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HYDROGEOLOGIC RESPONSE OF SMALL WATERSHEDS TO WILDFIRE

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TECHNICAL COMPLETION REPORT

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ABSTRACT:

Following the Santa Barbara, CA. Painted Cave Fire of June 25, 1990 an emergency watershed protection plan was implemented consisting of stream clearing, grade stabilizers, debris basins and research focusing on streambed changes on two different branches of Maria Ygnacio Creek, the main drainage of the burned area.

During the winter of 1990-1991, between 35 and 66 cm of rainfall and intensities up to 10 cm per hour for a five minute period were recorded. During the winter of 1991-1992, between 48 and 74 cm of rainfall and intensities up to 8 cm per hour were recorded. Even though there was moderate rainfall on barren, saturated soils, no major debris flows occurred in burned areas. The winter of 1992-1993 recorded total precipitation of about 170% of normal. Intensities were relatively low and no debris flows were observed. The response to winter storms in the first three years following the fire was a spectacular flushing of sediment, most of which was derived from the hillslopes. The debris basins trapped 30,000 m^3, the majority coming from the storm of March 17-20, 1991. Sediment transported downstream during the three winters following the fire and not trapped in the debris basins was eventually flushed to the estuarine reaches of the creeks below the burn area, where approximately 108,000 m^3 accumulated.

Changes in stream morphology following the fire were dramatic as pools filled with sediment which greatly smoothed longitudinal and cross sectional profiles. Major changes in channel morphology do occur following a fire as sediment derived from the hillslope is temporarily stored in channels within the burned area. However this sediment may quickly move downstream of the burned region, where it may accumulate reducing channel capacity and increasing the flood hazard.

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KEY WORDS: channels, chaparral watersheds, hydrogeology, sedimentation, stream dynamics, and wildfire

PROBLEM AND RESEARCH OBJECTIVES

Research Problem

The hydrogeologic response of small watersheds to wildfire is poorly understood. In some instances the response is spectacular resulting in high magnitude-debris flows, while in other cases the response is flushing of sediment by streams. The problem is that following a particular fire we are never certain which combinations of the possible events are more probable to occur. Answering this question is crucial for managing watersheds, particularly near urban areas of southern California.

Research Objectives

The important question to County Flood Control, as well as the city of Santa Barbara and other agencies responsible for protecting people from hydrogeologic disasters is: What is the likelihood of a high-magnitude debris flow occurring in the first year or two following the fire? A second question is: What will be the hydrologic response given a variety of scenarios concerning precipitation events? In this research we are also specifically testing the hypothesis that high-magnitude debris flows are relatively infrequent relative to production and flushing of sediment by stream processes. This hypothesis was first presented by Keller and others (1988) and Florsheim and others (1991) and is in need of further testing.

METHODOLOGY

The research approach consists of measurement and observations following the Painted Cave Fire of late June, 1990 at Santa Barbara, California. Hydrogeologic response to precipitation events will be determined by: 1) repeated survey of sediment trapped in the debris basins; and 2) resurvey of long profiles and cross profiles on study reaches upstream from the debris basins. Analysis of precipitation data from three continuously recording rain gauges in and near the watersheds, monitored by Santa Barbara County Flood Control, are used to couple hydrologic events to response of the watersheds.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Introduction

The first of California's recent series of destructive wildfires, the Painted Cave Fire of June 25, 1990 burned a 1214 ha (3000 acre) path from a 800 m mountain ridge through the urban corridor in Santa Barbara to only one km from the Pacific Ocean in a few hours (Figure 1). The fire claimed one life, burned 450 homes and caused approximately 300 million dollars in property damage. In response to the threat of flooding in following winter storms numerous flood prevention and hillside stabilization measures were undertaken by several different groups and agencies. Based upon limited historical information, the Santa Barbara County Flood Control and Water Conservation District with the assistance of the USDA Soil Conservation Service formulated an emergency watershed protection plan. Elements of this plan included stream clearing, grade stabilizers, and construction of debris basins on two different branches of Maria Ygnacio Creek. The goal was to protect the citizens and property in the floodway of the burned watershed. In addition to the flood prevention measures, a cooperative research project focusing on streambed changes was implemented in order to assess future post-fire sediment and debris flux.

The geology, fire boundary, as well as location of debris basins, rain gauges and stream gauging station is shown on Figure 2. Notice that the two watersheds are geologically different. The western watershed extends well into massive sandstones of the Coldwater Formation, where large boulders are produced. During the excavation for the debris basins, numerous debris flow deposits, containing boulders of several meters in diameter, were encountered. In contrast, in the eastern basin only relatively small debris is present. This results because the basin does not extend into massive sandstones units but is almost entirely in a generally softer, more easily eroded sandstone known as the Sespe Formation. Both debris basins were constructed with outlet and overflow structures at a cost of about $3.5 million. The capacity of the debris basin for the east fork was approximately 60,000 m^3 whereas as that of the west fork was unusual summer storm, 1991-1992 season rainfall ended at 112% of normal. In the winter of 1992-1993 the burned area received between 83-101 cm of rainfall and maximum intensities were 7 cm/hr for a five minute duration. Although total precipitation was approximately 170% of normal the intensities were relatively low (approximately one year return period).

Sediment Production

We estimated the burned area would produce approximately 234,000 m^3 of sediment. Loading rates for unburned areas, burned areas after one year, and burned areas after two years were used to arrive at the estimated sediment production following the Painted Cave Fire (Table 1). Noteworthy, San Jose Creek has a much higher average loading rate which correlates to a watershed which encompasses a higher rainfall regime and more erosive source region. Atascadero Creek, which all burn area creeks drain into rests in the urban corridor and therefore is not considered to contribute other than its normal sediment loading. These loading rates were arrived at between mutual discussions between the County Flood Control District, United States Forest Service, and Soil Conservation Service.

The Forest Service uses a range of numbers for estimating sediment discharge following wildfire depending on various parameters such as locality, soil type, underlying geology, burn intensity, and slope. From this initial range of numbers 111 m^3ha^{-1} (60 y^3a^{-1}) was used for burned areas the first year following fire and 37 m^3ha^{-1} (20 y^3a^{-1}) was used for burned areas the second year following fire. Unburned area loading rates (annual average loading rates) were taken directly from USFS numbers (Rowe and others, 1949). Applying these numbers to burned and unburned areas of the affected watersheds, Table 2 summarizes the estimated two-year sediment production. The annual average loading to the Atascadero Creek System, which feeds directly into the Goleta Slough is estimated to be 35,000 m^3. Altogether, we estimated approximately 234,000 m^3 (306,000 y^3) of sediment to be produced from the Painted Cave Fire burned watersheds, or 335% of normal for the two year period 1991-1992.

The actual sediment production following the 1990 Painted Cave Fire is the sum of sediment in the Goleta Slough and estuarine reaches of the Creeks below the burned area, the sediment currently in the debris basins, the sediment removed from the debris basins, and sediment discharged directly to the Pacific Ocean in suspension (Table 3). Several estimates could affect this calculation, the most significant being the estimated discharge to the Pacific Ocean as suspended sediment. It is estimated that approximately 76,000 m^3 (100,000 y^3) was discharged into the Pacific Ocean in the plume following the storm of March 17-20, 1991 (Will Anikouchine, personal communication). The suspended sediment discharge was prorated from actual measurements taken from the Ventura River discharge plume following the Wheeler Fire of 1985. The March 17-20, 1991 plume from Maria Ygnacio and Atascadero Creeks was by far was the largest discharge plume following the fire and we believe that 76,000 m^3 (100,000 y^3) is a conservative number for estimating discharge to the Ocean in suspension.

The debris basins during the 2 years following the fire trapped only 30,000 m^3 (13% of total) of sediment, allowing most to pass through to the estuarine reaches of the creeks where 108,000 m^3 accumulated over two years. However, the debris basins did delay a portion of the sediment passing through the basins thereby providing a buffer between the burned and unburned reaches of the stream channel. The debris basins effectively trapped nearly all the coarse material and debris flushed from the burned watersheds, which would have reduced downstream channel capacity, increasing the flood hazard. Dry ravel in stream channels amounted for only about 3600 m^3 of the total suggesting that 98% of the sediment produced was derived from the hillslopes.

Channel Morphology Changes

Changes in stream morphology following the fire were dramatic as pools where grade existed were scoured to bedrock and pools in areas without grade filled with sediment. This greatly smoothed longitudinal and cross sectional profiles. Figures 3 and 4 show longitudinal profiles of two study reaches of Maria Ygnacio Creek. Figure 3 shows a longitudinal profile of reach 2, west Maria Ygnacio Creek. These profiles are of our particular interest because they show the accumulation of three dry ravel cones which accumulated in the bed of the creek following the fire. Dry ravel is defined as the dry downslope surface flow of unconsolidated particles and may be the dominant process that facilitates accumulation of stored sediment in channels following wildfire. The dry ravel cones were removed by the first storm following the fire (February 27-March 2, 1991) as shown by the profiles surveyed on March 15, 1991. At that time sediment was generally deposited along the bed of the channel at most locations. Following the storms of March 17-20, 1991 most of the sediment which was temporarily stored was removed. The pattern of deposition and erosion of sediment in the channel is more clearly shown on Figure 4 which is a longitudinal profile of east Maria Ygnacio Creek. The January 19, 1991 profile is before the storm of February 27-March 2, 1991 which caused significant aggradation as shown by the March 6, 1991 profile. The extensive deposition of sediment in the channel from this storm suggests that the event was clearly transport limited. That is, so much sediment was being delivered to the stream channel from adjacent hillslopes that it could not be transported by the stream. The profile of March 20, 1991 follows the intensive storm of March 17-20 and shows that the sediment deposited by the first storm has been nearly all removed. Thus the second storm of the season (March 17-20) was clearly sediment limited. That is, the stream flow had sufficient power to transport all the available sediment as well as erode sediment previously deposited. Visual observations confirm that there is a definite sequence of scour and deposition following wildfires in the upper reaches of a burned watershed. Table 4 summarizes the response of Maria Ygnacio Creek to the first two storms following the Painted Cave Fire. The first storm resulted in transport limited conditions and deposition in the stream channel. The second storm produced a sediment limited flow and resulted in massive transport of sediment downstream. Thus the total response of the watersheds during the first year of storms was a major flushing of sediment. These events support our hypothesis that if precipitation intensities are low to moderate, a likely response to wildfire is fluvial transport of fine-grained sediment. A similar flushing of sediment was observed following the 1985 Wheeler Fire (Florsheim and others, 1991).

Deposition appears to play a more significant role in middle and lower, possibly estuarine reaches of creeks following wildfires. After two rain seasons following the Painted Cave Fire, the concern shifted from problems directly below the Fire Area to the estuarine reaches of the creeks. In fact by the winter of 1992-1993 most sediment had moved through the upper and middle parts of the drainage basin and was in storage in the estuarine reaches. Thus, while major changes in channel morphology do occur following a fire as sediment derived from the hillslopes is temporarily stored in channels in the burned area, this isn't the entire response. Depending on the rainfall distribution immediately following the fire eroded sediment may quickly be transported downstream of the burned region, to accumulate reducing channel capacity and increasing the flood hazard.

Discussion

Several of the measurements and estimates noted in this report could affect our calculations and should be the subject of further research. With the increasing urbanization of chaparral watersheds we need a better understanding of the processes which create a flood hazard following a wildfire. After a fire, tremendous amounts of debris and sediments are discharged into the water conveyance systems, where they accelerate flooding problems along the way. The historical perspective has been to assess a burn area after a fire in terms of watershed recovery, and rate augmented sediment flux in terms of years since the burn. Following the Painted Cave Fire of June 25, 1990 above average volumetric rainfall greatly accelerated the processes which moved sediment through the watersheds and into the estuarine reaches of the creeks. We suggest that watershed recovery can be described in terms of possible rainfall distributions as ideally shown on Figure 5. Hypothetically, with the variety of rainfall distribution curves (shown on Figure 5) one can assess the potential sediment production depending on the desired level of protection.

A conceptual model showing the concept of relationships between fire frequency, frequency of large magnitude floods and threshold of basin instability is shown on Figure 6. The model assumes that flood events are random and wildfires occur at a relatively constant frequency. The shorter lines represent flood events of low- to moderate-magnitude whereas the longer lines are floods of high magnitude. When watershed burns correspond with moderate magnitude flood events then sediment flushing is the likely response. These are the small blips on the top draft which shows relative sediment yield. These sediment flushing events transport several times the normal or average sediment discharge.

The center graph in Figure 6 shows the threshold of basin instability. The idea here is that coarse debris (too large to be normally transported by sediment flushing events) slowly builds up in drainage basins with time. If a watershed burn coincides with a high-magnitude flood event at a time when basin instability is also high then a large debris flow may result. In our hypothetical example two such events have occurred during the 600-year period. Dating of debris flow deposits by 14-C on charcoal deposited within the flows in a small drainage basin in Ventura County suggested that the recurrence interval of large debris flows is approximately an order of magnitude greater than the recurrence interval of wildfire in the area (Florsheim and others, 1991).

Conclusions

Following the Painted Cave Fire of June 25, 1990 no major debris flows were recorded, rather a relatively quick and spectacular flushing of sediment out of the burned watersheds. This was determined by the rainfall distribution. There was no significant rain on the burned watersheds for eight months after the fire. When rain did begin to fall it fell in abundance, speeding the flushing process, but was limited to moderate (five-year return period) intensities, reducing the chances of a debris flow. The sediment has clogged the estuarine reaches of the creeks below the burn area, creating a potential flood hazard. Channel morphology changes are significant, from scouring at higher elevations to deposition at lower elevations. This subject matter has limited background work and needs to be the focus of future research to better understand the relationship between rainfall and post-wildfire sediment fluxes.

Construction of the debris basins, although expensive, was a positive management decision. Even though the west basin overflowed twice in the first set of storms following the fire and the east basin overflowed once, the basins helped modulate the routing of sediment through the system. By storing sediment they allowed for greater downstream channel capacity during potential flood flow events. If there had been a large debris flow the basins would have trapped, held back or retarded the down valley movement of all but the largest debris flows.

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PAPER IN PREPARATION

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TABLE 1

Sediment loading rates for watersheds in the Painted Cave Fire area

Drainage	Burned Watershed ha	(ac)	Unburned Acres in Watershed ha	(ac)	Unburned Area Sediment Loading (Ann.Avg.Loading) m^3ha^{-1}	Burned Area Sediment Loading 1st Year m^3ha^{-1}	Burned Area Sediment Loading 2st Year m^3ha^{-1}
Maria Ygnacio West	456	(1,125)	604	(1,492)	6	111	37
Maria Ygnacio East	405	(1,000)	49	(122)	6	111	37
San Antonio	230	(567)	1,002	(2,473)	6	111	37
San Jose	96	(237)	1,714	(4,232)	9	111	37
Atascadero	Near Zero		452	(1,117)	6	--	--

TABLE 2

Estimated sediment production (1990-1991 and 1991-1992 water years) following the Painted Cave Fire (m^3)

Drainage	Total Sediment Production (Annual Average)	Total Sediment Production 1st Year (Burned & Unburned)	Total Sediment Production 2nd Year (Burned & Unburned)	Watershed Total Sediment Production (1991-1992)
Maria Ygnacio West	6,678	55,261	20,854	76,115
Maria Ygnacio East	2,745	46,174	15,590	61,764
San Antonio	7,601	32,195	14,854	47,049
San Jose	15,445	25,499	18,250	43,749
Atascadero	2,793	2,793	2,793	5,586
TOTALS	35,262	161,872	72,341	234,213

TABLE 3

Summary of post-fire sediment production (m^3)

Surveyed Amount in Goleta Slough	117,000
Pre-Fire Sediment (Bottom 0.61 m)	-8,000
Post-Fire Sediment in Goleta Slough	108,000
Sediment in Lower Reaches of Creeks (surveyed below debris basins)	8,000
Sediment in Debris Basins (what was not removed by S.B. Flood Control)	8,000
Sediment Removed by S.B. Flood Control from Debris Basins	23,000
Sediment Discharged to Pacific Ocean (a conservative estimate)	76,000
TOTAL	223,000

TABLE 4

Response of Marie Ygnacio Creek to the first two storms following the Painted Cave fire

Storm	Rainfall (cm)	Conditions	Response
Feb. 27-Mar. 2, 1991	27	Initial dry soil, dry ravel in channel, and on hillslopes	Sediment transported from hillslopes into channel. Transport--limited flow
Mar. 10-11, 1991	1	Moderate saturation of soil, sediment filling channel. Little sediment left on hillslopes	None
Mar. 13, 1991	1	Moderate saturation of soil, sediment filling channel. Little sediment left on hillslopes	None
Mar. 17-20, 1991	35-66	Saturated soil, sediment filling channel. Little sediment left on hillslopes	Sediment transported out of channel. Sediment--Limited flow
Mar. 24-26, 1991	1	Saturated soil, little sediment in channel. Little sediment left on hillslopes	None
Total	**65-96**		**Major flushing of sediment**

FIGURE CAPTIONS

Fig. 1. Fire history of the Santa Barbara area. Data from U.S. Forest Service, Santa Barbara Flood Control and Santa Barbara News-Press. Notice the entire front of the Santa Ynez Mountains has been burned since 1964. The average return period of fires at a particular site is 35-60 years (Byrne, 1979).

Fig. 2. Geology, fire boundary and location of debris basins, rain gauges and stream gauging station for the study of watersheds.

Fig. 3. Longitudinal profiles, reach, west Maria Ygnacio Creek. Location is shown on Figure 2. By November, 1990 three dry ravel accumulations filled the channel. These were removed by the first storm (February 27-March 2, 1991). The storms of March 17-20, 1991 removed more sediment from the channel (see profile of March 23, 1991).

Fig. 4. Longitudinal profiles of east Maria Ygnacio Creek. Location is shown on Figure 2. The January 19, 1991 profile is before the storm of February 27-March 2, 1991 which caused aggradation (see profile March 6, 1991). This sediment was removed by the March 17-20, 1991 event (see profile March 20, 1991).

Fig. 5. Idealized sediment production by stream flow processes (flushing) suggested by the data from Maria Ygnacio Creek.

Fig. 6. Idealized diagram showing concept of relationships between fire frequency, frequency of floods and threshold of basin instability. Points F are sediment flushing events. The greatest sediment yield at Points DF (debris flow) result from basin instability (threshold T is exceeded) following a fire and high-magnitude flood. (Modified after Schumm, 1977.)

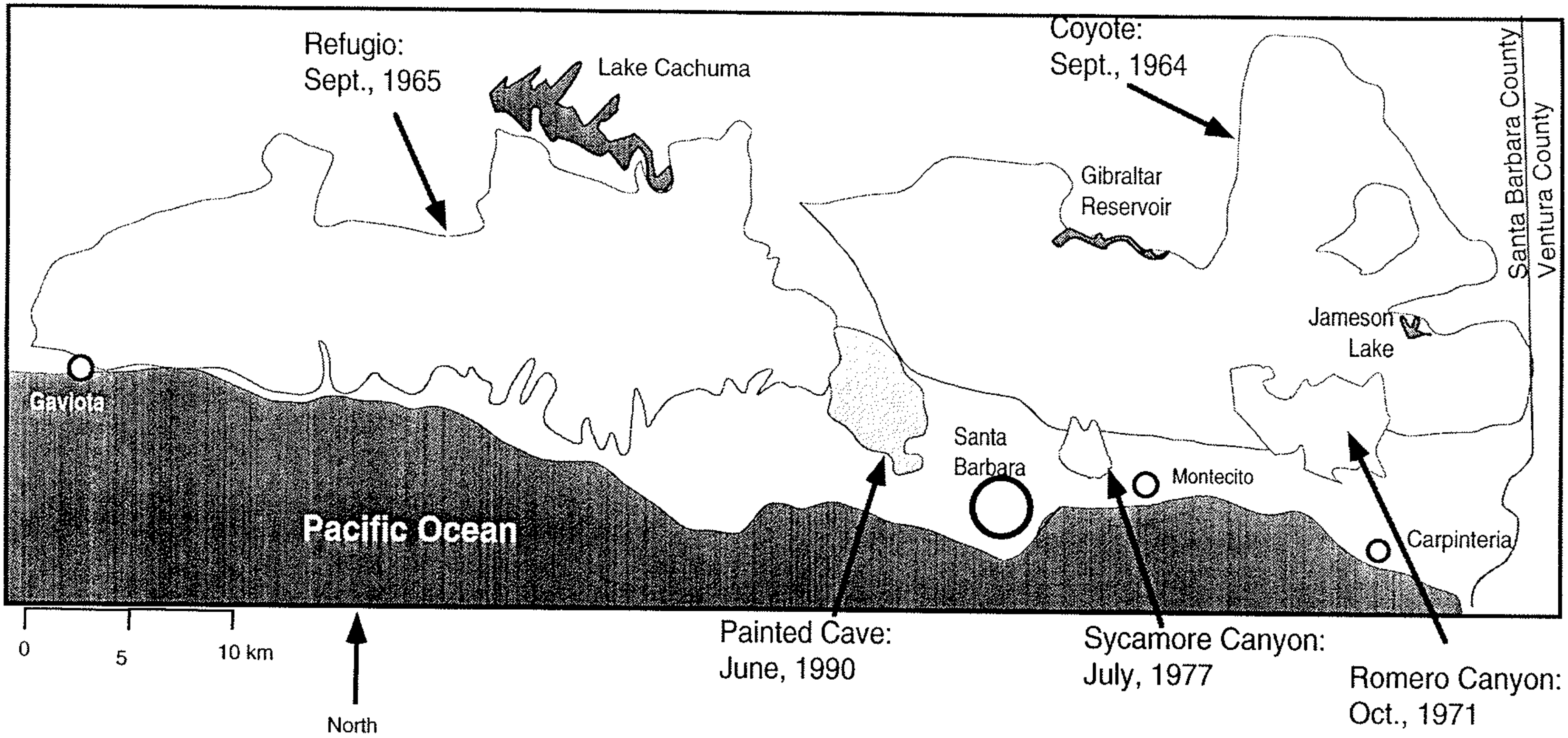
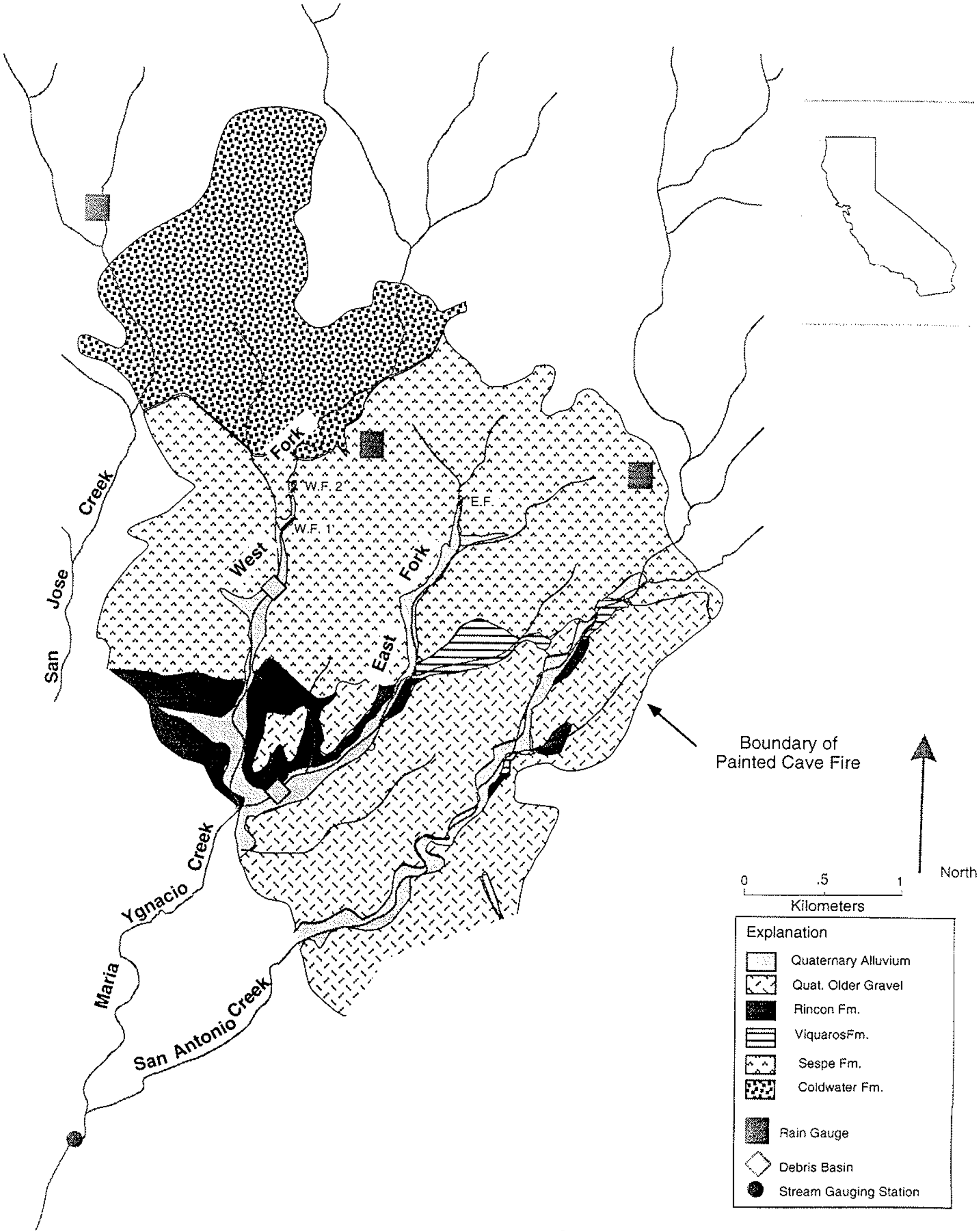


Figure 1. Fire History of Santa Barbara County, 1964- 1990. Almost the entire rangefront has burned in the past 35 years. The average return period of fires for a particular site is 35-60 years (Byrne, 1979). Catastrophic debris flows occurred following the Romero and Sycamore Canyon fires. After Santa Barbara News Press, U.S. Forest Service, Santa Barbara Flood Control.



Sources:

Geology simplified from Dibblee, 1988

Figure 2. Geology, Fire Boundary and location of study reaches, debris basins, rain guages, and stream guaging stations for the study watersheds. Study Reaches: W.F 1 - West Marie Ygnacio Reach 1; W.F 2 - West Marie Ygnacio Reach 2; E.F. - East Marie Ygnacio Reach 1

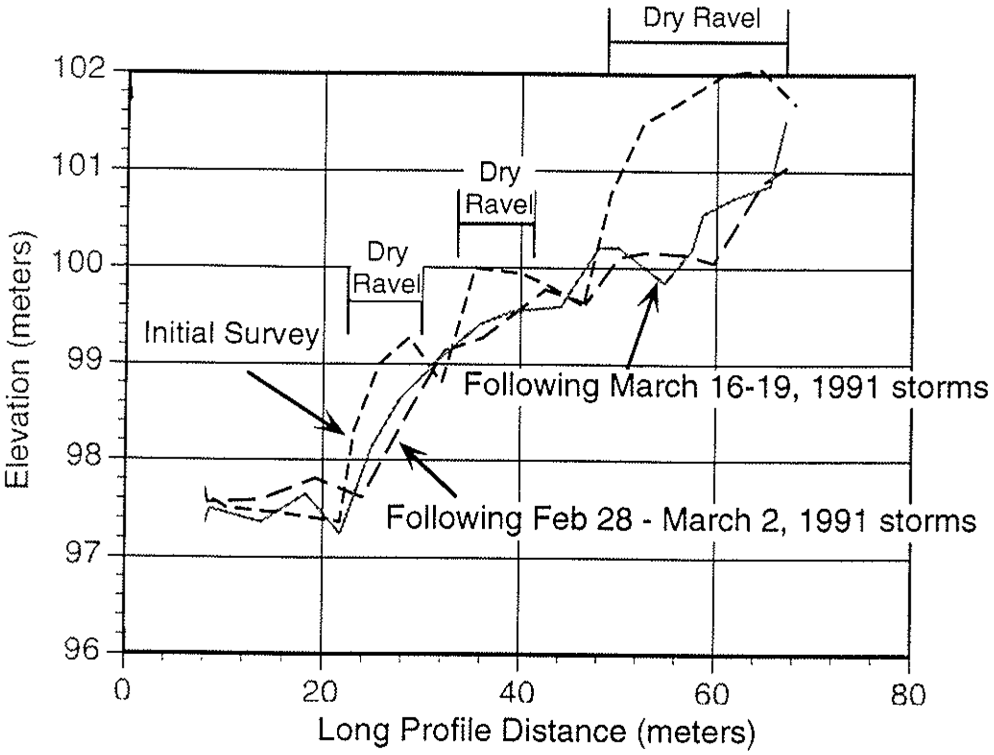


Figure 3. Long Profiles Reach 2 West Marie Ygnacio Creek. By the initial; survey on Nov 7, 1990, Dry ravel accumulation filled the channel. These ravel cones were destroyed by the Feb 28-Mar 2, 1991 storms, and the channel was filled with sediment. The storms of Mar 16-19, 1991 transported the sediment out of the reach.

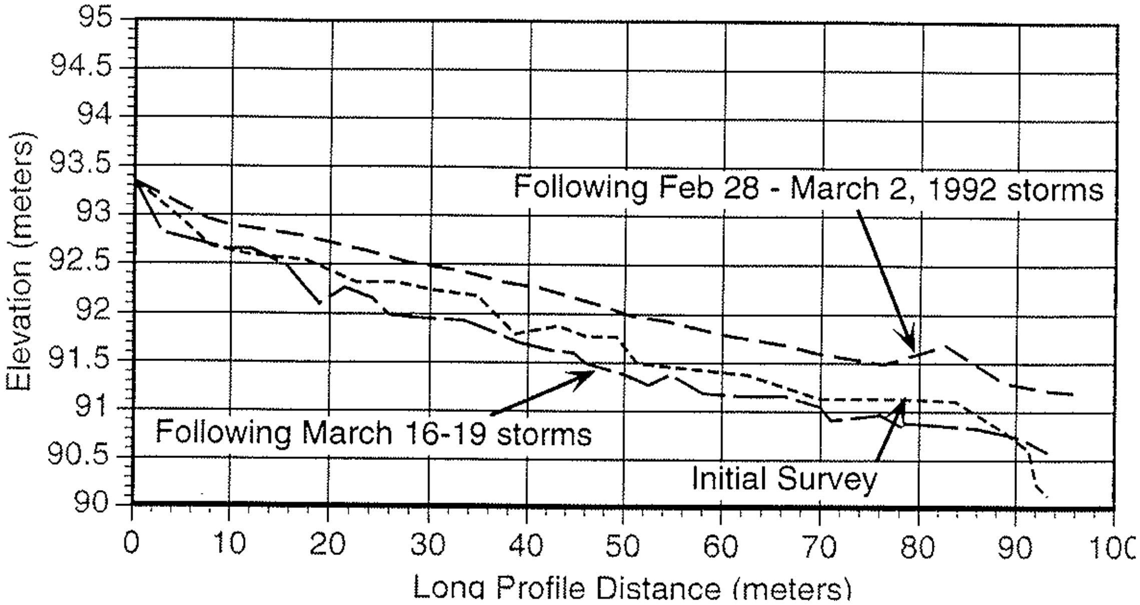


Figure 4. Long profile of East Marie Ygnacio creek. The inital survey was completed before storms occured. Significant aggradation occured within the reach during the storms of Feb 27- March 2, 1991. The storms of March 17-20, 1991, transported the accumulated sediment from the reach.

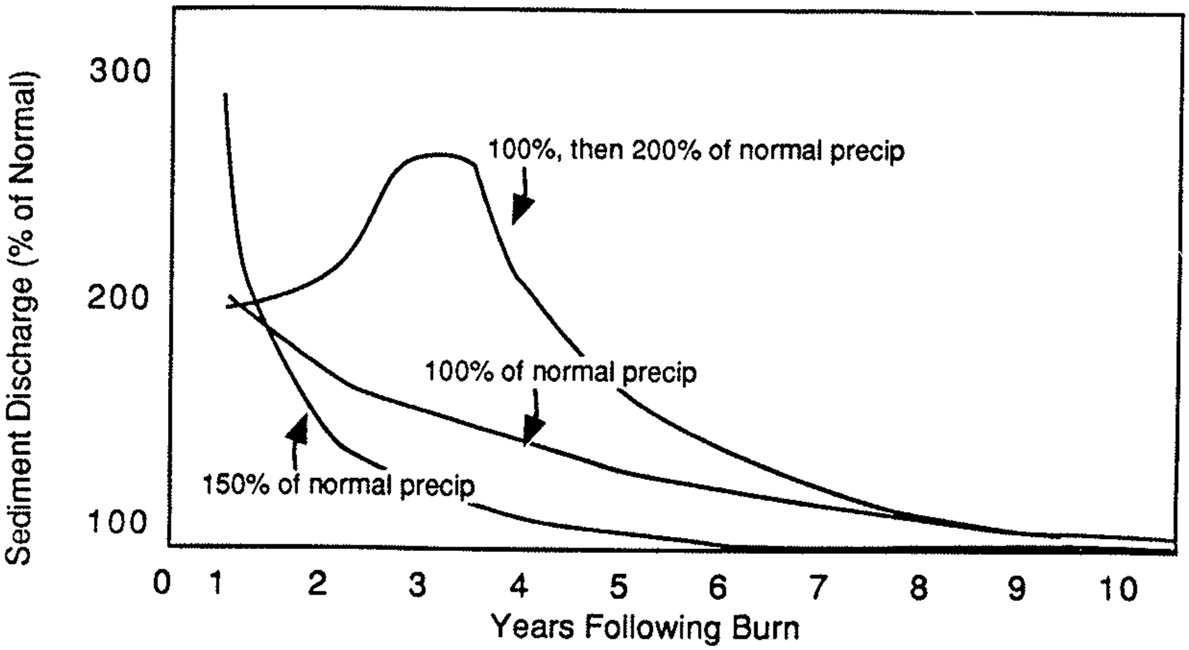


Fig. 5. Idealized sediment production by stream flow processes (flushing) suggested by the data from Maria Ygnacio Creek.

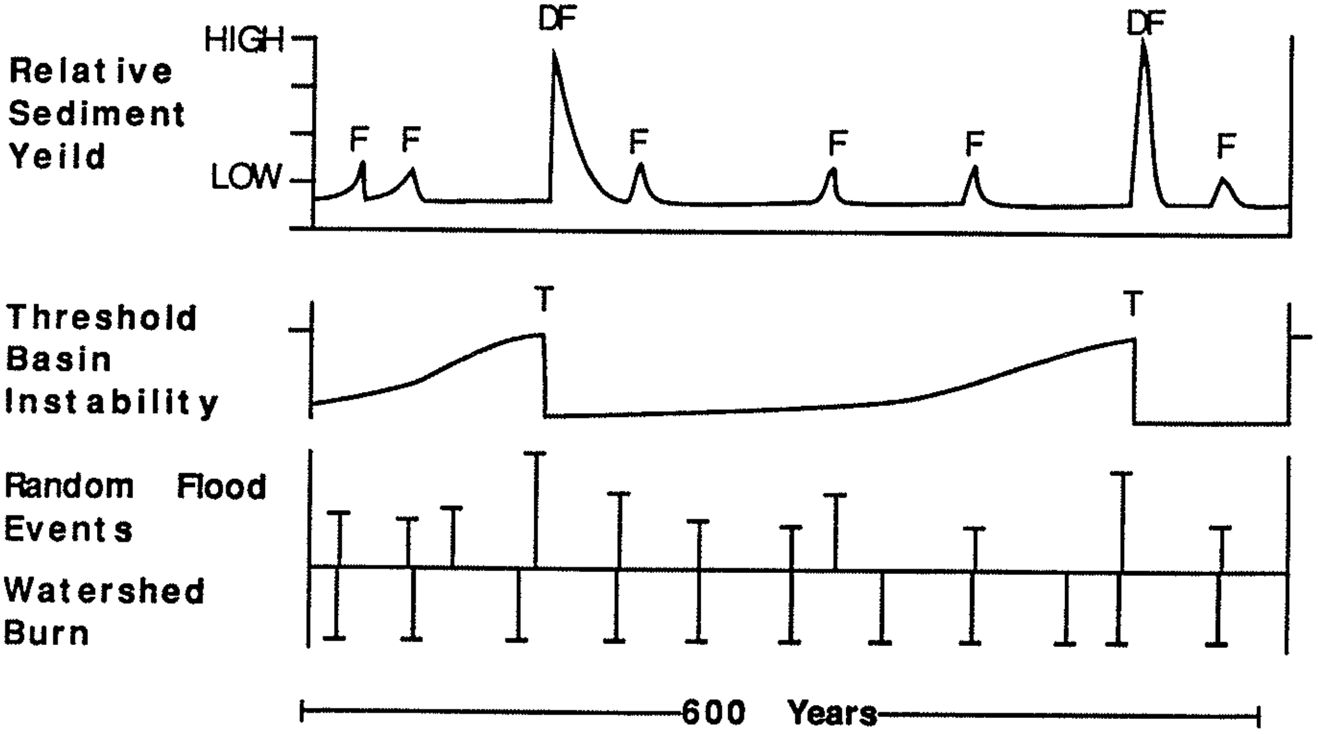


Fig. 6. Idealized diagram showing concept of relationships between fir frequency, frequency of floods and threshold of basin instability. Points F are sediment flushing events. The greatest sediment yield at Points DF (debris flow) result from basin instability (threshold T is exceeded) following a fire and high-magnitude flood. (Modified after Schumm, 1977.)