Paleoflood Investigations for Cherry Creek basin, Eastern Colorado

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Abstract

In 1950 when Cherry Creek dam, which is located in Denver, Colorado, was completed, the design flood was 5,126 m^3/s. Two recent probable maximum flood (PMF) estimates for the dam range from 14,840 to 18,750 m^3/s demonstrate the uncertainty in estimating extreme flooding in eastern Colorado. PMF difference is due in part to a lack of extreme rainfall and flood data in eastern Colorado. A paleoflood study was conducted to assist dam-safety officials in assessing the risk of large floods in Cherry Creek basin. An envelope curve encompassing maximum contemporary floods (19 sites) and paleofloods (99 sites) was developed for Cherry Creek basin streams; paleoflood data reflect maximum flooding during the last few hundred to many thousands of years. Maximum paleofloods in Cherry Creek range from about 1,050 m^3/s near Franktown (in about 5,000 to at least 10,000 years), about 2,100 m^3/s near Melvin (in about 1,500 to 5,000 years), and about 2,270 m^3/s at Cherry Creek Reservoir (also in about 1,500 to 5,000 years). Flood-frequency relations for Cherry Creek, which incorporate paleoflood data, indicate the 10,000-year flood (10^{-4} annual exceedence probability) ranges from about 1,200 m^3/s (near Franktown) to about 2,200 m^3/s (near Melvin). PMF estimates are about six to eight times larger than paleofloods in Cherry Creek basin. Additional research in flood hydrometeorology is needed to help dam safety officials evaluate potential safety problems related to large floods in Cherry Creek basin.

Introduction

Extreme or rare floods, with annual exceedence probabilities of about 10^{-3} to 10^{-7}, are of continuing interest to the hydrologic and engineering communities for purposes of planning and design of structures such as dams (National Research Council, 1988). The Bureau of Reclamation began conducting risk assessment studies using paleoflood hydrology for many of its dams in the mid-1990s (Ostenaa and Levish, 1995). The U.S. Army Corps of Engineers is implementing a risk assessment method to evaluate potential safety problems for its more than 550 dams to aid decision-makers in prioritizing investment decisions (Foster, 1999). Substantial uncertainty is associated with estimating flood magnitude and frequency, particularly those of extreme floods, in the Rocky Mountain region, which is due in large part to a lack of extreme flood data (Hansen et al., 1988; Jarrett and Costa, 1988; Jarrett and Tomlinson, in press).

In 1950, Cherry Creek Reservoir (fig. 1) was designed for a flood of 5,126 m^3/s with a flood-storage capacity of 2.06 x 10^8 m^3 (U.S. Army Corps of Engineers, written commun., 1997). Recently, methods used to estimate the probable maximum precipitation (PMP) values were developed for the Rocky Mountain region including most of eastern Colorado (Hansen et al., 1988). From these PMP values, the probable maximum flood (PMF) for Cherry Creek Reservoir was estimated in 1993 by the U.S. Army Corps of Engineers to be 18,750 m^3/s, thus, raising questions about the safety of Cherry Creek Dam. Using older PMP methods developed for areas east of the 105th meridian (Schreiner and Riedel, 1978), which is about the longitude of Denver, another PMF of 14,840 m^3/s was estimated (U.S. Army Corps of Engineers, written commun., 1997). The estimated cost for proposed modifications of the Cherry Creek dam is as high as $250 million (U.S. Army Corps of Engineers, written commun., 1997). Differences in flood estimates such as for Cherry Creek demonstrate the importance of reducing the uncertainty in estimating the magnitude and frequency of flooding in eastern Colorado.

The objective of the study was to estimate prior maximum flooding from evidence preserved in Cherry Creek and its tributaries and to incorporate paleoflood data in flood-frequency analysis.

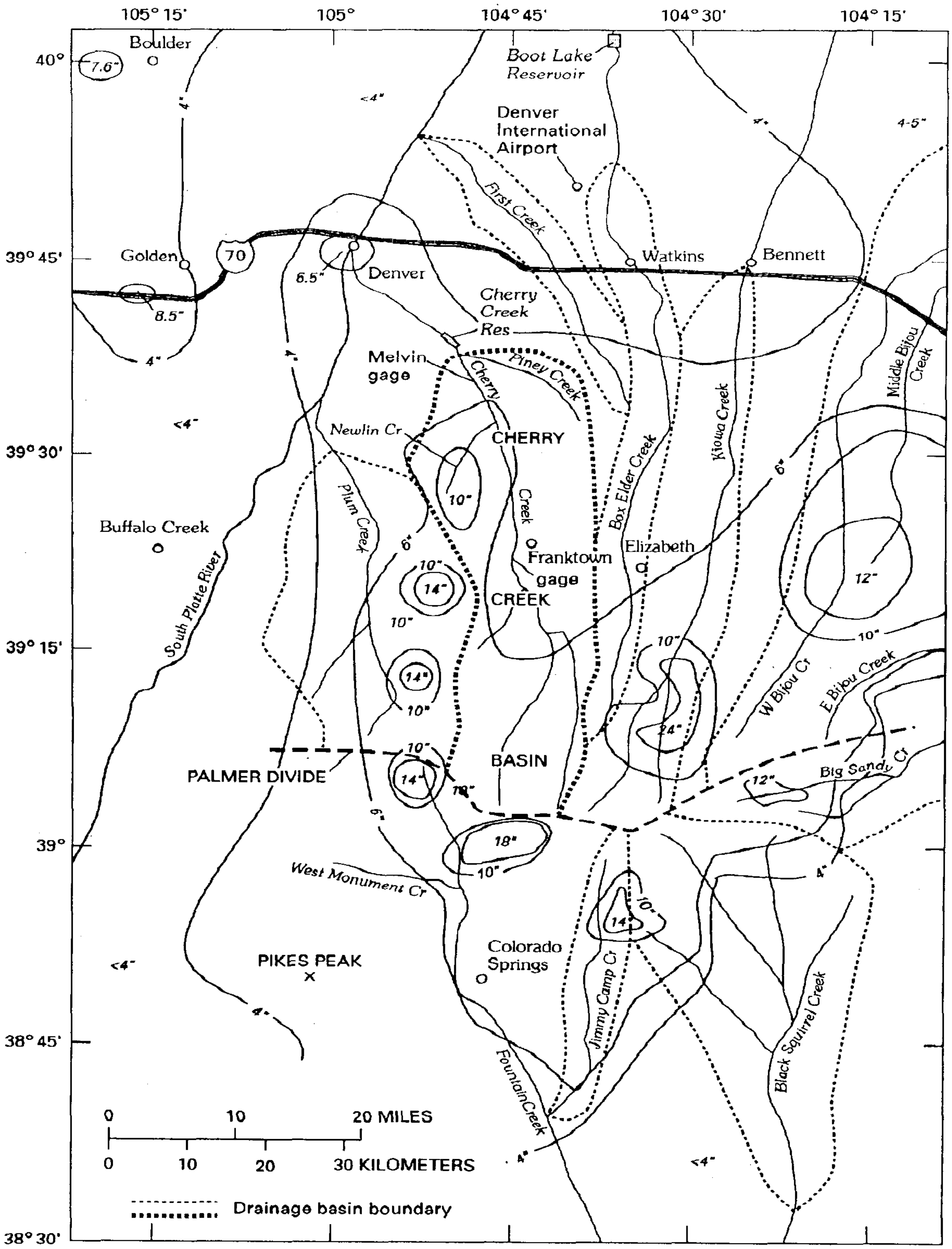

Figure 1. Location of paleoflood study for Cherry Creek basin. Basin boundaries are shown for the larger basins draining from the Palmer Divide. Maximum 24-hour rainfall isohyetals for large rainstorms in the study area also are shown.

Study Area

Cherry Creek has its headwaters on the Palmer Divide at an elevation of about 2,350 m and flows northerly to its confluence with the South Platte River (1,576 m) in Denver (fig. 1). In part due to lack of rainfall and flood data, it has commonly been assumed that the Palmer Divide has little orographic effect on extreme rainfall amounts and flooding (McCain and Jarrett, 1976; Livingston and Minges, 1987; Hansen et al., 1988). A long-standing issue is whether the Palmer Divide, the ridge that separates the South Platte and Arkansas River basins (fig. 1), has an orographic effect on rainfall and flooding in eastern Colorado. Major floods in eastern Colorado result from a southerly flow of low-level moist air from the Gulf of Mexico, which often crosses over the Palmer Divide (Collins et al., 1991). The Palmer Divide has a southern topographic relief as much as 1,035 m, thus, may be in the rain shadow of the Divide (fig. 1).

Cherry Creek basin primarily is underlain by Tertiary sedimentary rocks; sandstone, conglomerate, siltstone, claystone, and shale (Tweto, 1979). Unconsolidated surficial deposits (Pleistocene and Holocene) derived from eolian, colluvial, and fluvial processes cover much of the basin. Topography in the basin is moderately rolling except steep hills and ridges in the upper basin (U.S. Army Corps of Engineers, 1976). Soils primarily consist of well-drained, sandy loam, and some parts of the basin have exposed bedrock or shallow soils. Much of the basin has pasture and prairie grasses, agricultural crops, scrub oak, and ponderosa pine. Lower Cherry Creek basin has extensive residential, business, and industrial development.

Methodology

Paleoflood Investigations

Paleoflood hydrology is the study of past or ancient floods (Baker, 1987). Floods leave distinctive deposits and landforms in and along stream channels, as well as botanic evidence (Baker, 1987; Jarrett, 1990, 1991). Slack-water deposits of sand-sized particles, flood scars on trees, accumulation of woody-flood debris, erosion scars, and bouldery flood-bar deposits commonly used as indicators of past flood levels are called paleostage indicators (PSIs). When flows are large enough, streambed and bank materials are mobilized, transported, and deposited as new PSIs. In addition, non-inundation (NI) surfaces are geomorphic surfaces that have not been exceeded by floods, which would leave definitive erosional evidence, in a datable time span (Jarrett and Costa, 1988; Ostenaa and Levish, 1995). The strategy of a paleoflood investigation is to visit the most likely places where evidence of out-of-bank flooding, if any, might be preserved, and to identify non-inundation (NI) surfaces. Ideally, the highest PSIs would correspond with the lowest NI-surfaces, thus, providing similar estimates of paleoflood discharge.

Paleoflood discharge was determined from estimates of flood width and depth corresponding to the top of the PSIs (or lowest NI-surfaces) and channel slope for each cross section obtained during onsite visits to streams. The slope-conveyance and critical-depth methods (Barnes and Davidian, 1978) were used to estimate paleoflood discharge. Flow-resistance coefficients were estimated from methods derived from analyses of hydraulic data for Colorado rivers (Jarrett, 1985).

Age estimates for paleoflood deposits in this study were determined using relative-dating (RD) methods (Jarrett and Tomlinson, in press). RD methods used for this study primarily were degree of soil development, surface-rock weathering, surface morphology, and boulder burial. Surficial deposit age is based on post-depositional modifications that vary with age; immediately after deposition, the age is zero years. A composite relative age using several RD methods usually enables one to distinguish deposits of various ages. Although there are uncertainties with an individual RD ages, a composite age is more accurate. For the use here in attempting to identify the paleoflood record length for the largest flood during the Holocene, such uncertainties can be addressed in the flood-frequency analyses.

Regional Analyses of Flood Data

Predicting the upper limits of the magnitude of floods for has been a long standing challenge in flood hydrology. Envelope curves encompassing maximum floods in a relatively homogeneous hydrometeorologic region have long been used in flood hydrology. Regional analysis provides improved estimates of streamflow characteristics by decreasing time-sampling errors of short gagerecords by substituting space (many flood estimates in a region) for time (short gage record). Flood data for Cherry Creek basin streams (McKee and Doesken,1997) were compiled to develop envelope curves of peak discharge versus drainage area. Incorporating paleoflood data provides an opportunity to add a new level of confidence to envelope curves (Jarrett and Tomlinson, in press).

Flood-Frequency Relations

Flood-frequency relations were developed from an analysis of annual peak flows through 1997 for Cherry Creek near Franktown (06712000) and near Melvin (06712500), which is located about 3 km upstream from Cherry Creek Reservoir (fig. 1). Flood-frequency relations were developed using a Log-Pearson Type III frequency distribution (IACWD, 1981). IACWD guidelines were established to provide consistency in federal flood-risk management such as for handling low- and high- outliers, need for regionalized skew, and zero-flow adjustment. This analysis was done for various combinations of gage and paleoflood data available at each site. To help facilitate risk assessments of rare floods (e.g., defining the upper end of frequency curves), paleoflood data (magnitude and ages) were incorporated into the flood-frequency analysis to extend the gaged record.

Results

Paleoflood Investigations

Paleoflood data were obtained at 99 sites on streams in Cherry Creek basin. PSI data are readily identifiable onsite by coarse-grained flood deposits (figs. 2 and 3). Recent flood deposits in Cherry Creek basin typically are coarse, sandy gravel (often with cobble and boulder-sized clasts) and have little or no soil-profile development. Deposits with increasing age have soil-profile development, increased surface-rock weathering, muted surface morphology, and increased surficial flood deposit burial. Thick, clay-rich, fine-grained, well-developed soils (labelled colluvium on figs. 2 and 3) generally occur in non-flooded areas in the valley. Because these colluvial soils have few particle sizes larger than sand, they were not deposited by main stream flooding; rather, the sediments primarily originated from hillslope (sheetflow) runoff and eolian (wind-blown) sediments (R. Madole, USGS, pers. commun., 1997). These colluvial organic-rich soils, termed Piney Creek alluvium, were dated from a minimum of about 1,000 years to greater than 5,000 years (Hunt, 1954) and were the primary NI-surface used. Thus, a lack of erosional and depositional features provided a minimum age since floods have inundated these surfaces. These colluvial soils are easily eroded by flood waters (Matthai, 1969), thus, they also provide physical constraints on the present channel geometry since originally deposited (figs. 2 and 3). The other RD methods provided additional supporting relative age constraints.

In reaches where flood sediments were deposited as flood bars (PSIs) or use of NI-surfaces, peak discharges were computed with surveyed channel geometry and by subtracting the area of the estimated flood deposit (figs. 2 and 3; area below the surveyed channel geometry and dashed line). Paleoflood discharge (corresponding to the range of the PSIs or NI-surfaces such as shown in figs. 2 and 3) reflects the larger (conservative) estimate in the sensitivity analysis of factors affecting discharge reconstruction (e.g., changes in channel geometry, water slope, uncertainty in n values, reliability of PSI and NI-surface heights).

The largest paleoflood for Cherry Creek near Franktown (06712500) is about 1,050 m^3/s, which resulted from the failure of Castlewood Canyon Dam during a rainstorm (75 to 230 mm in about 9 hours) on August 3, 1933 (Matthai, 1969). Excellent paleoflood evidence (top of coarse bouldery flood-deposited sediments) for the 1933 flood is preserved at sites downstream from Castlewood Dam (fig. 2). The maximum paleoflood upstream from Castlewood Dam is about 850 m^3/s. The maximum paleoflood downstream from Castlewood Dam at the gage (06712000) near Franktown.

For comparison, data for floods in other streams in eastern Colorado (Jarrett, 1990; McKee and Doesken, 1997) were used to develop an envelope curve (fig. 4; data not shown). Maximum contemporary flooding in eastern Colorado is about 2.3 times greater than maximum paleofloods in Cherry Creek basin.

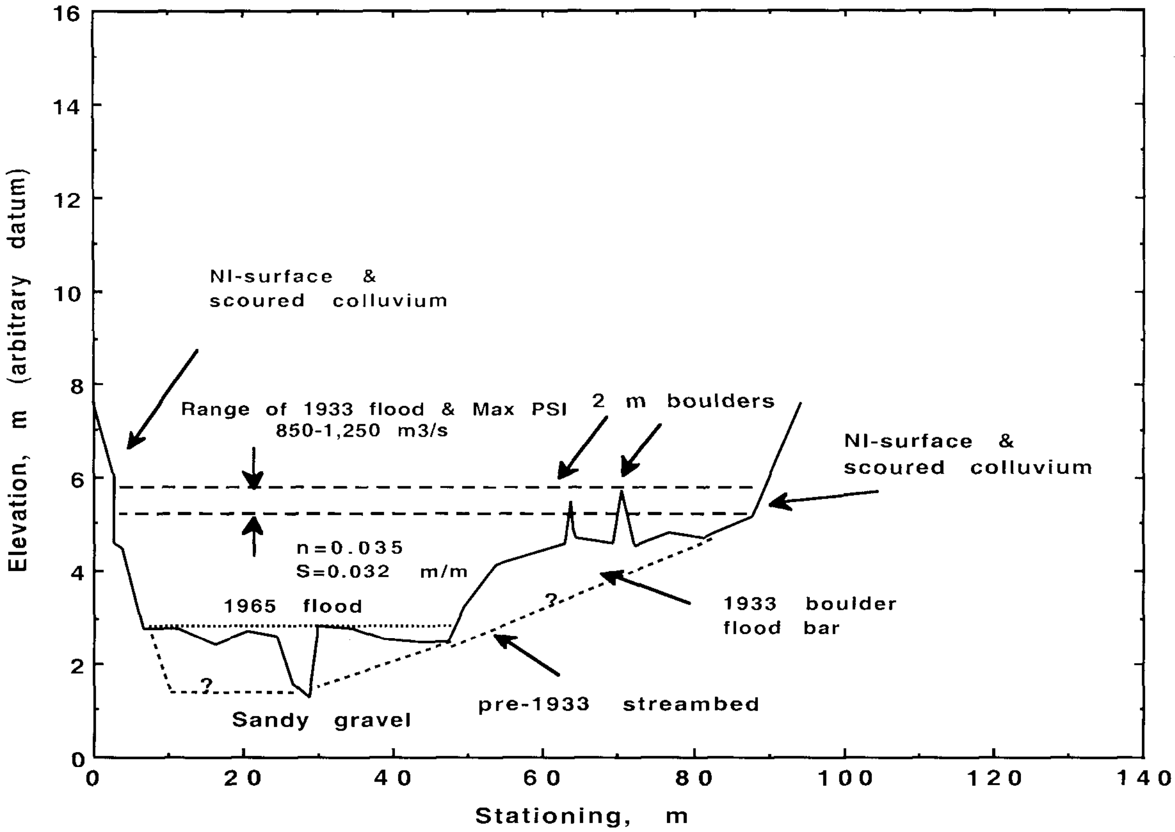

Figure 2. Channel cross section for Cherry Creek near Franktown streamflow-gaging station (0671200), which is located about 4 km south of Franktown. The highest paleostage indicator is constrained by uneroded, old colluvium (non-inundation, NI, surface) and a flood-deposited boulder bar (~215 x 100 x >3 m) deposited by the 1933 dam-failure flood.

This factor likely would be larger if paleoflood data were available for other eastern Colorado streams. For example, Jarrett and Tomlinson (in press) noted the addition of paleoflood data increased the contemporary envelope curve of flooding by about 20 to 25 percent for northwestern Colorado streams.

Local extreme rainfall (fig. 1) and flood data defining this eastern Colorado envelope curve appear to be associated with areas of high topographic relief (Jarrett, 1990). PMF values for selected streams in eastern Colorado, including Cherry Creek basin (Bullard, 1986; U.S. Army Corps of Engineers, written commun., 1997) with an enveloping curve are shown on figure 4. Generally, PMF values exceed the envelope curve of maximum contemporary floods in eastern Colorado by a factor of about 2.6. PMF values exceed the envelope curve for Cherry Creek by a factor of about six to eight for Cherry Creek basin, which suggests different flood-producing mechanisms.

Flood-Frequency Analysis

Flood-frequency relations for Cherry Creek developed using the recorded annual peak-flow data near Franktown (06712000) and near Melvin (06712500) are shown in figures 5 and 6. A second run incorporated paleoflood data in the frequency analyses; rectangles (figs. 5 and 6) bracket the estimated ranges of uncertainty of discharge and relative age (P) of a paleoflood. Although extrapolations of flood-frequency relations have uncertainties, they can be used to estimate the probability of extremely large floods when paleoflood data are available (Baker, 1987; Jarrett and Costa, 1988; Ostenaa and Levish, 1995).

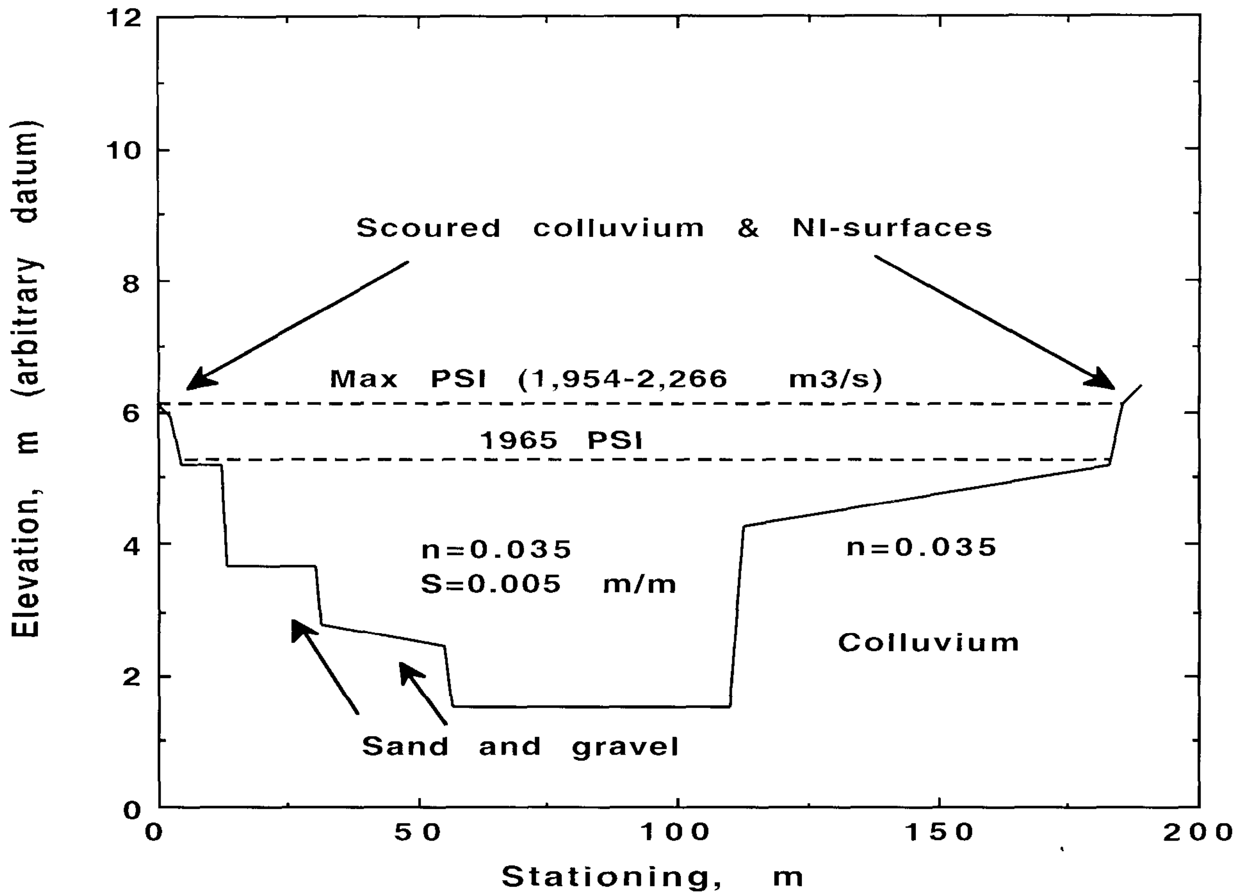

Figure 3. Channel cross section for Cherry Creek near Melvin streamflow-gaging station (06712500), which is located about 3 km upstream from Cherry Creek Reservoir. The highest paleostage indicator is constrained by uneroded, old colluvium (non-inundation, NI, surfaces).

PMF estimates for Cherry Creek also are shown on figures 5 and 6. Floods the magnitude of the design flood and PMF values for Cherry Creek have recurrence intervals far in excess of a 10,000 years (10^{-4} annual exceedence probability) based on the flood-frequency analyses incorporating the paleoflood data (figs. 5 and 6).

Discussion and Summary

Although paleoflood estimates involve uncertainties, they are based on interpretations of physical data preserved in channels and on floodplains for at least several thousand years. A sensitivity analysis of factors affecting paleoflood estimates was made. Where possible, paleoflood sites in this study were located in bedrock channels that minimize potential changes in channel geometry. For example, numerous headwater stream sites in Cherry Creek basin and near Castlewood Canyon have a bedrock streambed and undisturbed coluvial streambank material, that provide a stable-channel geometry for flood estimation. For completely alluvial sites, maximum-channel width is constrained by undisturbed colluvial soils along the main channel (fig. 3) that are at least 1,000 to 5,000 years old (Hunt, 1954). Because Cherry Creek is constrained by bedrock on the bed and walls, the 1933 paleoflood deposits probably represent the largest flood in at least 10,000 years. It was assumed that for the sites in relatively straight, uniform alluvial reaches, sediments were transport like on a giant conveyor belt. Thus, although some streambed erosion occurs during a flood, there probably is little net change in bed elevation; there is little evidence to suggest major changes in channel geometry for the paleoflood record length.

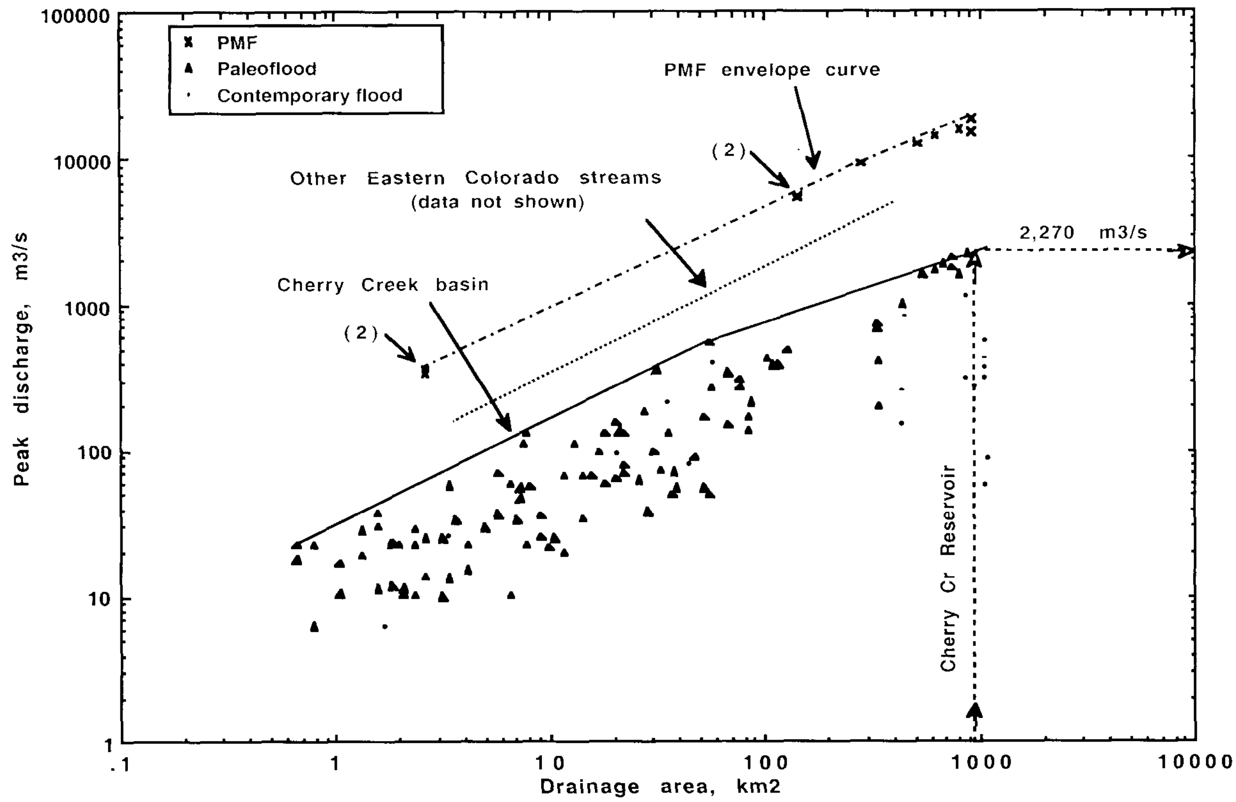

Figure 4. Relation of peak discharge for contemporary floods and paleofloods with drainage area for streams in Cherry Creek basin. Envelope curves for Cherry Creek basin floods, other eastern Colorado streams (data not plotted), and PMF values for eastern Colorado also are shown.

Analysis of the differences in flood-deposited sediments (new PSIs) and highwater marks (HWMs) of recent extreme floods for 122 sites in 90 streams of the western United States indicated that the elevation of the top of flood-deposited sediments (PSIs) generally are within ±0.2 of flood HWM elevations (Jarrett et al., 1996). Therefore, use of the top of flood-deposited sediments as PSIs provides a reliable estimate of the maximum paleoflood depth. This then helps reduce the uncertainty of paleodischarge estimates for streams in this study. Manning's n values were varied by ±25 percent, which is considered a reasonable range of uncertainty in flow-resistance coefficients. Alluvial-channel geometry can change with time, thus, estimating paleoflood discharge can be affected by channel change.

A large source of uncertainty of flood variability is effects from natural or anthropogenic climate change. Paleoflood estimates incorporate the effects of climatic changes on hydrology during the period of the paleoflood record (Jarrett, 1991). Certainly, moderate climate changes (or other changes such as wildfire effects on flooding or vegetation changes or agricultural land-use changes) have occurred during the Holocene, however, these effects are reflected in the maximum flood preserved at a site.

Paleoflood reconstructions for 99 sites in Cherry Creek basin provide data for large floods not available by other sources, provide a higher level of confidence in envelope curves of maximum flooding, and suggest that Cherry Creek basin flooding differs from other basins in eastern Colorado. Although the study area is relatively small, extreme rainstorms appear to be very localized (fig. 1; note, rain cells primarily resulted from different storms, Hansen et al., 1988), which help reduce interstation correlation in the regional analysis.

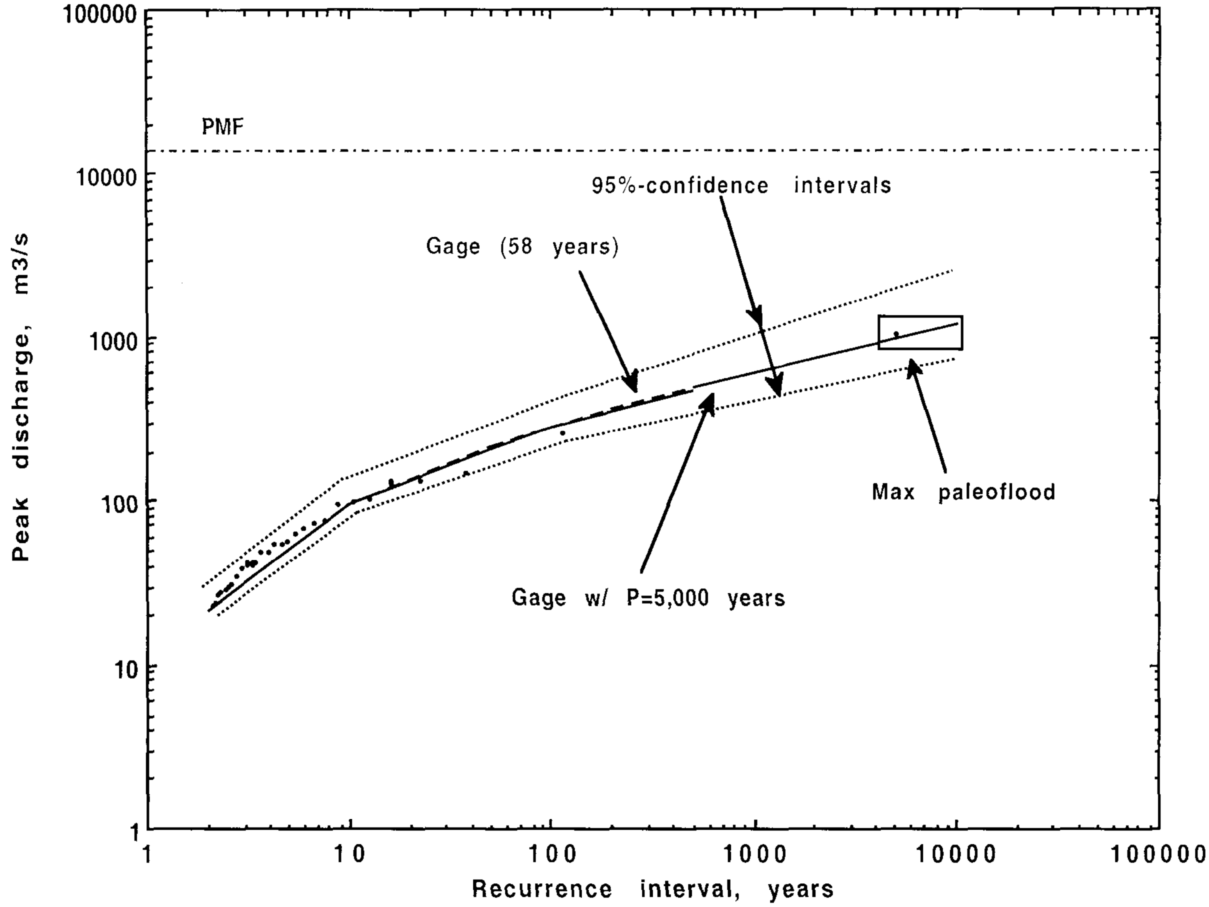

Figure 5. Flood-frequency relations for Cherry Creek near Franktown (06712000) with paleoflood data (shown as a rectangle, which reflects ranges for the magnitude and age of the paleoflood) with 95-percent confidence limits. The PMF estimate for this site (from fig. 4) is shown for comparison.

The causes for the smaller floods in Cherry Creek basin, while not well understood, probably is explained by several factors. First, the highest elevation of the Palmer Divide (~2,350 m; relief of about 1,035 m on the south side of the Divide) is located at the headwaters of Cherry Creek (north-draining basin) and may substantially deplete the available moisture for producing extremely large rainfall amounts (or rain-shadow effect). Second, localized relief (buttes and ridges with about 75 to 100 m of relief) also appears to affect location of maximum rainfall amounts, which historical dramatically decrease within a distance of about 3 to 6 km (fig. 1), and supports paleoflood study results. In addition, high infiltration rates for soils in much of Cherry Creek basin and over thirty flood retarding structures built by the U.S. Soil Conservation Service contribute to reduced flood runoff. Spatial variability of extreme rainfall affects not only peak discharge but also the volume of flood runoff, which in turn affects flood-control storage requirements.

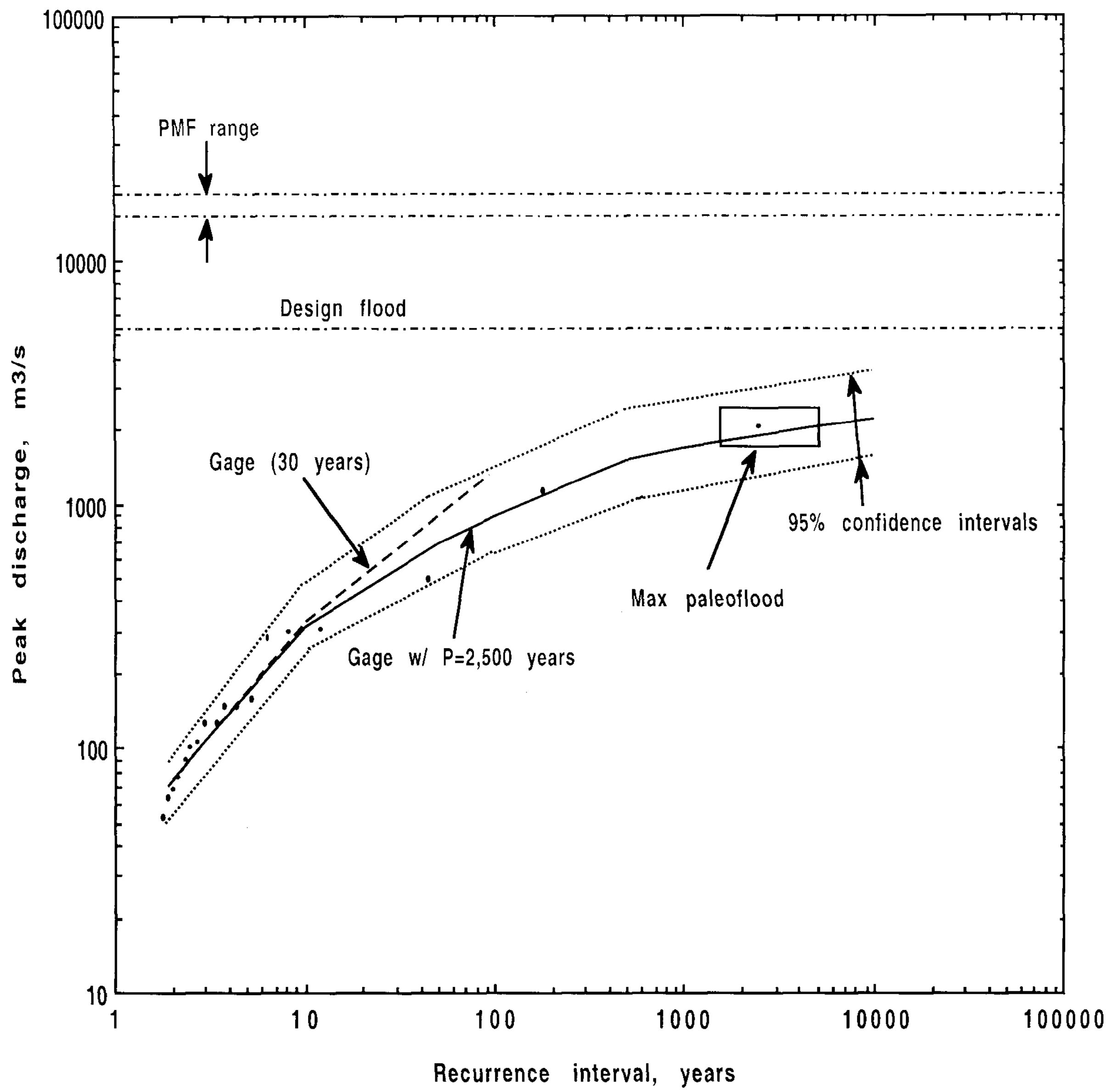

Figure 6. Flood-frequency relations for Cherry Creek near Melvin (06712500) with paleoflood data (shown as a rectangle, which reflect ranges of the magnitude and age for each paleoflood) with 95-percent confidence limits. The original design flood and probable maximum flood estimates for Cherry Creek Reservoir are shown for comparison.

There are over 10,000 dams in the Rocky Mountain region that may need to be modified for current PMP criteria during dam safety recertification. Large differences in maximum paleoflood and PMF values in eastern Colorado, elsewhere in the Rocky Mountains (Jarrett and Costa, 1988; Ostenaa and Levish, 1995; Jarrett and Tomlinson, in press), and the trend to use risk assessment studies for dam safety suggest additional hydrometeorologic research is needed to reduce uncertainties. Thus, it is important to develop methodologies that can be used by dam-safety officials.

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