Arctic and Alpine Research, Vol. 30, No. 1, 1998, pp. 40–50

Methodology and Implications of Maximum Paleodischarge Estimates for Mountain Channels, Upper Animas River Basin, Colorado, U.S.A.

Jonathan Pruess and
Ellen E. Wohl

Department of Earth Resources,
Colorado State University, Fort
Collins, Colorado 80523, U.S.A.
ellenw@cnr.colostate.edu

Robert D. Jarrett

Water Resources Division, U.S.
Geological Survey, Box 25046,
Denver Federal Center, Mail Stop
412, Denver, Colorado 80225, U.S.A.

Abstract

Historical and geologic records may be used to enhance magnitude estimates for extreme floods along mountain channels, as demonstrated in this study from the San Juan Mountains of Colorado. Historical photographs and local newspaper accounts from the October 1911 flood indicate the likely extent of flooding and damage. A checklist designed to organize and numerically score evidence of flooding was used in 15 field reconnaissance surveys in the upper Animas River valley of southwestern Colorado. Step-backwater flow modeling estimated the discharges necessary to create longitudinal flood bars observed at 6 additional field sites. According to these analyses, maximum unit discharge peaks at approximately 1.3 m^3 s^{-1} km^{-2} around 2200 m elevation, with decreased unit discharges at both higher and lower elevations. These results (1) are consistent with Jarrett's (1987, 1990, 1993) maximum 2300-m elevation limit for flash-flooding in the Colorado Rocky Mountains, and (2) suggest that current Probable Maximum Flood (PMF) estimates based on a 24-h rainfall of 30 cm at elevations above 2700 m are unrealistically large. The methodology used for this study should be readily applicable to other mountain regions where systematic streamflow records are of short duration or nonexistent.

Introduction

The estimation of high-elevation extreme rainfall and resulting flooding presents many difficulties to government and private agencies concerned with floodplain management, dissemination of flood warnings, risk assessment, and design of hydraulic structures in floodplains. A gradual shift toward greater recreational and residential use of mountain regions has placed greater numbers of people at risk from floods and has increased the need for effective flood hazard mitigation. Systematic records of precipitation and discharge in mountain regions tend to be sparse because of the historically low population densities of mountain regions and the high spatial variability of mountain hydroclimatology. The spatial variability also limits the accuracy of regional extrapolations from limited measurement sites. There is increasing documentation and awareness that historical rainfall and flood estimates have large uncertainties and are often overestimated (Jarrett, 1987, 1990, 1994; Grimm, 1993; House and Pearthree, 1995). Use of suspect rainfall and flood data has brought into question interpretations of flood methodologies.

The San Juan Mountains of southwestern Colorado exemplify these problems. The most notable high-elevation rainstorm in the Rocky Mountains occurred in Gladstone, Colorado, on 4–5 October 1911. The official U.S. Weather Bureau gauge at 3290 m recorded 21 cm of rainfall in 24 h. Current Probable Maximum Precipitation (PMP) estimates for the region, which were determined in part from the Gladstone storm, suggest that rainfalls of up to 30.5 cm per 24-h can occur at high elevations (above 2700 m) in this portion of the Rocky Mountains (Hansen et al., 1984). The PMP is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year" (Cudworth, 1989). The probable maximum flood (PMF) is derived directly from the PMP. The PMP estimates for the San Juan Mountain region have been interpreted to indicate a need to retrofit dam spillways designed for previous, lower PMP and PMF estimates. As of 1986, retrofitting only the 162 high-hazard dams in Colorado would cost approximately $184 million (Chagnon and McKee, 1986). (A high-hazard dam is defined by the U.S. Bureau of Reclamation (1988) as putting more than 6 lives in jeopardy as a result of failure, and causing "excessive economic loss.") Any uncertainties in PMP/PMF or other flood estimates thus translate into substantial economic issues. Because of this, substantial effort is being made to improve knowledge of flood hydrology in the Rocky Mountains. For example, methods used to estimate PMP and PMF are presently being reevaluated by various agencies involved with dam safety and water resource development in many areas of the U.S., particularly in the Rocky Mountain region.

Jarrett (1987, 1990, 1993) has suggested an elevation limit to rainfall-produced flash flooding that varies with latitude and distance from the moisture sources of the Gulf of Mexico and the eastern Pacific Ocean. There is no evidence that unit discharges (discharge divided by drainage area) have exceeded 1.1 m^3 s^{-1} km^{-2} along the Colorado Front Range above approximately 2300 m (Jarrett, 1987, 1990). If a similar elevation limit exists in other portions of Colorado, such as the San Juan Mountains, present flood estimates are probably unrealistically large, and the expensive retrofitting of dam spillways and other existing structures becomes unnecessary.

One means of resolving the uncertainties in estimating extreme flood magnitude for high-elevation channels is to use paleohydrologic indicators that record past floods. In the Animas River basin of the San Juan Mountains, such indicators commonly take the form of flood boulder bars, scour lines, and damaged vegetation. In this study we assessed extreme flood magnitude at high elevations in the Animas River basin using both

0004-0851/98 $7.00

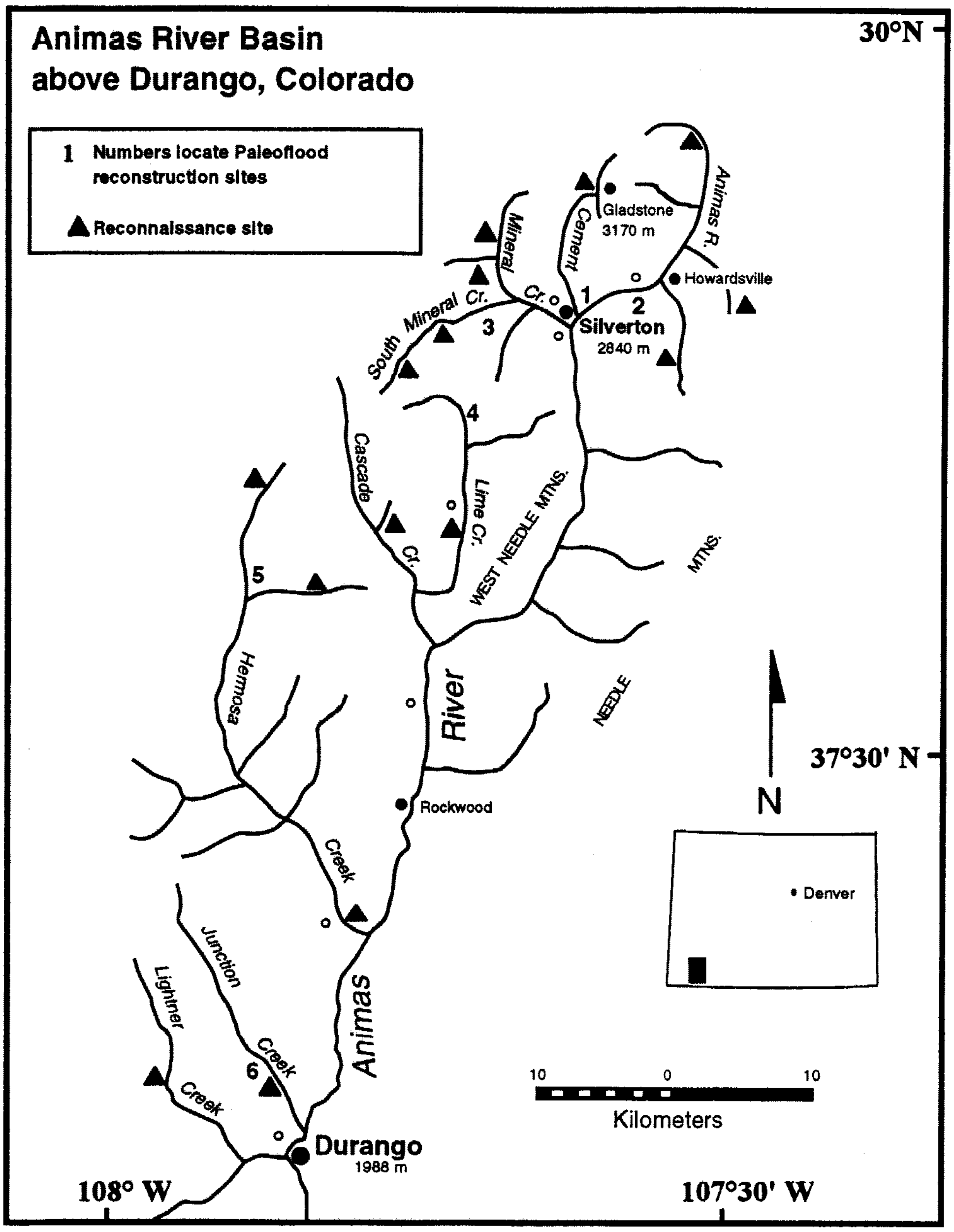

FIGURE 1. Location map of the study area. Reconnaissance sites are indicated by triangles; gage locations indicated by open circles; towns indicated by solid circles. Paleoflood study sites are 1 (Cement Creek, 2850 m), 2 (Animas River, 2910 m), 3 (South Mineral Creek, 2930 m), 4 (North Lime Creek, 3000 m), 5 (Hermosa Creek, 2750 m), and 6 (Junction Creek, 2190 m).

historical records and paleohydrologic indicators. We focused on (1) historical and meteorological records of the October 1911 flood, which is a key component of regional high-elevation flood estimates, and (2) physical evidence of flood magnitude at 17 sites in the upper Animas River basin. The methods described for the Animas River basin are readily applicable to other mountainous regions where estimates of flood magnitude are similarly uncertain.

Field Area

The upper Animas River drains an area of 1955 km^2 above Durango, Colorado, in the southwestern corner of the state (Fig. 1). The drainage basin ranges from 4292 to 1988 m in elevation, and is formed on a dissected portion of a Tertiary volcanic dome (Lipman et al., 1970). The broad valleys above the town of Silverton were produced during three episodes of Quaternary alpine glaciation (Richmond, 1954). Between Silverton and Rockwood the Animas valley is a bedrock gorge (avg. gradient 0.019 m m^{-1}) incised into Precambrian gneiss and schist (Larsen and Cross, 1956). Downstream from Rockwood, the Animas valley widens into a broad alluvial surface of much lower gradient (0.003 m m^{-1}).

Orographic effects produce a highly variable distribution of annual precipitation in the Animas River basin. Average annual precipitation generally increases with elevation, from 40 cm in Durango to 150 cm on the highest peaks, and falls mainly in the form of winter snow (Colorado Climate Center, 1984). Localized and short-lived summer thunderstorms contribute little runoff to stream flows.

Monthly discharge means for U.S. Geological Survey gauges near Howardsville (#09357500) and Durango (#09361500) (Fig. 1) clearly peak in June as a result of melting snowpack. A much smaller secondary peak may be produced by the large, dying tropical depressions that occasionally affect the San Juan Mountains during late summer and early fall. One of these storms (on 4–5 October 1911) produced the largest known 24-h high-elevation rainfall totals in the region (Roeske et al., 1978). Another such a storm on 5 September 1970 produced one of the largest historic floods in the Animas River valley, and has since become a key storm for the PMP estimates for southwestern Colorado.

Many of the channels within the upper Animas River basin were disturbed as a result of mining activities that began in the early 1870s and continued into the early 1920s. During the peak of the mining boom, the subalpine slopes surrounding the towns and mills were deforested, and historic debris-flow deposits are common along the steep, ephemeral slope tributaries. The mining was predominantly hard-rock or lode mining, but associated tailings dispersal and railroad construction directly impacted the stream channels. These anthropogenic impacts limited the number of field sites where geologic flood indicators could be used with present-day channel morphology to estimate paleoflood occurrence and magnitude.

Methods

Our estimates of flood magnitude along channels in the study area focused on three methods: qualitative estimation using (1) historical records and (2) a field reconnaissance checklist, and (3) quantitative estimation based on paleostage indicators and one-dimensional flow modeling. Historical photographs and local newspaper accounts for the study area were used mainly to evaluate the October 1911 storm.

FIELD OBSERVATIONS

A field checklist (Fig. 2) was designed to facilitate a reconnaissance survey of 15 channel sites within the study area. The checklist includes numerical scores based on observations, and data from channel geometry surveys and other quantitative measurements. It also includes channel classification (Montgomery and Buffington, 1993) as a tool for assessing a channel's potential sensitivity to flood or land-use disturbances.

The checklist provides a rapid means of comparing flash-flood evidence from several sites, and for conveniently documenting observations. Numerically scored observations were chosen to include several geologic and botanic indicators of flash-flooding likely to be preserved along mountain channels. The primary objective of these observations was to detect evidence of flash floods rather than the annual snowmelt-flood peak. The larger-magnitude flash floods create (1) distinctive sediment deposits, including relatively poorly sorted flood bars (Jarrett, 1990; Grimm et al., 1995), changes in grain-size distribution at tributary junctions (Grimm et al., 1995) and overbank slackwater sediments (Kochel and Baker, 1988; O'Connor et al., 1994); (2) changes in channel form, including scour and fill (Shroba et al., 1979) and truncated colluvium or banks (Baker, 1973; McCain et al., 1979; Wohl, 1995); and (3) botanic indicators, including lichen limits (Gregory, 1976), corrasion scars (Hupp, 1988), adventitious sprouts (Bryan and Hupp, 1984; Hupp, 1988) and distinct vegetational succession (Hupp, 1984, 1988). In contrast, longer-duration, lower-magnitude snowmelt floods create well-sorted cobble bars and in-channel deposits, minimal net change in channel cross sectional geometry, and only in-channel lichen limits. Observations of the flash-flood features listed above were supplemented by (1) clast-size measurements used to estimate the flow competence necessary to produce sediment deposits and changes in channel form (O'Connor et al., 1986; Wohl, 1992; O'Connor, 1993), and (2) soil development and tree ages indicating relative stability and age of depositional surfaces (Hupp, 1988; Wohl and Enzel, 1995). Finally, land use was evaluated to provide information on whether the study reach was likely to have been disturbed.

Scores for each of the categories on the checklist were combined and totaled. The total score was divided by the greatest possible score for that site, and then converted to a percentage rating. The greatest possible score for each site depended on features such as site elevation. For example, higher elevation sites had no woody riparian vegetation, so that impact scars were irrelevant. A high score for a site indicated abundant evidence of one or more large floods.

COMPUTATIONAL METHODS

Maximum discharge was estimated at two of the reconnaissance sites using Jarrett's (1984, 1992) regime-flow equations for mountain channels. These sites were judged to have had the least anthropogenic disturbance and the best cross-sectional control (the presence of bedrock). The other reconnaissance sites were judged to be unreliable for quantitative discharge estimation because of anthropogenic disturbance, lack of cross-sectional control, or evidence of debris flows. Because the sites used for discharge estimation had no evidence of overbank flows, we used a single surveyed cross section to estimate maximum within-bank discharge from

$$Q = 3.17\, A\, R^{0.83}\, S^{0.12} \tag{1}$$

where Q is discharge (m^3 s^{-1}), A is cross-sectional flow area (m^2), R is hydraulic radius (m), and S is water-surface slope (m m^{-1}).

Six field sites were chosen for a step-backwater analysis of maximum discharge (Fig. 1). Few ideal channel reaches for paleoflood reconstruction exist in the upper tributaries of the Animas River because of channel disturbance associated with the widespread mining activities. Three of the sites described here (Cement Creek, South Mineral Creek, North Lime Creek) were chosen because they are bedrock controlled and show little evidence of human disturbance. The remaining sites provide less well constrained discharge estimates because of potential channel change (scour and fill) during and after the flood.

Flood stage at each of the six sites was estimated from the apex of a coarse-grained longitudinal flood bar. Using a systematic evaluation of the relation between peak stage and height of paleostage indicators from record floods in several western states during 1995 and 1996, Jarrett et al. (1996) demonstrated that bar apex provides an excellent approximation (±5%) of peak stage along high-gradient mountain channels.

In mountain environments, care must be taken to avoid interpreting debris-flow deposits as flood deposits. Many questionable records of historic flood discharges along mountain rivers resulted from misinterpretation of debris-flow deposits as flood deposits (Costa and Jarrett, 1981; Jarrett, 1987), and from incorrect use of Newtonian flow equations to characterize mud or debris flows. In all cases, peak discharges estimated from debris flows are overestimated (Costa and Jarrett, 1981). Debris-flow deposits may be differentiated from flood deposits on the basis of degree of sorting, abrupt levees, lobe-shaped snouts, presence of finer supporting matrix and inverse grading (Costa and Jarrett, 1981; Costa, 1984), and lack of clast orientation (Jarrett and Waythomas, 1994).

Flood stage and surveyed channel geometry were used to estimate flood discharge with step-backwater analysis (Chow, 1959; Davidian, 1984). For each of the six reaches, water-surface elevations were computed for a series of surveyed cross sections using the program HEC2 (Hydrologic Engineering Center, 1990). Water-surface profiles for subcritical flow were calculated by setting the initial water-surface elevation at the downstream

Mountain Streams Paleoflood Checklist

Site: ______ Elevation (map) ______

USGS Topo. map name: ______ Site at tributary junction Y / N ; Main channel name ______

Catchment aspect: ______ Catchment size: ______ Photos: Roll# ____ Frame # ____ Tributary name: ______

Rank the items in the boxes below for each site visited. Cumulative site scores can then be compared to assess relative flood histories and magnitudes.

SEDIMENTS

(no)	Flash-flooding	(yes)
Well sorted, mostly small clasts	1 2 3 4 5	Poorly sorted, many large clasts
No change in grain size at tributary junctions	1 2 3 4 5	Increase in grain size at tributary junctions
Rilling and erosion absent on hillslopes	1 2 3 4 5	Rilling and erosion on hillslopes
Limited bars with small clasts	1 2 3 4 5	Flood bars with large clasts
Little slackwater deposition in expansions or tributaries	1 2 3 4 5	Slackwater deposits common in expansions or tributary mouths
Rounded clasts having been in channel a long time	1 2 3 4 5	Angular to subangular clasts that are new to channel
Cobble to small boulder moved	1 2 3 4 5	Large boulders moved

Total for sediments

CHANNEL FORM

(no)	Flash-flooding	(yes)
Little channel scour	1 2 3 4 5	Channel scour
Untruncated colluvium or banks	1 2 3 4 5	truncated colluvium or banks
Unincised channel	1 2 3 4 5	Incised channel
Sparse scour and deposition	1 2 3 4 5	Alternating scour and deposition
Controlled by large woody debris	1 2 3 4 5	Channel kept clear by frequent high flows
Unscoured tributaries	1 2 3 4 5	Scour in tributaries

Total for Channel form

VEGETATION

(no)	Flash-flooding	(yes)
Lichen cover on exposed rocks	1 2 3 4 5	Lichen cover stripped by high flows
Algae cover on submerged rocks	1 2 3 4 5	Algae removed by frequent high flows
Old vegetation on banks (little succession)	1 2 3 4 5	Young vegetation on banks and bars (succession)
Impact scars not evident	1 2 3 4 5	Many scarred trees
Well developed vegetation on bars	1 2 3 4 5	Vegetation regularly stripped from bars
Undisturbed vegetation	1 2 3 4 5	Bent or sprouting trees in overbank area

Total for Vegetation

Score Total ______
Total Scored ______
Rating in % ______ higher % indicates more flooding

SOIL AND COVER ON BARS:

Depth on bars:

in channel	thin / mod. / thick
on banks	thin / mod. / thick
in flood plain	thin / mod. / thick

SURVEY DATA:

Channel slope ______ width/depth ratio ______

width ______ depth ______

Cross section surveyed and plotted (Y / N)

DENDROCHRONOLOGY: (minimum ages)

TREE LOCATION	AGE (yrs)

CHANNEL CLASSIFICATION
From Montgomery and Buffington,

Valley Segment Level

- ☐ Unchanneled Colluvial Valley
- ☐ Channeled Colluvial Valley
- ☐ Bedrock Valley
- ☐ Alluvial Valley

Channel Reach Level

- ☐ Colluvial
- ☐ braided
- ☐ regime
- ☐ pool/riffle
- ☐ plane-bed
- ☐ step-pool
- ☐ cascade
- ☐ bedrock

Transport Limited ↕ Limited Supply

WOLMAN PEBBLE COUNT DATA:

At tributary juntions:

d above tributary junction ______

d below tributary junction ______

All other sites:

d ______

LAND USE:

Present

Within catchment : High / Moderate / Low
Within channel : High / Moderate / Low
Type of use ______

Historic

Within catchment: High / Moderate / Low
Within channel: High / Moderate / Low
Dates of activity ______

FIGURE 2. Sample paleoflood field checklist.

cross section equal to critical depth. Earlier studies (Jarrett, 1984, 1987, 1994; Trieste and Jarrett, 1987) suggest that supercritical flow seldom occurs in mountain channels, except locally and for short reaches.

The HEC2 program computed an energy-balanced water surface for the next upstream cross section, taking into account estimated head losses associated with roughness and channel expansions or contractions between cross sections. The water-surface profile for the entire reach was based on the cross-sectional water-surface elevations (Feldman, 1981). A range of discharges was used to develop stage-discharge relations at each cross section to bracket the range of paleostage indicators (PSI). At the Cement Creek, South Mineral Creek, and Animas River–Howardsville sites, coarse-grained flood bars served as PSI. Large woody debris served as PSI at the lower elevation sites on Junction Creek.

The stage-discharge relation at the farthest downstream cross section was not known for any of the step-backwater sites. Five trials were used with various combinations of discharges, stages, and roughness values at each of the sites in order to define "normal depth" water-surface profiles. Normal depth here refers to the depth at which different starting water-surface elevations converge upstream. If probable starting water-surface elevation downstream can be constrained within 1 to 2 m, water-surface profiles estimated with HEC2 will converge within a few cross sections. The cross sections below the water-surface convergence are not used in analysis. For each site, four sensitivity analyses were also conducted in which roughness coefficient was varied by ±25%, and the water-surface elevation was assumed to be 0.25 and 0.50 m greater than the PSI. The ranges chosen for the sensitivity analyses were based on analogous studies of mountain channel floods by Jarrett and Waythomas (1994), and represent what we judge to be the most probable range of roughness and water-surface elevations for these sites. Contraction and expansion coefficients were not varied from the standard values of 0.0 and 0.5, respectively; these coefficients have little influence on discharge estimates (Motayed and Dawdy, 1979; Jarrett and Malde, 1987). Roughness values were estimated using Jarrett's (1992) relation for mountain rivers:

$$n = 0.32\, S^{0.38}\, R^{-0.16} \qquad (2)$$

where n is Manning roughness coefficient, and S and R are in meters and as in equation (1). Roughness was also checked against Barnes's (1967) photographs of natural channels with verified n-values.

U.S. Geological Survey gauging station records from the WATSTORE data base (Hutchinson, 1975), a database of indirect discharge measurements for Colorado (Jarrett, 1987), and the paleoflood discharge estimates were used to refine flood magnitude-frequency relations at the Animas River and at the Junction Creek sites. For each site, a Log-Pearson Type III distribution was fit first to the systematic (gauged) data from that site, and then to a dataset including both the systematic discharges and the maximum paleoflood discharge from the site. These analyses used a flood-frequency analysis program developed by the U.S. Geological Survey that gives historical and paleoflood data a low weight relative to systematic data (Lepkin et al., 1979). Because the ages of the paleoflood indicators at the Animas River and Junction Creek sites are poorly constrained, a flood-frequency sensitivity analysis was conducted for each site by varying the age of the paleoflood discharge, and noting the effect of these changes on the 100-yr discharge estimate. We arbitrarily chose four possible ages; 83 yr (for the 1911 flood at the time of this study), 100 yr, 500 yr, and 1000 yr. This approach to flood magnitude-frequency relations provides only a first approximation, because systematic flood data are assumed to represent all discharges above a specified threshold during a known timespan, whereas the paleoflood data represent only the largest discharge during an unknown period.

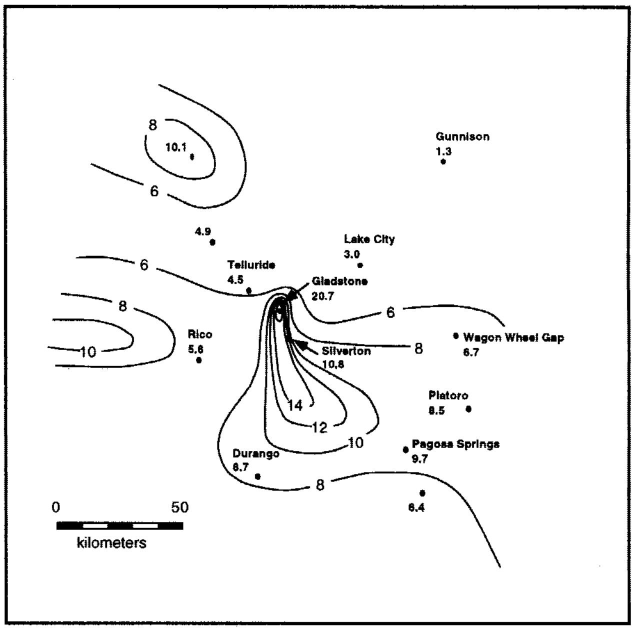

FIGURE 3. Adopted isohyets for the storm of 4–6 October 1911. Rainfall in centimeters (after U.S. Bureau of Reclamation Storm Files).

Results and Discussion

HISTORICAL EVIDENCE OF THE OCTOBER 1911 FLOOD

The October 1911 precipitation in the San Juan Mountains has been one of the primary sources of PMP estimates for the region. Estimates of the severity of the October 1911 storm in the San Juan Mountains are based on rainfall data in the U.S. Bureau of Reclamation Storm Files and on newspaper accounts of the resultant flooding. The largest rainfall measurement was a recorded 21 cm (8.15 in) during 24 h at Gladstone. Surrounding rainfall measurements are substantially lower (Fig. 3). Meteorologic data for the 1911 storm show that the low-pressure center of the storm moved very rapidly through the study area (averaging 67 km h^{-1}), and almost directly over Silverton and Gladstone (Hansen and Schwarz, 1981). The speed with which the storm moved is not consistent with the rainfall reported for Gladstone (Crow, pers. comm., 1994). Rainfall from fast-moving storms tends to be distributed widely in space and time, rather than concentrated (Hansen and Schwarz, 1981).

State and national newspapers reported widespread flood damage from the October 1911 storm in the Animas River valley, and newspaper accounts, photographs, and personal accounts clearly indicate severe damage to railroads and bridges in the lower Animas River valley and Durango. However, accounts in the newspapers published by communities in the upper Animas Valley, primarily *The Silverton Standard* and the *Silverton Weekly Miner,* and contemporary photographs from the region, indicate only minor flood damage in the upper basin. An account from *The Silverton Standard* best summarizes the situation:

> The damage [the flood] wrought while deplorable, was in no

FIGURE 4. Cement Creek in summer 1912 downstream from Gladstone, Colorado. A locomotive is traveling upstream along the right bank (at center right of photograph). Presence of willows encroaching on the channel (center background), and lack of extensive bar deposits or scour suggest the absence of pronounced flooding at this site in 1911. Photograph courtesy of Sundance Publishing, Ltd., and the San Juan Historical Society.

> instance nearly as great as that reported in the great daily journals through their sensational correspondents in the various surrounding towns. . . . In fact, as a community, we suffer fully as much, if not more, from this flood of exaggeration as we do from the temporary distress following the washouts.

In addition, a 1912 photograph of Cement Creek in the vicinity of Silverton and Gladstone suggest that substantial out-of-bank flooding did not occur in October 1911: established willows encroach upon the channel, and neither extensive bar deposits nor scour are visible along the channel (Fig. 4). This lack of flood evidence does not preclude the possibility of a major flood but, in combination with local written descriptions of flood damage, it suggests that the storm of October 1911 produced widespread rainfall of 3 to 10 cm (Fig. 3) in the upper Animas Valley, but not an extreme flood in the vicinity of Silverton.

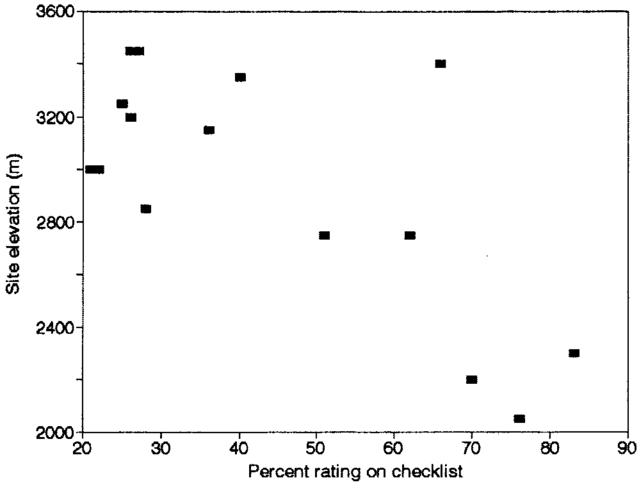

FIGURE 5. Plot of rating in percent from field checklist versus elevation of site evaluated. The point most clearly deviating from the trend is from the Animas River above Silverton. The flood boulder bar at this site may have been disturbed by human activities. The correlation between elevation and percent rating is significant at x *= 0.01 ($R^2 = 0.51$).*

RECONNAISSANCE FLOOD OBSERVATIONS AND THE FIELD CHECKLIST

The paleoflood checklist (Fig. 2) was intended as both a data collection template and a scoring tool to quantify flood evidence and facilitate comparisons between sites. However, the checklist proved most valuable for organizing data collection and suggesting regional trends. The results from the 15 sites to which the checklist was applied clearly demonstrate an inverse relation between percentage rating and elevation (Fig. 5), where a larger percent rating indicates more evidence of flooding. In other words, high-elevation channels in the San Juan Mountains contain fewer paleoflood indicators, which we interpret to result from a lack of flash floods at high elevations. The data collected in the checklist suggest a gradational relation between elevation and flooding rather than a distinct cutoff at any particular elevation. However, these results apply only down to 2000 m elevation; we were unable to locate appropriate field sites below this elevation.

It was important for the observer completing a checklist to modify scoring based on the specific field site, rather than determining scores for all categories at each site. One type of flood evidence might not be observed at a site, and might thus be scored low on the checklist, whereas another type of flood evidence might be abundant and scored high. The result is that the

TABLE 1

Discharge estimates from Jarrett's (1984, 1992) regime-flow equations, and step-backwater analyses[a]

Site	Elev. (m)	PSI Q unit Q (m^3 s^{-1})	Discharge[b] n + 25% n − 25% (m^3 s^{-1})	Discharge[c] ws + 0.25 m ws + 0.50 m (m^3 s^{-1})	PSI evidence	Largest gauged Q, year
Jarrett regime-flow equation						
South Mineral Creek	3250	6.9	—	—	—	—
		0.7				
South Fork Cement Creek	3200	1.0	—	—	—	—
		0.2				
Step-backwater analyses						
North Lime Creek	3000	4	3.8	8	scour line	
		0.59	4.5	16		
South Mineral Creek	2930	32	29	40	in-channel bars	
		0.67	34	50	break in bank slope	
Animas River	2910	70	58	91	mid-channel bar	56
		0.49	88	118	SWD; large woody deb.	1970
Cement Creek	2850	12	9	21	in-channel bar	
		0.23	12	34	oxidation stain on bedrock	9.7
					wall	1936
Hermosa Creek	2750	46	36	65	gravel flood bar	
		1.01	48	90	SWD	
Junction Creek	2190	87	68	118	flood bar	16.8
		1.29	125	155		1980

[a] PSI is paleostage indicator; n is Mannings roughness coefficient; ws is water-surface elevation.

[b] Column for each site lists discharge for different n values.

[c] Column for each site lists discharge for different water-surface elevation values.

scores for these two items effectively cancel each other if all scores for a site are tallied. For example, undamaged trees might grow on top of an older flood bar, but the checklist would record only 0 for tree scars and 5 for flood bars, which average to indicate only moderate flooding. In such a case, it seems reasonable not to score tree scarring, because the low score would be an artifact of young tree age. Similarly, some indicators might not be present at a site. High-elevation sites in the San Juan Mountains commonly do not have woody debris or woody vegetation large enough to be scarred.

Also, channel features that resemble flash-flood indicators may be produced by normal snowmelt floods. As an example, vegetative succession could be produced by lateral channel mobility along a meandering channel, as well as by frequent out-of-bank flooding. Similarly, debris flows could create boulder bars resembling flood bars. Care must thus be given to field interpretations; vegetational succession caused by channel meandering should be distinguished from vegetational succession caused by overbank flooding based on the presence of abandoned channel meander bends.

Finally, channels may not always exhibit the full range of potential responses to a flash flood. The 1982 Lawn Lake dam failure in Rocky Mountain National Park sent a peak discharge of 340 m^3 s^{-1} along the meandering Fall River (elevation 2580 m) (Jarrett and Costa, 1986). The previous peak discharge on the river was 16 m^3 s^{-1}. Extensive sand and gravel deposits obliterated the channel's preflood cobble bed, but meander cutoff, destruction of vegetation, channel scour, and bank destabilization did not occur because floodwaters spread across the broad valley of the Fall River. Less apparent evidence of the 1982 flood occurs in the form of fine sand and silt slackwater deposits emplaced on the floodplain. Recognition of this evidence requires detailed stratigraphic investigations.

In summary, when the paleoflood checklist is carefully applied, it may assist in evaluating evidence for past floods at a site. Scoring of the checklist was modified in that the percentage was calculated only from those indicators actually ranked at each site. The key to assessing the magnitude of flooding using paleohydrologic techniques may lie in the number of supporting characteristics present along a channel. Compilation of numerous ratings for a region may also indicate elevational trends in flood evidence.

PALEODISCHARGE ESTIMATION

Maximum unit discharges estimated for the South Mineral Creek and South Fork Cement Creek high-elevation reconnaissance sites, which did not have evidence of flows greater than bankfull, are given in Table 1. Both of these values are well below Jarrett's (1987, 1990) flash-flood threshold of 1.1 m^3 s^{-1} km^{-2}.

Discharge estimates for the six sites where step-backwater analysis was used are also listed in Table 1. Of these sites, only the lowest elevation (Junction Creek) site had a unit discharge exceeding 1.1 m^3 s^{-1} km^{-2}. For the six sites with systematic gauged or indirect discharge measurements, the paleostage indicators exceeded the systematic maximum discharge, suggesting that floods larger than those recorded by gauged and indirect measurements have occurred.

FLOOD-FREQUENCY RELATIONS

The ages of PSI at two sites were constrained primarily by botanical evidence. Relatively few trees grow on flood deposits in the Animas River basin, probably as a result of historic deforestation and continued firewood cutting, beaver activity, and

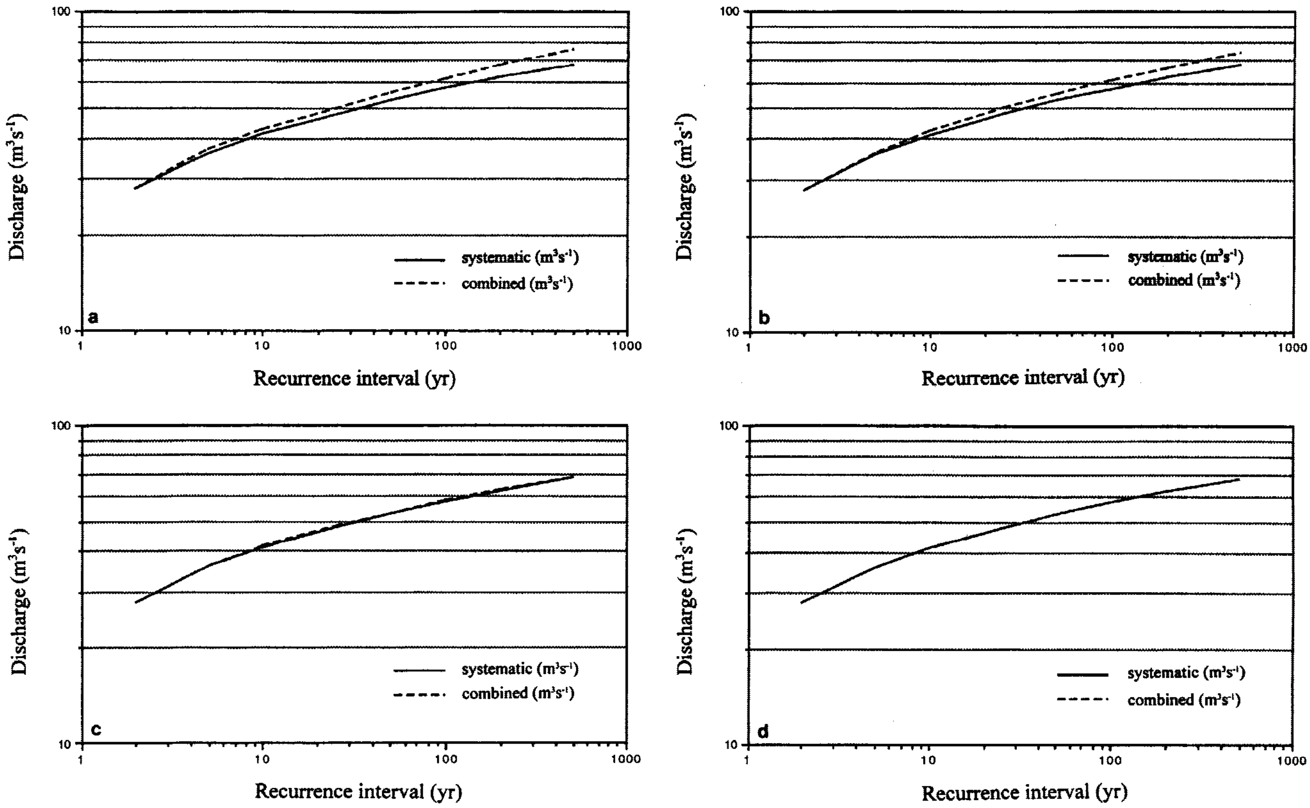

FIGURE 6. Magnitude-frequency relations for the Animas River site downstream from Howardsville, using systematic records and with the inclusion of paleoflood data. "Systematic" curve is only systematic data; "combined" is combined systematic and paleoflood data. (a) Paleoflood assigned an age of 83 yr; (b) paleoflood assigned an age of 100 yr; (c) paleoflood assinged an age of 500 yr; (d) paleoflood assigned an age of 1000 yr.

the lack of high, old flood deposits with well-developed soils. Therefore, we cored only one tree each at the Junction Creek and Animas River–Howardsville sites. The spruce tree growing on a mid-channel bar at the Animas River site was 31±1 yr old, suggesting that no flows capable of stripping young trees from the bar top have occurred since 1963. The ponderosa pine growing on a flood bar at the Junction Creek site was 50±5 yr old, suggesting that the bar surface has been stable and undisturbed since the 1940s. The ages of these trees do not preclude the possibility that the large flood deposits upon which they are growing were the result of the 1911 flood. However, lichen growth on fluvially deposited boulders, and well-developed organic soil horizons several centimeters in thickness, suggest that the deposits at the Animas River and Junction Creek sites are probably older than 1911.

Systematic data from continuous flow gauges from the Animas River site (47 yr of data) and the Junction Creek site (23 yr of data) were used to compute magnitude-frequency relations with the Log-Pearson Type III distribution. Assuming that the maximum paleoflood at each site occurred in 1911, the magnitudes and ages (83 yr) of the paleofloods were incorporated into the systematic data for the Log-Pearson Type III analysis. Finally, several additional magnitude-frequency relations were computed for the systematic record and for paleofloods of increasing age in order to evaluate the effect of uncertain paleoflood magnitude and age estimates. The resulting magnitude-frequency relations are summarized in Figures 6 and 7 and Table 2.

For the Animas River site, inclusion of the paleoflood data and uncertainties in the paleoflood age have very little effect on the 100-yr flood discharge, which varies by less than ±10%. By contrast, the paleoflood data change the 100-yr flood discharge for the Junction Creek site by up to 70%, depending on which paleoflood age is chosen. The greater effect of the Junction Creek paleoflood estimates results from the greater discrepancy between the paleoflood and the systematic maximum discharges, and the short systematic record at Junction Creek.

ANALYSIS OF REGIONAL PEAK FLOW DATA

The streamflow gauging station data and indirect discharge data for counties within and adjacent to the study area (San Juan, La Plata, Hinsdale, Mineral, and Archuleta counties) were combined with the paleoflood discharges estimated for this study. For each peak discharge, the unit discharge (discharge divided by drainage area) was computed and plotted against gauge or site elevation (Fig. 8) to determine whether a flash-flood elevation limit is present in the San Juan Mountains. The combined (gauged and indirect) unit discharges reach a maximum at 2400 m. The maximum paleoflood unit discharge is at 2200 m, although we do not have sites below 2200 m elevation because of the difficulty in finding undisturbed channel reaches on which to conduct paleoflood studies. All of these data points come from the south- or southwest-facing (windward) portion of the San Juan Mountains, and there is unlikely to be anything about the spatial location of stations that might obscure elevation trends. The envelope of the three combined datasets shows that unit discharge decreases at elevations below about 2100 m as percent contributing area for extreme rainstorms decreases, and factors such as pervious alluvial soils and lower gradient basin slopes promote infiltration. At higher elevations, most of the gauged

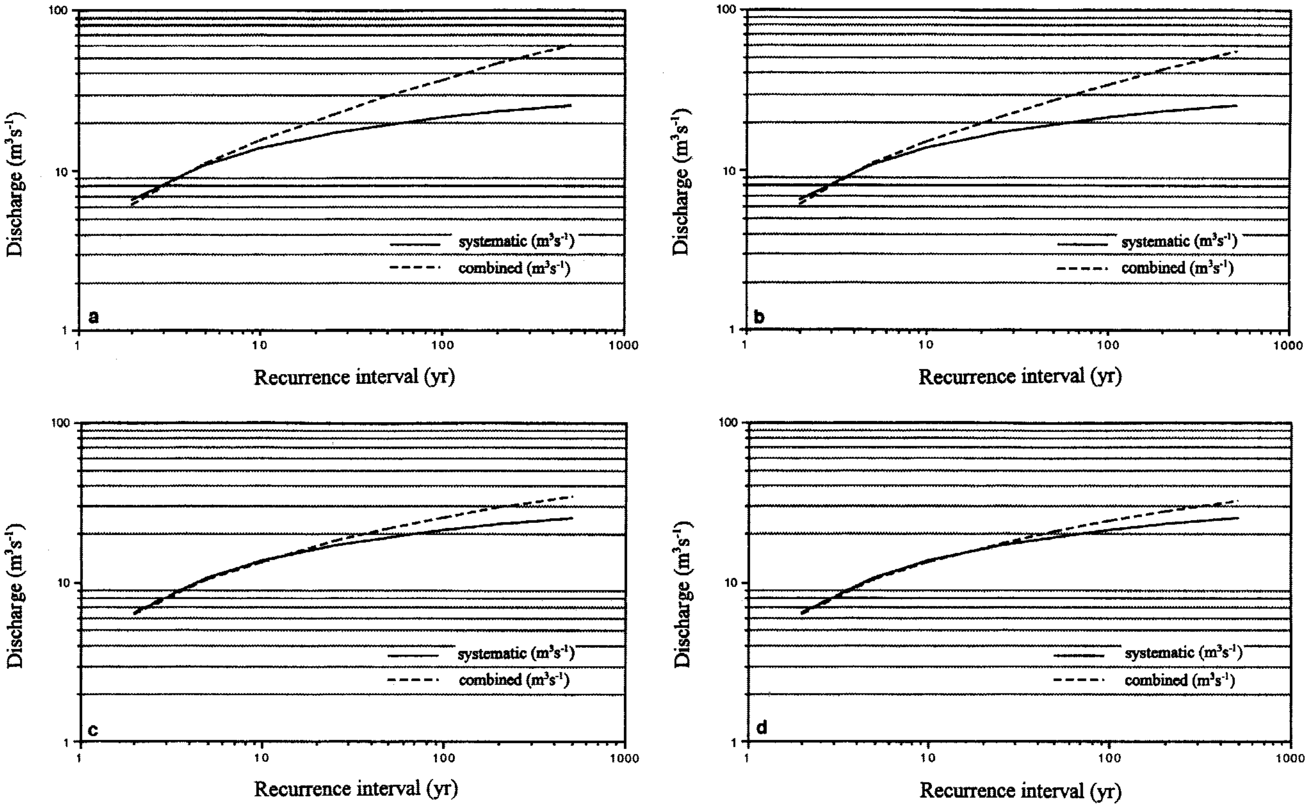

FIGURE 7. Magnitude-frequency relations for the Junction Creek site near Durango, using systematic records and with the inclusion of paleoflood data. (a) Paleoflood age 83 yr; (b) paleoflood age 100 yr; (c) paleoflood age 500 yr; (d) paleoflood age 1000 yr.

stream basins are less than 130 km^2 in area. Greater proportions of these basins are contributing runoff during storms, and storage effects are reduced, so unit discharges have the potential to be much higher at elevations above 2000 m. The fact that neither paleoflood estimates nor systematic data indicate large unit discharges at these high elevations suggests that extreme flash-flood-producing rainfalls do not occur above 2200–2400 m. This combined dataset thus expands the inferences drawn from Figure 5 to include lower elevation sites.

Jarrett (1987) concluded that a transition from intense rainstorm runoff and flash floods to snowmelt runoff and lower flows occurs between approximately 1980 and 2300 m in elevation within the Colorado Rocky Mountains. The results from the Animas River basin are consistent with Jarrett's conclusion.

TABLE 2

Comparison of the 100-yr flood at the Junction Creek site near Durango and the Animas River site near Howardsville for systematic data and combined systematic and paleoflood data[a]

	Junction Creek Q (m^3 s^{-1})	Animas River Q (m^3 s^{-1})
Systematic data	21	57
Combined data		
Paleoflood age (yr)		
83	36	62
100	34	61
500	25	58
1000	24	57

[a] The discharges for the combined data are calculated by combining gauge data with estimates of the maximum paleoflood and assigning a recurrence interval of 83, 100, 500, and 1000 yr to the maximum paleoflood.

Conclusions

The objective of the research summarized here was to evaluate the magnitude of extreme floods at high elevations of the San Juan Mountains in southwestern Colorado. We first focused on the October 1911 Gladstone storm, in which 21 cm of rain reportedly fell between 6 pm on October 4 and 6 pm on October 5. If accurate, this is the greatest recorded high-elevation 24-h rainfall in the Colorado Rocky Mountains, and thus serves as

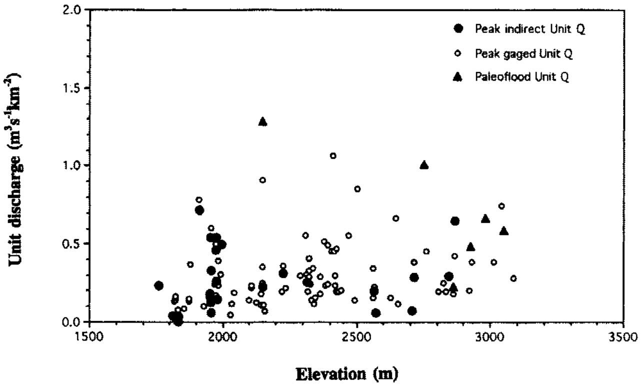

FIGURE 8. Unit discharge versus elevation for San Juan, Mineral, Archuleta, La Plata, and Hinsdale Counties, Colorado. Solid triangles represent data from this study, solid circles represent data from Jarrett (1987), and open circles represent U.S. Geological Survey gauging station data.

the basis for determining regional high-elevation PMF estimates. We could not directly evaluate the accuracy of this rainfall total. However, local newspaper accounts, contemporary photographs, and our field examinations of stream channels in the region strongly suggest that substantial out-of-bank flooding did not occur at high elevations in October 1911. We conclude that the reported rainfall is likely to be erroneously large.

We also used 15 reconnaissance field sites and 6 sites for which paleoflood discharges were determined to evaluate changes of maximum unit discharge with elevation in the upper Animas River valley. The results from the reconnaissance sites indicate an inverse relation between elevation and evidence of flooding above 2000 m. The results from the step-backwater analyses indicate that unit discharges reach a peak of approximately 1.3 $m^3 s^{-1} km^{-2}$ at about 2200 m elevation, and then decline in magnitude at higher elevations. Figure 8, combining gauged and indirect unit discharge values, also suggests a peak in unit discharge at between 2200 and 2400 m. These findings support Jarrett's (1987) general conclusions regarding unit discharges in the Colorado River basin, and help to define the elevation limit of extreme rainfall-produced flooding in the San Juan Mountains.

Our analyses of flood magnitude-frequency relations for two sites in the upper Animas River basin suggest that paleoflood records affect the Log-Pearson Type III estimate of the 100-yr flood only for basins with a short systematic record of gauged flows (here, about 20 yr), where the maximum paleoflood discharge is more likely to be substantially higher than the maximum gauged discharge.

The techniques used in this investigation should be readily applicable to other mountain regions. Where uncertainties in the estimation of PMP and PMF values may translate into substantial economic issues, the evidence of ungauged large floods recorded in botanical and geologic indicators should help to constrain estimates of extreme discharge magnitude and frequency.

Acknowledgments

We thank Joseph Capecius and Robert Snowhite for field assistance. We also thank Nolan Doesken and Loren Crow for assistance with meteorological data and interpretations; and Alan Nossaman and the staff at the Silverton Public Library for their insight into local history. Lisa Ely, Andrew Marcus, Alan Riggs, and Marsha Hilmes provided helpful reviews.

References Cited

Baker, V. R., 1973: Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington. *Geological Society of America Special Paper,* 144. 79 pp.

Barnes, H. H., Jr., 1967: Roughness characteristics of natural channels. *U.S. Geological Survey Water-Supply Paper,* 1849. 213 pp.

Bryan, B. A. and Hupp, C. R., 1984: Dendrogeomorphic evidence of channel morphology changes in an east Tennessee coal area stream. EOS, *Transactions, American Geophysical Union,* 65: 891.

Chagnon, D. and McKee, T. B., 1986: Economic impacts and analysis methods of extreme precipitation estimates for eastern Colorado. *Colorado State University Climatology Report,* 86–4. 75 pp.

Chow, V. T., 1959: *Open Channel Hydraulics.* New York: McGraw Hill. 680 pp.

Costa, J. E., 1984: Physical geomorphology of debris flows. *In* Costa, J. E. and Fleisher, P. J. (eds.), *Developments and Applications in Geomorphology.* New York: Springer-Verlag, 268–317.

Costa, J. E. and Jarrett, R. D., 1981: Debris flows in small mountain stream channels of Colorado and their hydrologic implications. *Bulletin of the Association of Engineering Geologists,* 18: 309–322.

Crow, L., 1994: Personal communication. Consulting meteorologist, 3064 South Monroe Street, Denver, Colorado 80210.

Cudworth, A. G., 1989: *Flood Hydrology Manual, A Water Resources Technical Publication.* U.S. Department of Interior, Bureau of Reclamation. 243 pp.

Davidian, J., 1984: Computation of water-surface profiles in open channels. *U.S. Geological Survey Techniques in Water Resources Investigations,* Book 3, chap. A14. 48 pp.

Feldman, A. D., 1981: HEC models for water resources system simulations: Theory and experience. *In* Chow, V. T. (ed.), *Advances in Hydrology.* New York: Academic Press, 297–423.

Follansbee, R. and Sawyer, L. R., 1948: Floods in Colorado. *U.S. Geological Survey Water-Supply Paper,* 997. 151 pp.

Gregory, K. J., 1976: Lichens and the determination of river channel capacity. *Earth Surface Processes,* 1: 273–285.

Grimm, M. M., 1993: Paleoflood history and geomorphology of Bear Creek basin, Colorado. MS thesis, Colorado State University, Fort Collins. 126 pp.

Grimm, M. M., Wohl, E. E., and Jarrett, R. D., 1995: Coarse-sediment distribution as evidence of an elevation limit for flash flooding, Bear Creek, Colorado. *Geomorphology,* 14: 199–210.

Hansen, E. M. and Schwarz, F. K., 1981: Meteorology of important rainstorms in the Colorado River and Great Basin drainages. *Hydrometeorology Report,* 50, National Oceanic and Atmospheric Administration, Washington, D.C. 167 pp.

Hansen, E. M., Schwarz, F. K., and Riedel, J. T., 1984: Probable maximum precipitation estimates, Colorado River and Great Basin drainages. *Hydrometeorology Report,* 49, National Oceanic and Atmospheric Administration, Washington, D.C. 161 pp.

House, P. K. and Pearthree, P. A., 1995: A geomorphologic and hydrologic evaluation of an extraordinary flood discharge estimate: Bronco Creek, Arizona. *Water Resources Research,* 31: 3059–3073.

Hupp, C. R., 1984: Dendrogeomorphic evidence of debris flow frequency and magnitude at Mount Shasta, California. *Environmental Geology and Water Science,* 6: 121–128.

Hupp, C. R., 1988: Plant ecological aspects of flood geomorphology and paleoflood history. *In* Baker, V. R., Kochel, R. C., and Patton, P. C. (eds.), *Flood Geomorphology.* New York: John Wiley. 335–356.

Hutchinson, N. E., 1975: WATSTORE—National water data storage and retrieval system of the U.S. Geological Survey—User's guide. *U.S. Geological Survey Open-File Report,* 75–246, 791 pp.

Hydrologic Engineering Center, 1990: *HEC2 Water Surface Profiles User's Manual.* U.S. Army Corps of Engineers, Davis, California. 47 pp.

Jarrett, R. D., 1984: Hydraulics of high-gradient streams. *Journal of Hydraulics Division, ASCE,* 110: 1519–1539.

Jarrett, R. D., 1987: Flood hydrology of foothill and mountain streams in Colorado. PhD dissertation, Colorado State University, Fort Collins. 239 pp.

Jarrett, R. D., 1990: Paleohydrologic techniques used to define the spatial occurrence of floods. *Geomorphology,* 3: 181–195.

Jarrett, R. D., 1992: Hydraulics of mountain rivers. *In* Yen, B. C. (ed.), *Channel Flow Resistance: Centennial of Manning's Formula.* Littleton, Colo.: Water Resources Publications, 287–298.

Jarrett, R. D., 1993: Flood elevation limits in the Rocky Mountains. *Proceedings, ASCE 1993 National Conference on Hydraulic Engineering and International Symposium on Engineering Hydrology.* San Francisco, 180–185.

Jarrett, R. D., 1994: Historic-flood evaluation and research needs in mountainous areas. *In* Cotroneo, G. V. and Rumer, R. R. (eds.), *1994 Hydraulic Engineering—Proceedings of the Symposium Sponsored by the American Society of Civil Engineers.* Buffalo, New York: American Society of Civil Engineers, 875–879.

Jarrett, R. D., Capesius, J. P., Jarrett, D., and England, J. F., Jr., 1996: 1995: where the past (paleoflood hydrology) meets the present, understanding maximum flooding. *Geological Society of America, Abstracts with Programs, 1996 Annual Meeting,* p. A110.

Jarrett, R. D. and Costa, J. E., 1986: Hydrology, geomorphology, and dam-break modeling of the July 15, 1982 Lawn Lake Dam and Cascade Lake Dam failures, Larimer County, Colorado. *U.S. Geological Survey Professional Paper,* 1369. 78 pp.

Jarrett, R. D. and Malde, H. E., 1987: Paleodischarge of the late Pleistocene Bonneville flood, Snake River, Idaho, computed from new evidence. *Geological Society of America Bulletin,* 99: 127–134.

Jarrett, R. D. and Waythomas, C. F., 1994: Geomorphology of Arthurs Rock Gulch, Colorado: paleoflood history. *Geomorphology,* 11: 15–40.

Kochel, R. C. and Baker, V. R., 1988: Paleoflood analysis using slackwater deposits. *In* Baker, V. R., Kochel, R. C., and Patton, P. C. (eds.), *Flood Geomorphology.* New York: Wiley. 357–376.

Larsen, E. S. and Cross, W., 1956: Geology and petrology of the San Juan Region, southwestern Colorado. *U.S. Geological Survey Professional Paper,* 258. 160 pp.

Lepkin, W. D., Delapp, M. M., Kirby, W. H., and Wilson, T. A., 1979: Instructions for peak-flow file in WATSTORE user's guide. *U.S. Geological Survey Open-File Report,* 79–1336-I, vol. 4, chap. 1. 204 pp.

Lipman, P. W., Steven, T. A., and Mehnert, H. H., 1970: Volcanic history of the San Juan Mountains, Colorado, as indicated by Potassium-Argon dating. *Geological Society of America Bulletin,* 81: 2329–2352.

McCain, J. F., Hoxit, L. R., Maddox, R. A., Chappel, C. F., Caracena, F., Shroba, R. R., Schmidt, P. W., Crosby, E. J., Hansen, W. R., and Soule, J. M., 1979: Storm and flood of July 31-August 1, 1976 in the Big Thompson River and Cache la Poudre River basins, Larimer and Weld Counties, Colorado. *U.S. Geological Survey Professional Paper,* 1115. 152 pp.

Montgomery, D. R. and Buffington, J. M., 1993: Channel classification, prediction of channel response, and assessment of channel condition. Timber, Fish, and Wildlife, Report TFW-SH10–93–002.

Motayed, A. and Dawdy, D. R., 1979: Uncertainties in step-backwater analysis. *Journal of the Hydraulics Division, ASCE,* 105: 617–622.

O'Connor, J. E., 1993: Hydrology, hydraulics and geomorphology of the Bonneville Flood. *Geological Society of America Special Paper,* 274. 83 pp.

O'Connor, J. E., Webb, R. H., and Baker, V. R., 1986: Paleohydrology of pool-and-riffle pattern development: Boulder Creek, Utah. *Geological Society of America Bulletin,* 97: 410–420.

O'Connor, J. E., Ely, L. L., Wohl, E. E., Stevens, L. E., Melis, T. S., Kale, V. S., and Baker, V. R., 1994: A 4500-year record of large floods on the Colorado River in the Grand Canyon, Arizona. *The Journal of Geology,* 102: 1–9.

Richmond, G. M., 1954: Modification of the glacial chronology of the San Juan Mountains, Colorado. *Science,* 119: 25.

Roeske, R. H., Cooley, M. E., and Aldridge, B. N., 1978: Floods of September 1970 in Arizona, Utah, Colorado, and New Mexico. *U.S. Geological Survey Water-Supply Paper,* 2052. 135 pp.

Shroba, R. R., Schmidt, P. W., Crosby, E. J., Hansen, W. R., and Soule, J. M., 1979: Storm and flood of July 31-August 1, 1976, in the Big Thompson River and Cache la Poudre River basins, Larimer and Weld Counties, Colorado. Part B. Geologic and geomorphic effects in the Big Thompson Canyon area, Larimer County. *U.S. Geological Survey Professional Paper,* 1115: 87–152.

Trieste, D. J. and Jarrett, R. D., 1987: Roughness coefficients of large floods. *In* James, L. D. and English, M. J. (eds.), *Irrigation and drainage division specialty conference, Irrigation Systems for the 21st Century,* Portland, Oregon, Proceedings. American Society of Civil Engineers, 32–40.

U.S. Bureau of Reclamation, 1988: *Downstream Hazard Classification Guidelines.* Assistant Comissioner, Engineering Research Technical Memorandum No. 11. 23 pp.

Wohl, E. E., 1992: Bedrock benches and boulder bars: Floods in the Burdekin Gorge of Australia. *Geological Society of America Bulletin,* 104: 770–778.

Wohl, E. E., 1995: Estimating flood magnitude in ungauged mountain channels, Nepal. *Mountain Research and Development,* 15: 69–76.

Wohl, E. E. and Enzel, Y., 1995: Data for paleohydrology. *In* Gregory, K. J., Starkel, L., and Baker, V. R. (eds.), *Global Continental Paleohydrology.* Chichester: John Wiley. 23–59.

Ms submitted October 1996
Revised ms submitted April 1997