseline conditions to determine natural variability of a number of different but representative channels in the National Seashore is strongly recommended. Within a single channel system, measurements of hydraulic geometry at different positions along the watershed could be made to establish an appropriate picture of the spatial and temporal variability of the watershed. Their land use history and/or vegetation type could stratify watersheds. Monitoring could be accomplished by a variety of different efforts and associated costs. At a minimum, establish some permanent cross sections that can be reoccupied, even after the event of fire, by having their coordinates fixed by Global Positioning Stations. Fireproofing of permanent benchmarks that fix

Table 3. Sediment Volumes in Alluvial Fan

	Volume cu/m (cu yd)	Min. Yield cu m/sq km (cu yd/sq mi)	Min. Yield tonnes/sq km (tons/sq mi)
1996 First Winter after Fire	1,833 (2,398)	256 (869)	379 (1,416)
1997 Second Winter After Fire	4,970 (6,500)	695 (2,355)	1,027 (3,836)
Total for two years	6,802 (8,897)	951 (3,224)	1,407 (5,251)
Average per year	3,401 (4,449)	476 (1,612)	704 (2,626)

elevation and location for existing cross sections and profiles is also recommended. Cross sections and profiles could be surveyed once a year for a decade for example, and then less frequently based upon analysis of the data. The length of the long profiles should be 20 times the bankfull width. With this minimal amount of background data, the magnitude and type of change following a significant event such us fire or major flood could be better understood and post fire remediation effectively planned. It is important for land managers to understand the resilience of a system to recover, but also to recognize when thresholds have been crossed that initiate instability.

If a greater level of background information is desired, continuously recording stream and rainfall gages can be established on a number of channels to characterize storm and base flow. Still wells are a less expensive alternative that can also be used to establish peak flood heights.

The map of Lower Muddy Hollow Site can be used in the future to make comparisons of bankfull width, planform, distribution of woody debris, and particle size. The longitudinal profile could also be resurveyed, but patience will be needed to wait for the time when the channel is not impenetrable.

If stream gauging in MHC channel is desired, a permanent weir is highly recommended. Without a stable cross section, efforts to try to develop a rating curve for discharge and gage height will be thwarted by unstable conditions of the bed or banks.

To best determine impacts of the fire and of recent land use effects on sedimentation rates, we recommend that a program of coring and dating sediments deposited in Muddy Hollow Reservoir should be conducted. If this effort is done in concert with coring of the remaining tidal marsh at the foot of the Muddy Hollow Reservoir and deep coring of sediments in the upland valley, it could be possible to develop both historical sedimentation rates and fire frequency prior to non-native settlement.

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