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Regional interdisciplinary paleoflood approach to assess extreme flood potential

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Abstract. In the past decade, there has been a growing interest of dam safety officials to incorporate a risk-based analysis for design-flood hydrology. Extreme or rare floods, with probabilities in the range of about 10^{-3} to 10^{-7} chance of occurrence per year, 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 National Research Council stresses that as much information as possible about floods needs to be used for evaluation of the risk and consequences of any decision. A regional interdisciplinary paleoflood approach was developed to assist dam safety officials and floodplain managers in their assessments of the risk of large floods. The interdisciplinary components included documenting maximum paleofloods and a regional analyses of contemporary extreme rainfall and flood data to complement a site-specific probable maximum precipitation study [*Tomlinson and Solak*, 1997]. The cost-effective approach, which can be used in many other hydrometeorologic settings, was applied to Elkhead Reservoir in Elkhead Creek (531 km^2) in northwestern Colorado; the regional study area was 10,900 km^2. Paleoflood data using bouldery flood deposits and noninundation surfaces for 88 streams were used to document maximum flood discharges that have occurred during the Holocene. Several relative dating methods were used to determine the age of paleoflood deposits and noninundation surfaces. No evidence of substantial flooding was found in the study area. The maximum paleoflood of 135 $m^3 s^{-1}$ for Elkhead Creek is about 13% of the site-specific probable maximum flood of 1020 $m^3 s^{-1}$. Flood-frequency relations using the expected moments algorithm, which better incorporates paleoflood data, were developed to assess the risk of extreme floods. Envelope curves encompassing maximum rainfall (181 sites) and floods (218 sites) were developed for northwestern Colorado to help define maximum contemporary and Holocene flooding in Elkhead Creek and in a regional frequency context. Study results for Elkhead Reservoir were accepted by the Colorado State Engineer for dam safety certification.

1. Introduction

Worldwide, floods are among the most destructive events related to meteorological processes. In the United States the average annual death toll of 125 is accompanied by about $2.4 billion in damages from floods [*Federal Emergency Management Agency* (*FEMA*), 1997]. Poor understanding of floods contributes to unnecessary loss of life and increased flood damage in some cases and, conversely, leads to costly overdesign of hydraulic structures located in floodplains for other situations [*Jarrett*, 1991, 1993; *Baker*, 1994]. Extreme or rare floods, with probabilities in the range of about 10^{-3} to 10^{-7} chance of occurrence per year, are of continuing interest to the hydrologic and engineering communities for purposes of planning and design of structures such as dams [*National Research Council* (*NRC*), 1988]. However, estimating the magnitude and frequency of extreme floods is difficult because of relatively short streamflow-gaging station record lengths.

For about the past 50 years the design criteria for construction of structures such as dams has included an estimate of the probable maximum flood (PMF) [*Cudworth*, 1989]. The PMF is an estimate of the maximum flood potential for a given drainage basin and is derived from an analysis of the probable maximum precipitation (PMP) [*Cudworth*, 1989]. Prior to about 1950, a variety of methods were used to obtain the magnitude of the design flood. The *NRC* [1988, 1994] recognized (1) the limited hydroclimatic data available to estimate PMP/PMF values for mountain basins less than about 1050 km^2, (2) the subjectivity and variation of PMP estimates among experienced meteorologists, (3) the critical need for regional analyses of extreme precipitation and flooding, (4) the need to use historic and paleoflood data, and (5) the potential use of probability-based methods for providing an alternative to the PMP/PMF approach. In an evaluation of extreme floods and the use of the PMF methodology to estimate design floods, the *Interagency Advisory Committee on Water Data* [1986] raised a major concern about PMFs being either dangerously small or wastefully large, and they emphasized the importance of accurately estimating the risk of extreme flooding. Thus the objective of a flood study should be to generate as much information as practicable about the flood potential at a site [*NRC*, 1988].

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The NRC stresses that this should be the basis for evaluation of the risk and consequences of any decision.

Efforts have been made to assign a frequency to the PMF, but they are subjective [*Interagency Committee on Water Data*, 1986; *NRC*, 1988]. There is disagreement about the range of frequency for the PMF and whether any frequency should be assigned to a deterministic PMF estimate. Extensions of flood-frequency relations to rare floods (e.g., 10,000-year recurrence interval) are tenuous for short streamflow records but are enhanced when paleoflood data are included in flood-frequency analysis [*Kochel and Baker*, 1982; *NRC*, 1988; *Jarrett*, 1987; *Jarrett and Costa*, 1988; *Levish et al.*, 1994; *Ostenaa and Levish*, 1995]. *Jarrett and Costa* [1988] proposed using regional flood-frequency estimates, which incorporated paleoflood information, to estimate recurrence intervals for rare floods including PMF values. These extensions provide an approach to place PMF estimates in perspective with regional gaged and paleoflood estimates of flood potential [*Jarrett and Costa*, 1988].

Paleoflood hydrology is the study of past or ancient floods [*Baker*, 1987]. *Kochel and Baker* [1982], *Gregory* [1983], *Baker et al.* [1988], *Costa* [1987c], *Stedinger and Baker* [1987], *Stedinger and Cohn* [1986], *Hupp* [1988], and *Jarrett* [1987, 1990b, 1991] provide summaries of paleoflood hydrology. Although most studies involve prehistoric floods, the methodology is applicable to historic or modern floods [*Baker et al.*, 1988; *Jarrett*, 1990b]. Paleoflood studies provide important information that can be used in risk assessments and in the assessment of climatic change on flooding and droughts [*Jarrett*, 1991]. Paleoflood data are particularly useful in providing upper limits of the largest floods that have occurred in a river basin in long time spans [*Jarrett*, 1990b; *Enzel et al.*, 1993].

A regional interdisciplinary paleoflood study was conducted in northwestern Colorado (Figure 1) to help assess the flood hydrology for Elkhead Reservoir in Elkhead Creek basin near Craig. The objective of the paleoflood study was to estimate prior maximum flooding during the Holocene from evidence preserved in the floodplain. The interdisciplinary components included documenting maximum paleofloods and regional analyses of contemporary (~155 years in Colorado) extreme rainfall and flood data in and near Elkhead basin. The major drainages within the regional study area are the Yampa River and White River basins. Hydroclimatic conditions are relatively homogeneous in northwestern Colorado [*Miller et al.*, 1973; *Kircher et al.*, 1985]. A primary focus of U.S. Geological Survey (USGS) interdisciplinary research is to develop cost-effective paleoflood techniques that can be used to complement meteorologic, hydrologic, and engineering methods to improve estimation of the magnitude, frequency, and risk of floods.

The paleoflood study was conducted for the Colorado River Water Conservation District to complement a site-specific PMP by *Tomlinson and Solak* [1997] and a PMF study by Ayres Associates, Inc. in Fort Collins, Colorado, for Elkhead Reservoir. Elkhead Reservoir was being recertified for hydrologic safety by the Colorado State Engineer. PMP estimates are considered of lesser reliability along the Continental Divide, which includes the upper Yampa River basin [*Hansen et al.*, 1977]. Therefore a site-specific PMP study was conducted to address issues raised by the *NRC* [1988, 1994] pertaining to the hydrometeorology for the basin and the surrounding geographically and climatologically similar region. Inherent in a site-specific PMP study are analyses of extreme storms that have occurred in the region since the generalized hydrometeorology report was published. Site-specific hydrometeorologic studies are being conducted because dam safety officials recognize the difficult problems inherent in PMP estimates in the Rocky Mountains. Utilization of an interdisciplinary regional paleoflood study provides additional supporting information for understanding the magnitude of the largest contemporary floods and paleofloods with estimates of the PMF potential for a particular basin.

2. Background

Substantial uncertainty and controversy exists in estimating flood magnitudes and frequencies, particularly those of extreme floods in the Rocky Mountains. This results from a misunderstanding of the complex hydrometeorological processes involved and a lack of data on extreme rainstorms and flooding. *Jarrett* [1993] made a systematic evaluation of flood-frequency estimates for 25 long-term streamflow-gaging stations throughout Colorado where published Federal Emergency Management Agency (FEMA) floodplain reports, which were derived by various methods, also were available. On average, the published FEMA 100-year flood is 35% greater than the gaged 100-year flood obtained by fitting a log-Pearson type III distribution to streamflow data for the 25 stations. Similar differences were identified for the 10-, 50-, and 500-year floods and demonstrate the need to improve flood-frequency estimates used for floodplain management and other uses in Colorado.

Interdisciplinary flood research in Colorado [*Jarrett and Costa*, 1983, 1988; *Jarrett*, 1987, 1990a, b; *Grimm*, 1993; *Pitlick*, 1994; *Waythomas and Jarrett*, 1994; *Pruess*, 1996; *Capesius*, 1996; *Pruess et al.*, 1998; *McKee and Doesken*, 1997] and in the Rocky Mountains [*Henz*, 1991; *Jarrett*, 1993; *Jensen*, 1995; *Buckley*, 1995; *Eastwood*, 1995; *Brien*, 1996; *Parrett*, 1997, 1998] provides new insight into the hydrometeorology of extreme flooding in the Rocky Mountains. In an analysis of USGS streamflow-gaging station and paleoflood data in the Rocky Mountain region, which included stations in New Mexico, Colorado, Wyoming, Idaho, and Montana, envelope curves of maximum unit discharges (maximum peak flow divided by drainage area) and gage elevation identified elevation limits for large unit discharges [*Jarrett*, 1993]. In Colorado the elevation limit is about 2300 m for an envelope curve value of 1 m^3 s^{-1} km^{-2} for basins less than about 10 km^2; as basin size increases, unit discharge decreases. Such low-magnitude unit discharges result in only minor flooding in Colorado; flows seldom exceed the top of the main-channel banks, and when they do, flow depths usually are insufficient to modify the floodplain. These peak discharges are caused primarily by snowmelt runoff, relatively small amounts of rainfall (as compared to lower-elevation rainfall amounts), or a combination of rainfall on snowmelt. Below about 2300 m in eastern Colorado, unit discharges as large as 38 m^3 s^{-1} km^{-2} have occurred. Above about 2400 m in Colorado, maximum observed 6-hour rainfall is about 100 mm; in eastern Colorado at lower elevations, maximum observed 6-hour rainfall is about 610 mm, which also is the maximum 24-hour value [*Hansen et al.*, 1978].

The interdisciplinary research cited above has provided definitive information that substantial flooding in Colorado has not been observed above an elevation of about 2300 m [*Jarrett*, 1987, 1990b, 1993; *Jarrett and Costa*, 1983, 1988; *Grimm et al.*, 1995; *Pruess*, 1996]. The limit varies somewhat because of

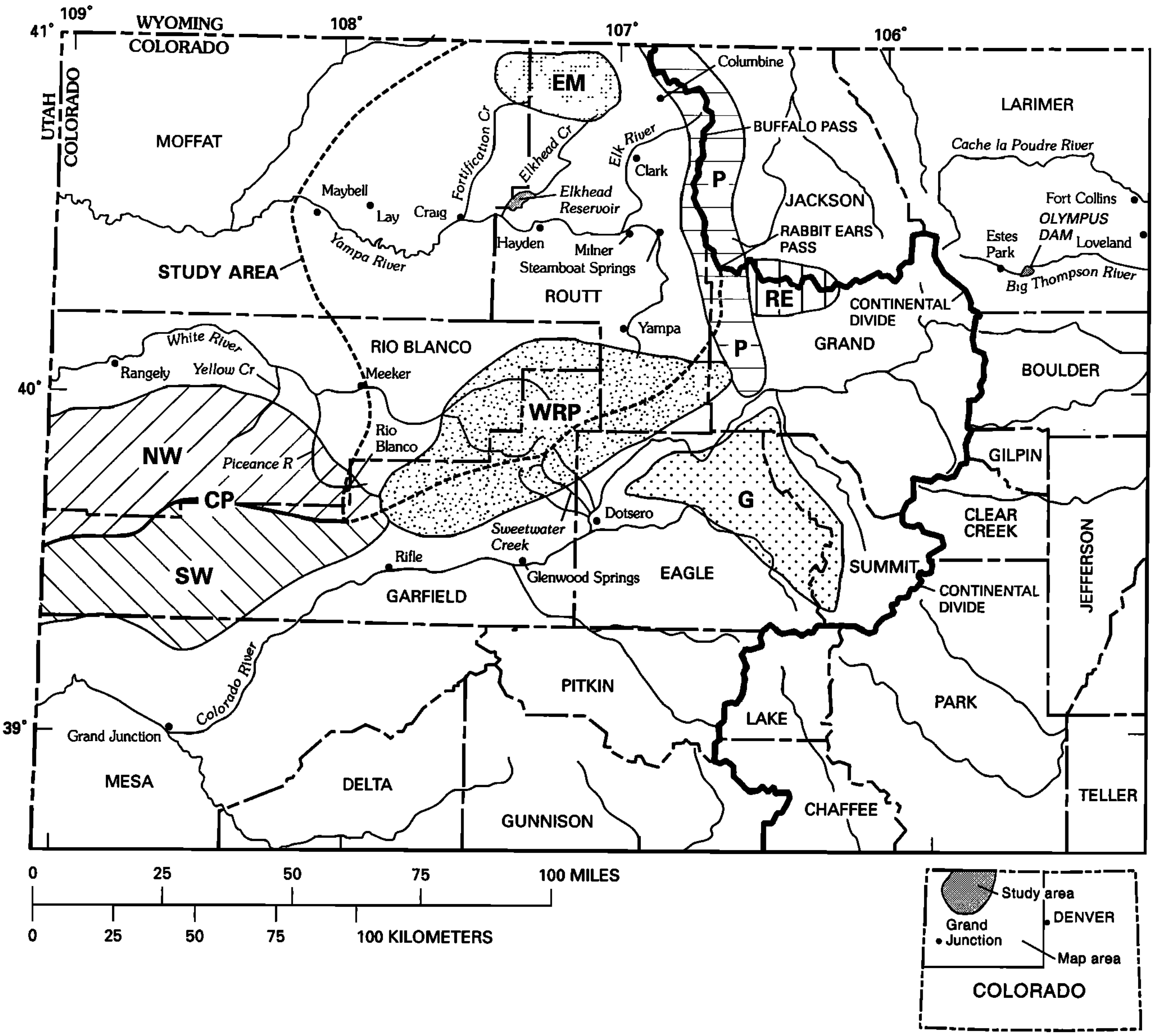

Figure 1. Location of the regional interdisciplinary paleoflood study area for northwestern Colorado, which is highlighted by the bold dashed line. The northwestern (NW) and southwestern (SW) Colorado topographic boundary formed by the Colorado Plateau (CP) are labeled and shown as hatched area. The White River Plateau (WRP) and Gore (G), Rabbit Ears (RE), and Park (P) mountain ranges are labeled and denoted with different patterns.

local/regional hydroclimatic variations and is somewhat lower in selected basins east of the Continental Divide [*Jarrett*, 1990b] and most basins west of the Continental Divide [*Jarrett*, 1993]. The elevation limit of about 1 m^3 s^{-1} km^{-2} seems to vary from about 2400 m in the southern Rockies to about 1700 m in the northern U.S. Rocky Mountains [*Jarrett*, 1993]. M. Quick (University of British Columbia, unpublished data, 1993) indicated that the elevation limit in the Canadian Rocky Mountains is somewhat lower than the elevation limit for the northern U.S. Rocky Mountains.

These results, which are supported by analyses of extreme rainfall data and paleoflood studies [*Jarrett*, 1987, 1990b; *Jarrett and Costa*, 1988; *Grimm*, 1993; *Waythomas and Jarrett*, 1994; *Pruess*, 1996; *Brien*, 1996] contrast dramatically from published values of PMP and PMF for the Rocky Mountains. PMP estimates are 250 mm in 6 hours and 510 mm in 24 hours in the upper Yampa River basin [*Hansen and Schwarz*, 1981; *Hansen et al.*, 1988]. For comparison, in eastern Colorado (Denver), PMP values are 675 mm in 6 hours and 920 mm in 24 hours [*Hansen et al.*, 1988]. J. F. Henz (Review of probable maximum precipitation in Wyoming—Level II, Phase 1 Report, draft, prepared for Wyoming's State Engineer's Office, 1991) reviewed the use and applicability of current PMP methodologies in Wyoming [*Hansen et al.*, 1988]. He concluded that additional meteorological research is needed to improve estimates of extreme precipitation in the Rocky Mountains of Wyoming. *Buckley* [1995] concluded that there are no significant rainstorms even remotely comparable to the magnitude of PMP estimates for mountains in Wyoming. *Eastwood* [1995] developed regional relations to estimate the frequency of extreme precipitation in the mountains of Wyoming. *Tomlinson and Solak* [1994, 1997] developed a site-specific methodology to determine PMP/PMF estimates. *Jensen* [1995] developed new criteria for computing PMP estimates for short-duration, small-area storms in Utah. His study resulted in significant decreases in extreme precipitation for Utah compared to currently used PMP estimates [*Hansen et al.*, 1977].

Large differences in estimates of extreme rainfall and flooding have substantial effects on dam safety. For example, a paleoflood study was conducted for the Bureau of Reclamation for Olympus Dam in Estes Park, Colorado, on the Big Thompson River [*Jarrett and Costa*, 1988]. Olympus Dam is located at an elevation of 2300 m, and the spillway was designed for a PMF of 637 m^3 s^{-1}. However, a revised PMF (Bureau of Reclamation, written communication, 1988), based on the revised PMP estimates [*Hansen et al.*, 1988], is 2380 m^3 s^{-1}. Paleoflood investigations by *Jarrett and Costa* [1988] indicated that the largest natural flood flow in the Big Thompson River upstream from Olympus Dam is 142 m^3 s^{-1} (6% of the revised PMF) during at least the past 10,000 years (since glaciation). This paleoflood information and a review of the existing and revised PMF values by the Bureau of Reclamation resulted in a decision not to modify the spillway for Olympus Dam at an estimated cost of $10 million (Bureau of Reclamation, written communication, 1988).

In part because of the interdisciplinary research, concerns and questions of extreme rainfall and flood design values for structures located in floodplains have been raised by state and federal dam safety officials for the Rocky Mountains. Most state agencies in the Rocky Mountain region have ongoing hydrometeorologic and paleoflood studies to revise methodologies to estimate extreme precipitation and flooding for dam safety because of recognized deficiencies in PMP estimates in mountainous areas. Colorado began studies to develop new methods to estimate extreme rainfall in the mountains [*McKee and Doesken*, 1997], and the second, 30-month phase recently began (A. Pearson, Colorado Dam Safety Office, written communication, 1999). The Bureau of Reclamation recently began a program to use a risk-based assessment, which incorporates paleoflood investigations to provide estimates of the magnitude and frequency of extreme floods, to assist with dam safety decision making [*Levish et al.*, 1994; *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]. In 1999 the American Society of Civil Engineers began a task committee on paleoflood hydrology as it relates to dam safety and risk-based assessments. The *NRC* [1988, p. 111] states that "Nonetheless, the expense of such studies is minor in relation to planning costs for major high-risk projects such as nuclear power plants or large dams. At present these opportunities are largely being ignored.... For critical projects the paleoflood data should at least be collected, appropriately weighed, and considered in the overall decision process leading to design." Thus it is important to develop methodologies that can be used by dam safety officials to make decisions about the probabilities of extreme floods.

3. Study Area

The Yampa River in northwestern Colorado originates on the White River Plateau (also known as the Flattops with a maximum elevation of 3808 m) and flows westerly through the Gore (3295 m), Rabbit Ears (3748 m), and Park (3725 m) mountain ranges (Figure 1). The White River originates on the White River Plateau and also flows westerly. The boundary between northwestern and southwestern Colorado is defined by the topographic divide between the White River and Colorado River basins (Figure 1), which has elevations ranging from about 2500 to 3800 m. Elevations at the downstream study limit are 1804 m at Maybell in the Yampa River basin and 1898 m at Meeker in the White River basin. Major Yampa tributaries include the Elk and Little Snake Rivers and Elkhead and Fortification Creeks. The regional study area is approximately 10,900 km^2.

Elkhead Creek has its headwaters in the Elkhead Mountains and flows southwesterly to its confluence with the Yampa River about 10 km east of Craig (Figure 1). Elkhead Creek basin has a drainage area of 531 km^2 at Elkhead dam. Elevations in the basin range from about 3307 m at the highest peak of the Elkhead Mountains to about 1890 m at its confluence with the Yampa River. The elevation of Elkhead Reservoir is about 1950 m. Distinct mountains and ridges define the north (~2900 m), east (~2400 m), and west (~2300 m) boundaries of the basin. The topography is rolling hills and valleys, except in the steeper, mountainous headwater areas. Elkhead Creek and numerous tributaries drain the mountains forming the basin boundary. Most streams in the study area are of higher gradient with slopes greater than 0.002 m m^{-1} [*Jarrett*, 1984], except the lower reaches of Elkhead Creek and the lower Yampa River. Cobble- and boulder-sized material make up the stream bed and fine-grained sediments compose the floodplain. Some lower-elevation tributary valleys to the Yampa and White Rivers are predominantly fine-grained alluvial fill.

Elkhead Creek basin is underlain by Cretaceous and Tertiary rocks (shale, sandstone, conglomerate, and coals) in the Lance, Lewis, Wasatch, Browns Park, Fort Union, and Iles formations; upper Tertiary intrusive rock, primarily porhyries of intermediate and basaltic composition, cover parts of the basin [*Tweto*, 1976]. Within the general study area, similar geologic formations as in Elkhead Creek basin with Precambrian rocks (granite, Quartz monzonite, granodiorite, Quartz diorite, and gabbro) and biotite and hornblend gneisses occur in the Park Range. Tertiary andesitic and basaltic lava flows from the Flattops and Elkhead Mountains with some intrusive rocks in the study area [*Tweto*, 1976]. Most of the Park Range, upper Elkhead Creek basin, and the Flattops experienced at least three Pleistocene glaciations [*Madole*, 1982, 1989, 1991a, 1991b, 1991c]. Flights of Pleistocene terraces along the Yampa River from about Steamboat Springs downstream to about Craig, probably from glacial processes, range from about a meter (early Holocene) to 183 m (620 ka) above the present floodplain; the average incision rate since 600 ka is 0.11 m ka^{-1} [*Madole*, 1991a]. Unglaciated tributaries lack the well-developed Pleistocene terraces, and Holocene terraces are relatively close to the valley floors [*Madole*, 1991a]. Loess, typically 1.3 to 2 m thick, of at least two ages is widespread in the Yampa River basin with the latest deposition in the late Pleistocene and possibly early Holocene [*Madole*, 1991a].

The majority of Elkhead Creek basin and regional study area has been mapped as low to moderately well-drained soils, except in limited higher elevation areas where bedrock is at or near the ground surface [*Soil Conservation Service*, 1982; *Natural Resources Conservation Service*, 2000]. At higher elevations in Elkhead Creek and the upper Yampa River and White

River basins, subalpine forests consisting of aspen, lodgepole pine, Douglas fir, and Engelmann spruce are common. In most lower parts of Elkhead Creek basin and Yampa River basin below Steamboat Springs, vegetation consists primarily of pinon pine, juniper, sagebrush, rabbit brush, and native grasses.

Mean annual precipitation in the basin varies from about 405 mm at Elkhead reservoir to slightly more than 760 mm near the headwaters [*Doesken et al.*, 1984]. Most annual precipitation falls as snow in the winter months. The largest precipitation amounts are limited to small parts of the basin at the highest elevations around the east and north rims of the basin. Within the larger context of the regional study area, mean annual precipitation ranges from over 1525 mm in the Park Range (the wettest area in Colorado) to 305 mm near Maybell to 406 mm at Meeker [*Doesken et al.*, 1984]. Frequent, localized convective rainstorms occur during the summer months. Convective storms have produced moderate flooding in small, steep basins with little vegetation at lower elevations in northwestern Colorado [*Jarrett*, 1987]. These basins are located in the western parts of the regional study area, particularly Piceance Creek and Yellow Creek basins. General rainstorms in northwestern Colorado can cover large areas but have not produced substantial flooding in historic times.

Flood-frequency analysis has long been done assuming stationarity of climatic and hydrologic processes [*Interagency Advisory Committee on Water Data*, 1981; *NRC*, 1999]. There is growing concern that climate naturally varies with time and that climate may be responding to anthropogenic effects; however, at present (2000), there is little information to assess these impacts on average or extreme conditions [*NRC*, 1999]. *Lins and Slack* [1999] analyzed contemporary peak streamflow data in the United States and were not able to detect significant trends. *Knox* [1993] documented increases in flood magnitude due to climate change in the upper Mississippi River basin, but these results are site-specific. *Ely* [1997] suggests evidence for climate and flood flow change over the last 1000 years, particularly the last 2 centuries in the southwestern United States. *England* [1998] noted that no explanation was provided for the apparent increase in floods and that only six of *Ely*'s [1997] 19 sites have records equal to or greater than 1000 years. Of equal importance, is that *Ely*'s [1997] study does not account for large uncertainties in estimating flood discharge averaging 60% as noted by *Jarrett* [1986, 1987, 1994].

Few climate change studies have been done for the Rocky Mountain region. Paleoclimatic studies by *Madole* [1986], *Elias* [1996], *Menounos and Reasoner* [1997], *Valero-Garces et al.* [1997], *Fredlund and Tieszen* [1997], *Smith and Betancourt* [1998], and *Vierling* [1998] used dendrochronology, pollen, diatoms, fossil bettle assemblages, carbonate geochemistry, isotopic evidence, and sediment stratigraphy, respectively, to document mean temperature and precipitation fluctuations. These research results are in good agreement that warming temperatures resulted in deglaciation of high mountain areas between about 13,000 and 12,000 years B.P. and that modern climate began about 9500 to 9000 yrs B.P. In this period of modern climate, average temperatures varied $\pm 1°$ to 2°C from contemporary mean summer temperatures. Average annual precipitation and average annual streamflow have varied by up to about 50% of modern mean values, but nearly similar variations have occurred during contemporary records [*Jarrett*, 1991]. However, inferring extreme variations from studies of average climate change is problematic. For example, extreme floods in Colorado such as resulted from the 1935 Hale and 1976 Big Thompson floods were imbedded in one of the worst droughts in contemporary records, whereas other extreme floods have occurred during wet periods, such as the 1965 Plum Creek flood [*Collins et al.*, 1991]. The paleoflood data described in this report provide a means to assess the effects of climate change on large floods during the Holocene.

4. Methodology

This section describes methods used to estimate paleoflood discharge, determine the paleoflood chronology, analyze regional precipitation and streamflow data, and conduct flood-frequency analyses. The strategy of a paleoflood investigation is to visit the most likely places where evidence of substantial flooding, if any, might be preserved. Because glaciation and glacial outwash "erases" evidence of floods, paleoflood evidence generally can be no older than the time since the last period of glaciation or about 12,000 years ago in the Rocky Mountains [*Madole*, 1991a]. For unglaciated basins the objective was to identify the largest flood that has occurred within the longest time period but limited to the Holocene when the climate variability has been relatively constant. Thus paleoflood investigations can identify physical evidence for the occurrence or nonoccurrence of substantial floods for very long time periods. Paleoflood data were collected for sites on Elkhead Creek and its tributaries and from numerous streams in the Yampa, White, and Little Snake Rivers basins in northwestern Colorado.

4.1. Paleoflood Discharge

Floods leave distinctive deposits and landforms in and along stream channels, as well as botanic evidence [*Baker*, 1987; *Baker et al.*, 1988; *Jarrett*, 1987, 1990b, 1991; *Hupp*, 1988]. Slack-water deposits of sand-sized particles [*Kochel and Baker*, 1982; *Baker et al.*, 1988], flood scars on trees, erosion scars, and bouldery flood-bar deposits commonly are used as indicators of past flood levels called paleostage indicators (PSIs) (Figure 2). When flows are large enough, streambed and bank materials are mobilized and transported [*Costa*, 1983; *Komar*, 1987; *Wilcock*, 1992]. Such mobilization and transport are a function of channel gradient. As gradient increases, smaller velocities and depths are required to move sediment on the bed of a stream [*Costa*, 1983]. When stream velocity, depth, and slope decrease, flowing water often is no longer competent to transport sediments, which are deposited as flood bars and slack-water deposits in the channel or on the floodplain (e.g., Figures 3 and 4). The types of sites where flow competence decreases and flood deposits commonly are found and studied include (1) locations of rapid energy dissipation, where transported sediments would be deposited, such as tributary junctions, reaches of decreased channel gradient, abrupt channel expansions, or reaches of increased flow depth; (2) locations along the sides of valleys in wide, expanding reaches where fine-grained sediments or slack-water deposits would likely be deposited; (3) ponded areas upstream from channel contractions; (4) the inside of bends or overbank areas on the outside of bends; and (5) locations downstream from moraines across valley floors where large floods would likely deposit sediments eroded from the moraines. Flood-transported sediments and woody debris can scar trees (Figure 5) and also accumulate on trees and other obstructions to provide a good indicator of flood height. The height of tree scars and the top of woody debris are used as indicators of approximate flood height [*Har-*

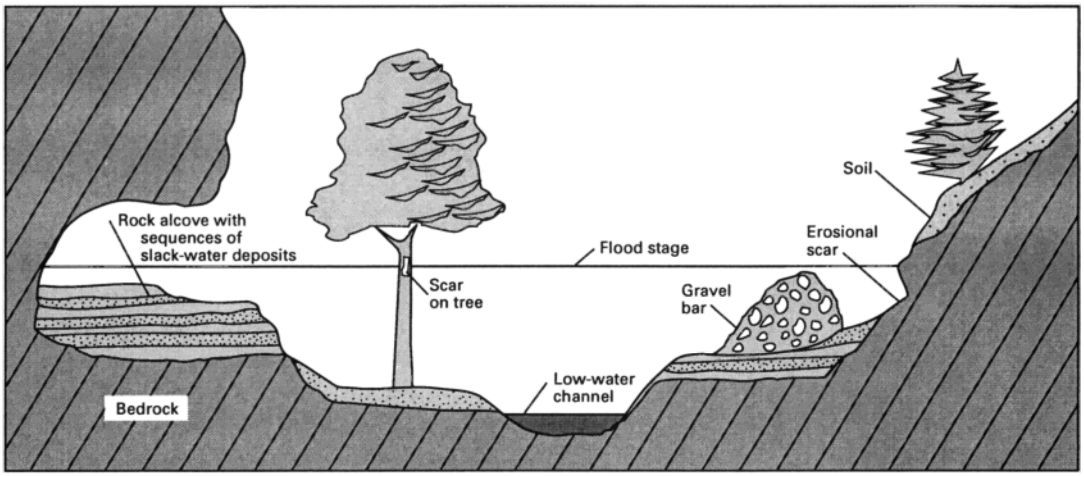

Figure 2. Diagrammatic section across a stream channel showing a hypothetical maximum paleoflood and various flood features preserved as paleostage indicators [*Jarrett*, 1991].

rison and Reid, 1967; *Hupp*, 1988; *Gottesfeld*, 1996]. A lack of scarring is an indicator that flooding has not occurred since establishment of trees on the floodplain. In semiarid streams, woody flood debris typically lasts 60 years or longer before completely decaying (D. Levish, Bureau of Reclamation, personal communication, 1998).

Paleoflood discharge was determined from estimates of flood width and depth corresponding to the elevation of the top of flood-deposited sediments (or PSIs) and channel slope obtained during on-site visits to streams. Hydraulic calculations are similar to indirect discharge estimates using high-water marks following floods, except PSI usually are older and may have greater uncertainty. Flood depth was estimated by using the PSIs in the channel or on the floodplain above the channel-bed elevation. Using the estimated flood depth and channel geometry, the width and cross-sectional area below the PSI elevation was determined. Because most streams in the study area are higher gradient (>0.002 m m^{-1}), paleoflood discharge was estimated using the critical-depth method [*Barnes and Davidian*, 1978], which has been suggested for use because flow in these streams usually is very near critical or slightly subcritical, particularly for large floods [*Jarrett*, 1984, 1986; *Trieste and Jarrett*, 1987]. The slope-conveyance method [*Barnes and Davidian*, 1978] was used to estimate paleoflood discharge in the few lower-gradient rivers (mostly mainstream Yampa River downstream from Craig). Flow-resistance coefficients for lower-gradient rivers were estimated from analysis of data for Colorado rivers [*Jarrett*, 1984, 1985]. Although flow-

Figure 3. Upstream view of flood-bar deposit for Lefthand Creek near Boulder, Colorado, with 1995 flood waters about 20 cm below the peak stage. Peak discharge was 34 m^3 s^{-1}, and the elevation of the top of flood bar (and a separate slack-water deposit of sand in far right center) equaled maximum flood elevation.

Figure 4. Cross-stream view of Roaring River alluvial-fan deposit from the 1982 Lawn Lake dam-failure flood. Peak discharge was approximately 340 $m^3\ s^{-1}$.

competence relations can be used to estimate the flow depth for surface-sediment sizes [*Costa*, 1983; *Levish et al.*, 1994], they do not take into account vegetation and localized turbulence, particularly on floodplain surfaces, and generally do not provide consistent results [*Pruess*, 1996]. Thus, in this study, for streams that have no overbank flood evidence (flood bars and erosional features), a PSI flow depth of less than 0.5 m (higher gradients) to 1 m (lower gradients) on the floodplain was used; these are considered flow depths which do not produce flood erosional or depositional evidence based on the author's extensive postflood studies in the Rocky Mountain region.

In paleoflood investigations, lack of physical evidence of the occurrence of floods is as important as discovering tangible on-site evidence of such floods [*Stedinger and Cohn*, 1986; *Jarrett*, 1987, 1990b; *Jarrett and Costa*, 1988; *Levish et al.*, 1994; *Ostenaa and Levish*, 1995]. The geomorphic evidence of floods

Figure 5. Downstream view of flood scars and woody debris from the 1982 Lawn Lake dam-failure flood (380 $m^3\ s^{-1}$); flow depth at survey rod (1.5 m) is approximately 30 cm above ground. Flood scars average about 1 m higher than the 1982 flood height.

in steep mountain basins [*Boner and Stermitz*, 1967; *Snipes et al.*, 1974; *Schwarz et al.*, 1975; *McCain et al.*, 1979; *Costa*, 1983; *Jarrett and Costa*, 1986; *Jarrett*, 1987, 1990b, 1991; *Grimm et al.*, 1995; *Waythomas and Jarrett*, 1994] is unequivocal (e.g., Figures 3–5). Paleoflood evidence is relatively easy to recognize and long lasting because of the quantity, morphology, and structure and size of sediments deposited by floods. Lack of movement of all sizes of clasts on a streambed with an unlimited size of clasts is a direct measure of flow competence [*Costa*, 1983; *Komar*, 1987; *Bull*, 1990; *Wilcock*, 1992] and an indirect measure of flood discharge. In many channels in Colorado, there is an "unlimited" size of clasts present in channels because of past glacial outwash or rockfall that are available for transport. Point, longitudinal, and transverse bars are built up of layers of silt, sand, gravel, cobble, and boulders from bed load to about the height of maximum flood water [*Jarrett et al.*, 1996]. For a given reach of channel the relation of maximum clast size in a flood deposit to the available clast size in the upstream channel was noted. Clasts show little reworking on the stream bed (random pattern due to winnowing of finer materials) when floods are small; however, large floods tend to produce well-developed, fluvial-depositional features. In addition, when flows exceed the main channel by even small depths (<0.5 m), coarser-grained bed material is transported onto the floodplain and deposited [*Jarrett et al.*, 1996] such as shown in Figure 3; thus lack of coarse material on floodplain surfaces indicated minimal inundation.

There are three main sources of uncertainty in paleoflood reconstructions [*Jarrett and Malde*, 1987]: selection of flow-resistance coefficients, channel changes, and representativeness of PSIs of flood height. Selecting flow-resistance coefficients, whether Manning's n value as in this study or other resistance forms (e.g., Darcy's or Chezy's), can be problematic for flood studies, particularly for paleoflood estimates when riparian vegetation may have been different and unquantifiable. *Jarrett* [1986] and *Trieste and Jarrett* [1987] indicate for most higher-gradient streams and many lower-gradient rivers, flow is about critical or slightly subcritical even in channels having substantial channel and floodplain vegetation prior to a flood. Large floods tend to remove most vegetation prior to the peak stage [*Matthai*, 1969; *McCain et al.*, 1979; *Phillips and Ingersoll*, 1998], and because flow is nearly critical, some of the uncertainty in estimating n values due to unquantifiable past vegetation is removed.

To minimize effects due to channel changes, the second source of uncertainty, cross sections were located in bedrock reaches or in relatively stable alluvial reaches. Although most of the Yampa River is alluvial, there are good constraints on relative stability or slight rates of incision during the Holocene [*Madole*, 1991a]. For alluvial tributary streams that may have undergone cyclical aggradation and degradation or if these cycles were difficult to ascertain, then very restrictive (conservative) ages were assigned to the paleoflood estimate, usually less than 100 years.

The third source of uncertainty in paleoflood reconstructions is maximum flood height inferred from PSIs. In most paleoflood studies, PSIs have been assumed to be slightly lower than maximum flood height [*Kochel and Baker*, 1982; *NRC*, 1988; *Baker et al.*, 1988]. New research on the elevation of the top of flood-deposited sediment (new PSIs) and high-water marks (HWMs) of recent flooding in 90 streams primarily in the western United States that has been done [*Jarrett et al.*, 1996] challenges this assumption. HWMs are the evidence of the highest stage reached by a flood and primarily consist of fine woody debris, leaves, grass, needles, other floatable materials and mud lines. These streams have drainage areas that range from about 0.004 km^2 to more than 6000 km^2. Peak discharge ranged from about 0.03 to 2500 $m^3\ s^{-1}$, and the majority were larger than 100-year floods. Stream gradient at these sites ranges from about 0.0007 to 0.35 $m\ m^{-1}$. The size of flood-deposited sediments ranged from silt to boulders more than 4 m in diameter; only those deposits considered to have long-term preservation potential were documented. Analysis of the differences in PSIs and HWMs indicates that the elevations of the top of flood-deposited sediments (PSIs) generally are within ± 0.2 m of flood HWM elevations. Therefore use of the top of flood-deposited sediments as PSIs for streams in this study provides a reliable estimate of the maximum paleoflood depth that is used to reconstruct the discharge of paleofloods.

Good HWMs for the 1995 near-record peak flows during fieldwork were established, which were not that much smaller than maximum paleofloods. Paleoflood techniques were used to estimate peak discharge for the 1995 flood where streamflow-gaging station estimates were available but without prior discharge knowledge. Although this comparative approach does not consider all the uncertainties, the comparison does provide an estimate of the uncertainty of the critical depth and slope-conveyance methods for estimating peak discharge in the study.

4.2. Paleoflood Chronology

In this study, a variety of relative-dating (RD) techniques were used to estimate the approximate length of time (age) corresponding to the highest flood deposits emplaced during the Holocene for subsequent use in flood-frequency analysis. RD techniques based on landform modification, rock-weathering features, and soil development have long been used to differentiate and map Quaternary deposits in the western United States with emphasis on dating glacial deposits [*Birkeland et al.*, 1979; *Colman and Pierce*, 1983; *Birkeland*, 1990]. Rock-weathering, soil, and geomorphic parameters all change with time [*Colman and Pierce*, 1983; *Birkeland et al.*, 1979]. Although much dating has involved fluvial deposits, ages primarily are determined with absolute-dating methods such as ^{14}C, thermoluminesce, and dendrochronology [*Kochel and Baker*, 1982; *Hupp*, 1988; *Colman and Pierce*, 1991]. Some investigators have used a variety of RD methods, which utilize the collective strengths of each method [*Burke and Birkeland*, 1979; *Harden*, 1986, 1990; *Waythomas and Jarrett*, 1994; *Mills and Allison*, 1995]. The chances of arriving at a valid approximate age is greatly enhanced if a variety of RD methods are measured [*Birkeland et al.*, 1979].

RD methods applied to surficial deposits are based on post-depositional modifications that vary with age [*Birkeland et al.*, 1979]. Field evidence of age is usually derived from soil properties, rock-weathering characteristics, changes in landform morphology, and lichenometry. Their usefulness for characterizing surficial deposits is related to the degree to which they can be quantified and to their rate of change [*Birkeland et al.*, 1979]. Episodic flooding produces deposits of different ages that can be separated by long periods; thus the deposits have distinctive properties that are amenable to measurement by RD methods. It is assumed that when flood-deposited sediments undergo transport and reworking during high-energy flood transport, the weathering "clock" essentially is reset to zero [*Waythomas and Jarrett*, 1994]. Certainly, a limitation is

Table 1. Description of Relative Dating Methods Used in Northwestern Colorado

Type of Relative Dating Method	Numerical Rating and Description[a]		
	0–3	4–6	7–10
Soil horizons	C (increasing O/A)	O/A/C	O/A/Btj/C
Rock weathering	fresh	partly weathered	very weathered
Pitting, %	<10, rare/incipient	30–70	>75, common
Grain relief, mm	<0.5	0.5–1	>1
Boulder burial, %	0–25	25–75	>75
Surface morphology			
Terrace scarp	angular	moderately rounded	well rounded
Slope	steep	moderately muted	extremely muted
Terrace tread	fresh longitudinal flood evidence	moderate transverse rills and gullies	extensive transverse rills and gullies
Lichenometry			
Largest thalli, mm	0–100	>150	>150
Rock coverage, %	<75	>75	>75

Abbreviation tj indicates incipient accumulation of silicate clay that has either formed in situ or is alluvial [*Birkeland*, 1984].

[a]A rating of 0 is modern or 0 years; 10 is early Holocene or about 10,000 years or older. The rating values are approximate, nonlinear, and applicable for northwestern Colorado river valleys.

the occurrence of large floods separated by a short time span where RD techniques (and even absolute techniques) may not be able to differentiate between several individual older deposits.

The most important factor for using RD techniques for fluvial deposits is to compare the deposits with flood deposits and other surfaces immediately adjacent (upslope and downslope) in a short reach (site). Within-stream factors would have zero age, whereas deposits and surfaces with increasing height above the channel have increasing age. Thus state factors (e.g., lithology, microclimate, climate, vegetation, and topography) are assumed to be held constant; therefore differences in weathering and soil-profile development are directly related to time at any individual site, which is the justification of RD methods [*Burke and Birkeland*, 1979; *Harden*, 1982; *Waythomas and Jarrett*, 1994]. Also, it is important to obtain ages using these different RD techniques for several samples within a reach of channel. Similar ages derived from different techniques result in increased confidence in the estimate [*Burke and Birkeland*, 1979; *Waythomas and Jarrett*, 1994]. Because the most limiting factor in age-dating studies is small sample size [*Harden*, 1990], dating numerous deposits along rivers helps increase the reliability of age determinations.

The focus of this study was to identify gross changes in RD features [*Burke and Birkeland*, 1979], which were then used to estimate maximum age of flood or noninundation surfaces. Age estimates for paleoflood deposits are based on relative-age criteria as proposed by *Burke and Birkeland* [1979], *Colman and Pierce* [1983], *Harden* [1982, 1986, 1990], and *Waythomas and Jarrett* [1994]. RD techniques used for this study were degree of soil development (S), surface-rock weathering (W), surface morphology (M), lichenometry (L), and boulder burial (B), although not all methods could be used at each site. For each of these criteria a numerical value from 1 to 10 was assigned, 1 representing modern channel deposits and 10 exhibiting greatest age corresponding to early Holocene or older (Table 1). For all RD methods as discussed for each except lichenometry, the rating scale is 1 for ~0 to 1000 years to a value of 10 for ~10,000 years. For lichenometry, 1 is modern and 10 is probably 3000 years or less. Finally, an average age and range of age uncertainty was determined.

4.2.1. Soils. There is a strong relation between degree of soil development and time, although rates of soil development vary widely [*Birkeland*, 1984; *Harden*, 1986, 1990]. Correlation of soil-profile development with soil chronosequences, dated with numerical techniques, is crucial when determining the relative age of surfaces [*Birkeland*, 1984; *Bull*, 1990]. Soils show a systematic and generally slow progressive soil-profile development with age. Readily available soil surveys provide useful data used in conjunction with field checking. The degree of development of the local soil profile was determined in the field by trenches and cut-bank exposures of flood deposits and terrace deposits. Age diagnostic parameters include the following: thickening of the total soils and development of the B horizon; increasing enrichment of the B horizons in secondary clay (an argillic horizon); presence, abundance, and thickness of clay films; increasingly diffuse horizon boundaries; abundance of calcium carbonate; oxidation depth; pan developments; and rubification of the B and C horizons [*Bilzi and Ciolkosz*, 1977; *Harden*, 1982; *Colman and Pierce*, 1983; *Birkeland*, 1984]. Conditions that increase the rate of soil development include the following: warm, humid climate; forest vegetation; high permeability; and flat topography. Conditions that tend to retard soil development are cold, dry climates, grass vegetation, low permeability, and steep slopes.

Alluvial soils are often thought of as being young or undeveloped, but this is not always true [*Gerrard*, 1981]. Soils on river terraces are often interpreted as alluvial and considered young, but since the majority of river terraces are of Pleistocene age, many such soils are well developed [*Gerrard*, 1981]. For example, *Madole* [1991a] identified numerous alluvial terraces up to 183 m above the present channel, but they have been dated to about 650 ka. Thus incision rates and time since inundation are important in developing flood chronology.

4.2.2. Surface-rock weathering. Ratios of fresh to weathered material, the abundance of pitting, and pit depth on rock clasts are useful for subdividing Holocene deposits by an age of 1000 years or more [*Benedict*, 1968]. It is assumed that abrasion of granite, rhyolite, and basalt clasts during flood transport removes most previous effects of weathering. The degree of surface-rock weathering of 25–50 of the largest flood-deposited clasts of the same lithology provides an indication of their relative age. Older deposits have extensive surface pitting, rougher surfaces, and increasing grain relief because of differential weathering of minerals. As less resistant minerals decompose, quartz and feldspar grains tend to stand out in relief. Pitting is common if present on more than 75% of the clast surfaces and is rare (or incipient) if present on less than 10% of the clast surfaces. Flood-deposited clasts are compared with end-member clasts from the streambed (fresh) and clasts much higher on the land surface (extremely weathered).

4.2.3. Boulder burial. Many recent flood deposits in Colorado (e.g., Figure 3) and other mountain rivers consist of little or modest amounts of matrix-supported cobble and bouldery deposits, particularly around surface clasts [e.g., *Matthai*, 1969; *McCain et al.*, 1979; *Costa*, 1983; *Waythomas and Jarrett*, 1994; *Jarrett et al.*, 1996]. Boulder burial refers to the percentage of the total boulder surface exposed above ground. For flood deposits the amount of cobble and boulder burial by addition of newer sediment at the site (colluvium, eolian, and slope wash) also can be used to estimate the relative age of a deposit [*Waythomas and Jarrett*, 1994]. Thus time or age since flood deposition is inferred from depth of burial. The older the deposit is, the greater is the percentage of these clasts that are covered by postflood deposition.

4.2.4. Surface morphology. Formation of stream terraces involves changes in the behavior of a fluvial system [*Bull*, 1990]. Terraces may form because of a variety of internal or external changes, climate, tectonics, base level, slope, complex response, and thresholds [*Patton and Schumm*, 1975, 1981; *Womack and Schumm*, 1977; *Bull*, 1990]. Remnants of the former streambed are preserved as terrace treads. Terrace features such as riser angle become muted with time by faunal, water, and wind action, and rates of change depend on factors such as cohesion of material, vegetation, and flow stress [*Lewin*, 1978; *Birkeland et al.*, 1979]. Younger terraces tend to be more angular and have steep slopes; with increasing age, terrace scarp slopes become flatter unless maintained by cut-bank erosion. Along rivers in glaciated basins in the Yampa River basin, early Holocene to late Pleistocene terraces, which are 1–2 m above the present floodplain, are covered with eolian (loess) deposits [*Madole*, 1991a]. These surfaces are relatively easily erodible if flooded thus providing unique sites for paleoflood investigations. Over time, local hillslope runoff produces transverse gullies or channels on terraces and colluvial surfaces; greater development generally requires longer time. Also, if alluvial (or colluvial) surfaces are inundated by flood waters, microchannels and surface deposits are produced longitudinally, which are somewhat similar to crevasse channels and splays [*Lewin*, 1978]. With time, geomorphic expression of these features is muted. Lack of such flood features or noninundation surfaces [*Jarrett and Costa*, 1988; *Levish et al.*, 1994; *Ostenaa and Levish*, 1995] provides an upper bound of flood height on a surface of known age.

4.2.5. Lichenometry. A common RD technique used for dating glacial deposits is lichenometry [*Benedict*, 1966, 1967, 1968; *White*, 1971; *Beschel*, 1973]. Its use has primarily been high-elevation or arctic climates, and the transfer value is limited, particularly for growth curves. *Rhizocarpon geographicum*, the most commonly used lichen for dating, grows throughout most of Colorado. Most lichenometric studies use a combination of maximum thallus diameter and percentage cover on clast surfaces to determine the ages of late Holocene deposits [*Benedict*, 1967, 1968; *Beschel*, 1973; *Birkeland et al.*, 1979]. Lichens, which grow on all but freshly exposed or deposited rock surfaces [*White*, 1971], take about 50 years to become established. Environmental factors known to affect the growth of *R. geographicum* include rock type, shading, temperature, moisture, and stability of the substrate, and thus they need to be factored into age assignments. Growth increases with coarser texture, moisture, temperature. Abrasion during sediment transport in higher-energy streams common to floods in mountain regions removes most lichen thus essentially resetting the time "clock" to zero for lichen growth. *Benedict* [1967, 1968] indicated that growth curves are fairly constant between 3125 m and 4047 m (corresponding to a mean air temperature change of about 6.6°C) for his sites along the crest of the Continental Divide in Colorado. *Benedict*'s [1967, 1968] sites are located about 80 km southeast of this study area. Lichen growth curves have a maximum age utility of about 3000 years in Colorado [*Benedict*, 1967, 1968], probably a shorter time at lower elevations in Colorado where climate is more conducive to faster growth rates. Maximum thalli diameter and percent lichen on similar rock types for 25–50 clasts on the flood deposit and other rock surfaces were made at each site.

4.3. Regional Analyses of Maximum Rainfall and Flood Data

A lack of flood evidence, particularly of extremely rare floods, in one basin such as Elkhead Creek basin could result from pure chance. Thus it is essential to ascertain the flood history for other basins in the region [*NRC*, 1988]. Regional analysis extends hydrometeorologic records and provides a tool to estimate discharge at ungaged sites [*Jarrett and Costa*, 1988; *NRC*, 1988; *Hosking and Wallis*, 1998]. In addition, regional analyses provide improved estimates of precipitation and streamflow characteristics for gaged sites by decreasing time-sampling errors for relatively independent samples.

Predicting the upper limits to the magnitudes of floods in a specific region has been a long-standing challenge in flood hydrology. Envelope curves encompassing maximum rainfall [*Linsley et al.*, 1982; *Jarrett*, 1987, 1990b] and floods in a homogeneous hydrometeorologic region have long been used in flood hydrology [*Crippen and Bue*, 1977; *Costa*, 1987a; *Jarrett*, 1987, 1990b; *Enzel et al.*, 1993]. Utilization of envelope curves for a hydrometeorologic region can be evaluated by examining maximum floods in nearby basins. A premise for envelope curves is that not all basins in the region are expected to have had the maximum flood, but no basin has yet had a flood that exceeds the envelope curve for the specific region. The primary limiting factors for extreme floods are amount, intensity, duration, and spatial distribution of rainfall, which includes orographic enhancement effects and basin slope [*Costa*, 1987b; *Pitlick*, 1994]. Incorporating paleoflood data for various basins in the region provides an opportunity to add a new level of confidence to envelope curves [*NRC*, 1988; *Enzel et al.*, 1993].

4.4. Rainfall Data

Extreme rainfall data for the last 100 years were compiled from 181 official precipitation gages and numerous supplemental rainfall-bucket surveys in western Colorado [*McKee and Doesken*, 1997]. Four, long-term precipitation stations in the study area, at Steamboat Springs, Hayden, Lay, and Meeker (Figure 1), have been operated from 61 to 94 years. Rainfall-bucket survey data, primarily collected by the National Weather Service, Army Corps of Engineers, and Bureau of Reclamation, were compiled for Colorado [*Jarrett*, 1987, 1990b] and updated through 1997 for this study. Although very little bucket data have been collected in recent years, several extreme rainstorms have been documented in northwestern Colorado since the early 1900s.

4.5. Streamflow Data

Streamflow data for 218 sites in the Yampa River and White River basins were compiled and used to assess extreme flooding in the region. U.S. Geological Survey and Colorado State Engineer streamflow records through 1998 are available from the U.S. Geological Survey's NWIS-W Data Retrieval system (http://waterdata.usgs.gov). These data were then used to develop an envelope curve of peak discharge versus drainage area for northwestern Colorado. Unit discharge can be used to infer both maximum rainfall intensities and spatial extent of rainstorms [*Jarrett*, 1990b]; the data were used to develop an envelope curve for unit discharge versus elevation.

4.6. Flood-Frequency Relations

To help facilitate risk assessments of rare floods for dam safety officials and floodplain managers, flood-frequency relations were developed from an analysis of annual peak flows through 1998 for selected streamflow-gaging stations in northwestern Colorado where paleoflood data are available. A variety of distribution functions and estimation methods are available for estimating a flood-frequency distribution [*NRC*, 1999]. Flood-frequency relations normally are developed using a log-Pearson type III frequency distribution [*Interagency Advisory Committee on Water Data*, 1981] referred to as Bulletin 17B (B17B) and the expected moments algorithm (EMA) [*Cohn et al.*, 1997; *England*, 1998]. B17B guidelines were established to provide consistency in federal flood-risk management for handling low and high outliers, for recognizing the need for regionalized skew, and for zero-flow adjustment, for example.

EMA is an efficient approach for incorporating historical and paleoflood data and uses the log-Pearson III distribution [*Cohn et al.*, 1997; *NRC*, 1999]. The *NRC* [1999] recognized the need to follow the spirit of the guidelines such as when using EMA. The EMA is used as the generalization of the conventional log-space method of moments and makes more effective use of historical and paleoflood data in a censored-data framework [*England*, 1998; *NRC*, 1999]. EMA explicitly incorporates the number of known and unknown discharges above and below a threshold, number of years in the historic/paleoflood period, and knowledge of the number of years when no large floods have occurred [*Cohn et al.*, 1997; *England*, 1998]. The difference between B17B and EMA is the treatment of historic and paleoflood data [*England*, 1998]. For B17B the gage record is used to fill in the censored (unknown) floods, whereas EMA computes the expectations for flow data below the threshold and weights this value by the number of censored values [*England*, 1998]. A comprehensive review of the EMA, censoring thresholds and analyses of contemporary and paleoflood data is provided by *England* [1998].

For this study, several alternative flood-frequency distribution estimates were determined for the study sites in northwestern Colorado using EMA to better use the long paleoflood records. This analysis was done for various combinations of gage and paleoflood data available at each site. Low outliers were adjusted using the B17B procedure to externally eliminate low outliers that affected the fit of the upper end of the curve to the data, which is similar to discharge threshold censoring [*Cohn et al.*, 1997; *Levish et al.*, 1994; *NRC*, 1999]. Censoring below a threshold can account for an assumed distribution not fitting the "true" distribution at a site [*NRC*, 1999]. Low outliers in Colorado often result from modest streamflow diversions for irrigation of hay meadows during low-flow years, but in normal years these diversions have minimal (<5%) effect on peak flows [*Jarrett*, 1987]. Historical and paleoflood data also are censored samples because only the largest floods are recorded. Paleoflood data (magnitude and ages) were incorporated into the flood-frequency analysis to extend the gaged record. In the EMA analysis the paleoflood discharge was specified as a range, and EMA runs were made for the range in age (Table 2) for a site.

5. Results

5.1. Paleoflood Investigations

Paleoflood data from on-site studies of 88 sites throughout the study area are provided in Table 2. Although not all tributary streams in the northwestern Colorado were documented (because of inaccessibility to private property), sites were selected such that paleoflood data were collected downstream from tributaries on the main stream or similar to "nested" sites. For each site, drainage area, elevation, channel slope, type of PSI (either flood bar (FB) or noninundation surface (NI), width, depth, velocity, flood discharge corresponding to the maximum PSI (e.g., Figure 6), and sediment-size data, where available, are presented. Site selection was dependent on finding good PSIs (FB and NI) throughout a 50 to 300 m length (length dependent on size of channel). Ideally, each site would have a FB and a NI surface. Sites were primarily in straight, uniform reaches where local aggradation or degradation would be least. General scour appears to have been small during the Holocene. According to *Madole* [1991a], there has been about a meter of degradation along most the Yampa River during the Holocene. Paleoflood evidence along the upper Yampa River primarily was midchannel bars. These bars (islands) were interpreted as erosional remnants of the late Pleistocene channel rather than depositional features, and thus maximum paleofloods using present channel geometry may be slightly overestimated. Some streams have had little bed material movement (Table 2), and only NI evidence exists, but if the NI surface is consistent in the reach of river, then the maximum paleoflood discharge was considered reliable. If a reach of the same channel had similar paleoflood discharges at several sites, the discharge estimate was considered more reliable. For alluvial channels the discharge was considered less reliable and reflected in an assigned short age of 100 years, which is when much of the channel arroyos developed in Colorado [*Patton and Schumm*, 1975, 1981; *Womack and Schumm*, 1977].

RD data using the criteria shown in Table 1 also are summarized in Table 2. For each site the weathering characteristics for each of the RD methods used, their numerical rating, estimated age, and reliability (range) of age estimates, are provided. Assigning a numerical rating, an age, and range in age for each RD method used is subjective; however, if all methods used suggest similar numerical ratings, then the composite age estimate is likely more reliable. Although individual RD ages are rather crude and may provide different relative ages of a surface, a composite relative age using several methods clearly enables one to distinguish deposits of various ages. Although the error of individual RD ages can be ±50% [*Birkeland*, 1990], composite age is likely more accurate. For use

Table 2. Paleoflood Estimates for Streams in Elkhead Creek Basin and Nearby Streams in the Regional Study Area in

Site	Stream	DA, km²	Elevation, m	S, m m⁻¹	Width, m	Depth, m
						Yampa River
1	Yampa River at Steamboat Springs	1564	2041	0.01	38.6	2.6
	Yampa River at Steamboat Springs 1995 peak				33.5	1.2
	Yampa River at Steamboat Springs 1995 peak					
2	Yampa River near Hayden—total	3704	1929		119	
	Yampa River near Hayden—MC			0.004	61	3.6
	Yampa River near Hayden—OB				58	0.5
3	Yampa River at Craig—total	4481	1885		137	
	Yampa River at Craig—MC			0.003	76.2	3.1
	Yampa River at Craig—OB			0.003	61	0.6
	Yampa River at Craig 1995 peak				76.2	2.3
	Yampa River at Craig 1995 peak					
4	Yampa River near Maybell total	8806	1795	0.001	183	
	Yampa River near Maybell—MC			0.001	67.1	4
	Yampa River near Maybell—LB			0.001	122	0.6
	Yampa River near Maybell 1995 peak			0.001	51.8	3
	Yampa River near Maybell 1995 peak					
						Williams Fork
5	Williams Fork near Hamilton total	1036	1905			
	Williams Fork near Hamilton—MC			0.01	30.5	1.8
	Williams Fork near Hamilton—OB				22.9	0.6
	Williams Fork near Hamilton 1995 peak				22.9	1.4
	Williams Fork near Hamilton 1995 peak					
6	Sulphur Gulch near mouth	5.7	1884	0.01	4.6	0.9
7	Ute Gulch near mouth	4.9	1899	0.01	6.1	0.6
8	Castor Gulch near mouth	10	1905	0.01	3	0.9
9	Morapos Creek near mouth	161	1905	0.01	9.1	1.5
10	Morapos Creek below Deer Creek	148	1945	0.01	9.1	1.5
11	Williams Fork above Morapos Creek total	829	1908	0.01		
	Williams Fork above Morapos Creek—MC				22.9	2.1
	Williams Fork above Morapos Creek—OB				18.3	0.6
12	Williams Fork above Morapos Creek total	803	1914	0.01		
	Williams Fork below West Gulch—MC				22.9	1.8
	Williams Fork below West Gulch—OB				15.2	0.5
13	West Gulch near mouth	4.7	1920	0.01	6.1	0.6
14	Waddle Creek near mouth	62	2012	0.01	9.1	0.6
15	Deal Gulch near mouth	7.8	1945	0.01	6.1	0.6
16	Jeffway Gulch near mouth	18	1954	0.01	6.1	0.6
17	Spring Gulch near mouth	9.1	1958	0.01	7.6	0.9
18	Williams Fork above Spring Gulch total	699	1958	0.01		
	Williams Fork above Spring Gulch—MC				15.2	1.8
	Williams Fork above Spring Gulch—OB				16.8	0.8
						Tributaries to
19	Dry Creek near Hayden	135	1932	0.01	7.6	1.5
20	Stokes Gulch near Hayden	32	1943	0.01	6.1	1.5
21	Sage Creek upstream Dam near Hayden	9.1	2243	0.01	3	0.6
22	Sage Creek dam failure 60 m downstream total			0.02		
	Sage Creek—LB				9.1	0.9
	Sage Creek—MC				12.2	2.7
23	Sage Creek dam failure 120 m downstream			0.01	30.5	1.5
24	Boxelder Gulch near Axial	39	1844	0.01	4.6	1.5
25	Milk Creek near Axial	272	1902	0.01	6.1	1.2
26	Stinking Gulch near Iles Grove	62	1939	0.01	15.2	0.9
27	Good Spring Creek near Axial total	104	1935	0.01		
	Good Spring Creek near Axial—MC				6.1	1.2
	Good Spring Creek near Axial—OB				15.2	0.5
28	Good Spring Creek near Mount Streeter	91	1999	0.01	9.1	0.9
29	Wilson Creek near Axial	70	1920	0.01	6.1	1.2
30	Morgan Gulch tributary near Lay	9.8	1878	0.01	6.1	1.2
31	Morgan Gulch near Lay total	169	1850	0.01		
	Morgan Gulch near Lay—MC				12.2	1.5
	Morgan Gulch near Lay—OB				15.2	0.9
32	Big Gulch near Lay	210	1890	0.003	15.2	1.2
33	Lay Creek near Lay at U.S. Highway 40	259	1885	0.01	13.7	1.5
34	Lay Creek at Lay	479	1875	0.01	33.5	1.5
35	Pine Ridge Gulch near Craig	23	1899	0.01	9.1	1.5
36	Cedar Mountain Gulch near Craig	12	1897	0.01	9.1	1.2
37	Fortification Creek at Craig—1984 total	668	1887	0.002		
	Fortification Creek at Craig—1984 MC				10.7	3

Northwestern Colorado

Velocity, m s^{-1}	Q, m^3 s^{-1}	Q_{gage} Difference, %	Q, %	Q/A, m^3 s^{-1} km^{-2}	D_{bed}, mm	D_{FB}, mm	Type	RD Method	Age, years	Reliability, years	Remarks[a]
Basin											
3.1	311		25	0.2	610	305	FB, NI	S9, W9, M9, L9, B8	9000	±2000	1
2.4	100	−4.8					HWM				
	105						gage				
	651		25	0.2			FB, NI	S9, W8, M7, L7, B7	9000	±2000	
2.7	593										1, 2
2	58										
	687		30	0.2			NI	S8, W8, M8, B9	5000	3000	
2.6	614										1, 2
2	73										
2.1	372	11.4					HWM				
	334						gage				
	865		30	0.1			NI	S8, M8, B10	5000	3000	1
2.7	729										1, 2
1.8	136										1
2.1	337	−10.6					HWM				1
	377						gage				
Basin											
	178		30	0.2			FB, NI	S6, W8, M6, L8, B5	5000	±1000	
2.7	153				610	152					1
1.8	25										
2.1	67	−10.7					HWM				
	75						gage				
2.4	10		25	1.8	610	152	FB, NI	S5, W10, M9, B9	5000	±1000	1, 4
2.1	8		25	1.6	914	152	FB, NI	S5, W10, M9, B9	5000	±1000	1, 4
2.1	6		25	0.6	610	152	FB, NI	S5, W8, M7, B8	5000	±1000	1
2.1	30		30	0.2	305	152	NI	S5, W6, M5, B7	1000	±500	1
1.8	25		30	0.2	305	152	NI	S6, W5, M6, B6	1000	±500	1
	139		30	0.2			NI	S5, W6, M5, B8	1000	±500	
2.4	119				610	152					1
1.8	20										
	127		30	0.2			NI	S4, W7, M6, B7	1000	±500	
2.7	115				610	152					1
1.8	13										
2.4	9		25	1.9	610	152	FB, NI	S9, W8, M7, B7	5000	±1000	1, 4
1.5	8		25	0.1	305	102	FB, NI	S8, W8, M7, B7	5000	±1000	1, 4
2.1	8		25	1	305	102	FB, NI	S9, W8, M7, B7	5000	±1000	1, 4
2.1	8		25	0.5	457	102	FB, NI	S7, W8, M7, B7	5000	±1000	1, 4
1.8	13		25	1.4	610	102	FB, NI	S9, W7, M8, B7	5000	±1000	1, 4
	91		30	0.1			FB, NI	S6, W8, M7, B8	5000	±1000	
2.4	68				610	203					1
1.8	23										
Yampa River											
2.1	25		30	0.2			NI	S8, W7, M6, B7	1000	±500	1, 4
2.1	20		30	0.6			NI	S9, W6, M7, B8	1000	±500	1, 2, 4
1.5	3		30	0.3	305	76	NI	S7, W7, M6, B8	1000	±500	1, 4
	166		25				FB, NI	S1, W2, M1, B1			3
2.7	23										3
4.3	143				762	762					3
4	184		25		762	762	FB, NI	S1, W1, M1, B1			3
1.8	13		30	0.3	305	102	NI	S8, W9, M7, B6	100	1000	1
2.1	16		30	0.1	305	102	NI	S8, W8, M7, B5	100	1000	1, 4
2.1	30		30	0.5	305	152	NI	S8, W9, M7, B7	100	1000	1, 4
	26		30	0.3			NI	S9, W8, M8, B6	100	1000	1
2.1	16				610	152					1
1.5	11										
1.5	13		30	0.1	610	127	NI	S7, W9, M8, B7	100	1000	1
2.1	16		30	0.2			NI	S8, W9, M8, B7	100	1000	1, 2, 4
2.1	16		25	1.6			FB, NI	S8, W9, M7, B9	500	1000	1, 2, 4
	75		25	0.4			FB, NI	S9, W9, M7, B7	500	1000	
2.4	45										1, 2
2.1	30										
2.1	40		30	0.2			FB, NI	S10, W9, M8, B9	500	1000	1, 2
2.4	51		30	0.2			NI	S8, W9, M7, B7	500	1000	1, 2
2.4	125		30	0.3			NI	S9, W9, M6, B8	500	1000	1, 2
2.4	34		30	1.5			NI	S8, W9, M8, B7	500	1000	1, 2, 4
2.4	27		30	2.3			NI	S8, W8, M7, B6	500	1000	1, 2, 4
	80		25	0.1			HWM				
2.1	69										1, 2

Table 2. (continued)

Site	Stream	DA, km^2	Elevation, m	S, $m\ m^{-1}$	Width, m	Depth, m
						Tributaries to
	Fortification Creek at Craig—1984 RB				19.8	0.5
	Fortification Creek at Craig 1995 peak	129	1887	0.002	9.1	2.3
	Fortification Creek upstream Craig—1995 total	124	1893	0.003	27.4	
	Fortification Creek upstream Craig—1995 MC				9.1	1.5
	Fortification Creek upstream Craig—1995 OB				18.3	0.3
39	Coal Bank Gulch near Hayden	2.1	1966	0.01	6.1	0.3
40	Trout Creek near Milner	518	1990	0.01	19.8	1.5
41	Walton Creek near Steamboat Springs	109	2161	0.03	18.3	1.5
42	Burgess Creek near Steamboat Springs	7.8	2225	0.05	9.1	1.2
43	Spring Creek near Steamboat Springs	18	2195	0.03	16.8	0.9
44	Soda Creek near Steamboat Springs	52	2057	0.01	13.7	1.2
45	Butcherknife Creek near Steamboat Springs	10	2134	0.02	10.7	0.9
46	Fish Creek near Steamboat Springs	62	2188	0.04	12	1.2
	Fish Creek near Steamboat Springs 1995 peak				13.7	0.8
	Fish Creek near Steamboat Springs 1995 peak					
						Elkhead Creek
47	Elkhead Creek downstream U.S. Highway 40 near Craig	645	1905	0.003	15.2	2.7
	Elkhead Creek downstream U.S. Highway 40 near Craig—1995 peak				15.2	2
	Elkhead Reservoir (1995 peak outflow)					
48	Elkhead Creek downstream Elkhead Reservoir total	634	1907	0.002	70.1	
	Elkhead Creek downstream Elkhead Reservoir—LB				45.7	0.6
	Elkhead Creek downstream Elkhead Reservoir—MC				15.2	2.1
	Elkhead Creek downstream Elkhead Reservoir—RB				9.1	0.9
49	Brown Gulch near Craig	2.3	1948	0.01	3	0.6
50	Wadell Gulch near Craig	4.7	1957	0.01	9.1	0.6
51	Little Cottonwood Creek near Craig	2.1	1996	0.01	3	0.3
52	Cottonwood Gulch near Craig	5.4	1987	0.01	3	0.6
53	Long Gulch at County Road 18 near Craig	5.2	2012	0.01	3	0.8
54	Long Gulch at County Road 29 near Craig	5.7	1996	0.01	3	0.9
55	Long Gulch tributary at County Road 18 near Craig	2.3	2012	0.01	3	0.5
56	Long Gulch at County Road 36 near Craig	18	1914	0.01	3	0.9
57	Elkhead Creek upstream Elkhead Reservoir	443	1954	0.01	18.3	2.1
58	Calf Creek near Craig	30	2015	0.01	6.1	1.8
59	Elkhead Creek at County Road 56 near Craig	246	2015	0.01	18.3	1.5
60	Elkhead Creek downstream North Fork Elkhead Creek 1	231	2076	0.02	15.2	1.8
61	Elkhead Creek downstream North Fork Elkhead Creek 2 total	231	2073	0.01	26.2	
	Elkhead Creek downstream North Fork Elkhead Creek 2—MC				12.2	1.7
	Elkhead Creek downstream North Fork Elkhead Creek 2—OB				14	0.5
						Elk River
62	Slate Creek near Milner	3.6	2085	0.02	3	0.6
63	Hot Spring Creek near Mad Creek	25	2042	0.01	6.1	1.2
64	Mad Creek near Mad Creek	97	2057	0.02	21.3	1.4
65	Big Creek near Mad Creek	98	2060	0.02	12.2	1.4
66	Elk River at Clark at gage	559	2213	0.01	30.5	2
67	Willow Creek near Elk Ridge	189	2256	0.01	15.2	1.5
68	Willow Creek downstream Steamboat Lake	130	2408	0.01	10.7	1.5
69	Hahns Peak tributary near Hahn's Peak	0.8	2694	0.01	1.2	0.6
70	Willow Creek downstream Hahns Peak Lake	18	2484	0.01	6.1	1.2
71	Willow Creek tributary near Hahn's Peak	6.5	2493	0.01	2.4	0.9
72	Ways Gulch at Hahn's Peak	6.5	2460	0.01	3	0.8
73	Elk River at Elk Ridge	275	2268	0.01	19.8	2.4
74	Hinman Creek near Elk Ridge	35	2316	0.01	7.6	0.9
75	Coulton Creek near Elk Ridge	12	2310	0.01	6.1	0.9
76	Elk River near Hinman Campground	259	2329	0.01	18.3	2.1
77	North Fork Elk River at Middle Fork	104	2435	0.02	12.2	1.8
78	Middle Fork Elk River upstream North Fork	54	2451	0.01	15.2	1.2
79	Elk River near Milner	1070	2045	0.01	52.9	1.8
	Elk River near Milner 1997 peak	1075	2009	0.003	38.0	1.6
	Elk River near Milner 1997 peak	1075	2009	0.003		
						Little Snake
80	King Solomon Creek near Columbine	30	2576	0.01	6.1	1.2
81	Independence Creek near Columbine	6.5	2621	0.01	3	0.9
82	Independence Creek tributary near Columbine	1.3	2624	0.02	2.4	0.6
83	Hahns Peak tributary to Independence Creek	0.8	2688	0.1	2.4	0.3
						White River
84	Piceance Creek at Rio Blanco	23	2219	0.01	10.7	0.6

Velocity, m s^{-1}	Q, m^3 s^{-1}	Q_{gage} Difference, %	Q, %	Q/A, m^3 s^{-1} km^{-2}	D_{bed}, mm	D_{FB}, mm	Type	RD Method	Age, years	Reliability, years	Remarks[a]
Yampa River											
1.2	11										1
1.8	38			0.3			HWM				1
	37		25	0.3			FB, HWM				
2.1	30										1
1.2	7										1
1.5	3		30	1.4			NI	S8, W9, M7, B6	100	1000	1, 2, 4
2.1	64		25	0.1			FB, NI	S6, W6, M8, L8, B7	1000	1000	1, 2
3.8	105		25	1	914	305	FB, NI	S8, W9, M9, L10, B8	9000	±2000	1, 2
3	34		25	4.4			FB, NI	S7, W9, M9, L9, B6	6000	±1000	1, 2
2.4	37		25	2.1			FB, NI	S8, W9, M9, L10, B7	6000	±1000	1, 2
2.7	46		25	0.9			FB, NI	S8, W9, M9, L10, B8	6000	±1000	1, 2
2.4	24		25	2.3			FB, NI	S7, W9, M9, L8, B7	6000	±1000	1, 2
3.1	45		25	0.7	1067	305	FB, NI	S8, W9, M9, L10, B8	9000	±2000	1
2.4	25	4.2					HWM				
	24						gage				
Basin											
3	127		30	0.2	305	152	FB, NI	S8, W9, M9, B7	5000	±1000	1
1.8	55	−6.8					HWM				1
	59						gage				
	135		30	0.2			FB, NI	S8, W9, M9, B7	5000	±1000	
1.5	42										1
2.4	79				305	76					1
1.5	13										1
2.1	4		30	1.7			NI	S6, W7, M6, L4, B8	100	1000	1, 2, 4
2.1	12		30	2.6			NI	S6, W7, M5, L3, B8	100	1000	1, 2, 4
1.5	1		30	0.7			NI	S8, W7, M6, L5, B5	100	1000	1, 2, 4
2.1	4		30	0.7			NI	S6, W7, M6, L4, B8	100	1000	1, 2, 4
1.5	4		30	0.7			NI	S7, W7, M6, L4, B6	100	1000	1, 2, 4
1.5	4		30	0.7			NI	S5, W7, M6, L4, B5	100	1000	1, 2, 4
1.8	3		30	1.1			NI	S6, W7, M6, L4, B8	100	1000	1, 2, 4
2.4	7		30	0.4			NI	S6, W7, M6, L4, B7	100	1000	1, 2, 4
2.4	95		30	0.2	610	152	FB, NI	S9, W9, M8, L8, B10	8000	±2000	1, 2
2.1	24		30	0.8			NI	S6, W7, M6, L4, B9	1000	±500	1, 2
3.1	85		25	0.3	762	260	FB, NI	S9, W7, M6, L8, B8	5000	±1000	1, 2
3	85		30	0.4	914	254	FB, NI	S8, W7, M8, L8, B9	5000	±1000	1
	95		30	0.4							
3.9	81				762	152	FB, NI	S6, W8, M9, L4, B8	5000	±1000	1
2	14										
Basin											
2.1	4		30	1.1			FB, NI	S6, W7, M6, B8	500	1000	1, 2, 4
2.4	18		25	0.7			FB, NI	S9, W9, M8, L9, B9	8000	±2000	1, 2
2.4	71		25	0.7	914	305	FB, NI	S7, W8, M9, L10, B7	8000	±2000	1
2.4	41		25	0.4	762	305	FB, NI	S8, W7, M6, L8, B9	8000	±2000	1
4.4	268		25	0.5	762	381	FB, NI	S9, W9, M9, L9, B9	9000	±2000	1
2.7	64		30	0.3			FB, NI	S7, W8, M7, L9, B8	7000	±2000	1, 2
2.1	35		30	0.3			FB, NI	S6, W8, M9, L7, B9	5000	±1000	1, 2
1.8	1		30	1.7			FB, NI	S6, W7, M6, L4, B9	1000	1000	1, 2
2.1	16		30	0.9			NI	S5, W7, M8, L8, B8	1000	1000	1, 2
2.1	5		30	0.7			FB, NI	S5, W7, M6, L4, B6	1000	1000	1, 2, 4
1.8	4		30	0.7			FB, NI	S4, W8, M6, L8, B9	1000	1000	1, 2, 4
3	147		30	0.5			FB, NI	S8, W7, M7, L10, B8	7000	±2000	1, 2
2.4	17		25	0.5			FB, NI	S9, W8, M9, L8, B8	7000	±2000	1, 2
2.4	14		25	1.1			FB, NI	S8, W8, M6, L7, B9	6000	±1000	1, 2
3	119		25	0.5	1524	254	FB, NI	S9, W7, M8, L9, B8	8000	±2000	1
3	68		25	0.7			FB, NI	S7, W8, M9, L10, B7	8000	±2000	1, 2
2.7	51		30	0.9			FB, NI	S6, W7, M6, L7, B8	8000	±2000	1, 2
2.5	238		30	0.2			FB, NI	S6, W8, M9, L7, B9	5000	±1000	2
3	182	11.7	25	0.2			HWM				2
	163						gage				
River Basin											
2.1	16		30	0.5			FB, NI	S8, W7, M9, L7, B8	5000	±1000	1, 2
1.5	4		30	0.7			FB, NI	S6, W6, M7, L8, B7	5000	±1000	1, 2
1.5	2		30	1.8			FB, NI	S8, W7, M7, L7, B9	5000	±1000	1, 2
1.8	1		30	1.7	305	76	FB, NI	S5, W7, M6, L8, B6	3000	±1000	1
Basin											
2.1	14		30	0.6			NI	S5, W7, M4, L5, B4	500	1000	1, 2, 4

Table 2. (continued)

Site	Stream	DA, km^2	Elevation, m	S, $m\ m^{-1}$	Width, m	Depth, m
						White River
85	Sheep Creek near Meeker	49	1905	0.01	7.6	1.5
86	Flag Creek near Meeker	135	1920	0.01	9.1	1.5
87	White River near Meeker	2093	1905	0.003	45.7	2.4
	White River near Meeker 1995 peak	2093	1905		41.1	1.7
	White River near Meeker 1995 peak	2093	1905			
88	Curtis Creek near Meeker	41	1948	0.01	9.1	0.9

Abbreviations are as follows: S is estimated water slope at site. Percent difference is Q_{gage} percent difference of 1995 peak discharge estimated using paleoflood techniques from high-water marks and at the streamflow-gaging station independently obtained from a well-defined stage-discharge relation. $Q\%$ is estimated total uncertainty of paleoflood discharge estimate given in percent. Q/A is unit discharge. D_{bed} is maximum particle size on the streambed available for transport. D_{FB} is maximum particle size transported to the flood bar. Type is type of evidence used to determine peak discharge. FB is bouldery flood bar, NI is noninundation surface, HWM, high-water mark, and GAGE is streamflow-gaging station. RD method is the method used which considers degree of soil development (S), surface-rock weathering (W), surface morphology (M), lichenometry (L), and boulder burial (B), although not all methods could be used at each site. Numerical values from Table 1 are listed for each RD method. Age is the composite age for the paleoflood record length. Reliability is the estimated uncertainty of composite age; positive value only indicates age may be longer by this amount. Abbreviations with streams are as follows: DA, drainage area; MC, main channel; OB, overbank; and LB, left bank.

[a]Definitions of numerals are as follows: 1, no substantial flooding on floodplain; 2, water too deep to estimate particle size or unavailable; 3, flood caused by dam failure; and 4, underfit stream.

here in attempting to identify the paleoflood record length for the largest flood during the Holocene, such uncertainties can be addressed in the EMA flood-frequency analyses.

Soil development, boulder weathering, and surface morphology seemed to have the best consistency (Table 2) and thus potential for assigning ages either individually or combined. Available soil and surficial geology reports for the study area [*Soil Conservation Service*, 1982; *Madole*, 1982, 1989, 1991b, 1991c; *Natural Resources Conservation Service*, 2000] were helpful in assigning ages, particularly for NI surfaces. However, near-stream alluvial deposits with extensive soil development sometimes were mapped as fresh alluvial deposits. This was attributed to the fact that the primary purpose of soil surveys is the determination of agricultural productivity or building site potential. Thus floodplains may have received less attention during mapping. Boulder burial had a fair consistency in the study area. However, it appeared to have more variability; because compared to boulder burial data in the Front Range of Colorado [*Waythomas and Jarrett*, 1994], there is usually much more fines deposited around the cobble and bouldery material during flooding. Thus there is some "age" immediately after flooding. Lichenometry, while having poten-

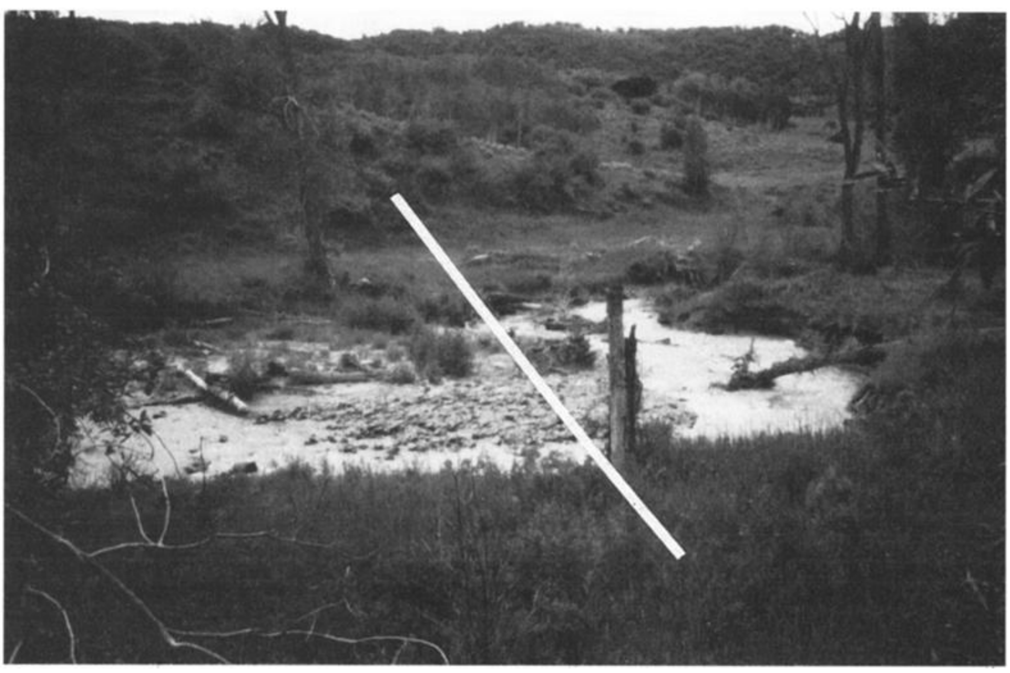

Figure 6. Small, low-relief, flood-bar deposits define the maximum paleostage indicator (PSI) for Elkhead Creek downstream from North Fork Elkhead Creek. The view is downstream and toward the left bank; line denotes location of cross section in Figure 7. Well-developed alluvial and colluvial soils (Table 2) on the valley floor define the noninundation surface for the maximum PSI range. Paleoflood discharge is 85 $m^3\ s^{-1}$ ($\pm25\%$) in about 5000 years (±1000 years).

(continued)

Velocity, m s^{-1}	Q, m^3 s^{-1}	Q_{gage} Difference, %	Q, %	Q/A, m^3 s^{-1} km^{-2}	D_{bed}, mm	D_{FB}, mm	Type	RD Method	Age, years	Reliability, years	Remarks[a]
Basin											
2.4	28		30	0.6			NI	S9, W5, M6, L4, B8	100	1000	1, 2
2.1	30		30	0.2			NI	S8, W7, M6, L7, B9	100	1000	1, 2, 4
3.1	340		25	0.2			FB, NI	S8, W9, M8, L7, B9	5000	±1000	1, 2
2.3	158	5.3					HWM				
	150						gage				
2.4	20		30	0.5			NI	S5, W8, M6, L5, B7	100	1000	1, 2, 4

tial for dating recent flood surfaces, reveals the least information because of numerous factors affecting lichen growth. These factors made it difficult to estimate relative ages, and the method is likely limited to ages considerably less than 3000 years for most of the study area. The weathering of flood boulders and lichen colonization of boulder surfaces may be complicated by the effects of forest and range fires [*Birkeland*, 1984; *Bierman and Gillespie*, 1991]. If the outer part of the boulder spalls after a fire, the boulder weathering "clock" is essentially reset, and rock-weathering features record the time elapsed since the last episode of fire. If spall evidence is present, then rock-weathering and lichen-cover data provide only minimum age estimates. No spalled surfaces on rocks or spall detritus was evident at sites in the study area. Age reliability (ranges) for alluvial channels with arroyo development (e.g., site 24 in Table 2) is an estimate of the conservative age. Because of the scope of this investigation, use of field soil morphology and development indexes [*Bilzi and Ciolkosz*, 1977; *Burke and Birkeland*, 1979; *Meixner and Singer*, 1981; *Harden*, 1982] were not used, but they could provide better age control.

No evidence of substantial flooding was found in any investigated stream in Elkhead Creek basin or streams in the northwestern Colorado study area. If substantial flooding were common in the study area, evidence should be present. The maximum paleoflood discharge for four sites in Elkhead Creek upstream from Elkhead Reservoir ranged from 79 to 95 m^3 s^{-1} (sites 57, 59, 60, and 61 in Table 2). Considering the estimated total uncertainty associated with each paleoflood discharge ("Q, %" in Table 2), the best estimate is 85 m^3 s^{-1} ± 25% in about 5000 years (±1000 years). No tree scarring or flood-transported woody debris was identified on floodplain surfaces, except associated with the Sage Creek Dam failure flood near Hayden (sites 22 and 23 in Table 2) and in lowland areas along the lower Elkhead Creek and Yampa River downstream from about Milner. The peak discharge resulting from failure of the dam was about 175 m^3 s^{-1} (average for sites 22 and 23), which provides an analog for PSIs for a large flood in the study area. Local residents reported that the dam failed in the mid-1980s from seepage through the dam and was not related to a meteorologic event. This is supported by the maximum paleoflood data of about 3 m^3 s^{-1} for Sage Creek immediately upstream from the dam (site 21 in Table 2).

Intermittent streams in northwestern Colorado show little evidence of substantial runoff and are underfit streams for the basin size and broad valleys. An underfit stream is one that appears too small to have eroded the valley in which it flows. Valley bottoms are relatively broad and completely covered with native grasses and often have well-developed soils. It is unlikely that a channel could undergo degradation and aggradation without leaving any evidence such as terraces and without showing evidence of substantial age (thousands of years) on the valley floor. A lack of channel development is due to (1) little seasonal snowpack [*Doesken et al.*, 1984] and thus relatively little snowmelt runoff versus high mountain streams and (2) the basin location above the elevation for substantial rainfall runoff.

It is particularly noteworthy that for many channels having coarse-grained bed material, these sediments have not been mobilized and deposited as flood bars and slack-water deposits. Data on maximum particle size in the channels (D_{bed}) and on flood bars (D_{FB}) presented in Table 2 help demonstrate lack of flow competence. In all but the very fined-grained channels, the largest particles in flood bars are smaller than particles available for transport in the channels, suggesting that large floods have not occurred during the Holocene. The few in-channel bars that exist are small, have low relief, and particle sizes of cobble or smaller, and suggest insufficient flow to mobilize readily available streambed material (Figures 6 and 7). Similarly, for fine-grain material streams the in-channel bars also are poorly developed and exhibit low relief. Coarse material in the streambed of many streams in northwestern Colorado (derived from conglomerate, basalt, and Precambrian rocks) is slightly reworked glacial outwash gravel (e.g., Figure 6). Had substantial flooding taken place, coarse streambed material would be transported onto the floodplain [e.g., *McCain et al.*, 1979; *Jarrett and Costa*, 1988; *Jarrett*, 1990b; *Waythomas and Jarrett*, 1994] such as shown in Figures 3 and 4, which would be preserved until a larger flood emplaced higher deposits.

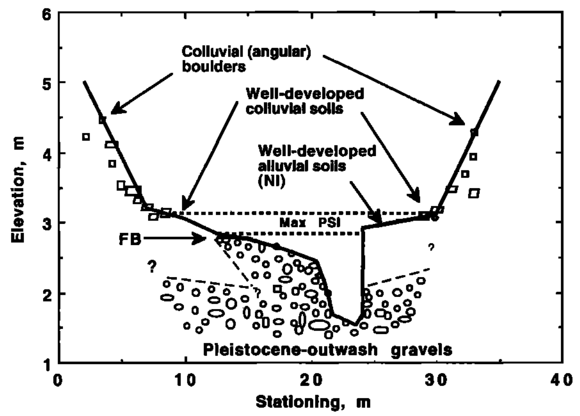

Figure 7. Graph of channel cross section for Elkhead Creek downstream from North Fork Elkhead Creek shown in Figure 6.

During on-site visits, peak discharge using 1995 HWMs also was estimated for seven sites at streamflow-gaging stations (Table 2, type is "gage"). These estimates using the critical-depth and slope-conveyance methods were compared to the peak discharge for 1995 obtained from gage records to help assess the accuracy of paleodischarge estimation methods. The estimated discharges generally are within about 10% of the gaged discharge (Table 2, "Q" and "Q_{gage} Difference" columns) thus showing that the methods used to estimate paleoflood discharge are reliable. However, additional sources of uncertainties (e.g., channel change) are more difficult to quantify. Attempts to estimate other uncertainties in discharge are reflected in terms of discharge uncertainty (Table 2, "Q, %" column) and age (Table 2, age).

Paleoflood estimates in bedrock channels generally were assigned an uncertainty of 25%, whereas alluvial channels were assigned an uncertainty of 30%. Paleoflood estimates in alluvial channels with minor arroyo development, though the age of NI surfaces are very old, were assigned an age of 100 years to account for historical arroyo development. Additional confidence in paleoflood estimates is exhibited when multiple sites are used and results are similar. For example, for Elkhead Creek downstream from Elkhead Reservoir, paleoflood estimates ranged from 127 $m^3 s^{-1}$ to 135 $m^3 s^{-1}$ (sites 47 and 48 in Table 2), a difference of about 3%. Similarly, paleoflood estimates along Elkhead Creek upstream from the reservoir increase consistently from 79 $m^3 s^{-1}$ to 135 $m^3 s^{-1}$ with increasing drainage area.

Streams in northwestern Colorado have few coarse flood deposits on the floodplain. Where present, the deposits are either associated with the record snowmelt flooding in 1984, or the deposits are very old (Table 2). The fact that streams in northwestern Colorado have no substantial paleoflood evidence is important, because it indicates the lack of substantial flooding in Elkhead Creek basin is not due to chance. The paleoflood data then were used to help define the regional maximum flooding and for flood-frequency analyses in northwestern Colorado.

5.2. Regional Analyses of Maximum Rainfall and Flood Data

5.2.1. Maximum rainfall. A relation between maximum 24-hour rainfall and elevation for the study area in northwestern Colorado is presented in Figure 8; this relation was constructed from documented rainstorms from about 1900 through 1990 [*Jarrett*, 1990b] and was updated through 1997 with recent data [*McKee and Doesken*, 1997]. Although there has been an extensive program for documenting extreme rainstorms in Colorado, there have been few intense flood-producing rainstorms documented in northwestern Colorado (triangles on Figure 8). The maximum 24-hour rainfall data for 181 stations and bucket surveys in southwestern Colorado also are shown on Figure 8 for comparison to help define the northwestern Colorado region. The maximum 24-hour amount for northwestern Colorado is 82 mm (Meeker). Maximum monthly values for northwestern Colorado only slightly exceed record maximum 24-hour amounts for southwestern Colorado (Figure 8), dramatic evidence of large relative difference in flood-producing rainfall from northwestern to southwestern Colorado. The maximum rainfall amount for southwestern Colorado is about 150 mm in a few hours for Sweetwater Creek (1976) and for Dove Creek in 24 hours (1972) [*McKee and Doesken*, 1997]; these areas are influenced by the flow of moist air from the southwest [*Collins et al.*, 1991]. Maximum 24-hour rainfall in southwestern Colorado is somewhat larger than in northwestern Colorado but is substantially less than the maximum 6-hour rainfall amounts of up to 610 mm in eastern Colorado. Of particular interest in western Colorado, maximum 24-hour precipitation amounts fell as snow and are presented as snow-water equivalent (SWE) (Figure 8, open squares).

A subjective, indirect indicator of the occurrence of intense rainfall and associated flooding is the development of rill (light) and or gully (deep) erosion on hillslopes [*Jarrett*, 1990b; *Jarrett and Browning*, 1999]. Generally, erosion potential increases as slope steepens; steeper slopes usually require comparatively small amounts of rainfall before substantial erosion occurs, although erosiveness also depends on the type of soil,

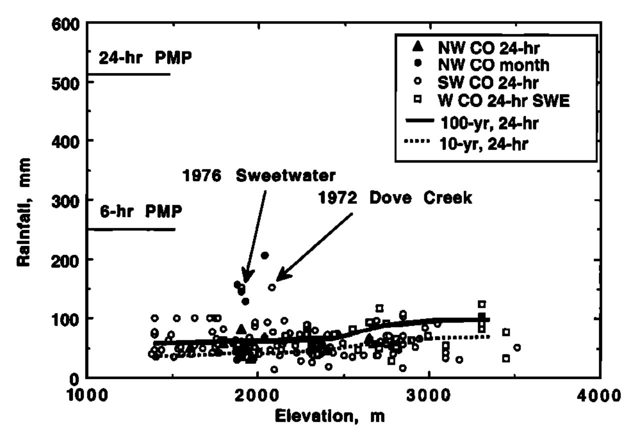

Figure 8. Maximum 24-hour and maximum monthly precipitation for northwestern (NW) Colorado and maximum 24-hour precipitation for southwestern (SW) Colorado [*Jarrett*, 1987, 1990b; *McKee and Doesken*, 1997]. Two of the largest southwestern Colorado rainstorms (Sweetwater Creek and Dove Creek) are noted. It is important to note that numerous large snowstorms reported as snow-water equivalent (SWE) account for some of the largest 24-hour precipitation amounts in all of western (W) Colorado. The 10-year and 100-year, 24-hour duration rainfall amounts [*Miller et al.*, 1973] are shown to place contemporary rainfall data into a frequency context. The 6-hour and 24-hour duration probable maximum precipitation (PMP) values [*Hansen et al.*, 1977] are also shown for comparison.

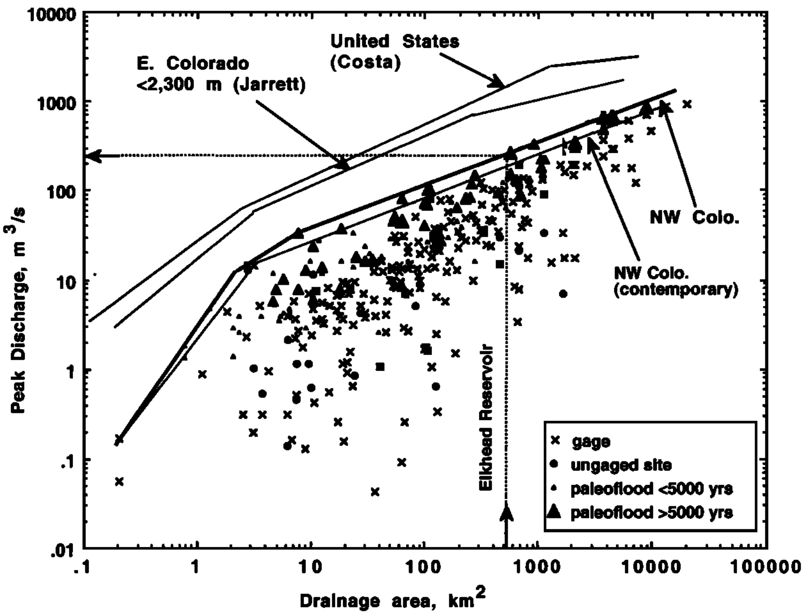

Figure 9. Relation between contemporary and paleoflood peak discharge and drainage area with envelope curves for northwestern Colorado. Envelope curves of maximum flooding for eastern Colorado [*Jarrett*, 1990b] and for the United States [*Costa*, 1987a] are shown for comparison.

vegetation cover, and infiltration rate [*Gilley et al.*, 1993]. For example, as little as 25 to 50 mm of rain in a few hours can produce rill erosion on bare, poorly drained soils on steep slopes [*Hadley and Lusby*, 1967; *McCain et al.*, 1979; *Jarrett*, 1990b; *Jarrett and Browning*, 1999]. Thus a lack of rill erosion is a good indicator that intense rainfall is uncommon or that erosion healing rates are high. Extensive rill and deep gully erosion are common in areas subject to intense rainfall. For example, gullies up to 2 m deep formed on hillslopes in the Big Thompson River basin where rainfall exceeded 150 mm in a few hours during the rainstorm of July 31, 1976 [*McCain et al.*, 1979]. *Jarrett and Browning* [1999] used geomorphic techniques to relate hillslope erosion with rainfall data for an extreme rainstorm on July 12, 1996, in Buffalo Creek, located in the foothills near Denver. Their geomorphic estimated maximum hourly rainfall of 115 mm, which was determined immediately after the storm, compared with 130 mm independently derived in 1998 from Doppler radar signatures and upper air observations [*Henz*, 1998]. Part of the subjectivity in using hillslope erosion is estimating the time rills and gullies remain [*Jarrett and Browning*, 1999]. Rill and gully networks formed during extreme rainstorms such as in 1965 and 1976 in eastern Colorado [*McCain et al.*, 1979; *Matthai*, 1969] and west central Colorado [*Jarrett*, 1990b] have changed little in the intervening years. Conversely, in regions of the Rocky Mountains not subject to intense rainfall, there is a general sparsity of hillslope erosion evidence on slopes where evidence should have been preserved had large rainstorms occurred.

On-site inspection indicated that rills and gullies are small or nonexistent in basins above about 2000 m in northwestern Colorado. Lack of rilling throughout such a large area provides additional supporting evidence of the absence substantial rainstorms in recent times. Hillsides having sparse vegetation and comprised of sand or finer-grained soils such as in Piceance Creek and Yellow Creek basins have rill and gully erosion, but these basins are in the far southwestern part of the regional study area. However, no hillslopes have gully development similar to basins at lower elevations in eastern Colorado that are subject to large, intense rainstorms.

Rainfall-frequency relations developed for Colorado [*Miller et al.*, 1973] can be used to assess the frequency of contemporary rainfall data. Superimposed on Figure 8 are the 10-year and 100-year, 24-hour duration rainfall frequency relations developed from *Miller et al.* [1973] along an east-west transect from the crest of the Park Range to Maybell. For comparative purposes the 6-hour and 24-hour PMP estimates for Elkhead Reservoir are shown on Figure 8. *Hansen et al.* [1977, Figure 5.7] compared the ratio of the 24-hour PMP estimates to 100-year, 24-hour rainfall frequency estimates for the western United States (e.g., for Colorado using *Miller et al.* [1973]); they suggest reasonable ratios between 2.8 and 5. For Elkhead Reservoir the ratio is 8.4 (510 mm/61 mm). Although there may be some uncertainty in estimating rainfall frequencies, the ratio adds further support to the conclusion that PMP estimates for the Colorado Rockies may be too large. High mountain barriers (Figure 1) reduce the available atmospheric moisture from the Pacific and Gulf of Mexico to northwestern Colorado [*Tomlinson and Solak*, 1997].

5.2.2. Maximum flooding. Records from 198 streamflow-gaging stations in northwestern Colorado, primarily in the Yampa River and White River basins, were analyzed; some have peak-flow data since the early 1900s. These gages are fairly uniformly distributed in the study area. To help define the maximum flood potential for northwestern Colorado, flood data from 20 ungaged sites that define maximum flooding from intense, localized rainstorms in northwestern Colorado [*Jarrett*, 1987, 1990b; data available at http://waterdata.usgs.gov], also were incorporated into the database. Maximum peak discharge is 940 $m^3 s^{-1}$, drainage areas ranged from 0.21 to 19,840 km^2, gage elevation ranged from 1595 to 3200 m, and there were a total of 3512 station years of record. A relation of maximum discharge, including paleoflood data, and drainage area with the envelope curve for northwestern Colorado is shown in Figure 9. The largest gaged rainfall-produced flood of 190 m^3

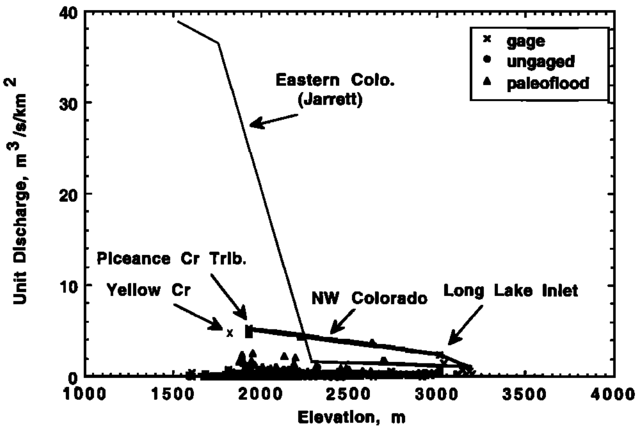

Figure 10. Relation between maximum unit discharge and elevation with envelope curve for northwestern Colorado and eastern Colorado [*Jarrett*, 1990b].

s^{-1} occurred in Yellow Creek near Rangley (streamflow-gaging station 09306255, drainage area of 679 km^2). This flood was a hyperconcentrated flow that resulted from a localized rainstorm storm over less than about 50 km^2 of the steep, sparsely vegetated basin (U.S. Geological Survey, unpublished data, 1978). For rivers draining higher mountain areas in the study area, peak flows are dominated by snowmelt runoff. For comparison, the envelope curves for streams below 2300 m in eastern Colorado [*Jarrett*, 1990b] and for the United States [*Costa*, 1987a] also shown on Figure 9 help demonstrate the lower-magnitude flooding in northwestern Colorado. Maximum flooding in eastern Colorado is about 3 times larger than for similarly sized streams ($>\sim 3$ km^2) in northwestern Colorado. Maximum flooding in eastern Colorado streams is slightly smaller than maximum flooding in the United States (Figure 9).

The envelope curve (Figure 9) of maximum flooding can be used to estimate the hypothetical maximum flood for Elkhead Creek at Elkhead Reservoir. For a drainage-basin size at the reservoir (531 km^2) the corresponding maximum flood is about 240 m^3 s^{-1}. The maximum paleoflood estimate of 135 m^3 s^{-1} (Table 2, site 48) for Elkhead Creek downstream from Elkhead Reservoir is 56% of the envelope curve value.

The maximum unit discharge for streams in northwestern Colorado (Figure 10) is 5.2 m^3 s^{-1} km^{-2} for Piceance Creek tributary (2.8 km^2) near Rio Blanco (streamflow-gaging station 09306042) resulting from a localized rainstorm [*Jarrett*, 1987]. Four other small streams have had unit discharges greater than 3 m^3 s^{-1} km^{-2} resulting from intense, localized rainfall (Figure 10). The largest unit discharge in the highest mountains in the Park Range (Long Lake Inlet, Figure 10) is located in the area of maximum snowfall and represents maximum snowmelt runoff in northwestern Colorado. For comparison, maximum unit discharge is about 38 m^3 s^{-1} km^{-2} for small streams ($<\sim 10$ km^2) below 2300 m in eastern Colorado; the envelope curve for eastern Colorado is provided for comparison [*Jarrett*, 1990b]. Such a small maximum unit discharge in northwest Colorado is significant in that the storm occurred in the Yellow Creek and Piceance Creek basin where steep hillslopes with sparse vegetation exacerbate runoff. Although maximum unit discharge gradually decreases with elevation in northwestern Colorado (Figure 10), the decrease is much more pronounced in eastern Colorado, where lower elevations are subject to extreme rainstorms (intensity, amount, and size) and thus severe flooding. Above about 2300 m in northwestern Colorado, unit discharges are slightly higher than east of the Continental Divide, which reflects the maximum snowmelt runoff from the Park Range.

5.3. Flood-Frequency Analysis

Flood-frequency relations with EMA for selected streams in northwestern Colorado (Table 3) were developed using the recorded annual peak-flow data and paleoflood data (Table 2). Flood-frequency analyses were done using the paleoflood discharge, which was varied by the estimated uncertainty (e.g., site 61 in Table 2, 95 m^3 s^{-1} $\pm$ 25% for the Elkhead Creek gage). The paleoflood record length of time (age) and the age reliability (range) for the maximum paleoflood (Table 2) was used to define the paleoflood record length in the analysis (e.g., 5000 $\pm$ 1000 years for the Elkhead Creek gage).

Because regional skew estimates [*Interagency Advisory Committee on Water Data*, 1981] were developed over 30 years ago and do not incorporate paleoflood data, two EMA runs were made. The first EMA runs used station skew (Table 3). Then, to assess if regional skew may affect results, station skews (Table 2) were reviewed to assess if regional skew relations with station drainage area, period of record (station and paleoflood record length), and gage elevation. There were no statistically significant relations, perhaps because of using only eight stations, homogeneity of the study area, or the narrow range of skew about zero (-0.15 to $+0.17$) for these sites, which suggests paleoflood data may provide a stable at-site skew. Therefore a second set of EMA runs was made using the arithmetic average of the at-site skew values as a regional skew (-0.03) (Table 3), which is essentially a lognormal distribution, and these are considered the preferred curves.

The 95% confidence limits were approximated using the B17B approach. Confidence limits only reflect parameter and peak discharge uncertainties; uncertainties such as best model, representative data, proper identification of censoring thresholds, and selection of proper skew are more difficult to quantify and were not included. In addition, the effects of climate change (natural or anthropogenic) may be the greatest source of uncertainty, and they are difficult to quantify [*NRC*, 1999]. Thus confidence limits do not reflect the total uncertainty in the frequency analysis (limits are too narrow), but no method is currently available to make such an assessment.

Estimated flood quantiles listed in Table 3 for the eight streamflow-gaging stations reflect the average age and average discharge for the maximum paleoflood (Table 2). Flood-frequency relations for EMA for Elkhead Creek near Elkhead incorporating paleoflood data (the rectangle brackets the likely range of discharge and age for the maximum paleoflood) and station skew are shown on Figure 11. EMA results using the regional (average) skew of -0.03 also are listed in Table 3 and shown on Figure 11. It is not surprising that EMA frequency relations using the regional skew are not that different from the station relations (-4% difference for the 10,000-year flood in Table 3) because the at-site skew values have small variation.

A flood-frequency relation is needed at Elkhead Reservoir; however, there is no streamflow-gaging station close enough to the reservoir to transfer (scale) the gaged frequency estimates with the commonly used drainage-area ratio approach [*Hosking and Wallis*, 1997]. Regional flood-frequency relations available for western Colorado were developed by *Kircher et al.*

Table 3. Flood-Frequency Analyses for Selected Streams in Northwestern Colorado

Stream	Station/ Source	Gage Record, years	Drainage Area, km^2	Elevation, m	Skew, log	2 Years $m^3 s^{-1}$	10 Years $m^3 s^{-1}$	50 Years $m^3 s^{-1}$	100 Years $m^3 s^{-1}$	500 Years $m^3 s^{-1}$	1000 Years $m^3 s^{-1}$	10,000 Years $m^3 s^{-1}$	EMA at 10,000 Years With Regional Skew, %
Walton Creek near Steamboat Springs	9238500	20	110	2149	−0.04	38	54	67	73	85	90	108	
					−0.03	39	56	68	73	85	101	106	2
Walton Creek near Steamboat Springs	FEMA					38		65	76	159			
Yampa River at Steamboat Springs	9239500	91	1564	2041	−0.12	102	150	188	202	237	251	297	
					−0.03	100	149	188	204	242	257	311	−4
Yampa River at Steamboat Springs	FEMA					102		187	227	566			
Elk River at Clark	9241000	65	559	2215	0.17	76	111	143	157	190	204	256	
					−0.03	79	113	140	152	177	188	224	−14
Elk River at Milner	9242500	21	1075	2009	−0.15	112	150	176	186	208	217	245	
					−0.03	109	146	174	184	208	218	250	−2
Yampa River below diversion near Hayden	9244410	21	3704	1945	−0.11	218	328	416	451	531	565	677	
					−0.03	213	321	410	447	532	568	691	−2
Elkhead Creek near Elkhead	9245000	44	166	2086	0.07	27	44	59	65	78	84	104	
					−0.03	25	42	57	64	79	86	110	−5
Elkhead Creek at Elkhead Reservoir	Kircher et al.		531			23	40	55	61	76	85	105	
Elkhead Creek at Elkhead Reservoir	Ayres		531	1951		27		74	88	164			
Yampa River near Maybell	9251000	85	8832	1798	−0.04	280	422	539	587	699	748	911	
					−0.03	280	422	539	587	699	745	906	1
White River near Meeker	9304500	90	1955	1920	−0.01	90	143	188	208	253	272	340	
					−0.03	91	143	188	207	251	270	336	1
EMA average					−0.03								−4

FEMA is Federal Emergency Management Agency; EMA is expected moments algorithm.

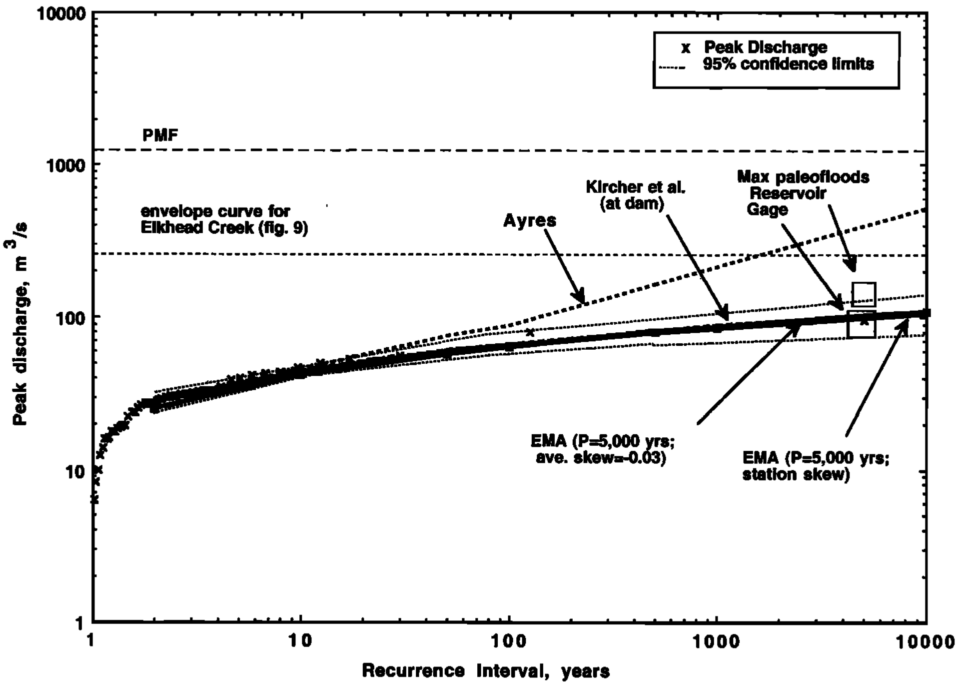

Figure 11. Flood-frequency relations for Elkhead Creek at Elkhead Reservoir [*Kircher et al.*, 1985] with paleoflood data (shown as a rectangle) at the reservoir; near Elkhead gage (0924500) with paleoflood data (shown as a rectangle) using at-site and average skew with 95% confidence limits. *P* denotes the paleoflood length of record. The envelope curve value (Figure 9) for maximum flooding in the Holocene is also shown. The flood-frequency relation and probable maximum flood for Elkhead Reservoir (Ayres Associates, Inc., Fort Collins, Colorado, unpublished data, 1996) are shown for comparison.

[1985] that can be used to estimate these relations at an ungaged site such as Elkhead Reservoir. *Kircher et al.* [1985] developed regression relations for 33 flow characteristics, which include mean annual and mean monthly discharges, flow-duration series, peak discharge, and minimum and maximum 7-day discharges for recurrence intervals from 2 to 500 years. These relations were developed for four hydrologically distinct regions in western Colorado using records from 264 streamflow-gaging stations by relating gage flow characteristics with basin physiographic and climatic explanatory variables. The regression relations developed from 67 gages in northwestern Colorado [*Kircher et al.*, 1985, Table 8], which are a function of drainage area and mean annual precipitation, were used to estimate flood-frequency relation for Elkhead Creek at Elkhead Reservoir. The regional regression relations for northwestern Colorado have a mean standard error estimate of 63% [*Kircher et al.*, 1985].

At Elkhead Reservoir the drainage area is 531 km^2, and the mean annual precipitation for the basin is 635 mm. The flood-frequency relation for Elkhead Creek at Elkhead Reservoir (Figure 11 and Table 3) was estimated using the work of *Kircher et al.* [1985]. The frequency curve in Figure 11 was extended linearly. The 100-year flood estimate for Elkhead Creek is about 61 m^3 s^{-1} at Elkhead Reservoir [*Kircher et al.*, 1985] and compares with 64 m^3 s^{-1} at the gage using EMA (Table 3). The estimated recurrence interval for the maximum paleoflood (135 m^3 s^{-1}) at Elkhead Reservoir is slightly more than 10,000 years (Figure 11) [*Kircher et al.*, 1985], and the 10,000-year flood is about 110 m^3 s^{-1} (Table 3). The 10,000-year flood estimate is 104 m^3 s^{-1} at the Elkhead gage (Table 3). The flood-frequency relation for the Elkhead Creek gage (Figure 11 and Table 3), which has about 30% of the drainage area at the reservoir, is similar to the regional relation. The similarity of the relations are likely because the majority of the basin between the gage and the reservoir contributes little additional peak runoff from snowmelt and rainfall.

Also shown on Figure 11 is the regional envelope value of maximum flooding for Elkhead Reservoir from Figure 9. For comparative purposes the PMF estimate shown for Elkhead Creek at the dam (Ayres Associates Inc., written communication, 1996) is 1020 m^3 s^{-1}, which is 4 times larger than the envelope curve discharge value for Elkhead Reservoir, and the recurrence interval for a flood the magnitude of the PMF exceeds 10,000 years (Figure 11). The maximum paleoflood in the last 5000 years for Elkhead Creek near Elkhead Reservoir is about 13% of the site-specific PMF estimate.

6. Discussion

Paleoflood techniques and rainfall-runoff modeling (including PMP/PMF methods) have inherent assumptions and limitations that produce uncertain flood estimates. Although paleoflood estimates also involve uncertainties, the estimates are based on interpretations of physical data preserved in channels and on floodplains during the past 5000 to 10,000 years in northwestern Colorado. Paleoflood uncertainties primarily are related to possible postflood changes in channel geometry and flood heights interpreted from PSIs. Where possible, paleoflood estimates are obtained in bedrock-controlled channels that minimize changes in channel geometry; there is little evidence that major changes in channel geometry have occurred in alluvial channels in the study area. Because beds of most rivers in the study area are relatively armored with cobble and boulders and floodplain sediments typically are fine-grained but stable for long periods (Table 2), paleoflood reconstructions reflect relatively stable conditions. The HWM-PSI relations developed from recent floods in the western United States [*Jarrett et al.*, 1996], which included several documented 1995 floods in northwestern Colorado, help to reduce the uncertainty of paleodischarge estimates. In addition, when using paleoflood techniques to estimate peak discharge of recent large floods where gaged flood data were available to assess the reliability, the paleoflood estimates were within about 10% of large gaged floods and further document the value of the critical-depth method (Table 2). Therefore paleoflood estimates for this study are believed to have total uncertainties of about 25 to 30%.

The greatest sources of uncertainty on flood variability are natural or anthropogenic climate change (variability) effects. 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) have occurred during the Holocene; however, these effects are reflected in the maximum flood preserved at a site. Paleoflood data where the maximum age during which the flood occurred is at least 5000 years are denoted with large, solid triangles, and small, solid triangles denote a maximum age of less than 5000 years (Figure 9). The envelope curve of maximum flooding incorporating the paleoflood data (Figure 9) is about 20 to 25% larger than contemporary maximum flooding in about the past 100 years since streamflow monitoring began (Figure 9). This modest increase likely is due to the large spatial extent of the database and relatively low-magnitude flooding in northwestern Colorado. Variability in climate and basin conditions during the Holocene does not appear to have had a large impact on flood magnitude, and the assumption of stationarity may be valid for the upper end of the flood-frequency curves in the study area. Thus the envelope curve (Figure 9) probably reflects an upper bound of flooding during the Holocene in northwestern Colorado.

More quantification (e.g., using one-dimensional or two-dimensional hydraulic modeling to calculate paleoflood discharges, using absolute-age dating of flood deposits, more robust flood-frequency parameter estimation procedures, regional flood-frequency analysis with paleoflood data, etc.) would improve the accuracy of individual paleoflood estimates and better quantification of uncertainties. However, the interpretation that no substantial flooding has occurred during the Holocene in northwestern Colorado, including Elkhead Creek, would not differ. While use of complex procedures might provide a more precise quantitative description of the data, discharge and frequency estimates of extreme floods in a basin may be readily estimated by the paleoflood techniques described above that provide a cost-effective approach.

A critical assumption for calculation of PMP estimates is geographic transposition of storm events from geographically and climatologically similar locations to watershed of interest. However, the *NRC* [1994] cautions that storm transposition and moisture maximization need to be for a slightly different location in the same climatic region. Regional analyses of rainfall, streamflow, and paleoflood data in the present study provide information to evaluate the assumptions about large rainstorms in northwestern Colorado.

The assumption that large rainstorms or rain on snow produce large floods in the Rocky Mountains [*FEMA*, 1976; *Hansen et al.*, 1977, 1988] has implications for dam safety and floodplain management. Although a number of streamflow-gaging stations in the Yampa River basin had over 75 years of record, but no large rainfall floods, these long-term gaged data were assumed not to be representative of extreme flood potential from rainfall by *FEMA* [1976]. Thus the flood hydrology for some studies was based on transposing distant, large rainstorms from Arizona, New Mexico, and southwestern Colorado into northwestern Colorado and using rainfall-runoff modeling to adjust the upper end of the gaged flood-frequency relation [*FEMA*, 1976]. The flood-frequency relation for Elkhead Creek at Elkhead Reservoir developed by Ayres Associates, Inc. (written communication, 1996) (Figure 11 and Table 3) essentially is the same as the flood-frequency relations from this study up to about the 20-year flood. The Ayres relation sharply increases above the 20-year flood, falls outside the confidence limits of the regional flood-frequency relations above the 50-year flood, exceeds the maximum paleoflood for the basin at a recurrence interval of about 150 years, and exceeds the envelope curve value of 250 $m^3 s^{-1}$, which is not reasonable hydrologically.

Similar to Elkhead Creek, the FEMA and gaged flood-frequency relations for the Yampa River at Steamboat Springs (Table 3 and Figure 12), where data collection began in 1904, have good agreement to about the 50-year flood. For larger recurrence intervals the FEMA relation increases sharply and does not fall within the 95% confidence limits for the flood-frequency relation based on streamflow data. In addition, the FEMA 500-year flood is almost double the maximum paleoflood estimate of 311 $m^3 s^{-1}$. The PMF for Stagecoach Reservoir located on the Yampa River upstream from Steamboat Springs (Figure 12) also far exceeds a 10,000-year recurrence interval. Similar results for Walton Creek near Steamboat Springs are listed in Table 3.

The difference for larger recurrence intervals primarily results from transposition of distant rainstorms over basins in northwestern Colorado and then using rainfall-runoff modeling to estimate the upper end of flood-frequency relation as well as the PMF. The gage and paleoflood data provide information that can be used to refine assumptions used to estimate extreme flooding using storm transposition and rainfall-runoff modeling to at least a recurrence interval of 5000 years. The paleoflood data provide no support for sharp upward slope increase of the frequency curve.

To help place the flood and paleoflood data in a regional probabilistic context, the EMA relations (with average/regional skew) for the eight stations (Table 3) were plotted versus drainage area (Figure 13). Although flooding results from several factors (basin slope, precipitation indices, vegetation, etc.) other than drainage area, there is a fairly good relation between gaged sites. In addition, the envelope curve defined by the paleoflood data also can be placed in a probability context.

The site-specific PMP study conducted for the Elkhead Creek drainage basin west of the Continental Divide in northwestern Colorado revisited various issues related to the PMP under the explicit conditions which exist at Elkhead Reservoir and other reservoirs in northern Colorado [*Tomlinson and Solak*, 1997]. These issues included a physical accounting of the effect of topography on storm transpositioning, downslope wind flows under PMP storm conditions, and high-altitude moisture depletion. The combined results of the hydrologic

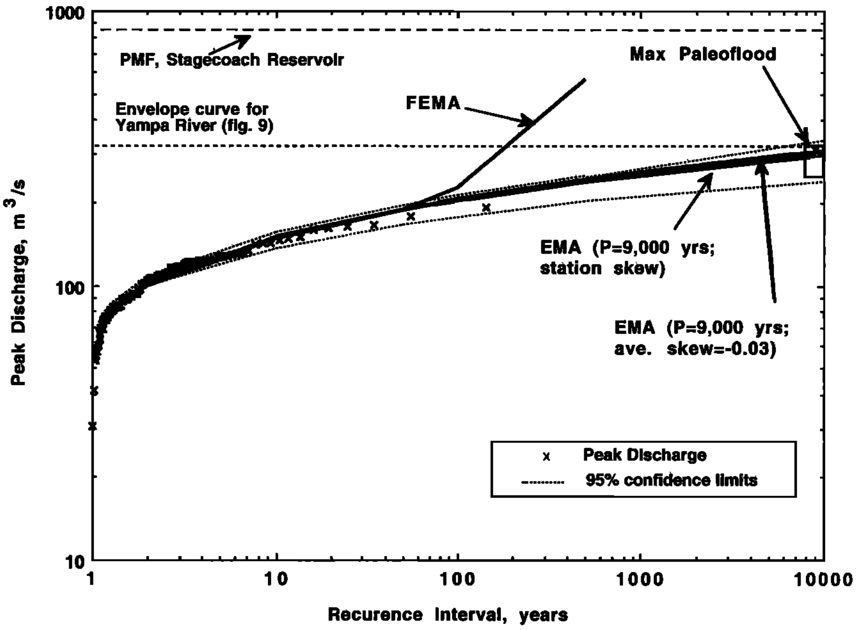

Figure 12. Flood-frequency relations for the Yampa River at Steamboat Springs gage (09239500) and paleoflood data (shown as rectangle) using at-site and average skew with 95% confidence limits. *P* denotes the paleoflood length of record. The envelope curve value (Figure 9) for maximum flooding in the Holocene is also shown. The flood-frequency relation for the Yampa River at Steamboat Springs derived from rainfall-runoff modeling [*Federal Emergency Management Agency*, 1976] and the probable maximum flood for Stagecoach Reservoir on the Yampa River upstream from Steamboat Springs are shown for comparison.

modeling which routed the excess rainfall and snowmelt through Elkhead Reservoir and paleoflood study results showed that the Elkhead Dam would not be overtopped from the site-specific PMP. These results were accepted by the Colorado State Engineer for dam safety certification with no modifications to the existing structure.

7. Conclusions

A regional, interdisciplinary paleoflood approach provides a more thorough assessment of flooding and with site-specific PMP/PMF studies provides dam safety officials with new information to assess extreme flood potential. Interdisciplinary

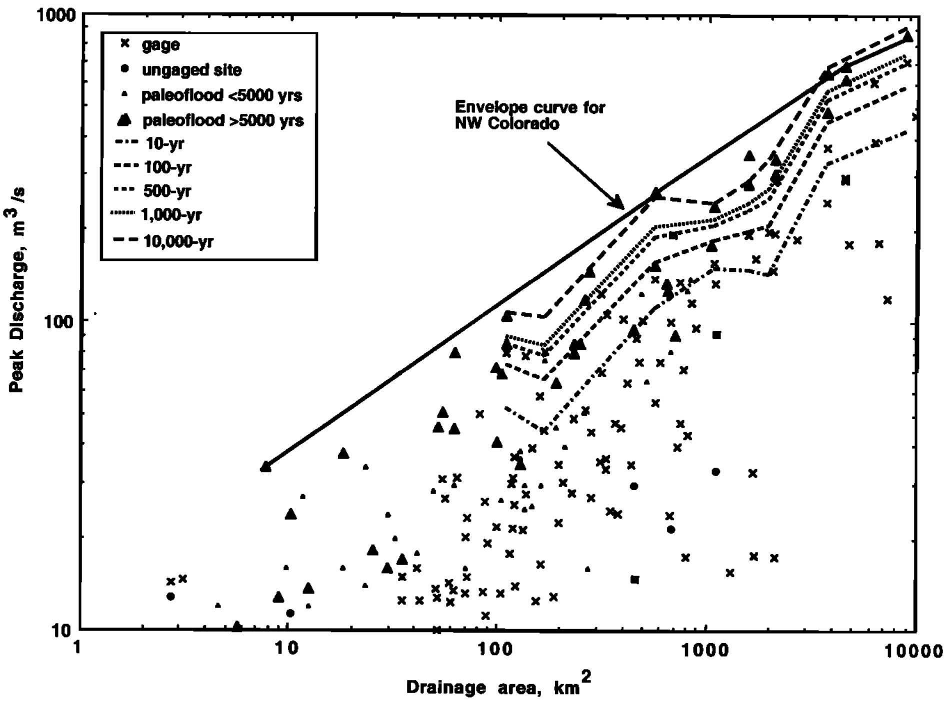

Figure 13. Relation between contemporary and paleoflood peak discharge and drainage area with flood-frequency curves for eight stations (Table 3) superimposed for northwestern Colorado.

components include documenting maximum paleofloods and regional analyses of contemporary extreme rainfall and flood data in a basin and in a broader regional setting. Site-specific PMP studies were conducted to better understand extreme rainfall processes by analyzing the rainstorms with similar hydroclimatic conditions [*Tomlinson and Solak*, 1997]. The approach provides scientific information to help determine the delicate balance between cost of infrastructure and public safety.

The approach was applied to Elkhead Reservoir on Elkhead Creek (531 km^2) near Craig in the Colorado Rocky Mountains. On-site paleoflood investigations to determine maximum paleoflood magnitudes and regional analyses of extreme rainfall and flood data in northwestern Colorado, primarily in the Yampa River and White River basins (10,900 km^2), were conducted. Bouldery flood deposits and slack-water sediments, which are preserved for many thousands of years, were used to estimate flow depth of paleofloods. A variety of relative dating techniques (degree of soil development, surface-rock weathering, surface morphology, lichenometry, and boulder burial) were used to determine the paleoflood record length for paleoflood deposits and noninundation surfaces. Peak discharge for a paleoflood deposit was obtained primarily using the critical-depth method, which had a discharge uncertainty of about 25–30% for most study sites. Maximum paleofloods provide physical evidence of an upper bound on maximum peak discharge for any combination of rainfall or snowmelt runoff in northwestern Colorado in at least the last 5000 to 10,000 years. Envelope curves of maximum rainfall and flood data were developed for contemporary data and for the paleoflood data. Maximum 24-hour rainfall for northwestern Colorado is about 150 mm in about the past 100 years, which provides additional support for the lack of flood and paleoflood evidence. Maximum rainfall and flooding in northwestern Colorado is substantially less than in eastern Colorado, which is subject to some of the most extreme rainfall flooding in the United States. Large floods, if as hypothesized by transposition of large rainstorms into northwestern Colorado, would have left paleoflood evidence in at least one of the streams studied.

The envelope curve of paleoflood data is about 20 to 25% of the envelope curve defined with contemporary data alone. This suggests that effects of climate change and other factors (wildfire and vegetation changes) during the Holocene have not had a dramatic impact on maximum flooding in northwestern Colorado. Flood-frequency analyses were made for eight gages with the expected moments algorithm, which makes better use of historical and paleoflood data. Frequency data were superimposed on the envelope curves to help place the contemporary and paleoflood data and associated envelope curves in a probability context. The maximum paleoflood of 135 $m^3\ s^{-1}$ for Elkhead Creek at Elkhead Reservoir is about 13% of the site-specific PMF of 1020 $m^3\ s^{-1}$. The estimated 10,000-year flood is about 170 $m^3\ s^{-1}$ at Elkhead Reservoir. The lack of substantial rainstorms and flood evidence in northwestern Colorado probably is explained by high mountain barriers, which substantially reduce the available atmospheric moisture from the Pacific Ocean or Gulf of Mexico. The results of the site-specific PMP/PMF study and the regional interdisciplinary paleoflood study showed that Elkhead Dam would not be overtopped from the site-specific PMP. These results were accepted by the Colorado State Engineer for dam safety certification with no modifications to the existing structure.

Changnon and McKee [1986] estimated the cost for modifying just the 162 high-risk dams in Colorado to the PMP standards [*Hansen et al.*, 1988] to be approximately $184 million. This modification cost appears low as the estimated modification cost for proposed modifications of the Cherry Creek dam are as high as $250 million for Cherry Creek dam near Denver, Colorado (U.S. Army Corps of Engineers, written communication, 1997). 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. Thus, given the large differences in maximum paleoflood and PMF values in the Rocky Mountains, it seems prudent to conduct additional hydrometeorologic and paleoflood research to help reduce the uncertainty in estimates of maximum flood potential. This regional interdisciplinary paleoflood approach, which is cost-effective, can be used in other hydrometeorologic settings to improve flood-frequency relations and provide information for a risk-based approach for hydrologic aspects of dam safety.

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