

Flood History Reconstruction in Frijoles Canyon Using Flood-Scarred Trees

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Abstract.-- Unexceptional summer storms triggered large floods on the Rito de los Frijoles in 1977 and 1978, shortly after the intense La Mesa Fire of 1977 burned this watershed. Large numbers of trees growing on or near the stream bank in Frijoles Canyon were scarred during these flood events. Such scars provide a record of the occurrence of past flood events which I used to reconstruct the flood history of the canyon. I compared the reconstructed flood history with existing fire history data to test the hypothesis that large floods have occurred following large-scale fires in the past.

I sampled 36 scarred trees at several localities along the Rito de los Frijoles. The flood scars were crossdated using reference chronologies I developed from scarred and unscarred trees in the canyon. I surveyed channel cross-sections and the top heights of the flood scars above the stream level, and then reconstructed paleoflood discharges using the slope-area method.

The riparian tree-ring chronology extends to the early 1600s, represented by at least five trees back to the mid-1700s. The scar dates range from 1773 to 1985, with most of the scar dates falling in 1977 and 1978. Floods were also identified for 1866, 1904, 1951, and 1972. Other than 1977, only the 1773 flood(?) scar matches a major fire year in the local fire scar record - this suggests that fire intensity, rather fire extensiveness, is the major factor leading to post-fire flooding in this watershed. Flood discharge estimates reconstructed from flood scars correspond well with the USGS estimates for the historic floods of 1977 and 1978. The flood scar evidence in Frijoles Canyon indicates that there have been at least four floods comparable to the 1978 flood in the last two centuries, and at least seven floods as large as the flood of 1977 during that time.

INTRODUCTION

Deforestation caused by severe forest fires exerts an important influence on flooding and debris flows by causing increased runoff and erosion (Wells 1987). The catastrophic La Mesa Fire at Bandelier National Monument in June of 1977 was followed a few weeks later by a large flood on the Rito de los Frijoles in Frijoles Canyon. This flood was larger than any that had been previously recorded in the watershed, and was itself exceeded the following year by an even larger flood, in July of

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1978 (U.S. Geological survey 1978, 1979, Purtymun and Adams 1980). The storm events associated with these floods were not particularly exceptional, but a large portion of the watershed had been intensely burned, contributing to decreased infiltration capacity of the soils, and reduced retardation of surface runoff. These factors combined to produce very rapid runoff and high sediment yield from relatively moderate rainfall events (White and Wells 1984).

Large numbers of trees growing on or near the stream bank in Frijoles Canyon were scarred during these flood events. These scars provide a record of the occurrence of past flood events and can be used to reconstruct the flood history of the canyon.

Establishment of a flood chronology provides additional insight for the interpretation of fire history at Bandelier National Monument. The flood history can be compared with the fire history produced by the analysis of fire scars (Allen 1989, Touchan *et al.* 1996) to test the hypothesis that large floods have tended to occur following large-scale fires in the past.

Flooding is a very important process in fluvial geomorphology and riparian ecology. In mountainous and semiarid terrain, infrequent large-magnitude floods may be the most important process involved in channel change, sediment transport, and landscape change in general (Wolman and Gerson 1978, Kochel 1988). Flooding exerts profound influence on species composition and population dynamics of riparian communities (White 1979, Hupp 1988), and also drastically affects human activities. Detailed knowledge of past flood regimes is essential to the complete understanding of fluvial systems, and for the realistic assessment of future probabilities of flood risks.

Large floods are linked to important climatic events, and appear to be somewhat independent of total annual precipitation. It appears that catastrophic flooding is episodic over scales of hundreds to thousands of years. This observation is based in part on slackwater deposit evidence from the Southwest over the scale of thousands of years (Webb *et al.* 1988). Evidence from flood-scarred trees in the Colorado River basin suggests that large floods have occurred in distinct episodes over the last several hundred years as well (McCord 1990). Thus the analysis of flood-scarred trees provides evidence of one aspect of climate change (large floods) over the last several centuries. Flood scars occur on the upstream-facing sides of trees growing along rivers, streams, and minor drainages, and are caused by the impact of flood-borne debris (Sigafos 1964, Harrison and Reid 1967, Yanosky 1982, Gottesfeld and Gottesfeld 1990, McCord 1990 and 1996). The damage caused by these impacts may be easily recognized and can be accurately dated to the exact calendar year by dendrochronological methods. Unlike fire scars, the damage often does not extend to the base of the trees. Such scars are probably caused by the impact of floating logs and branches; scars extending to the ground level are more likely to have been caused by the impact of boulders, cobbles, and gravel moving by

bouncing and rolling along the streambed. Flood scars may usually be distinguished from fire scars based on their morphology and orientation relative to the stream channel, but there may be ambiguity in some cases if the damage extends all the way to ground level. In many cases the season of the occurrence of the damage can be determined, and the event can sometimes be dated to within a month or two if it occurs during the growing season. Therefore different storm types (winter frontal type, summer convective cell type, and fall tropical storm or hurricane type) can be distinguished.

The heights of flood-scars above the stream channel provide accurate information on stage, or flow depth of past floods, and are thus good paleostage indicators. This paleostage information has been used in conjunction with stream channel geometry to successfully reconstruct discharge for floods of known magnitude. The technique shows excellent agreement with the known flood record, for both magnitude and frequency (Harrison and Reid 1967, McCord 1990).

METHODS

I sampled 36 scarred trees at several localities along the Rito de los Frijoles (in Frijoles Canyon), from the Upper Crossing to about two kilometers upstream of the Visitor Center (Figure 1). A total of 152 increment core samples were taken from living scarred trees. Cross-sections were also taken with handsaws from three dead snags. In addition, 71 increment core samples were taken from 32 unscarred trees. The scars were crossdated using reference chronologies produced from the collection of scarred trees and from the additional collections from unscarred trees. Most of the scarred trees had visible scars on the outside of the tree, but in a few cases cores from trees that were apparently unscarred were found to have scars that had been closed over by subsequent growth of the trees. The scar dates and time ranges of the trees used in the chronology were made into a flood event chronology (Figure 2) to graphically illustrate the flood history of the watershed. The flood event chronology produced in this manner is similar in appearance to a fire history chronology.

A reach of the stream just upstream from the Ceremonial Cave site was extensively studied in order to estimate the discharge of the post-fire floods. This reach of the canyon bottom has some important features which make it a good choice for the reconstruction of the discharge of prior floods. There is a straight segment of stream about 100 meters in length which is fairly constant in its gradient and cross-sectional shape. There are numerous scarred trees in this reach, most of which have scars at about the same height above the stream, two to three meters, indicating a fairly constant depth for the scarring event in this reach. This study reach presents a reasonably simple hydraulic situation, so that the discharge may be modelled with some confidence.

The heights of the tops of the highest scars from the 1978 flood were taken to represent the water surface during the flood crest stage, and the discharge was estimated using the slope-area method (Dalrymple and Benson 1967). The slope-area method, commonly used for the indirect estimation of stream discharges, uses the Manning equation (Williams 1988) to determine mean flow velocity, which is given by

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

where V is the velocity, R is the hydraulic radius (the channel cross-sectional area divided by the length of the wetted perimeter of the cross-section), S is the water surface slope or channel gradient, and n is a resistance factor related to the roughness of the channel bed, called the Manning roughness coefficient. The product of the mean velocity times the cross-sectional area is equal to the discharge.

The channel slope and cross-section was surveyed at several stations in this reach, along with the positions of the tops of the flood scars. From the survey data I plotted the longitudinal profile of the stream channel bottom, added the positions of the tops of the scars to the same plot, and then fit an envelope curve over the tops of the highest scars. Finding that this curve was almost exactly parallel to the channel bottom profile, I concluded that it was a good representation of the water surface profile at the flood crest stage. I ignored the lower scars, reasoning that some of the trees would be injured and scarred during the rising and receding stages of the flood. Using the survey measurements and the inferred water surface for the 1978 flood, I computed the channel cross-sectional area and the length of the wetted perimeter of the channel at three stations. I chose a value of 0.05 for the Manning roughness coefficient after consulting the tables in Albertson and Simons (1964) and making a comparison of the channel characteristics of this reach to those of the smaller streams described in Barnes (1967). The slope and channel cross-section measurements were then used with the Manning equation to estimate the mean flow velocity and discharge, which I calculated in cubic meters per second (m³/sec), and then converted to cubic feet per second (CFS).

Discharges were also estimated for the 1977 flood and for five probable floods prior to that, although the information obtained from the scars caused by the 1977 and earlier floods was not adequate to define the water surface with much confidence. A flood in August of 1991 left a well-defined line of debris at about a meter or so above the stream bank, well below the scars from the 1978 flood. This debris line was surveyed, and the inferred water surface was used to estimate the discharge, so that it could be compared to the discharge reported by the US

Geological Survey at the gage downstream near the Monument headquarters.

RESULTS

Flood Scar Dates

The flood scar dates on trees from Frijoles Canyon are summarized and shown as a flood event chronology in Figure 2. The scar dates range from 1773 to 1985, with most of the scar dates falling in 1977 and 1978. Floods were also identified for 1866, 1904, 1951, and 1972. No scars were found dating from the August 1991 flood. The chronology extends to the early 1600s, represented by at least five trees back to the mid-1700s.

Data for the flood-scarred trees are summarized in Table 1, including species, locations, tree dates, and scar dates. Heights above the channel bottom are shown for the scars in the surveyed stream reach where I estimated the water surface profiles for the various floods. For the trees upstream of the surveyed reach, the heights of the scars above the base flow water surface are shown. The scars from the 1977 flood (marked by single asterisks) are more common in the upstream reaches, and are generally a meter or two higher than they are in the lower reaches. In contrast, virtually all of the 1978 scars (double asterisks) appear in the downstream portion of the stream where the discharge was estimated, and are generally a meter or so higher than the 1977 scars in this reach of the stream. This suggests that the 1977 flood was more widespread than the 1978 flood, and was of greater magnitude in the upper part of the watershed.

Field inspection of the scars in the Ceremonial Cave study reach seemed to indicate that they had been caused by the same flood event. When the wood was crossdated, however, it became apparent that they are a mixed population, about half of them from 1978, but also including scars from 1977 and other years. Where seasonality could be determined, most of the trees scarred in 1978 show clearly that the damage occurred in the middle portion of the earlywood, consistent with a mid-summer flood event. Replicated scars, injuries, and growth suppressions in this reach dating from 1773, 1905, 1951, and 1972 indicate that there were floods in those years also.

In the upstream part of this reach there is an overflow channel about 60 meters long, off to the right (looking downstream) of the main channel. This channel is a shortcut path across a meander bend just upstream from the straight reach, and is about one meter in elevation above the current active channel. Scarred trees in the overflow channel indicate that it becomes active during high flows. A scar on a ponderosa pine growing on the edge of the channel dates to 1866; other trees have more recent scars from 1951, 1972, and 1977 (Table 1). No scars from 1773, 1905, or 1978 were found here. The debris line from the August 1991 flood, which comes to just below the mouth of the overflow channel, is not present in the channel itself, indicating that the 1991 flood was not large enough to cause the

overflow channel to be used.

About a kilometer upstream from the Ceremonial Cave reach one of the scars dated to 1773. This scar is on a large ponderosa pine dating back to the early 1600s. Downstream from this tree two other old ponderosas had internal (closed over) scars that also dated to 1773, and two others showed a severe growth suppression starting in 1773. On two of these trees, the 1773 scar can be clearly seen to be in the early part of the earlywood growth layer, showing that the damage was initiated during the early part of the growing season.

Reconstructed Flood Discharge Estimates

The channel characteristics and the velocity and discharge calculations for the 1978 flood at three cross-sections in the surveyed study site near Ceremonial Cave are shown in Table 2. The mean values, standard deviations, and coefficients of variation (CV) are also given. The mean discharge for the three stations is 2704 CFS. The discharge estimate for all eight floods that were reconstructed are shown in Table 3. Standard deviation and CV are given only for those floods where the water surface was defined by scars in at least two different spots along the study reach.

DISCUSSION AND CONCLUSIONS

The distribution of the flood dates suggests that the occurrence of floods in Frijoles Canyon is largely independent of the occurrence of fire. Of the pre-1977 flood dates, only one (1773) occurs in a fire year or in the following year. The interpretation of the 1773 scars is complicated by the widespread occurrence of a fire in that year (Allen 1989, Touchan *et al.* 1996). It seems reasonable to suspect that only very intense fires would sufficiently alter the watershed characteristics to increase its susceptibility to massive runoff from moderate rainfall events. The 1773 fire was widespread, and it is possible that it was such an intense fire, but that is not known with any certainty.

It is also possible that the 1773 scars and growth suppressions that I observed on riparian ponderosas in Frijoles Canyon were actually fire scars, and not related to floods at all. Two of the five trees showing 1773 scars or subsequent suppressions may be too far away from the present stream channel to have been reached by flood waters. Of the remaining three (on or near the stream bank), one has an internal scar and one has a growth suppression after 1773. Only one shows an external scar; the scar is facing upstream and has the general appearance of a typical flood scar, but unlike "classic" flood scars, it extends all the way to the base of the tree. Many flood scars do extend to the tree base, but this makes it difficult to rule out the possibility that it may be a fire scar. There is no charcoal on the scar, but this also does not rule out fire as the cause, because a tree scarred only a single time by fire may not show any charring if the bark was not burned through, as is typically

the case when trees are fire-scarred for the first time.

Nevertheless, the scar does not really look very much like a fire scar. It does not have the typical triangular-shaped "catface" pattern, and the outline is irregular rather than smooth. There is a narrow strip of thin bark down the center of the scar connecting the upper and lower borders of the scar, with bare wood showing on either side of it. Growth continued under this narrow strip after 1773 (though highly suppressed), indicating that this portion of the cambium was not killed by the scarring event. I know of no fire scars showing such a feature. The general appearance of this scar is very much that of a flood scar; if it is a fire scar, it is one of a very unusual character. More rigorous criteria to distinguish flood scars from fire scars would be very useful.

Virtually all of the scars on the conifer trees could be reliably dated using the riparian conifer chronologies for both ponderosa pine and Douglas-fir that have been prepared from the Frijoles Canyon ponderosa pine and Douglas fir specimens. Of the 19 scarred conifer trees sampled, 22 scars out of 24 have been dated from 17 of the trees. However, only 12 out of 17 scars on the deciduous trees have been dated from 10 trees out of 15 sampled, due to the lack of a sufficiently robust chronology to crossdate them against. The deciduous trees (primarily cottonwood and boxelder) display much greater between-tree variation in ring width, making it very difficult to crossdate single specimens against what are fairly weak chronologies based on insufficient numbers of trees. More robust chronologies using many more specimens of these species will likely be necessary in order to reliably crossdate all of the flood scars on the hardwoods.

The value of 2704 CFS for the discharge estimate of the 1978 flood is fairly close to the figure of 3030 CFS reported by the U.S. Geological Survey (1979) for the same flood on the basis of slope-area measurements made at a site about 500 meters downstream. The standard deviation of the discharge estimates at the three cross-sections is 117 CFS; the coefficient of variation is 4.3%, showing good agreement between the three stations.

It is encouraging to see such close agreement between the three stations, especially since there were proportionally larger differences in most of the channel characteristics. In any reach of a channel, if there are no tributaries or diversions between stations the discharge at any cross section should be the same as the discharge through any other cross section. This is due to a fundamental principle of fluid motion known as the *continuity equation* (Albertson *et al.* 1960). Only the water depth at channel center is as similar at the three stations as the discharge estimates, and the channel depth is not used in the Manning equation. There was a dispersion of 13% between the three cross-sectional areas, and nearly 20% between the wetted perimeter lengths, but when the cross-sectional areas were divided by the frictional effects of the wetted perimeters, the resulting hydraulic radii were considerably more similar (CV = 7.5%). The

channel slope dispersions ($CV = 15\%$) were partially offset by the different hydraulic radii, leading to fairly similar velocities ($CV = 8.9\%$). The velocity at station 3 was lower than that at the other two stations, but the cross-sectional area was larger, so that the product of the velocity times cross-sectional area (discharge) was quite similar for all three stations ($CV = 4.3\%$).

The discharge estimates for the floods in 1977 and earlier years are less certain, because there were fewer trees with flood scars from those years that could be used to define the water surface. The water surface for 1977 is fairly well defined by scars on five trees in the study reach, two of them from above the three surveyed cross sections, and three of them from below. The discharge estimate of 724 CFS is slightly larger than the slope-area estimate of 653 CFS made by the U.S. Geological Survey (1978), but is in reasonably close agreement. The 1972 event is defined in the study reach on only two trees from upstream of the measured cross-sections. These scars were partly concealed under 1977 scars, at about the same height as the 1977 scars, leading me to the conclusion that the 1972 flood may have been about as large as the 1977 flood. The 1951 flood is defined by a scarred tree in the study reach above the measured cross sections, and by two other trees with internal scars, one near cross section 3, and the other about 30 meters downstream. The water level seems to have been nearly as high as it was in 1978.

The magnitudes of the 1905, 1866, and 1773 floods are considerably more uncertain, because the water levels were inferred on the basis of only one or two scarred trees for each of the floods. I inferred the water level for the 1905 flood on the basis of an internal scar from a tree in the meander bend above the cross sections, and on an internal injury in a tree near cross section A-A'. The 1866 flood is represented by a single scar on a large ponderosa pine growing on the right bank of the overflow channel. This flood may have been even larger than the 1978 flood. The 1773 water level was inferred from an internal scar on one tree near cross section 3. No survey data was obtained for this scar, but based on the location of the tree it appears that the water level may have been at least as high as it was in 1951, and possibly as high or higher than 1978.

The water surface for the August 19, 1991 flood was well defined by the survey data from the debris line, but my estimate of 374 CFS for the discharge is not in good agreement with the figure of 105 CFS reported by the U.S. Geological Survey (1992) for the crest-stage partial-record station located downstream from Monument headquarters. I can only speculate as to why the figures do not agree. One possibility is that the stream was temporarily dammed during the flood in the Ceremonial Cave reach by coarse debris such as logs and branches, allowing the line of fine debris that I observed to be left stranded at a level higher than the running water, but I consider this possibility to be fairly unlikely. It is also possible that the Manning roughness coefficient for this stream should be larger for relatively low

flows due to the large boulders that are in the channel. It has been noted that some streams have larger channel roughness factors at lower flood levels (Barnes 1967), but the difference is usually less than a factor of two, which would not be enough to explain the discrepancy here.

The flood scar evidence in Frijoles Canyon indicates that there have been at least four floods comparable to the 1978 flood in the last two centuries, and at least seven floods as large as the flood of 1977 during that time. There are many more flood-scarred trees in Frijoles Canyon that have not been sampled. It would be useful to sample more of these scarred trees in order to increase the robustness of the estimates on the occurrence of the earlier floods. In addition it would be very desirable to prospect and sample flood-scarred trees in other canyons in adjoining portions of New Mexico, in order to build up a more regional picture of the flood history in this area.

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FIGURE CAPTIONS

Figure 1. Locations of sample areas for flood-scarred trees in Frijoles Canyon.

Figure 2. Flood-scarred trees in Frijoles Canyon. Horizontal lines represent individual trees. Black triangles represent flood scars, open triangles other injuries or growth disturbances. Trees are arranged from top to bottom in order proceeding downstream.