ENGINEERING TECHNICAL REPORT

EFFECTS OF RAINSTORMS ON WATER AND SEDIMENT RUNOFF
FOLLOWING THE 1996 WILDFIRE
BUFFALO CREEK, COLORADO

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Effects of rainstorms on water and sediment runoff following the 1996 wildfire, Buffalo Creek, Colorado

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Abstract A basin-wide, monitoring approach provides important information to assess the effects of wildfire on water and sediment runoff, assess the effects of watershed-rehabilitation activities, determine watershed recovery time, and help manage forest ecosystems. The approach is flexible, requires minimal resources, and complements comprehensive instrumented monitoring in a short amount of time. The approach was applied to the mountain community of Buffalo Creek, Colorado, which had a catastrophic wildfire on May 18, 1996. Subsequent rainstorms produced 9 floods larger than a 100-year (pre-fire conditions) flood as well as numerous smaller floods. Rates of flood runoff in 1997 were about the same as in 1996, which indicate persistent effects from the fire and minimal watershed recovery. On July 12, 1996, about 130 mm of rain fell in an hour and was about a 1,000-year event. This extreme rainstorm produced a flood about 10 times larger than the 100-year (pre-fire) flood. On Sand Draw, and other small tributaries in burned basins near the center of the storm, peak dischargeswere larger than the 1,000-yr flood. Unburned basins in areas of maximum rainfall had minimal water and sediment runoff. Study results were used to help the National Weather Service determine threshold-rainfall amounts that could produce flash flooding in the Buffalo Creek area. Large quantities of sediment continue to be transported in burned-area streams since the fire. Most of this sediment is deposited in Strontia Springs Reservoir, which is a major water supply for Denver located a few km downstream from the burned area. Investigations of alluvial sediments indicate at least 10 wildfire-flood sequences during about the past 2,500 years in the Buffalo Creek area. Study results indicate that prehistoric fires and subsequent increased runoff prior to fire suppression of the last century contribute to cyclical, geomorphic instability.

Introduction

"Wildfire is a natural occurrence in this tinder-dry climate. But when humans put themselves in harms's way, a natural phenomenon can be transformed into a natural disaster." (Denver Post, Firefight Starts at Home, p. 4G, July 20, 1997).

Communities are encroaching into forested-mountain areas in many parts of the United States, particularly at the urban interface near metropolitan areas in the western United States. This growth has significantly increased the risk of natural hazards to people living in or visiting forested areas. Floods and debris flows, particularly in recently burned watersheds, pose a serious threat to human life, property, and the environment. California suffers an average annual billion dollars in costs and loses to wildfires (Weise and Martin, 1995). Increased risks remain for several years or decades until burned areas sufficiently recover to pre-burn conditions (Evenstad and Rasely, 1995). Recent wildfires and associated flood and debris-flow hazards in southern California (Florsheim et al., 1991; Weise and Martin, 1995); Helena, Montana (Parrett, 1987); Yellowstone National Park (Meyer et al., 1995; Ewing, 1996); Storm King Mountain, Colorado (Cannon et al., 1995); the Wasatch Mountains in Utah (Evenstad and Rasely, 1995); Boise, Idaho; Bandelier National Monument, New Mexico; and Mesa Verde National Park, Colorado (all in 1996) emphasize the potential risk for loss of life, property damage, and costs associated with hazard mitigation and watershed rehabilitation. The effects of flood runoff, sediment delivery, geomorphic changes, watershed recovery time, and the linkages among them are poorly understood for burned watersheds. Watershed, sediment, and ecosystem models may not be applicable without modifications for assessing changes due to burned areas (Weise and Martin, 1995). The focus of this study was to develop a flexible, cost-efficient, monitoring and analysis approach that can be quickly implemented following wildfires wherever they may occur.

Research was undertaken to monitor and determine the risk of hazards and to help mitigate, to the extent possible, loss of life and property damage from water and sediment runoff related to wildfire areas. Extensive coordination was made with the various government agencies involved with hazard mitigation, particularly the National Weather Service (NWS). An integral part of our research focuses on helping to determine threshold-rainfall conditions, which will change with time, that could cause hazardous flooding in burned areas. Additional research objectives are to: 1.) determine the length of time for the basin to return to pre-fire conditions; 2.) assess the effectiveness of watershed-management practices used to mitigate water and sediment runoff; 3.) compile literature on wildfire-hazard mitigation; and 4.) develop a paleoflood-based monitoring program that provides data needed for subsequent ecological and forest rehabilitation activities. Limited resources preclude extensive, instrumented data-collection efforts. There also is a likelihood floods may not occur in instrumented basins. Monitoring needs to begin immediately after a wildfire because important data are lost shortly after each storm and hazard-mitigation efforts. Monitoring in burned and unburned areas consists of determining rainfall amounts, peak flows, and channel agradation and degradation.

The study approach was applied to the community of Buffalo Creek, located about 50 km southwest of Denver, Colorado (fig. 1). On May 18, 1996, an intense wildfire, now known as the Buffalo Creek wildfire, burned about 50 km^2 of forest. Following the fire, rainstorms produced nine, 100-year or larger flash floods (pre-fire conditions). Two people were killed and several million dollars in public and private property damage were caused by the largest flood on July 12, 1997 (Colorado Water Conservation Board, 1997). Additionally, about $ five million dollars were spent fighting the fire and on watershed-rehabilitation efforts (USFS, written commun., 1998). Colorado is the first state in the Nation to create a statewide wildfire fire assessment map, which outlines areas most vulnerable to catastrophic wildfires (USFS, written commun., 1997). Buffalo Creek is located in a moderate fire-hazard area, thus, illustrating the potential hazards in other wildland-urban interface areas.

Background

Wildfires, which change flood and sediment production, are a natural process critical to maintaining healthy ecosystems and have occurred numerous times in the western United States during about the last 8,000 years (Weise and Martin, 1995; Meyer et al., 1995). In 1997, wildfires burned more than 25,000 km^2 in the western United States, which was the most area since 1952 (National Interagency Fire Center, written commun., 1997). Substantial resources are directed towards mitigation of water and sediment runoff in burned areas; however, little is known about the effectiveness of watershed-rehabilitation practices. Most studies done to assess the effects of wildfires on watershed hydrology have been for chaparral vegetated areas (dense, low evergreen oaks) in southern California (e.g., Florsheim et al., 1991; Weise and Martin, 1995). Fewer studies have been done for other forest ecosystems, and most of these focus on sediment runoff (e.g., White and Wells, 1981; Parrett, 1987; Meyer et al., 1995; Cannon et al., 1995; Ewing, 1996). Because southern California has different vegetation and soil types than other forested areas in the United States, study results may not be transferable or may need to be modified for different forest ecosystems. Hydrophobic (water-repellent soil) conditions often develop after a wildfire from the combustion of vegetation and decomposing organic matter, which produces aliphatic hydrocarbons that move as a vapor through the soil and substantially reduce infiltration (USFS, 1979a). Hydrophobic soils, decreased vegetation cover, and reduced surface storage following wildfires dramatically increase the potential for extreme flooding, and sediment transport and deposition (USFS, 1979b). Fire-suppression activities make it difficult to estimate the natural frequency of fires from historical fire records.

One goal of state and federal (e.g., USFS, BLM, and NPS) forest managers is to balance maintaining healthy forest ecosystems and minimizing hazards to the public and property. In the late 1950s, after more than half a century of active fire suppression, which increased the threat of catastrophic wildfires, greater emphasis was placed on prescribed burning in forest lands to reduce the buildup of fuelwood (Weise and Martin, 1995). Since 1984, prescribed burning has been used on an average of 1,200 km^2 per year in US national forests, which have a total area of 773,000 km^2 (USFS, written commun., 1997). The effects of fire intensity on water and sediment runoff and the ecosystem are poorly understood.

Study Area

The community of Buffalo Creek is located in the foothills of the Colorado Rocky Mountains of unincorporated Jefferson County within Pike National Forest near the confluence of Buffalo Creek and North Fork (NF) South Platte River (fig. 1). The community, at an elevation of about 2,012 m, consists of several hundred homes within a montane forest (predominantly lodgepole and ponderosa pine, douglas fir, and aspen). Topography is rugged and soils are shallow, moderately well drained, and composed of coarse sandy gravel (Colorado Water Conservation Board, 1997). Bedrock on average is about 1 m below land surface, but is exposed on many steeper hillslopes. Accumulation of organic litter (duff) on unburned forested areas averages about 60 mm. The climate is semiarid and mean annual precipitation is about 400 mm, much of which falls as snow from about October through April. Many streams are ephemeral in the study area and flow into Buffalo Creek and the NF South Platte and South Platte Rivers, which primarily are fed by melting snowpack and trans-basin flow diversions. Flood flows in the vicinity of Buffalo Creek can result from intense, localized thunderstorms, generalized rainstorms, and spring snowmelt (Jarrett, 1990). Long-time residents reported no significant flooding in the Buffalo Creek area in at least 70 years. The 1996 wildfire, driven by strong winds, burned most vegetation and produced hydrophobic soils in much of the burned area, making the area more susceptible to flooding (Colorado Water Conservation Board, 1997).

Methods

No systematic precipitation, streamflow, and sediment monitoring networks existed in Buffalo Creek prior to the wildfire. Therefore, data collection consisted of determining rainfall, peak flow, and sedimentologic data for most streams in the Buffalo Creek area. Rainfall-bucket survey data were obtained throughout the Buffalo Creek area for each rainstorm. In addition, paleoflood and sedimentologic data were used to estimate rainfall amounts and spatial variability (Jarrett, 1990. In 1997, four recording precipitation and three streamflow gages were placed in the Buffalo, Morrison, and Spring Creek basins by the USGS in cooperation with the Denver Water Department (John Moody, USGS, written commun., 1997). In early 1997, the NWS provided 13 Buffalo Creek residents with non-recording precipitation gages to assess the spatial variability of rainfall, monitor flood potential, and assess/refine rainfall estimates from Doppler radar (NWS-WSR-88). Because few gages were located in the burned area and very localized nature of convective storms, basin-wide monitoring continued for each runoff event.

Paleoflood hydrology is the study of flood-transported sediments and botanic information from past floods preserved in stream channels and is particularly useful in providing hydrometeorologic data for ungaged basins (Jarrett, 1990, 1991). Most studies involve prehistoric floods, but the methodology also is applicable to studying modern floods. Rainfall amounts on sparsely vegetated hillslopes (burned or unburned) can be inferred from the amount of hillslope erosion (rills, gullies, and headcuts), maximum size of sediments transported, and depositional characteristics. The paleoflood rainfall estimates can be compared with other sources of rainfall data (gaged, bucket survey, and radar) or they can provide rainfall data when no other source exists.

Because of the hazards and flashy nature of floods in burned areas, peak discharges were estimated using the slope-conveyance method (Barnes and Davidian, 1978) for streams in the Buffalo Creek area after each rainstorm. Sites were selected primarily where bedrock is exposed across the channel. A few sites were located in alluvial channels; reaches selected were relatively straight and uniform, which reduces potential errors due to channel change. In such reaches, net change in total-flow area probably are small for one flood, although sediment loads may be large. Cross section data were collected for channels in burned and adjacent unburned basins. Monitored basins range from about 0.1 km^2 to the total burned area of about 50 km^2. The burned area is located just upstream from the South Platte River at South Platte streamflow-gaging station (06707500) shown on figure 1, which has a total drainage area of 6,680 km^2 The flood of record is 53 m^3/s, which resulted from snowmelt, since the gage was installed in 1904. Peak-discharge data were estimated for 75 sub-basins in the study area having different basin characteristics such as vegetation cover, burn intensity, watershed aspect and slope, sediment sizes, and watershed-rehabilitation measures. Onsite data also were collected for subsequent storms that produced runoff. Monitoring is planned until water and sediment runoff in the burned area has returned to near-normal.

For burned and unburned basins, data also were collected to: a.) estimate hillslope erosion; b.) estimate channel agradation and degradation; c.) approximate volumes of channel and alluvial-fan deposits; and d.) identify past fire and flood deposit sequences in the alluvial stratigraphy. This monitoring complements sediment studies being conducted by other USGS and USFS scientists and helps validate channel change estimates from aerial photographs taken before and after the fire.

Results and Discussion

Most efforts have concentrated on monitoring numerous floods and providing preliminary information for hazard-mitigation and forest managers. Results are presented for the storm and flood of July 12, 1996, the effects of the fire on flooding, and assessing watershed-rehabilitation efforts.

July 12, 1996 Storm and Flood

Maximum rainfall from bucket-survey data for the July 12, 1996 storm was about 80 mm in an hour in the community of Buffalo Creek and headwaters of Spring Creek (fig. 2). Before additional rainstorms, the extent of fresh rill and gully erosion was compared to rainfall-bucket amounts without gaged rainfall data. Hillslope erosion then was used to estimate rainfall in areas without rainfall data. Hillslopes (burned or unburned) with sparse vegetation and less than about 25 mm rain had some sediment movement and minimal rill development (fig. 3a). Hillslopesthat received about 50 mm of rain had rills about 75 mm deep and 50 mm wide (fig. 3b). Hillslopes that received about 75 mm of rain had numerous gullies up to 0.5 m deep and a meter wide (fig. 3c). Numerous gullies up to a meter deep and 3 m wide (fig. 3d) were documented about 5 km south of Buffalo Creek near the headwaters of Sand Draw, Spring Creek, Shinglemill Creek, and Spring Gulch. The gullies were used to infer a maximum 1-hr rainfall amount of at least 115 mm. Rill and gully erosion data were used to graphically display comparisons and to draw an isohyetal map (fig. 2). Rainfall amounts decreased rapidly outside the burned area and the storm covered about 50 to 75 km^2. The rainfall isohyetal pattern estimated from NWS-WSR-88 radar by the National weather Service (written commun., 1996) during the July 12, 1996 storm is also shown on figure 2. The NWS estimated the maximum rainfall was about 80 mm.

Henz (1998) analyzed Doppler radar signatures and upper-air observations for the July 12 storm. His approach differs from the NWS radar estimate in that interpretations have been validated with ground-truth rainfall data for a network in the Denver area during about the past 15 years. Henz estimated maximum rainfall of about 130 mm in about an hour with the cell located near the head of Spring Creek with similar isohyetal patterns, but oriented slightly different (fig. 4). Henz's preliminary results had the storm footprint located about 3 km southeast of the present center in Spring Creek (Henz Meteorologic Services, written commun., 1997). However, the geomorphic rainfall estimates indicated a lack of rainfall (fig. 3a) and essentially no runoff in Henz's preliminary estimated area of maximum rainfall. Areas having extreme flood runoff (next section) were not located below Henz's preliminary storm footprint. Henz used our results to better locate the storm footprint (fig. 4). Therefore, it appears that geomorphic techniques provide good estimates of rainfall amounts and very good estimates of spatial variability when compared with Henz's estimates from Doppler radar. Henz's rainfall estimates are considered the most reliable for the July 12, 1996 storm because they are based on . The geomorphic rainfall data also provide valuable information to assess the reliability of radar estimated rainfall, which are used for flash-flood forecasting and other purposes.

The 100-year, 1-hr rainfall is about 55 mm for the Buffalo Creek area (Miller et al., 1973). Diller (1997) analyzed 24-hr, annual maximum rainfall values for 50 stations near Buffalo Creek having a similar climate regime. He conducted a regional rainfall-frequency analysis using the method of L-moments (Hosking and Wallis, 1997). The regional 1-hr rainfall frequency curve developed by Diller (fig. 5) is within 5 percent of the rainfall-frequency relation of Miller et al. (1973). The recurrence interval was about 1,000 years for the July 12, 1996 maximum rainfall (130 mm) in about 1-hr in Buffalo Creek.

Maximum water depths as much as 4 m occurred within 30 minutes of the storm's onset in Buffalo Creek (fig. 6), Spring Creek, and the NF and South Platte Rivers. High-water marks (HWMs) generally were good-to-excellent and comprised of charcoal, leaf, and needle litter, silt, bent grass, and wash lines. HWMs were used to estimate the water slope and flood depth for each cross section. Peak discharge estimated with the slope-conveyance (S/C) method usually is less accurate than estimates using multiple cross sections. However, estimates provided here reflect an average of several S/C estimates along a reach of channel. These estimates probably are more accurate than a single S/C estimate because of a good agreement of estimates along a channel. The S/C uncertainty in discharge estimates is caused primarily by n values, bulking of flow with sediment and debris, and channel changes. Estimates of uncertainties are shown in parentheses. The peak discharge estimate was 450 m^3/s (+/-20%) for Buffalo Creek near the NF South Platte River (fig. 1, site 1; fig. 6). This estimate reflects runoff from the burned area in Buffalo Creek and its tributaries (notably Sand Draw, Spring Gulch, Shinglemill Creek, and Morrison Creek). Sand Draw, with a drainage area of about 3.6 km^2 (figs. 1 and 7, site 2), had an estimated peak discharge of 200 m^3/s (+/-25%). The estimated peak discharge was 510 m^3/s (+/- 25%) for Spring Creek upstream from its confluence with the South Platte River (fig. 1, site 3). Maximum flooding occurred in Spring Creek because the basin has slopes greater than about 30 percent, extensive bedrock exposure, hydrophobic soils, maximum rainfall occurred in its headwaters, and the storm moved from west to east down the basin.

The South Platte River streamflow-gaging station (06707500) measures the cumulative runoff from the 1996 burn area (fig. 1, site 4), but principally from Buffalo and Spring Creeks. The S/C estimated peak discharge was 325 m^3/s (+/- 20 %), reflecting attenuation of flood peaks from Buffalo and Spring Creeks. The July 12, 1996 peak stage in the South Platte River at South Platte gage stilling well was 1.52 m lower than excellent high-water marks (HWMs), probably due to an insufficient size intake to fill the large-volume, stilling well. The peak discharge using the incorrect gage height (estimated during the storm) from the rating curve was only 81 m^3/s; it is likely the entire flood hydrograph is suspect. Incorrect gage recordings are a serious concern for flash-flood detection and issuing warnings to the public.

Large quantities of sediments were mobilized on hillslopes and in channels in the burned area during the July 12th flood (eg., figs. 3c and 7). A distinct black, burn boundary on rocks in pre-flood surfaces was used as a reference to estimate the general surface erosion from sheet wash. Care was taken to estimate the general erosion rather than the local erosion around the rock. In addition, pillars of soil were preserved under some surface rocks and metal objects on the burned areas. About a hundred hillslope measurements throughout the study area suggest an average of about 10 mm of erosion. The area of maximum sheet wash was limited to the headwaters of Shinglemill Creek, Spring Gulch, Sand Draw, and the upper third of Spring Creek (e.g., figs. 3c and 3d) and was used to help define the area of maximum rainfall (fig. 4).

Locally, small streams produced up to 6 m of scour, primarily by headcutting (fig. 3c). Hundreds of trees, some as large as 0.75 m in diameter, toppled into the floodwaters, which exacerbated flood damages. Sediments moved on hillslopes ranged from silt to cobble-sized material, and 2.5-m diameter boulders were transported in some channels (fig. 8). The distinct black, burn boundary on undisturbed trees and rocks in channels (fig. 9) were used to define pre-fire channel-bed levels and estimate the amount of channel change. Many tributaries degraded during the July 12th flood (fig. 9), although locally agradation (1-2 m) occurred along Buffalo, Spring, and Shinglemill Creeks and on alluvial fans at tributary junctions in burned areas. Many new fans had dimensions of about 100 m x 30 m x 1.5 m (fig. 7). September 1996 reservoir releases increased flows in the NF South Platte River that were capable of transporting sediments from the Buffalo

Creek fan to South Platte, which produced about a meter of agradation in pools. For many burned basins, the location of exposed bedrock or firm ground used to estimate discharge changed for each storm (within +/- ~100 m of other sites) due to shifting channels. Therefore, a fixed streamflow-gaging station may not produce reliable records without the use of a costly control (e.g., weir, flume) or may need to be moved.

Flood-transported sediments and debris in Spring Creek dammed the South Platte River to a depth of about 3 m, which caused backwater (ponding) and reduced the peak flow from Spring Creek. The peak flow was 240 m^3/s (+/- 20%) in the South Platte River downstream from Spring Creek (fig. 1, site 5), about 270 m^3/s less than the Spring Creek peak flow. Without this ponding and attenuation of the Spring Creek flood, the peak flow at the South Platte River gage could have been as large as 595 m^3/s.

Effects of the Buffalo Creek Wildfire

Two approaches were used to estimate the effect of the fire on flood runoff. First, July 12, 1996 flood data for severely burned and unburned basins, which had similar rainfall amounts, were plotted against contributing drainage area (fig. 10). Peak discharge from severely burned basins was 20-40 times larger than for unburned basins. Unburned basins within areas of maximum rainfall had minimal runoff, which likely reflects rainfall interception by the duff in unburned areas; in addition, basin slopes in unburned areas generally are 20 percent or less. Slightly burned areas, which might have similar runoff as prescribed-burn watersheds, had substantial flood and sediment runoff, but less than moderately- and severely-burned basins. A number of severely-burned basins in areas near maximum rainfall had unit discharges (peak discharge divided by drainage area) of about 60 $m^3/s/km^2$; the maximum unit discharge is about 40 $m^3/s/km^2$ for all previous Colorado floods (Jarrett, 1990). Since the fire, rainstorms have produced 9 floods (5 in 1996 and 4 in 1997) larger than the estimated 100-year (pre-fire) flood (FEMA, 1986); most storms were preceded by 5 to 10 mm of rainfall. Continued flooding from small rainstorms and having similar runoff as in 1996 indicate that little watershed recovery has occurred by the fall of 1997.

Flood-frequency relations for Sand Draw and the South Platte River at South Platte with corresponding July 12, 1996, peak discharges are shown on figure 11. Trans-basin diversions were assumed to be negligible on large flood peaks and hence the upper end of the frequency relation for the South Platte River. On July 12, 1996, peak discharges in small, burned basins such as Sand Draw, Spring Creek, Spring Gulch, and Shinglemill Creek were about 10 times larger than the 100-year flood. On Sand Draw, and other small tributaries in burned basins near the center of the storm, peak discharges exceeded the 1,000-yr flood.

The second approach compared flood data for burned areas in Buffalo Creek with other Colorado Front Range foothill extreme floods resulting from about 150 to 175 mm of rain in about an hour in similar basins (slopes, soils, vegetation) that were unburned (fig. 10). Maximum rainfall on July 12, 1996 for Buffalo Creek in burned areas is similar to large rainfall amounts for unburned basins in Colorado. Maximum peak discharges for the July 12, 1996 rainstorm produced flood peaks about 1.5 times larger than floods in unburned basins elsewhere in the Colorado Front Range (fig. 10). A number of severely-burned basins in areas near maximum rainfall had unit discharges (peak discharge divided by drainage area) of about 60 $m^3/s/km^2$; the maximum unit discharge is about 40 $m^3/s/km^2$ for all previous Colorado floods (Jarrett, 1990). The combined peak discharge for Buffalo Creek and Spring Creek is about 960 m^3/s (~50 km^2 contributing burned area), which is greater than the 1976 flood of 883 m^3/s in the Big Thompson River (McCain et al., 1979) from a contributing area of about 250 km^2. Clearly, the wildfire had a major role in the severity of flooding in Buffalo Creek. Because the area of maximum rainfall was within the burned area, rainfall-runoff modeling is necessary to estimate potential flood runoff, without the fire.

Effects of Watershed Rehabilitation

Watershed-rehabilitation efforts utilized to help restore the Buffalo Creek burned area include aerial and ground seeding; bonded-fiber matrix; soil tilling; contour tree felling; log and strawbale check dams; and untreated natural recovery (Casey Clapsaddle, USFS, written commun., 1996).

Extensive efforts to mechanically break up hydrophobic soils and slow water and sediment runoff began very soon after the fire. Most efforts were in basins posing greatest risk to the public: Sand Draw, Spring Gulch, and Shinglemill Creek. A moderate flood on June 12, 1996 (Casey Clapsaddle, USFS, written commun., 1996) and the severe flash flood on July 12, 1996 washed out most of the initial rehabilitation efforts. Small amounts of water were applied to burned areas (simple infiltration tests) in 1996 and 1997. Generally, no water infiltrated and small droplets of water formed, indicating hydrophobic soils in 1996. During the wet spring of 1997, applied water infiltrated rapidly, even on very steep hillslopes (>30 %). However, after the soils dried, infiltration was low due to reformed hydrophobic conditions or other factors. Data monitoring in this study complements an instrumented, paired-basin analysis being conducted by Casey Clapsaddle to assess the rehabilitation efforts used in Shinglemill Creek and Morrison Creek basins (burned area was left untreated).

Despite extensive rehabilitation efforts in burned area, smaller rainstorms after July 12 in 1996 and in 1997 produced similar rates of runoff (fig. 10). On August 31, 1997, a 63 mm rainfall in about 30 minutes over the headwaters of Sand Draw, produced a flash flood of about 34 m^3/s from about 1.5 km^2, which reflect persistent conditions that exacerbate flash-flood potential and minimal watershed recovery. Natural debris (trees and sediment) present in many channels appeared to help slow water and sediment runoff for many events. In addition, small runoff events (as much as ~3 m^3/s) from burned hillslopes that reached channels having thick (>3 m) pea-gravel sediments such as in Sand Draw often infiltrated in a short distance. Long-time residents indicated that since the fire, streams in the burned area have more flow that usual.

Base flows as small as 0.2 m^3/s after the July 12, 1996, flood were competent to incise and erode much of the new alluvial fans. Many fans had several agradation-degradation cycles for small events (peak flows of ~1-2 m^3/s) since the fire, which reflects channel instability. Lower tributaries reaches that agraded on July 12, 1996, generally had degraded by about a meter by the end of 1997, but hillslope erosion continues to contribute sediment to channels. Sediment from the burned area continued to be transported through the NF and South Platte Rivers to Strontia Springs Reservoir. About 75 percent of Denver's water comes through the reservoir, which has a capacity of about 9.74 hm^3. From May 1996 to October 1997, about 0.31 hm^3 of sediment washed into the reservoir compared to about 0.14 hm^3 in the 13 years since the reservoir was built (Denver Water Department, written commun., 1997). Snowmelt runoff in the NF and South Platte Rivers likely will continue to move large amounts of wildfire-produced sediments towards the reservoir.

Geomorphic investigations of alluvial sediments in the burned and unburned (in 1996) areas indicate at least 10 fires/flood sequences have occurred in the study area prior to 1996 (fig. 12). At least one paleoflood was larger than the July 12, 1996 flood, and runoff after several of the prehistoric fires produced much thicker alluvial deposits than following the 1996 wildfire. Radiocarbon dating of organic material in alluvial sediments in a Buffalo Creek tributary indicated that these sequences span about the last 2,500 years (John Elliott, USGS, written commun., 1997). Additional investigations will help determine the long-term fire and flood history in the region, which could help forest managers develop policy for prescribed burns and other management practices.

Study results can be used to develop and verify hydrologic- and sediment-budget models for burned watersheds. In conjunction with the NWS, study results and rainfall-runoff modeling was conducted to help determine threshold-rainfall amounts for flash-flood conditions. These results were used to refine flash-flood warnings, particularly to minimize the number of false alarms that can cause complacency of those at risk. The Colorado Water Conservation Board (1997) prepared an emergency response, hazard-mitigation, and awareness plan for government officials, residents, and visitors in the Buffalo Creek area.

Studying only the Buffalo Creek area can not provide answers to all questions about wildfire hazards in other forest ecosystems. Thus, additional paleoflood studies are needed for burned (wildfire and prescribed burn) watersheds this century in the Rocky Mountain region. These could include, but are not limited to, Storm King Mountain, Colorado (1994), Black Tiger in Boulder, Colorado (1988), Bandelier National Monument, New Mexico (1996), Mesa Verde National Park, Colorado (1996), Yellowstone National Park, Montana (1988), and Boise, Idaho (1959, 1996). Interdisciplinary research will provide scientific information for wildfire, forest ecosystem, and hazard managers. Because of the uncertainty of where future wildfires and floods may occur, a mobile monitoring approach as described here helps provide much of the necessary information.

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Illustrations Captions

1. Map of the Buffalo Creek study area showing the extent of May 18, 1996 wildfire (heavy-dashed line) and selected flood sites. Flood-site locations are: 1. Buffalo Creek at Buffalo Creek; 2. Sand Draw near Buffalo Creek; 3. Spring Creek near South Platte River; 4. South Platte River at South Platte streamflow-gaging station 06707500 (gage); and 5. South Platte River downstream from Spring Creek. Inset map at lower right shows the general location of the study area near Denver and Colorado Springs, Colorado. One-hour rainfall amounts in millimeters from bucket survey shown as "x." Isohyetal patterns for the July 12, 1996 rainstorm from the National Weather Service estimated from Doppler radar (NWS-WSR-88) showing maximum 1-hr rainfall of about 80 mm.

2. Map of Buffalo Creek showing rainfall-bucket survey data and isohyetal patterns for the July 12, 1996 rainstorm from paleohydrologic interpretations. Paleohydrologic rainfall estimates were made four days after the storm.

3. Photographs showing hillslope rill and gully development for 1-hr rainfall amounts for July 12, 1996 of: a.) less than about 25 mm of rain with minimal rills; b.) about 50 mm of rain produce 75 mm by 50 mm rills; c.) about 75 mm of rain produced extensive rilling and about 500 mm deep gully formation; and d.) gully development up to 1 m deep and 3 m wide, which was used to infer the area of maximum rainfall of at least 115 mm in an hour (fig. 2).

4. Maps of Buffalo Creek showing isohyetal patterns for the July 12, 1996 rainstorm using Doppler radar (NWS-WSR-88) developed by Henz (1998). Maximum 1-hr rainfall was estimated to be about 130 mm and the total rainfall was about 170 mm for July 12, 1996.

5. One-hour rainfall frequency relation for Buffalo Creek developed by Diller (1997) including the estimated maximum 1-hr rainfall of about 160 mm for Buffalo Creek on July 12, 1996 (Henz, 1998).

6. Schematic cross section with hydraulic properties for the July 12, 1996 flood in Buffalo Creek near the North Fork South Platte River at Buffalo Creek, Colorado.

7. Upstream view of Spring Creek on July 16, 1997 with the South Platte River in the foreground (flow left to right). Flood-deposited sediments were about 1.5 m thick at the center of the fan.

8. Downstream view of Shinglemill Creek near Buffalo Creek showing a 600-mm diameter, flood-transported boulder lodged in a 1-m diameter cottonwood tree. The boulder is 2.5 m above the channel bed (at the tree) and about 1.5 m above the high-water marks from the July 12, 1996 flood.

9. Upstream view of Sand Draw about 1 km upstream from Buffalo Creek showing distinct black, burn boundary from the May 18, 1996 wildfire. The boundary was used to define pre-fire, channel-bed levels and estimates of the amount of channel change at this flood (about 0.5 m here).

10. Relation between peak discharge and contributing drainage area for rainstorms in 1996 and 1997 in the Buffalo Creek area, Colorado. Lines show approximated 1-hour storm rainfall for burned and unburned basins. Flash-flood data for extreme rainstorms for similar, unburned basins in the Colorado Front Range foothills help assess the effects of the fire on flooding in Buffalo Creek.

11. Flood-frequency relations for pre-fire basin conditions for Sand Draw at Buffalo Creek (FEMA, 1986) and the South Platte River at South Platte (06707500) from an frequency analysis of annual peak-flow data. Peak discharges for the July 12, 1996 flood for Sand Draw and at the South Platte River at South Platte also are shown.

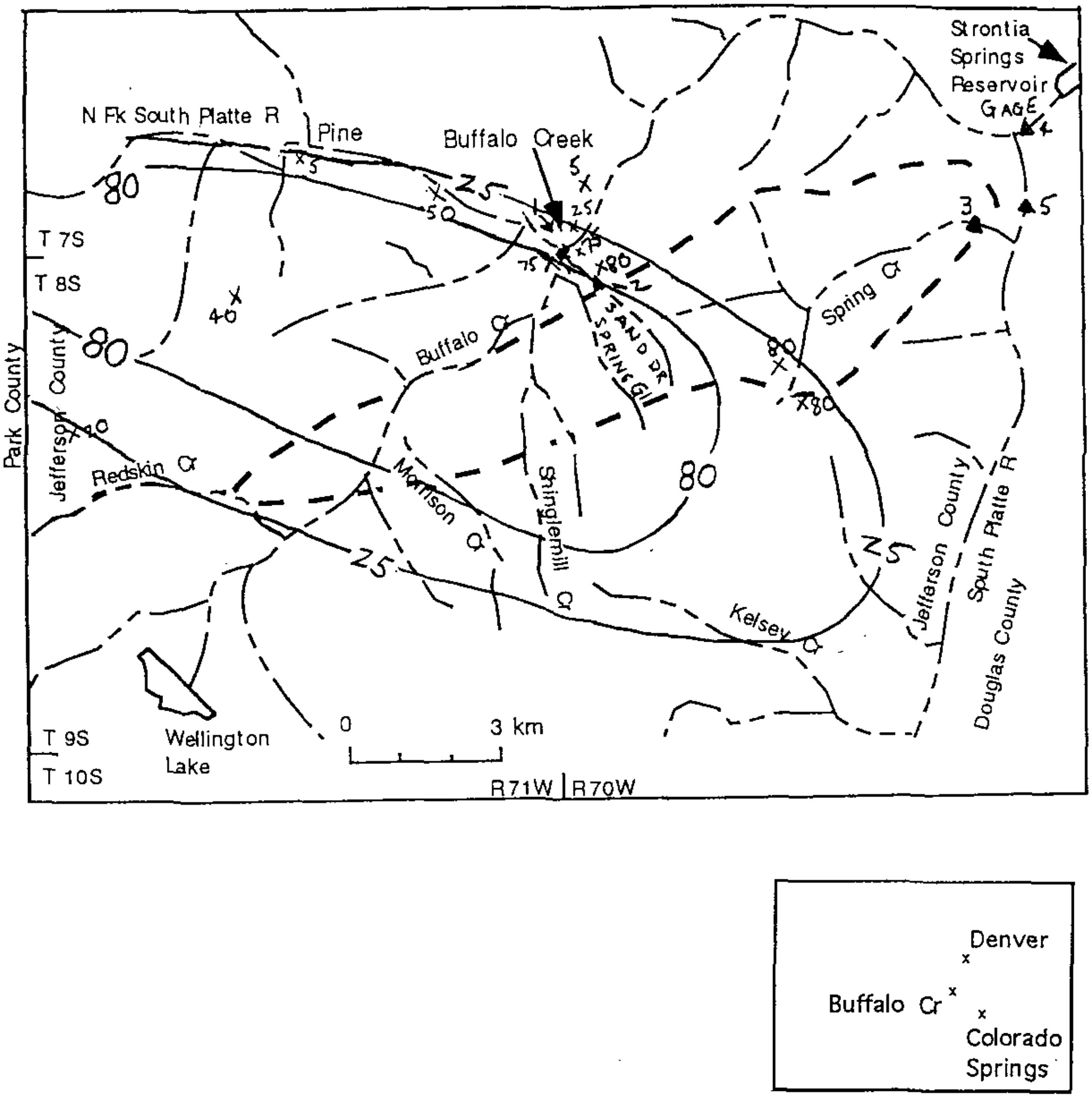

Strontia Springs Reservoir
GAGE
N Fk South Platte R
Pine
Buffalo Creek
Spring Cr
Buffalo Cr
SAND DR
SPRING GU
Park County
Jefferson County
Redskin Cr
Morrison Cr
Shinglemill Cr
Kelsey Cr
Jefferson County
South Platte R
Douglas County
T 7S
T 8S
T 9S
T 10S
Wellington Lake
0
3 km
R71W
R70W
80
80
80
25
25
25
5
5
50
25
75
72
80
40
20
80
80
1
2
3
4
5
Denver
Buffalo Cr
Colorado Springs

FIG 1.

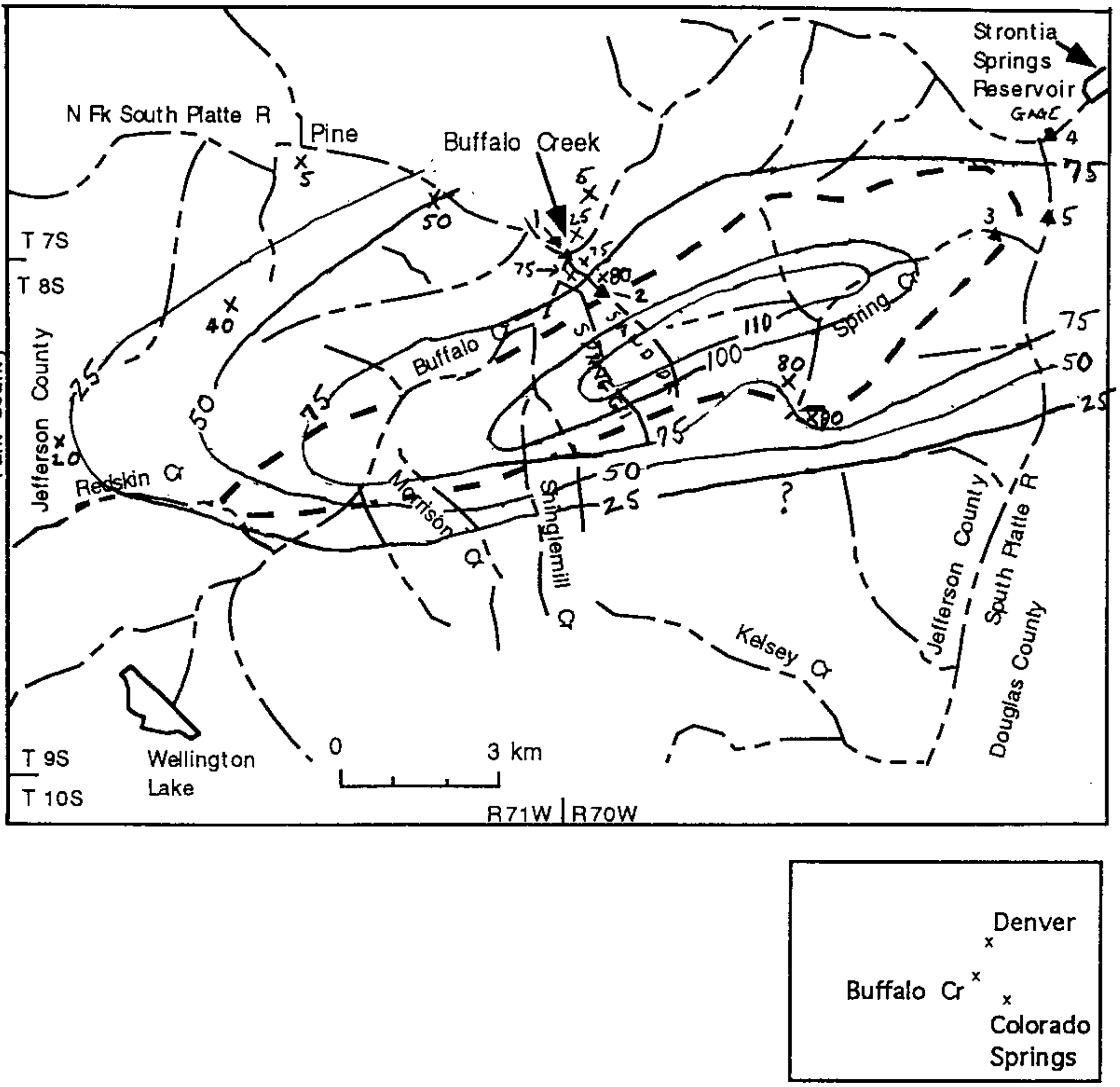

Strontia Springs Reservoir
GMC
N Fk South Platte R
Pine
Buffalo Creek
T 7S
T 8S
T 9S
T 10S
Park County
Jefferson County
Redskin Cr
Buffalo Cr
Spring Cr
Morrison Cr
Shinglemill Cr
Kelsey Cr
Jefferson County
South Platte R
Douglas County
Wellington Lake
0
3 km
R71W
R70W
25
50
75
100
110
5
40
20
80
4
45
3
2
?
Denver
Buffalo Cr
Colorado Springs

FIG. 2

Fig 3a

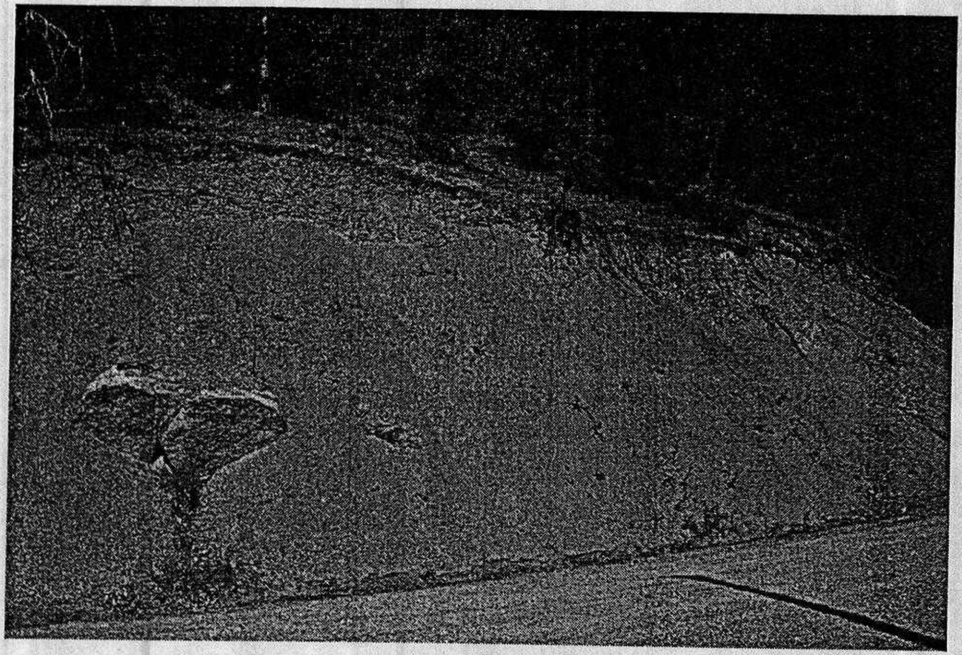


Fig 3b

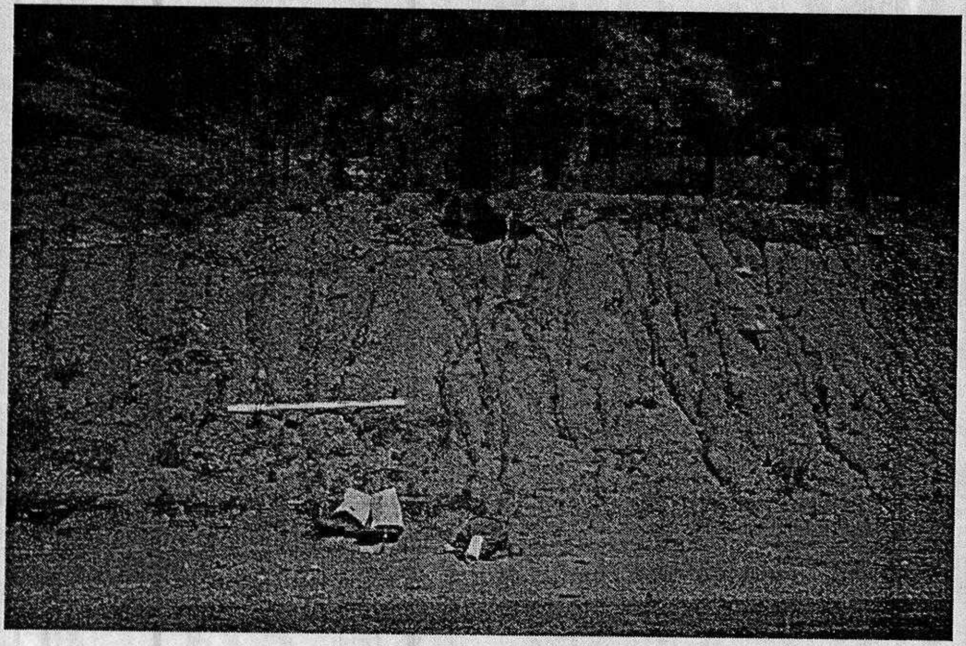
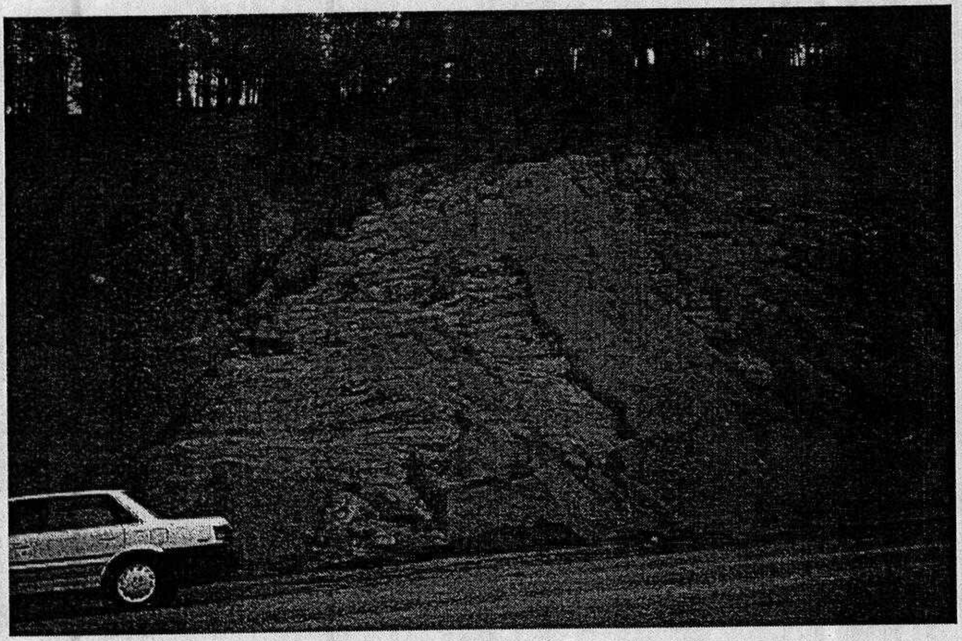
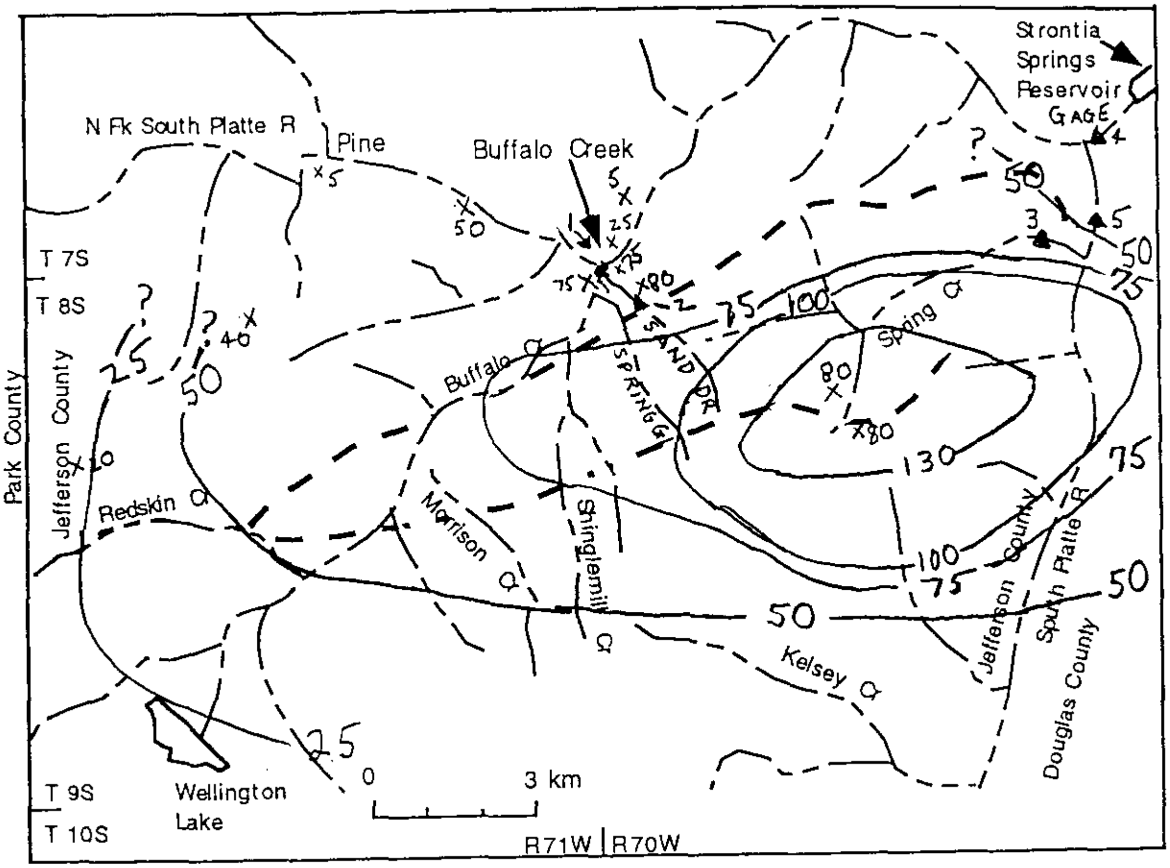


Fig 3c

Fig 3d




Strontia Springs Reservoir
GAGE
4
N Fk South Platte R
Pine
5
Buffalo Creek
5
50
25
75
75
80
?
50
3
5
50
75
T 7S
T 8S
?
?
40
25
50
Park County
Jefferson County
10
Redskin Cr
Buffalo Cr
75
100
SAND SPRING DR
Spring Cr
80
80
130
75
Morrison Cr
Shinglemill Cr
100
75
Jefferson County
South Platte R
50
50
Kelsey Cr
Douglas County
25
0
3 km
T 9S
T 10S
Wellington Lake
R71W | R70W

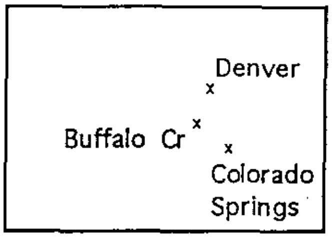
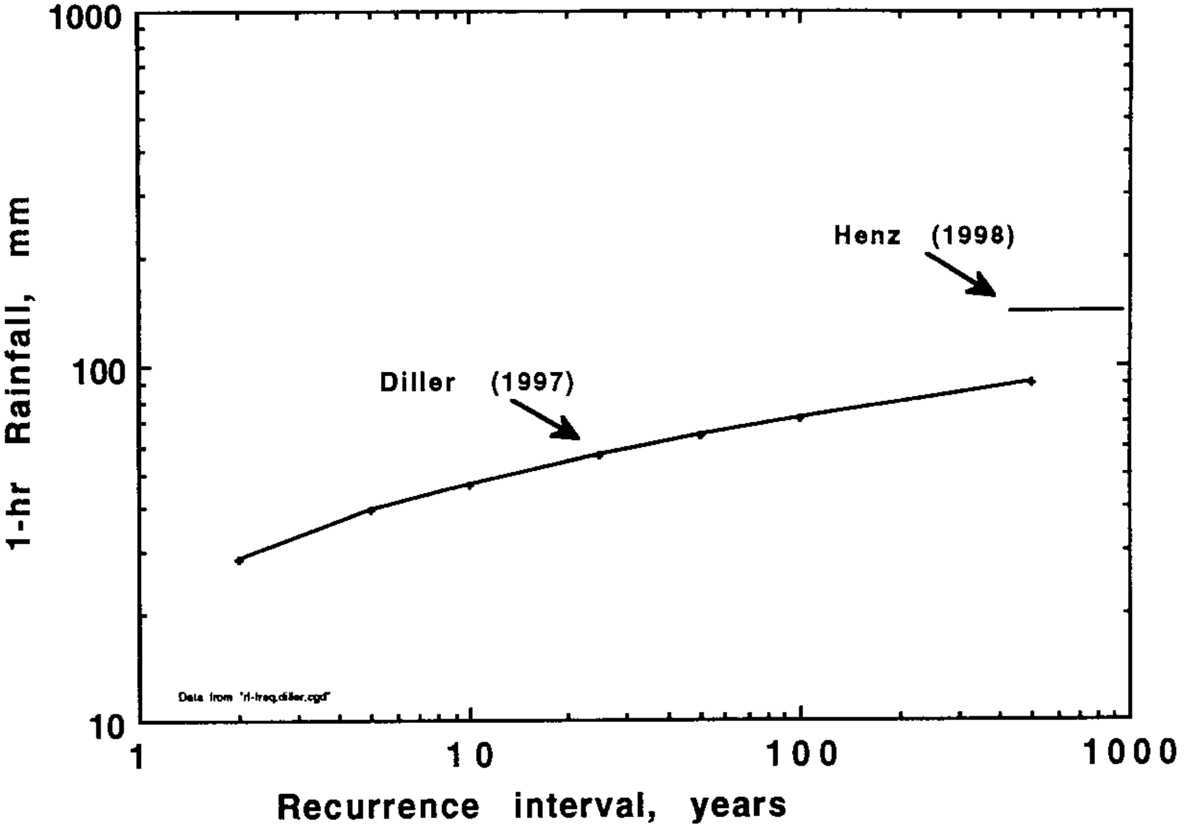

Denver
Buffalo Cr
Colorado Springs

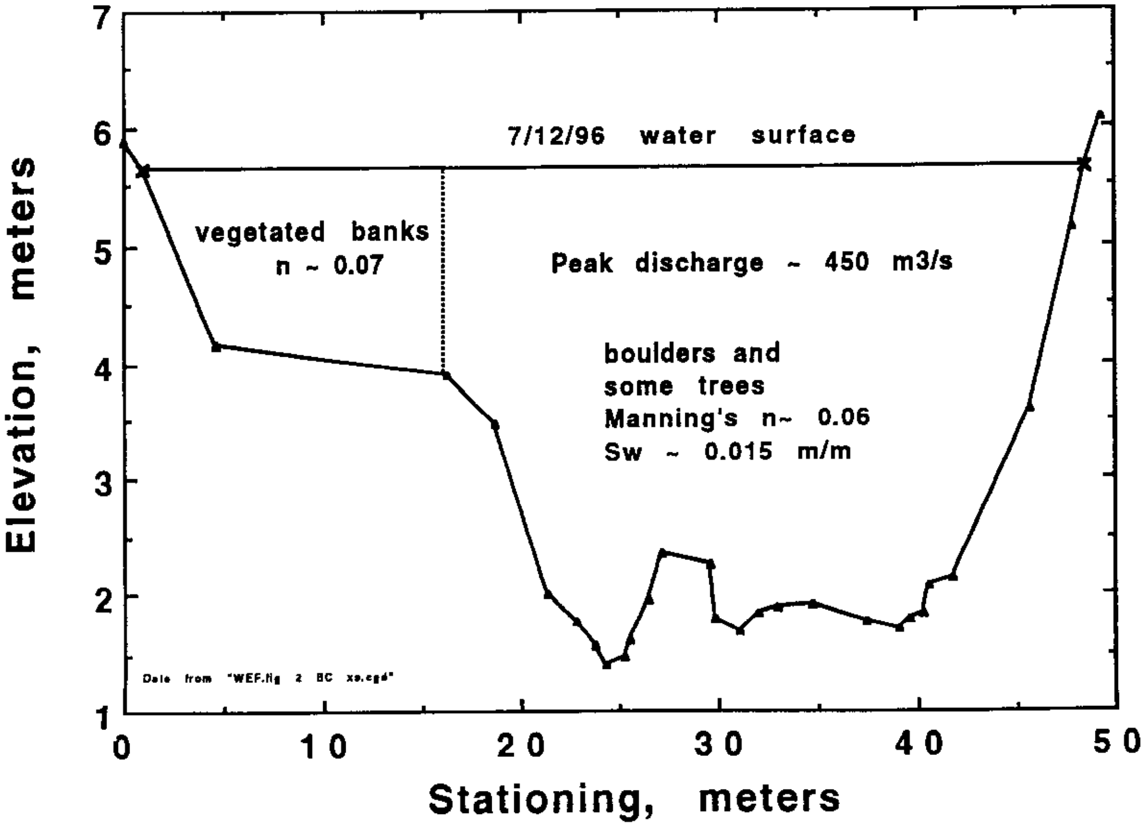
FIG 4

FIG. 5



Data from "rl-freq.diller.cgd"

FIG. 6



Data from "WEF.fig 2 BC xs.cgd"

FIG. 7

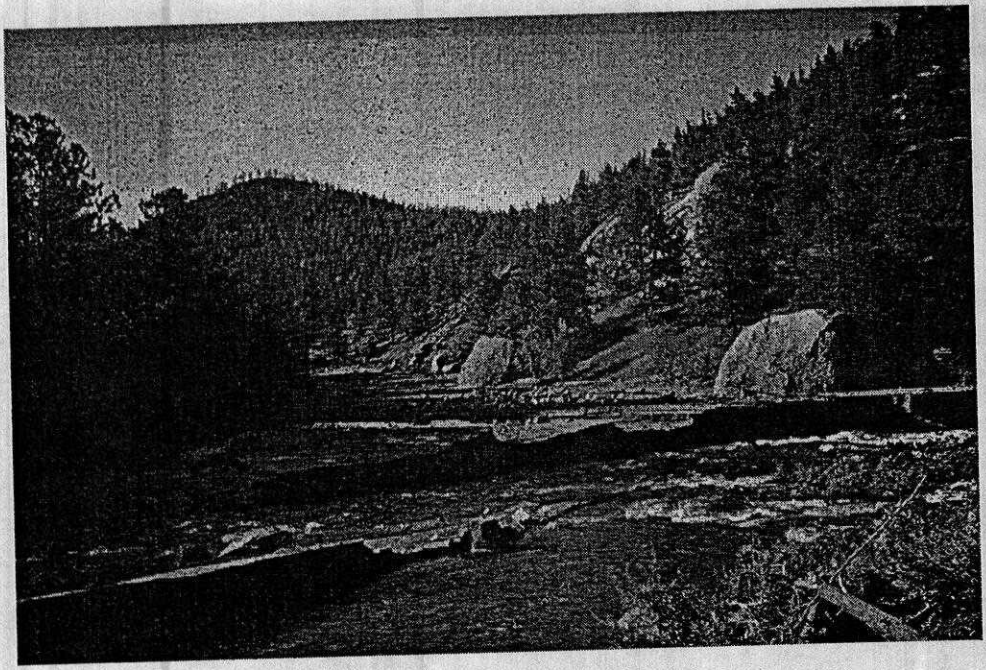


FIG 8

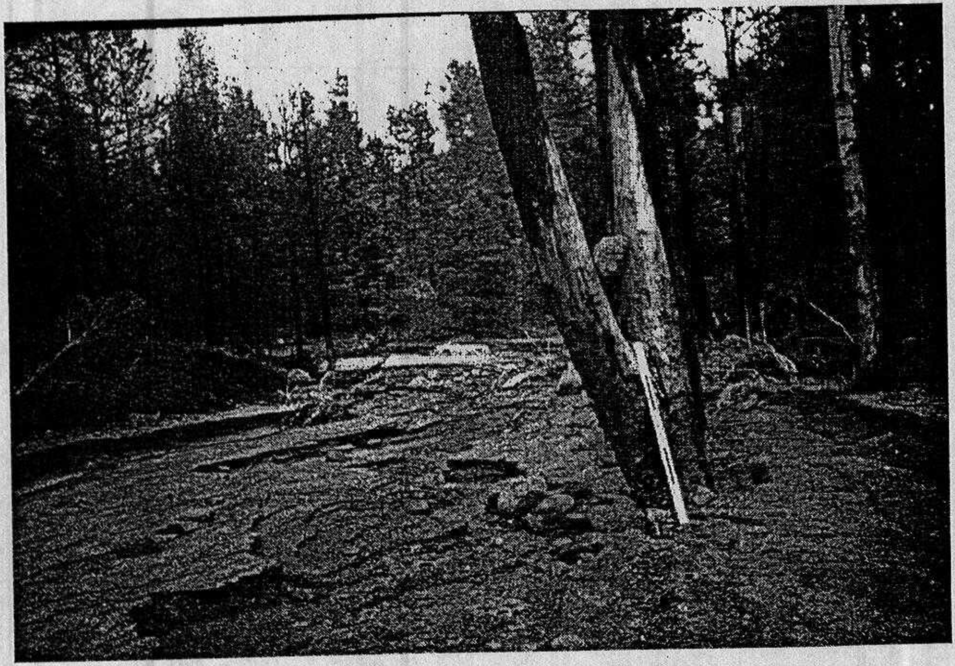
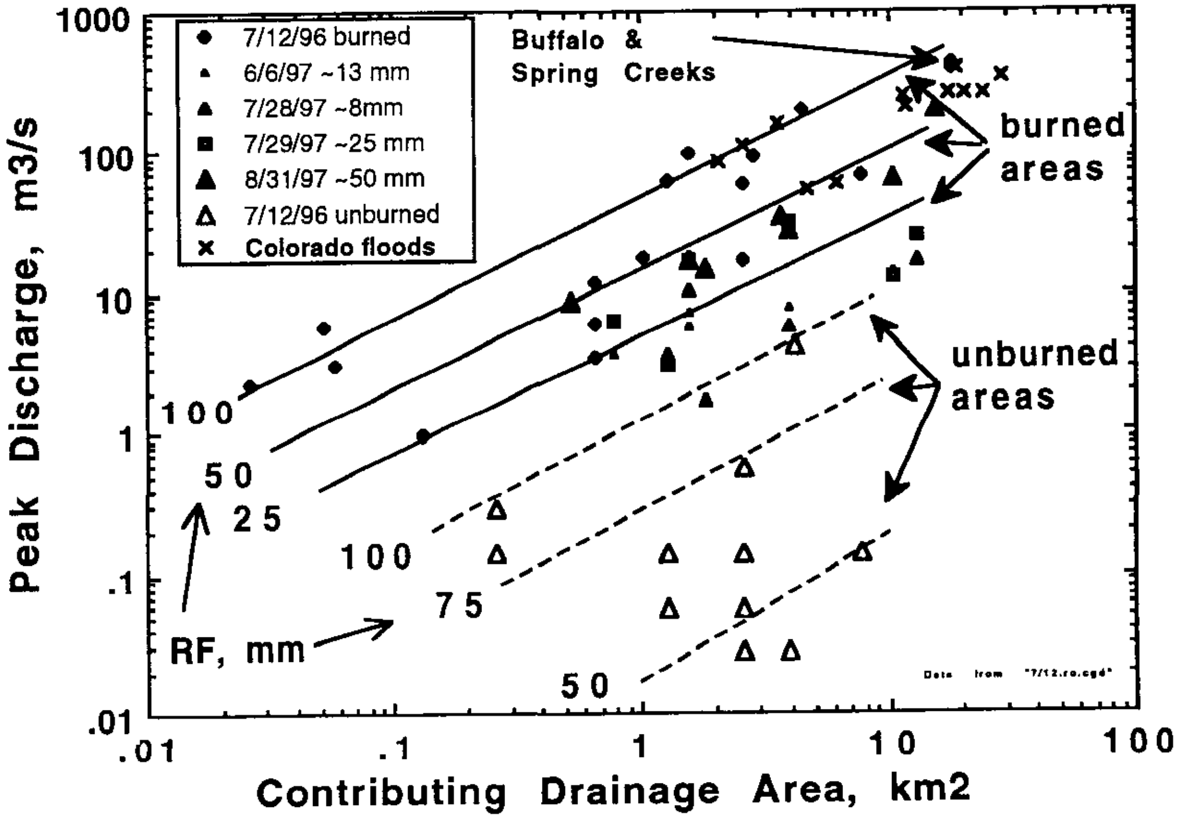
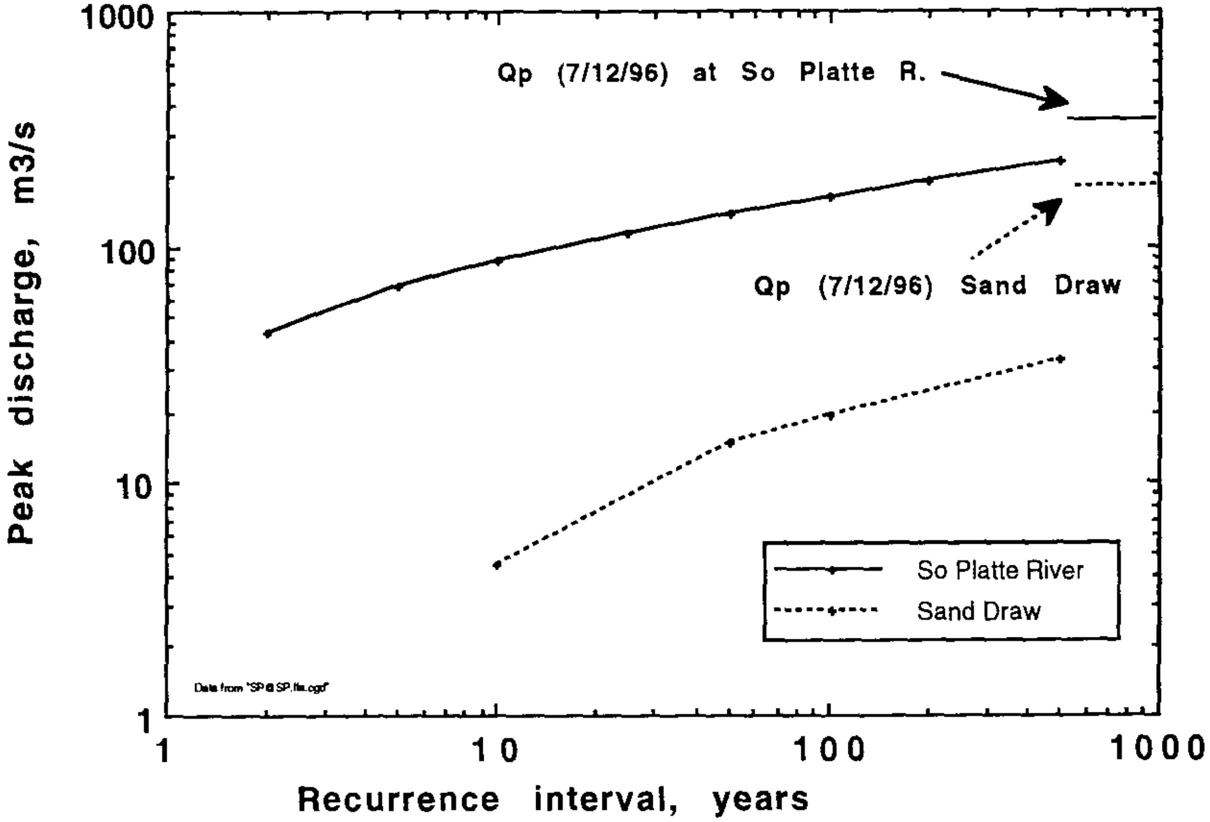


Fig 9


BURN
BOUNDARY

Fig 10


● 7/12/96 burned
▴ 6/6/97 ~13 mm
▲ 7/28/97 ~8mm
■ 7/29/97 ~25 mm
▲ 8/31/97 ~50 mm
△ 7/12/96 unburned
× Colorado floods
Buffalo & Spring Creeks
burned areas
unburned areas
100
50
25
RF, mm
100
75
50
Data from "7/12.ro.cgd"
Peak Discharge, m3/s
1000
100
10
1
.1
.01
.01
.1
1
10
100
Contributing Drainage Area, km2


1000
100
10
1
Peak discharge, m3/s
1
1 0
1 0 0
1 0 0 0
Recurrence interval, years
Qp (7/12/96) at So Platte R.
Qp (7/12/96) Sand Draw
So Platte River
Sand Draw
Data from "SP@SP.fits.cgd"

F/G. 11