RESULTS OF PALEOFLOOD INVESTIGATIONS FOR SPRING, RAPID, BOXELDER, AND ELK CREEKS, BLACK HILLS, WESTERN SOUTH DAKOTA

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ABSTRACT

Flood-frequency analyses for the Black Hills area are especially important because of severe flooding of June 9–10, 1972, that was caused by a large mesoscale convective system and resulted in at least 238 deaths. This paper summarizes results of paleoflood investigations for six study reaches in the central Black Hills. Stratigraphic records and resulting long-term flood chronologies, locally extending more than 2,000 years, were combined with observed and historical flood information to derive flood-frequency estimates. Results indicate that floods as large as and even substantially larger than 1972 have affected most of the study reaches. Results of the paleoflood investigations provide better physically based information on low-probability floods than has been previously available, substantially improving estimates of the magnitude and frequency of large floods in the central Black Hills and reducing associated uncertainties. Collectively, the results provide insights regarding regional flood-generation processes and their spatial controls, enable approaches for extrapolation of results for hazard assessment beyond specific study reaches, and provide a millennial-scale perspective on the 1972 flooding.

Keywords

Paleoflood, slack-water deposits, stratigraphic records, flood-frequency analyses

INTRODUCTION

Flood-frequency analyses for the Black Hills of western South Dakota are especially important and technically challenging (Sando et al. 2008) because of severe flooding of June 9–10, 1972, along the eastern flanks of the Black Hills (Schwarz et al. 1975). Flooding was caused by a large mesoscale convective system and resulted in at least 238 deaths (Carter et al. 2002). Many 1972 peak flows are high outliers (by factors of 10 or more) in records that date back to the early 1900s for some streamgages.

In appropriate environments, an efficient means of reducing uncertainties regarding probabilities of flood recurrence is to augment observed records by using paleohydrologic techniques (Stedinger and Baker 1987)—typically using stratigraphic and paleobotanical evidence to determine ages and magnitudes of previous large floods predating observed records (paleofloods). This paper provides a condensation of a much lengthier report by Harden et al. (2011) on paleoflood investigations for the Black Hills area that included analyses of stratigraphic evidence, timing, and magnitudes for large floods on Spring Creek, Rapid Creek (two reaches), Boxelder Creek (two subreaches), and Elk Creek. Driscoll et al. (2011) also provided additional information regarding implementation of this study, for which the primary objective was to improve flood-frequency characterization of especially large (low-probability) floods for the six study reaches through paleoflood investigations. Agencies cooperating with the U.S. Geological Survey included the South Dakota Department of Transportation, Federal Emergency Management Agency, city of Rapid City, and West Dakota Water Development District. An abbreviated overview of results of paleoflood investigations for the Black Hills area was provided by Driscoll et al. (2012).

STUDY AREA AND METHODS

The study area (Figure 1) included the Spring Creek, Rapid Creek (two reaches), Boxelder Creek (two subreaches), and Elk Creek drainage basins within the central Black Hills. Long-term frequency analyses were developed from paleoflood investigations within the six study reaches and were based on multiple sites of stratigraphic analysis within each reach in conjunction with geochronology and hydraulic modeling.

The primary evidence for past large floods consists of stratigraphic records formed of fine-grained sediment deposits preserved in slack-water environments. These deposits accumulate and can record multiple floods where (1) velocities are relatively low, which can allow deposition of suspended sediment and (2) conditions are suitable for preservation. Numerous locations in canyons along the eastern flanks of the Black Hills provide excellent environments for (1) deposition and preservation of stratigraphic sequences of late-Holocene flood deposits, primarily in overhanging ledges, alcoves, and small caves flanking the streams, and (2) hydraulic analyses for determination of associated flow magnitudes.

The formation and identification of slack-water deposits is enhanced by igneous and metamorphic rocks of Precambrian and Tertiary age within the headwaters of all study basins (Figure 1). These rocks weather to produce micaceous sand fine enough to be readily entrained during large floods, and thereby creating large suspended-sediment loads, but sufficiently coarse to settle rapidly in slack-water environments producing depositional sequences. Five of the study reaches (all except the reach upstream from Pactola Reservoir along Rapid Creek) are in Paleozoic sedimentary rocks (Ordovician- and Cambrian-age Deadwood Formation through the Permian-age lower Spearfish Formation). Here the distinctly

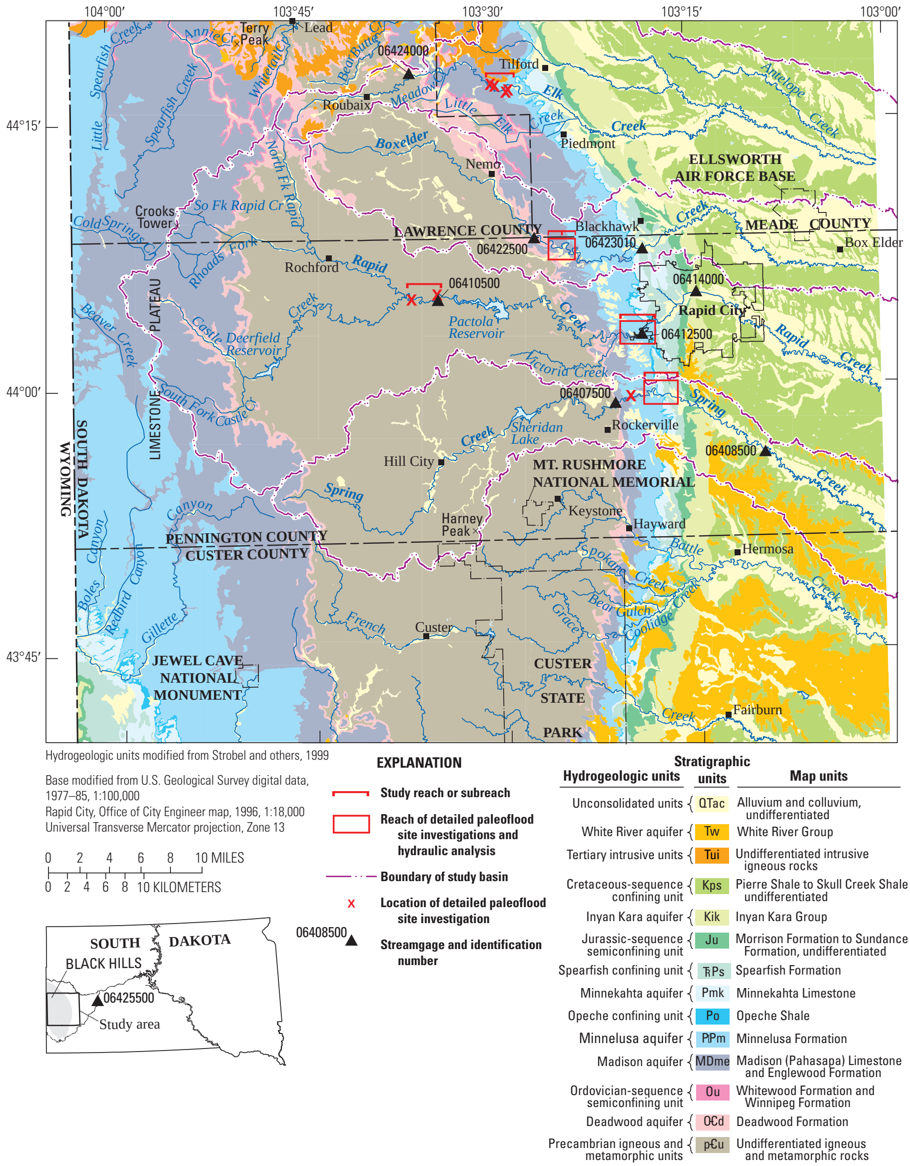


Figure 1. Distribution of hydrogeologic units within the Black Hills area, locations of detailed paleoflood site investigations, and locations of selected streamgages.

micaceous sands derived from the headwater areas are unambiguously distinguishable from deposits of local tributaries, slopewash, or sediment spalling from cave and alcove ceilings and walls, none of which contain mica. Another key aspect is the long-term stability of the channel and valley geometry, providing persistent sites of slack-water deposition and increasing confidence in hydraulic computations of past floods from modern channel geometry. All study reaches are in narrow valleys laterally constrained by steep bedrock slopes where flood stages change markedly with flow, thus improving reliability of flow estimates derived from elevations of flood deposits. Additionally, bedrock formations are exposed locally in channel thalwegs for all study reaches, indicating that streams are flowing on relatively thin alluvial deposits with limited potential for channel scour. An estimated long-term regional erosion rate of 0.08 feet per thousand years (Harden et al. 2011) is consistent with the premise of overall channel stability for the last several thousand years.

The overall approach consisted of (1) interpreting individual chronologies of flood stages from stratigraphic analysis and age dating of slack-water deposits for multiple sites within a study reach; (2) estimating peak-flow magnitudes associated with elevations of flood evidence; (3) interpreting an overall paleoflood chronology for each study reach; and (4) conducting quantitative flood-frequency analyses incorporating all relevant peak-flow information that included the paleoflood information, observed peak-flow records, and historical flood accounts.

Paleoflood chronologies were derived primarily from stratigraphic analysis and age dating of flood slack-water deposits, which are methods now widely used for quantifying unrecorded floods (Baker 1987; Kochel and Baker 1988). In many locations, searches for appropriate sites were guided by visible flood evidence from 1972, which commonly could be distinguished from older evidence based on knowledge of the 1972 flow rate, deposit flotsam (particularly beverage containers, milled wood, and plastic debris), and the degree of weathering of flood deposits or entrained organic material. Stratigraphy was exposed in small pits that typically were excavated through slack-water deposits to either bedrock or large and immovable rockfall. At some sites, several pits were excavated in search for the most complete record. Where possible, stratigraphic sequences were examined at multiple elevations at individual sites, as well as at multiple sites within reaches, in order to more precisely define the history of deposition at different stages.

The stratigraphy provided information on the number of floods and their relative ages, with more recent flood deposits on top of, or inset against, older deposits. Ages of individual flood deposits and the total length of record preserved in the stratigraphy were obtained by standard geochronologic techniques. The primary technique was radiocarbon analysis using carbon-14 (Stuiver and Polach 1977) of organic detritus, including charcoal, wood fragments, bark, pine cones and needles, and rodent fecal pellets that were deposited within and between individual flood deposits. Optically stimulated luminescence (Bradley 1999; Walker 2005) and cesium-137 analyses (Holmes 1998) were used occasionally for dating deposits less than about 300 years old, which cannot be precisely dated by radiocarbon analyses, and for dating deposits with insufficient organic material for radiocarbon dating. For the six study reaches, the stratigraphy and geochronology from analyzed sites were distilled into an interpreted chronology of the number, magnitude, and timing of large floods for each reach.

For computation of long-term flood-frequency analyses, the paleoflood chronologies derived from the stratigraphy and geochronology were combined with observed annual peak-flow records (U.S. Geological Survey 2010) for selected streamgages (Figure 1). These records were compiled and adjusted relative to drainage area to be directly comparable to the paleoflood chronologies determined for each study reach and are referred to as gaged records within this paper. Historical flood accounts pre-dating gaged records also were incorporated in analyses for Rapid Creek and Elk Creek.

A key aspect of any paleoflood record is estimation of flow magnitudes for floods preserved in stratigraphic records. The elevation of a slack-water deposit represents a minimum value for the peak stage of the emplacing flood (Baker 1987; Kochel and Baker 1988). For purposes of hydraulic calculations, stage evidence is related to modern channel and valley geometry, which introduces an additional assumption that changes in geometry have been sufficiently small for the time represented by the stratigraphic record so as to not substantially affect calculations of flow rate. This assumption likely is satisfied in the rock-bound study reaches, where the common presence of bedrock in channels and along valley margins is indicative of overall stability, especially with respect to hydraulic controls on stages of large floods.

The primary method for estimating peak-flow magnitudes was application of the one-dimensional, steady-flow River Analysis System (HEC-RAS) model developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers (2008a, 2008b). Simulations using the HEC-RAS model, in conjunction with detailed topographic data, were used to estimate flows for the study reaches along Spring Creek, Boxelder Creek, and the "lower" reach of Rapid Creek, which is just west of Rapid City and downstream from Pactola Reservoir (Figure1 1). The HEC-RAS model and the required reach-scale topographic datasets were not justified for Elk Creek and the "upper" reach of Rapid Creek (upstream from Pactola Reservoir), where paleoflood evidence was sparser than for other study reaches. Instead, flow estimates were derived by applying the Manning equation (Benson and Dalrymple 1967) or critical-flow equation (Grant 1997) for cross sections at sites of stratigraphic analysis.

Two analytical models with capabilities for incorporating paleoflood data in flood-frequency estimation were applied: (1) the FLDFRQ3 model (O'Connell 1999; O'Connell et al. 2002) and (2) the PeakfqSA model (Cohn et al. 1997, 2001; Griffis et al. 2004). For both models and all reaches, flood-frequency analyses were computed assuming log-Pearson Type III frequency distributions and were performed for two primary flood-record scenarios: (1) analysis of gaged records only; and (2) analysis of all available data, which may include the gaged records, historical flood accounts and associated "perception" thresholds, and paleofloods and thresholds. Analysis for scenario 1 (gaged records only) was conducted as a baseline analysis and provided a basis for comparison of incremental effects when including all available data. Analyses resulting from scenario 2, which include all available data and associated perception thresholds, were considered by Harden et al. (2011) as the best estimates of flood recurrence (flood-frequency estimates) for low-probability floods. Flood-frequency estimates were determined only for recurrence intervals of 25 years or larger (annual exceedance probabilities of 0.04 or smaller, which means a flow with a 4-percent chance of being exceeded in any given year). Results were not reported for smaller recurrence intervals because several study reaches are within "loss-zone settings" described by Sando et al. (2008), and accurate characterization would have required additional analyses beyond the study scope.

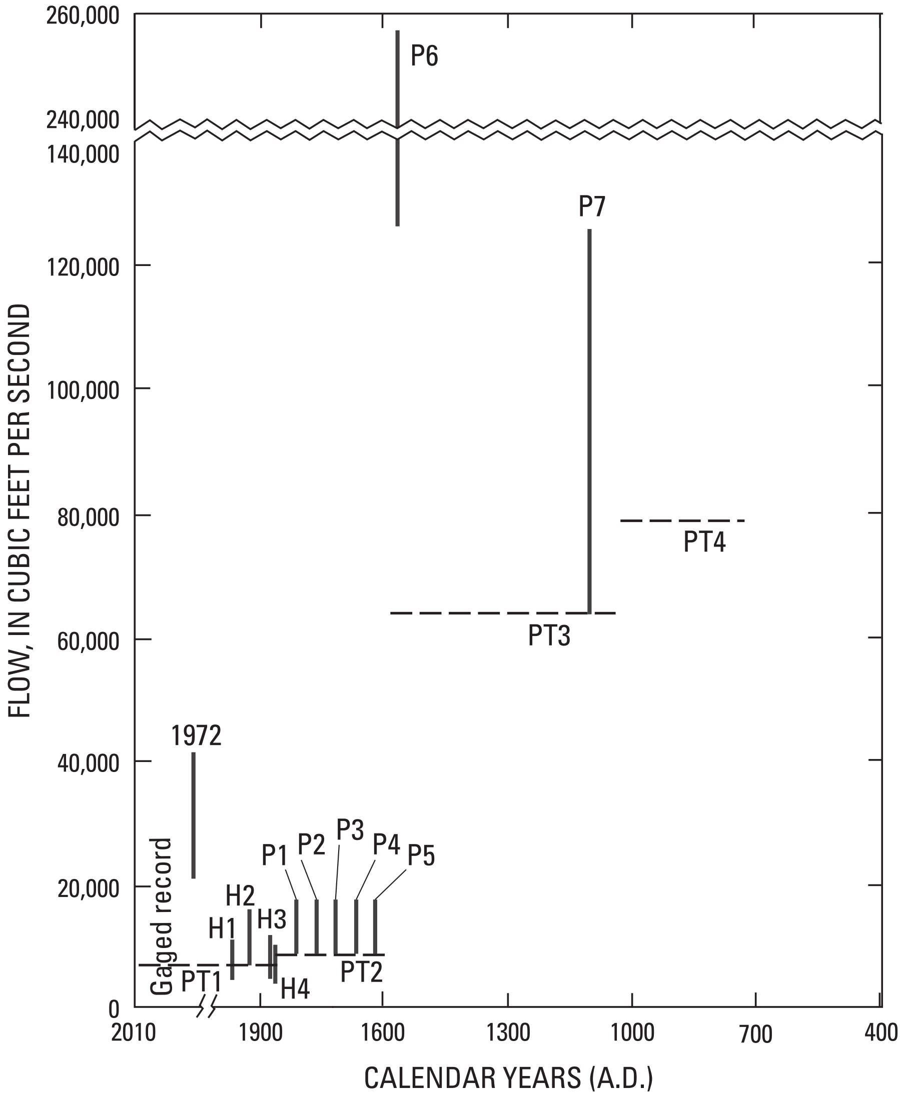
An advantage of the PeakfqSA model (relative to the FLDFRQ3 model) is that it maintains the overall structure and moments-based approach of procedures recommended in Bulletin 17B "Guidelines for Determining Flood Flow Frequency" (Interagency Advisory Council on Water Data 1982). Because the PeakfqSA model is most consistent with procedures adopted by most Federal agencies for flood-frequency analysis, results from the PeakfqSA analyses were used as the primary basis for summarizing results and for comparing results among the six study reaches.

CENTRAL BLACK HILLS FLOOD FREQUENCY: RESULTS, SYNOPSIS, IMPLICATIONS, AND APPLICATION

Example Results. An example long-term flood chronology for the lower reach of Rapid Creek (Figure 2) includes 86 years of non-continuous gaged peak-flow records spanning 1905–2009, four historical floods (1878, 1883, 1907, and 1920), and seven paleofloods. Figure 2 also shows (1) estimated uncertainty ranges for large flow values that are considered within the analytical models used for flood-frequency analyses, and (2) date ranges for four perception thresholds associated with selected historical and paleoflood events. The largest gaged flow of 31,200 cubic feet per second (ft^3/s) in 1972 has been substantially exceeded by two especially large paleofloods of at least 128,000 and 64,000 ft^3/s that occurred about 440 and 1,000 years ago, respectively.

Flood-frequency analyses for the lower reach of Rapid Creek (Figure 3) were performed for the two scenarios using the FLDFRQ3 and PeakfqSA flood-frequency models. Inclusion of the historical and paleoflood information (scenario 2, Figure 3B) markedly improves estimates of low-probability floods—most clearly indicated by substantial narrowing (relative to results for the gaged records only, scenario 1, Figure 3A) of the range of the 95-percent confidence limits, especially for the largest recurrence intervals.

The analysis using the PeakfqSA model for scenario 2 (accounting for all available information) is most consistent with procedures adopted by most Federal agencies. The PeakfqSA model results for the lower Rapid Creek reach and all other study reaches are summarized in Table 1, which provides a comparison between the short-term analyses (scenario 1, gaged records only) and long-term analyses (scenario 2, all available data). For the lower Rapid Creek reach, the 100-year quantile estimate for the long-term analysis is 14,000 ft^3/s (Table 1), with 95-percent confidence limits of 8,350 and 24,600 ft^3/s (Figure 3). By contrast, the short-term analysis yields a smaller 100-year quantile estimate of 8,720 ft^3/s, but with a much larger 95-percent confidence interval of 4,070–104,000 ft^3/s. Thus, inclusion of all available data increases the 100-year quantile estimate by about 61 percent and reduces the 95-percent confidence interval by about 84 percent. Similarly, consideration of all available data increases the magnitude of the 500-year quantile estimate by about 73 percent and reduces the 95-percent confidence interval by about 90 percent.



EXPLANATION

H4 **Uncertainty ranges for the 1972 flood, four historical floods (H1–H4), and seven paleofloods (P1–P7)**

PT1 **Date ranges for four perception thresholds (PT1–PT4)**

Gaged record (excluding 1972) includes 85 peak-flow values (1905–2009) of 2,600 cubic feet per second and smaller

Figure 2. Long-term flood chronology for lower Rapid Creek reach.

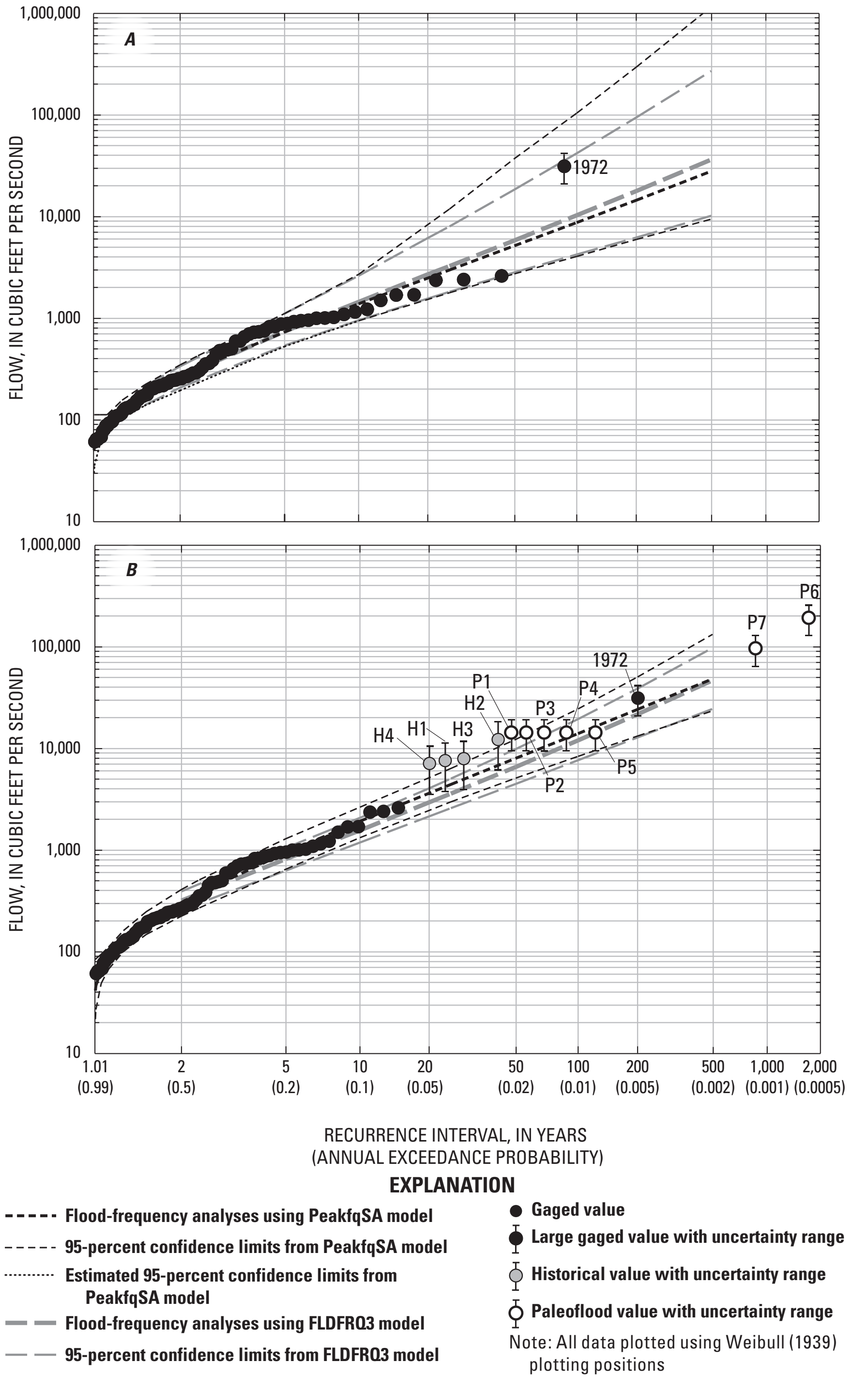


Figure 3. Flood-frequency analyses for lower Rapid Creek reach for A, gaged records only, and B, all available data that incorporate the long-term flood chronology from figure 2.

Harden et al. (2011) provided numerous additional details regarding reach and site conditions; stratigraphic, age-dating, and hydraulic analyses; interpretations of overall paleoflood chronologies; and results of flood-frequency analyses for all of the six study reaches. The paleoflood investigations for the example lower reach of Rapid Creek are of particular importance because of proximity to

Table 1. Summary of flood-frequency analyses and large flows for paleoflood study reaches. [All analyses from PeakfqSA model. Short-term analyses are for gaged records only. Long-term analyses incorporate all available information. ft³/s, cubic feet per second; % reduction, percent reduction in 95-percent confidence interval for analysis with all available data, relative to analysis for gaged records only; --, no data]

DATA DESCRIPTION	PEAK-FLOW ESTIMATE, IN FT³/S FOR ASSOCIATED RECURRENCE INTERVAL (ANNUAL EXCEEDANCE PROBABILITY) 25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)	FLOW (FT³/S) FOR SELECTED PALEOFLOODS Largest	Second largest	LARGEST GAGED FLOW (FT³/S)
Spring Creek (drainage area = 171 square miles)								
Short-term	2,010	3,620	6,290	10,700	20,800	--	--	21,800
Long-term	2,480	4,530	7,960	13,600	26,900	56,400	18,200	--
% reduction	72.9	85.4	89.6	92.4	94.9	--	--	--
Lower reach of Rapid Creek (actual drainage area = 81 square miles; adjusted drainage area between streamgages 06410500 and 06412500 = 375 square miles)								
Short-term	2,990	5,160	8,720	14,500	27,900	--	--	31,200
Long-term	4,410	7,950	14,000	24,100	48,300	128,000	64,000	--
% reduction	66.7	79.0	83.8	87.1	90.5	--	--	--
Upstream reach of Rapid Creek (drainage area = 294 square miles)								
Short-term	1,500	2,200	3,160	4,450	6,850	--	--	2,460
Long-term	1,590	2,350	3,390	4,770	7,340	12,900	12,000	--
% reduction	57.3	69.7	78.3	83.1	86.6	--	--	--
Upstream subreach of Boxelder Creek (drainage area = 98 square miles)								
Short-term	4,680	9,980	20,600	41,700	103,000	--	--	30,800
Long-term	3,350	6,120	10,800	18,500	36,500	40,500	39,000	--
% reduction	95.5	98.3	99.3	99.7	99.9	--	--	--
Downstream subreach of Boxelder Creek (drainage area = 112 square miles)								
Short-term	5,750	12,800	27,900	59,300	157,000	--	--	50,500
Long-term	3,200	5,920	10,600	18,500	37,400	61,300	52,500	--
% reduction	97.8	99.3	99.7	99.9	100	--	--	--
Elk Creek (drainage area = 40 square miles)								
Short-term	1,650	2,980	5,340	9,480	20,000	--	--	10,400
Long-term	3,510	6,670	12,400	22,500	48,300	83,000	80,000	--
% reduction	79.3	91.3	96.2	98.4	99.4	--	--	--

urban populations. However, the available paleoflood chronology for this reach pre-dates construction of Pactola Dam, which regulates most of the contributing drainage area for this reach (Figure 1). Thus, paleoflood investigations also were conducted in an upper reach of Rapid Creek (upstream from Pactola Reservoir). The paleoflood chronologies for lower and upper Rapid Creek are distinctively different, with an especially rich history of very large floods for lower Rapid Creek and a much sparser record with much smaller flows for upper Rapid Creek. The distinctive differences in chronologies and resulting flood-frequency analyses raise questions regarding (1) regional peak-flow characteristics relative to climate, geology, and physiography; and (2) the more pragmatic issue of how to apply results of flood-frequency analyses downstream from Pactola Dam. Some of the differences in chronologies may owe to less than optimum conditions along upper Rapid Creek for accumulation and preservation of slack-water sediments (few alcoves and caves flank this reach), thereby resulting in incomplete records. More plausible, however, is that the physiography and climate of the upper part of Rapid Creek result in small peak flows, relative to downstream reaches, as further described within the remainder of this paper.

Synopsis and Regional Assessment. Results of the paleoflood investigations provide improved flood-frequency estimates for each of the six study reaches and facilitate comparisons among and within individual drainage basins. For simplification, only the flood-frequency analyses from the PeakfqSA model are considered herein. The overarching result of incorporating the paleoflood information is substantially narrowed confidence intervals, relative to those for the short-term flood-frequency analyses (Table 1). In all cases, 95-percent confidence intervals about the low-probability quantile estimates (100-, 200-, and 500-year recurrence-intervals) are reduced by at least 78 percent relative to similar analyses of the gaged records only. In some cases, 95-percent uncertainty limits have been reduced by 99 percent or more. This result is the logical outcome of including the much longer records of the large paleofloods provided by the stratigraphic records.

For all study reaches except the two Boxelder Creek subreaches, quantile estimates for the long-term flood-frequency analyses are larger than for the short-term analyses (Table 1), which results from incorporation of paleofloods substantially larger than the largest gaged flows. The largest differences are for lower Rapid Creek and Elk Creek. For lower Rapid Creek, the 100-year quantile estimate increased by 61 percent (from 8,720 to 14,000 ft^3/s), and the 500-year quantile estimate increased by 73 percent (from 27,900 to 48,300 ft^3/s). For Elk Creek, the 100- and 500-year quantile estimates increased by about 130 and 140 percent, respectively.

For both subreaches of Boxelder Creek, the long-term quantile estimates are substantially smaller than the short-term quantile estimates (Table 1) and largely reflect effects on the short-term analyses of the largest gaged flows (1972) and another relatively large flood in 1907 (Driscoll et al. 2010). The short-term quantile estimates for both subreaches are substantially larger than for the other study reaches. The long-term quantile estimates for the two subreaches are very similar and reflect paleoflood chronologies that were independently determined. Although the stratigraphic records cannot be precisely correlated between the two subreaches, the general similarities between results help affirm the overall study approaches.

The two largest paleofloods for each study reach (Table 1) and the largest gaged flow (all of which are from 1972, with the exception of upper Rapid Creek) are shown in Figure 4 relative to the low-probability quantile estimates from the long-term flood-frequency analyses and a regional envelope curve from Crippen and Bue (1977) for "region 11" that includes the Black Hills area. Two datasets are plotted for lower Rapid Creek—one based on the whole drainage area and one based on an "adjusted" area of 81 m², which is the intervening drainage area between representative streamgages 06410500 and 06412500 at the two Rapid Creek study reaches. A key issue for this study was flood-frequency characteriza-

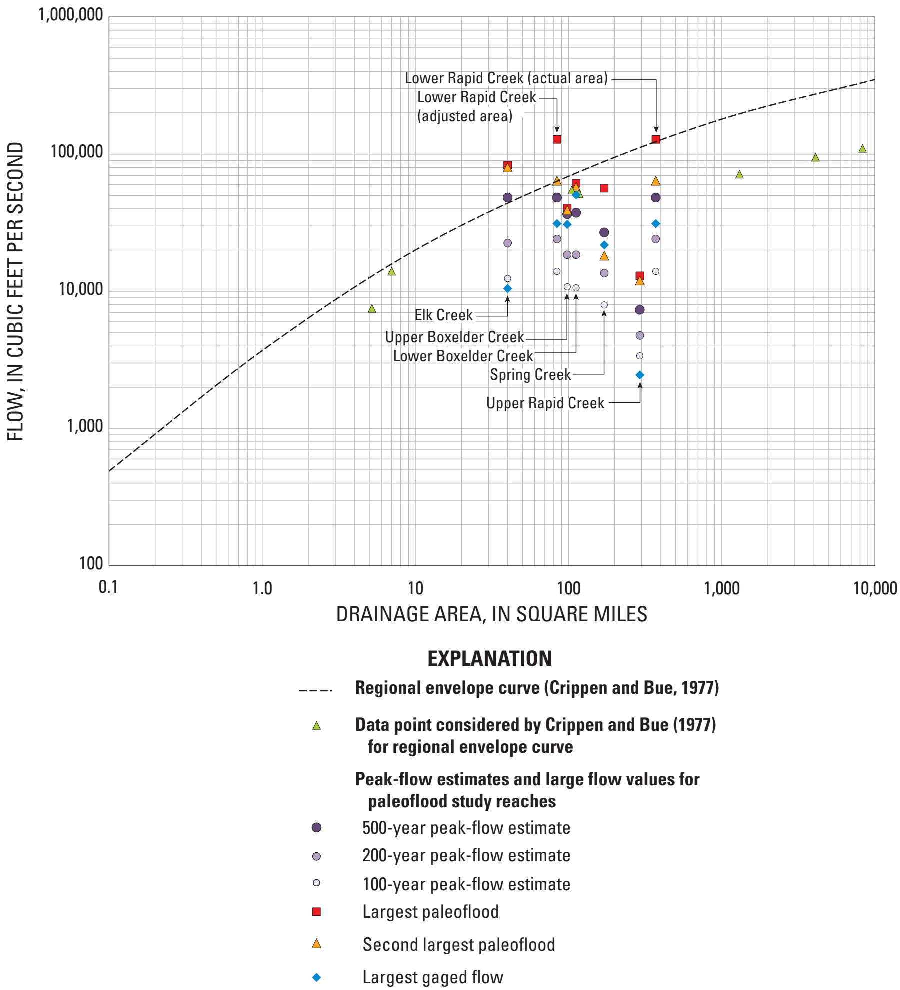


Figure 4. Results of peak-flow frequency analyses for selected stream reaches, relative to regional envelope curve.

tion for modern (regulated) conditions for lower Rapid Creek, and this adjusted area was postulated as the primary contributing area for low-probability floods during pre-regulation conditions. The largest paleofloods and quantile estimates for upper Rapid Creek are about an order of magnitude smaller than for lower Rapid Creek and strongly support the hypothesis of distinctly different regimes for large-flood generation for the two reaches.

The area-adjusted quantile estimates for lower Rapid Creek (Figure 4) plot close to those for the two subreaches of Boxelder Creek, which are nearly identical, and magnitudes for all of these quantile estimates are similar to those for Elk Creek, for which the drainage area is less than one-half of that for all of the other study reaches (Table 1). The 500-year quantile estimate for Elk Creek plots slightly above the regional envelope curve and is exceeded by the two largest paleofloods by a factor of almost two.

Implications for Flood Generation. Driscoll et al. (2010) postulated that potential for heavy rain-producing thunderstorms (storm potential) and associated flooding are smallest on the relatively flat top of the Limestone Plateau (located along the Wyoming/South Dakota border, Figure 1), with storm and flood potential increasing in an easterly direction. The eastern Black Hills are susceptible to the most intense orographic lifting associated with convective storm systems and also have high relief, thin soils, and narrow and steep canyons—factors favoring generation of exceptionally heavy rain-producing thunderstorms and promoting runoff and rapid concentration of flow into stream channels. In contrast, storm potential in and near the Limestone Plateau area is much lower than for the steeper flanks of the Black Hills. Storm runoff is further reduced by relatively gentle topography, substantial infiltration into the limestone, and extensive flood-plain storage.

The gradient in flood-generation processes is reflected in results of this study, for which some of the most compelling evidence is the disparity between results of the paleoflood investigations for the two Rapid Creek study reaches (Figure 1). Large parts of the upper Rapid Creek drainage basin are within the Limestone Plateau and other high-elevation areas where reduced flood potential is postulated (Driscoll et al. 2010; Sando et al. 2008). The upper reach composes about 78 percent of the drainage area of the lower reach (294 versus 375 mi^2, respectively; Table 1). Stratigraphic records for the upper reach indicate two paleofloods during the last 1,000 to 2,000 years of at least 12,000 and 12,900 ft^3/s, which substantially exceed the largest gaged flow of 2,460 ft^3/s (Table1). These floods are small, however, compared to the contributing drainage area and plot much lower than paleofloods recognized from stratigraphic deposits within all of the other study reaches (Figure 4). Moreover, the largest paleoflood of at least 128,000 ft^3/s for lower Rapid Creek is larger by a factor of about 10, despite having a drainage area that is less than 30 percent larger than that for the upper reach.

Perhaps the most compelling evidence of enhanced flood generation in the eastern Black Hills is provided by Elk Creek, which has had two paleofloods of at least 80,000 ft^3/s (Table 1) in the last 2,000 years from a drainage area of only 40 mi^2. The headwaters of Elk Creek are northeast of the contiguous geologic outcrops that compose the Limestone Plateau (Figure 1), and the entire upper watershed drains the steep northeastern flanks of the Black Hills. In contrast to the three other (and larger) study basins, there is no ambiguity regarding the area contributing to the large Elk Creek flows, demonstrating that exceptional floods can be generated entirely within the eastern Black Hills.

Application for Hazard Assessment. The paleoflood investigations provide substantially improved knowledge of low-probability flood recurrence for use in flood-hazard assessments. Results are directly applicable, however, only to the specific study reaches and in the case of Rapid Creek, only to pre-regulation conditions. Thus, extrapolation is required for applications beyond the study reaches.

The flood-frequency estimates are most applicable near the study reaches, which primarily are within the eastern margin of the central Black Hills (Figure 1), where flood generation and runoff processes may be different than for up-stream and downstream reaches. Areas west of the eastern flank of Black Hills, particularly in and near the Limestone Plateau area, likely are outside the area of most intense rainfall and peak-flow generation. Downstream from the Min-nekahta Limestone, which is the easternmost canyon-confining Paleozoic rock unit (Figure 1), flood plains widen substantially for all four study basins. Thus,

Table 2. Summary of normalized values for peak-flow estimates and selected large flows for paleoflood study reaches.

		NORMALIZED[2] LONG-TERM PEAK-FLOW ESTIMATE (FROM TABLE 1) FOR ASSOCIATED RECURRENCE INTERVAL (ANNUAL EXCEEDANCE PROBABILITY)					NORMALIZED[2] PALEOFLOOD AND GAGED FLOW VALUES (FROM TABLE 1)		
PALEO-FLOOD STUDY REACH	EXP. AREA[1]	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)	Largest paleo-flood	Second largest paleo-flood	Largest gaged flow
Spring Creek	21.9	113	207	364	622	1,230	2,580	832	997
Lower reach of Rapid Creek (actual area)	35.0	126	227	400	688	1,380	3,650	1,830	890
Lower reach of Rapid Creek (adjusted area)	14.0	316	569	1,000	1,730	3,460	9,160	4,580	2,230
Upper Rapid Creek	30.3	53	78	112	158	242	426	396	81
Upstream sub-reach of Box-elder Creek	15.7	214	391	690	1,180	2,330	2,590	2,490	1,970
Downstream subreach of Boxelder Creek	17.0	189	349	625	1,090	2,200	3,610	3,390	2,980
Elk Creek	9.15	384	729	1,360	2,460	5,280	9,070	8,750	1,150

[1]Exp. area is the drainage area for the study reach (from table 1, in square miles) raised to the 0.6 power.
[2]Normalized values were computed by dividing flow (in cubic feet per second) by Exp. area.

flood peaks derived from convective storm systems affecting the Black Hills typically attenuate markedly once they pass into the plains east of the Black Hills (Driscoll et al. 2010).

Although the regional envelope curve (Figure 4) provides a visual approach for comparing results among study reaches, more rigorous "normalizing" with respect to drainage area allows specific comparisons among basins and provides a basis for extrapolating results beyond the specific study reaches. Table 2 shows long-term quantile estimates and large flow values from Table 1 that have been normalized by dividing by drainage area raised to the 0.6 power. This follows analyses of Sando et al. (2008), who normalized large flows in developing a "Black Hills regional mixed-population" approach to address the complexities of flood-frequency estimation for the area. Table 2 includes the actual drainage area for the lower Rapid Creek study reach as well as an "adjusted" area that represents the intervening area of 81 mi^2 downstream from the upper Rapid Creek reach.

The normalized values (Table 2) further illustrate the distinct flood regime of upper Rapid Creek, for which the largest normalized paleoflood value is only 17 percent of the next smallest values (Spring Creek and the upstream subreach of Boxelder Creek) and only about 5 percent of that for Elk Creek. Similarly, normalized quantile estimates for all other study reaches are much larger than for upper Rapid Creek—approaching or exceeding by a factor of 10 for most cases. Normalized quantile estimates for Elk Creek, the two subreaches of Boxelder Creek, and the area-adjusted reach of lower Rapid Creek are relatively similar, varying by less than a factor of 2.5. The largest normalized gaged-flow value is for the downstream subreach of Boxelder Creek, which exceeds those for the upstream subreach and the area-adjusted reach of lower Rapid Creek by a factor of about 0.5.

The normalized quantile estimates allow for extrapolating low-probability flood recurrence to appropriate locations near the paleoflood study reaches. An appropriate approach is to use the normalized quantile estimates from Table 2 as index values that can be "scaled" to other locations of interest by multiplying by drainage area raised to the 0.6 power (same exponent as used for normalizing). Examples are provided in Table 3, which shows scaled quantile estimates for selected streamgages (Figure 1) and comparisons with estimates from Sando et al. (2008), who defined a regional "high-outlier" probability distribution that was combined (using joint-probability theory) with site-specific probability distributions for individual streamgages. This approach resulted in divergence from the site-specific ("ordinary peaks") distributions to increasingly larger peak-flow estimates for recurrence intervals larger than about 50 to 100 years. Except for the upper Rapid Creek reach, the quantile estimates derived from the paleoflood studies and scaled to the streamgage areas are larger than those from Sando et al. (2008).

Extrapolation of results to streamgage locations also allows broader evaluation of recurrence intervals for the 1972 flooding and other large measured flows. For example, the 1972 flow for the Spring Creek study reach was 21,800 ft^3/s (largest gaged flow; table 1), which corresponds with a recurrence interval approaching 400 years. The area for upstream streamgage 06407500 (163 mi^2) is very similar to that for the paleoflood study reach (171 mi^2). Thus, the scaled quantile

Table 3. Flood-frequency analyses scaled to drainage areas for selected streamgages. [Scaled (area), peak-flow estimates, in cubic feet per second (ft³/s), for location of streamgage derived by scaling from peak-flow estimates and drainage areas, in square miles (mi²), for appropriate paleoflood study reaches from table 2, based on exponential (0.6 power) drainage-area adjustment; --, no data]

SOURCE OF PEAK-FLOW ESTIMATES	DRAIN-AGE AREA (M²)	PEAK-FLOW ESTIMATE, FT³/S, FOR ASSOCIATED RECURRENCE INTERVAL (ANNUAL EXCEEDANCE PROBABILITY)					1972 PEAK-FLOW (HARDEN ET AL., 2011)
		25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)	
Station 06407500, Spring Creek near Keystone, S. Dak.							
Scaled (171 mi²)	163	2,400	4,400	7,730	13,200	26,100	20,000
From Sando and others (2008)	163	1,270	1,920	3,170	6,150	23,600	20,000
Station 06408500, Spring Creek near Hermosa, S. Dak.							
Scaled (171 mi²)	206	2,760	5,060	8,900	15,200	30,100	13,400
From Sando and others (2008)	206	935	1,180	1,670	4,800	27,000	13,400
Station 06412500, Rapid Creek above Canyon Lake near Rapid City, S. Dak.							
Scaled[1] (81 mi²)	154	3,460	6,230	11,000	18,900	37,900	31,200
From Sando and others (2008)	154	1,020	1,450	2,150	3,750	11,800	31,200
Station 06414000, Rapid Creek at Rapid City, S. Dak.							
Scaled[1] (81 mi²)	193	4,790	8,630	15,200	26,300	52,500	50,000
From Sando and others (2008)	193	2,400	3,380	4,760	7,240	17,900	50,000
Station 06410500, Rapid Creek above Pactola Reservoir at Silver City, S. Dak.							
Scaled[2] (201.6 mi²)	294	1,280	1,880	2,700	3,810	5,840	252
From Sando and others (2008)	294	1,640	2,540	4,260	7,950	27,100	252
Station 06422500, Boxelder Creek near Nemo, S. Dak.							
Scaled (98 mi²)	94.4	3,280	5,990	10,600	18,100	35,700	30,100
From Sando and others (2008)	94.4	1,440	2,100	3,120	5,660	17,200	30,100
Station 06423010, Boxelder Creek near Rapid City, S. Dak.							
Scaled (112 mi²)	127	3,460	6,380	11,400	19,900	40,200	--
From Sando and others (2008)	127	1,250	1,990	2,990	5,680	20,400	--
Station 06424000, Elk Creek near Roubaix, S. Dak.							
Scaled (40 mi²)	21.6	2,430	4,610	8,590	15,500	33,400	--
From Sando and others (2008)	21.6	530	696	967	1,870	6,980	--

[1]Scaled using unregulated area downstream from Pactola Dam, relative to an "adjusted" area of 81 mi² for the paleoflood study reach.
[2]Scaled using unregulated area downstream from Deerfield Dam.

estimates (Table 3) are nearly identical to the long-term estimates for the study reach (Table 1), and to an estimated 1972 flow of 20,000 ft^3/s that similarly has a recurrence interval approaching 400 years. The 1972 flood peak along Spring Creek attenuated to about 13,400 ft^3/s for downstream streamgage 06408500 (table 3), where another large flow of 6,910 ft^3/s occurred in 1996 (U.S. Geological Survey 2010). Recurrence intervals for these 1972 and 1996 flows are slightly less than 200 and 100 years, respectively, based on the scaled quantile estimates (Table 3); whereas, recurrence intervals from Sando et al. (2008) are much larger (substantially exceeding the 200-year quantile estimate) and seemingly are less reliable. Because streamgage 06408500 is located about 8 miles downstream from the outcrop of the Minnekahta Limestone (Figure 1), extrapolation within this domain may be considered questionable. However, this example illustrates the utility of considering information from multiple sources in evaluating low-probability flood recurrence.

Scaled quantile estimates for streamgages 06412500 and 06414000 along lower Rapid Creek (Table 3) are larger than those from Sando et al. (2008) by factors ranging from about two to five. Quantile estimates for both streamgages were scaled relative to the adjusted area of 81 mi^2, which approximates the intervening drainage area between the two Rapid Creek paleoflood study reaches. Recurrence intervals for the 1972 peak flows of 31,200 and 50,000 ft^3/s are about 500 years, relative to scaled quantile estimates for these two streamgages. In contrast, recurrence intervals for the 1972 peak flows largely exceed 500 years relative to the quantile estimates by Sando et al. (2008). The importance and challenges of estimating flood recurrence are exemplified by Rapid Creek, where many of the 238 known deaths from the 1972 flooding occurred. The appropriateness of the drainage-area adjustment for resolving pre- and post-regulation conditions could not be explicitly evaluated. However, the scaled values for streamgages 06412500 and 06414000 (Table 3), with unregulated drainage areas of 54 and 93 mi^2 (Harden et al. 2011), are similar to long-term quantile estimates for the Elk Creek study reach (Table 1), for which the drainage area of 40 mi^2 is not affected by regulation.

Scaling for streamgage 06410500 along upper Rapid Creek (Figure 1) was performed relative to an unregulated area of 201.6 mi^2 downstream from Deerfield Reservoir (Table 3), which is consistent with a drainage-area adjustment used by Sando et al. (2008). The scaled quantile estimates reflect the absence of evidence for large paleofloods in this study reach and are substantially smaller than those from Sando et al. (2008), who stated that the mixed-population analysis "probably results in overestimation of peak flows for large recurrence intervals for stations where drainage areas are primarily within the limestone-headwater setting." The largest gaged flow for streamgage 06410500 is 2,460 ft^3/s (Table 1) and has a recurrence interval of about 100 years.

Scaled quantile estimates for the upstream and downstream streamgages (06422500 and 06423010) along Boxelder Creek (table 3) are very similar and were scaled relative to results for the upstream and downstream subreaches (Table 2). The largest differential is for the 500-year recurrence interval, for which values differ by about 10 percent. For the upstream streamgage, recurrence intervals for the large 1907 and 1972 flows (16,400 ft^3/s, U.S. Geological

Survey 2010; and 30,800 ft^3/s, Table 1, respectively) are slightly less than 200 and 500 years, respectively, based on the scaled quantile estimates (Table 3). Flow estimates for 1907 and 1972 are not available for the downstream streamgage (06423010); however, the 1972 flow of 50,500 ft^3/s for the downstream paleoflood study subreach (Table 1) exceeds the 500-year quantile estimate (37,400 ft^3/s) by about 35 percent.

Scaled quantile estimates for streamgage 06424000 along Elk Creek (Table 3) are about 5 to 10 times larger than those from Sando et al. (2008). However, the scaled estimates probably are more reliable than estimates by Sando et al. (2008), which were based on a short period of record (1992–2001) that did not include the large floods of 1907 and 1972. Recurrence intervals are slightly less than 100 years for large 1972 and 1907 flows for the study reach (Table 1) that were estimated by Harden et al. (2011) as 10,400 ft^3/s for both years.

Summarized estimates of recurrence intervals for 1972 flooding show that the recurrence interval of nearly 100 years for the Elk Creek study reach is small relative to other study reaches along the eastern margin of the Black Hills and to the two large paleofloods (80,000–83,000 ft^3/s) recorded by stratigraphic deposits along Elk Creek. The 1972 flow for the Spring Creek study reach was 21,800 ft^3/s, which has a recurrence interval of about 400 years. Recurrence intervals are about 500 years for the floods of 1972 along the lower Rapid Creek reach and for the upstream subreach of Boxelder Creek. For the downstream subreach of Boxelder Creek, the large 1972 flood magnitude (50,500 ft^3/s) exceeds the 500-year quantile estimate by about 35 percent.

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