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Late-Holocene Flood History, Flood-Frequency, and Paleoclimate Analysis of the Central
Black Hills, South Dakota

by

Tessa Maureen Harden

A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Environmental Science and Resources: Geology

Dissertation Committee:
Andrew G. Fountain, Chair
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Portland State University
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Abstract

Stratigraphic records in four basins in the central Black Hills in combination with hydraulic calculations show that all basins have experienced multiple large floods in the last 2,000 years with flow rates substantially larger than those gaged historically. Flood-frequency analyses for the study reaches account for 29 paleofloods inferred from interpretation of stratigraphic records locally extending back 1,000 to almost 2,000 years. The addition of paleoflood data to the gaged and historical data significantly reduced uncertainties related to flood-frequency. For all study reaches the 95-percent confidence intervals about the low-probability quantile estimates (100-, 200-, and 500-year recurrence-intervals) were reduced by at least 78 percent relative to those for the gaged records only. In some cases, 95-percent uncertainty intervals were reduced by 99 percent or more.

Additionally, a stratigraphic record of 35 large paleofloods and four large historical floods during the last 2,000 years (including several floods not used in the frequency analyses due to age constraints) reveal four flooding episodes at A.D.: 130-40, 640-670, 900-1290, and 1410 to present. During the Medieval Climate Anomaly (~A.D. 900-1300) the Black Hills experienced 13 large floods compared to nine large floods in the previous 800 years. This high concentration of large flooding events were likely caused by: 1) instability of air masses caused by stronger than normal westerlies; 2) larger or more

frequent hurricanes in the Gulf of Mexico and Atlantic Ocean; and/or 3) reduced land covering vegetation and an increase in forest fires caused by the severe drought. By examining the response of streamflow to the MCA, it seems likely that if severe long-term drought conditions persist for the Black Hills region, an increase in the frequency and magnitude of large floods can be expected.

The Black Hills paleofloods represent some of the largest known floods, relative to drainage area, for the United States. Many of the other largest known United States floods are in areas with physiographic and climatologic conditions broadly similar to the Black Hills—semi-arid and rugged landscapes that intercept and focus heavy precipitation from convective storm systems.

Acknowledgments

This dissertation would not have been possible without the patience, knowledge, expertise, and guidance of my advisor Dr Jim O'Connor with the USGS Oregon Water Science Center. I cannot thank him enough for the time he spent in the field and in the office making suggestions, giving advice, and helping with all aspects of this project. He is a wonderful mentor and has definitely made me a better scientist. I would also like to thank Dan Driscoll with the USGS South Dakota Water Science Center for his tireless effort on this project and his vast knowledge of the study area as well as principles of hydrology. Without Dan I'd still be out wandering the wilds of the Black Hills.

Many thanks go to Dr Andrew Fountain for his advice, confidence and support through the Portland State graduate school experience and for always being available. I'd also like to thank the rest of my committee, Drs Scott Burns, Heejun Chang, and Jennifer Allen, for their flexibility, support and ideas.

Special thanks to the South Dakota Department of Transportation, FEMA, USGS, Western Dakota Water Development District and the City of Rapid City who all contributed funds for this research. Thanks, also, to the many landowners who allowed access to sites on their property.

Lastly, I would like to show my gratitude to my parents, Barbara and Larry, who were always very positive and encouraging through every aspect of this process even when they were not 100% sure of what they were encouraging.

Table of Contents

Abstract.....	i
Acknowledgments.....	iii
List of Tables.....	v
List of Figures.....	vi
Preface.....	ix
 Chapter 1 Developing Long-term Flood Histories for use in Flood-frequency Analyses.....	 1
 Chapter 2 Flood-Frequency Analyses from Paleoflood Investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, South Dakota.....	 45
 Chapter 3 Central Black Hills Flood-Frequency: Synopsis and Implications.....	 153
 Chapter 4 Late-Holocene Flood Probabilities in the Black Hills, South Dakota With Emphasis on the Medieval Climate Anomaly.....	 177
 Chapter 5 Black Hills Flooding: Summary.....	 203
References.....	209
 Appendices	
A. Geochronology.....	224
B. Modern Peak-Flow Chronologies.....	231
C. Schematic Diagrams.....	256

List of Tables

Table	Page
1. Drainage areas and periods of peak-flow record for selected streamgages and locations near study reaches.....	27
2. Modern peak-flow chronologies for paleoflood study reaches.....	38
3. Summary of critical-flow computations for Temple of Doom Alcove, Spring Creek.....	61
4. Summary of long-term flood chronology used in flood-frequency analysis for Spring Creek.....	63
5. Flood-frequency analyses for Spring Creek.....	66
6. Summary of longer-term flood chronology used in flood-frequency analysis for lower Rapid Creek reach.....	87
7. Flood-frequency analyses for lower Rapid Creek.....	89
8. Summary of Manning equation computations for selected locations along upper Rapid Creek.....	97
9. Summary of long-term flood chronology used in flood-frequency analysis for upper Rapid Creek.....	103
10. Flood-frequency analyses for upper Rapid Creek reach.....	105
11. Summary of long-term flood chronology used in flood-frequency analysis for upstream sub-reach of Boxelder Creek.....	121
12. Flood-frequency analyses for upstream sub-reach of Boxelder Creek.....	123
13. Summary of long-term flood chronology used in flood-frequency analysis for downstream sub-reach of Boxelder Creek.....	133
14. Flood-frequency analyses for downstream sub-reach of Boxelder Creek.....	136
15. Summary of critical flow computations for Dracula's Ledge, Elk Creek.....	143
16. Summary of long-term flood chronology used in flood-frequency analysis for Elk Creek.....	148
17. Flood-frequency analyses for Elk Creek.....	150
18. Summary flood-frequency analyses and large flows for paleoflood study reaches.....	156
19. Paleofloods used to create CPDF plots.....	182

List of Figures

Figure	Page
1. Distribution of hydrogeologic units within the Black Hills area, locations of detailed paleoflood site investigations, and locations of selected streamgages.....	3
2. Geologic cross section A-A'	7
3. Photographs showing examples of bedrock outcrops in channels.....	10
4. Topographic information and selected details of hydraulic analysis for Spring Creek reach.....	46
5. Photographs showing examples of geomorphic setting along Spring Creek reach...	47
6. Gaged peak-flow chronology for Spring Creek.....	49
7. Results of hydraulic model calibration runs for Spring Creek reach.....	50
8. Photographs showing setting and examples of stratigraphy for Superscour Alcove, Spring Creek.....	52
9. Schematic diagram showing paleoflood information for Superscour Alcove, Spring Creek.....	53
10. Schematic diagram showing paleoflood information for Hailstorm Alcove, Spring Creek.....	55
11. Schematic diagram showing paleoflood information for John Doe Alcove, Spring Creek.....	57
12. Schematic diagram showing paleoflood information for Temple of Doom Alcove, Spring Creek.....	58
13. Channel cross section and relevant elevations for Temple of Doom Alcove, Spring Creek.....	60
14. Chronology of especially large floods for Spring Creek.....	64
15. Results of flood-frequency analyses for Spring Creek.....	69
16. Topographic information and selected details of hydraulic analysis for lower Rapid Creek reach.....	72
17. Gaged peak-flow chronology for lower Rapid Creek reach.....	73
18. Results of hydraulic model calibration runs for lower Rapid Creek reach.....	75
19. Schematic diagram showing paleoflood information for Outhouse Alcove, lower Rapid Creek reach.....	77
20. Schematic diagram showing paleoflood information for Spider Alcove, lower Rapid Creek reach.....	78
21. Schematic diagram showing paleoflood information for Meister Alcove, lower Rapid Creek reach.....	80
22. Schematic diagram showing paleoflood information for High Alcove, lower Rapid Creek reach.....	81

23. Schematic diagram showing paleoflood information for Lost Alcove, lower Rapid Creek reach.....	83
24. Schematic diagram showing paleoflood information for Black Socks Alcove, lower Rapid Creek reach.....	84
25. Graphical representation of chronology of especially large floods for lower Rapid Creek reach.....	86
26. Results of flood-frequency analyses for lower Rapid Creek reach.....	92
27. Gaged peak-flow chronology for upper Rapid Creek reach.....	94
28. Channel cross section and relevant elevations for Gage House Alcove, upper Rapid Creek reach.....	95
29. Channel cross section and relevant elevations for Schist and Blue Ribbon Alcoves, upper Rapid Creek reach.....	98
30. Schematic diagram showing paleoflood information for Schist and Blue Ribbon Alcoves, upper Rapid Creek reach.....	99
31. Schematic diagram showing paleoflood information for Gage House Alcove, upper Rapid Creek reach.....	101
32. Long-term flood chronology for upper Rapid Creek reach.....	102
33. Results of flood-frequency analyses for upper Rapid Creek reach.....	107
34. Topographic information and selected details of hydraulic analysis for Boxelder Creek reach.....	110
35. Gaged peak-flow chronology for upstream sub-reach of Boxelder Creek.....	111
36. Gaged peak-flow chronology for downstream sub-reach of Boxelder Creek.....	113
37. Results of hydraulic model calibration runs for Boxelder Creek reach.....	115
38. Schematic diagram showing paleoflood information for Joan's Cave, upstream sub-reach of Boxelder Creek.....	116
39. Schematic diagram showing paleoflood information for Enob Alcove, upstream sub-reach of Boxelder Creek.....	118
40. Chronology of especially large floods for upstream sub-reach of Boxelder Creek...	120
41. Results of frequency analyses for upstream sub-reach of Boxelder Creek.....	125
42. Schematic diagram showing paleoflood information for Custer Gap Alcove, downstream sub-reach of Boxelder Creek.....	127
43. Schematic diagram showing paleoflood information for Second Story Alcove, downstream sub-reach of Boxelder Creek.....	128
44. Schematic diagram showing paleoflood information for Trail Alcove, downstream sub-reach of Boxelder Creek.....	129
45. Schematic diagram showing paleoflood information for pit C in Kitty's Corner Alcove, downstream sub-reach of Boxelder Creek.....	131
46. Chronology of especially large floods for downstream sub-reach of Boxelder Creek.....	135
47. Flood- frequency for downstream sub-reach of Boxelder Creek.....	138
48. Gaged peak-flow chronology for Elk Creek.....	140

49. Channel cross sections and relevant elevations for Dracula's Ledge, Elk Creek....	142
50. Schematic diagram showing paleoflood information for Dracula's Ledge, Elk Creek.....	145
51. Chronology of especially large floods for Elk Creek.....	147
52. Results of flood-frequency analyses for Elk Creek.....	152
53. Paleofloods and maximum gaged flows for selected stream reaches, relative to national and regional envelope curves.....	159
54. Results of peak-flow frequency analyses for selected stream reaches, relative to regional envelope curve.....	161
55. Cumulative flood probability curve for the central Black Hills during the late-Holocene.....	187
56. Cumulative probability distributions of the 100-year or greater floods for each of the 4 reaches in the study area.....	190
57. Flood magnitude for the 39 largest floods, including 4 historical floods, in the Black Hills during the last 2,000 years.....	191
58. The Black Hills CPDF curve compared to selected climate proxies in the last 1,500 years.....	193

Preface

The first three chapters of this dissertation are the paleoflood history and flood-frequency analyses of four drainages in the central Black Hills, South Dakota. This research was done for a project for the USGS and published as Scientific Investigations Report 2011-5131. Funding for the project came from the USGS as well as the South Dakota Department of Transportation, FEMA, the Western Dakota Water Development District, and the City of Rapid City. With consideration of the funding agencies and the strict formatting requirements of the USGS, English units are used. Conversion factors are listed below. The fourth chapter utilizes information from the first three chapters (timing, magnitude, recurrence intervals of large floods). This chapter was prepared to be submitted to a professional scientific journal and therefore the formatting is slightly different. For example, the use of Latin abbreviations (et al.), common in scientific literature, is found only in chapter 4. The fifth chapter is a summary of the first four.

Conversion Factors

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.590	square kilometers (km ²)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)

Chapter 1

Developing Long-term Flood Histories for use in Flood-Frequency Analyses in the Central Black Hills, South Dakota

Introduction

Estimates of the frequency of large riverine flows (peak-flow or flood-frequency estimates) serve many purposes, including (1) design of dams, highways, and many other types of infrastructure; (2) land-use planning and zoning; and (3) establishment of rates for flood insurance and other floodplain management purposes. Consequently, the importance of flood-frequency estimates has motivated substantial work, mainly involving statistical techniques, toward improving estimates of the magnitude and frequency of especially large and rare (low-probability) floods. An inherent limitation of nearly all such approaches, however, is that estimates of infrequent phenomena are needed and the observational records generally are short (typically less than 100 years for the Black Hills area) relative to the recurrence of low-probability floods. In this study, observational and historical records of flooding are supplemented with stratigraphic evidence of large floods over the last 1,000 to 2,000 years for four drainage basins in the central and eastern Black Hills of South Dakota, thereby substantially lengthening the record of large floods and allowing for much more confident prediction of the magnitude and frequency of low-probability floods for these streams.

Flood-frequency analyses for the Black Hills of western South Dakota are technically challenging and of substantial local interest and importance, chiefly as a result of the large and damaging flooding of June 9–10, 1972, along the eastern flanks of the Black Hills. Flooding was caused by a large mesoscale convective system and resulted in at least 238 deaths and more than \$160 million (about \$664 million in 2002 dollars) in damage (Carter and others, 2002). Flooding was especially severe within Rapid City (Schwarz and others, 1975), where a 10-mile (mi) long corridor along Rapid Creek was devastated (Larimer, 1973). Exceptional flooding also affected Battle and Spring Creeks to the south, and Boxelder, Elk, and Bear Butte Creeks to the north (Figure 1).

As of 2011, peak flows from the 1972 flooding still remain as peaks of record for 14 streamgages in the Black Hills area (Driscoll and others, 2010). Despite streamflow records (observational records or gaged records) that date back to the early 1900s for some of the affected river systems, the 1972 peak flow exceeds the next largest flow by a factor of 10 for 8 of these streamgages, and by almost 20 times for 2 streamgages. As described by Sando and others (2008), such disparities or high outliers create substantial uncertainty for peak-flow frequency analyses for affected streams. Without additional information, it is difficult to reasonably estimate the frequency of such large flows: Is the record of the last 100 years typical? Or are flows such as 1972 exceptionally rare, recurring only at a millennial or even rarer frequency?

These questions recently were highlighted by severe thunderstorms on August 17, 2007, which caused heavy precipitation and flash flooding near Hermosa and Piedmont in

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

the eastern Black Hills. As described by Driscoll and others (2010), the 2007 storm system caused the most substantial flooding in the Black Hills area since 1972 and resulted in a peak flow along Battle Creek near Hermosa that was only slightly smaller than the record 1972 flood at the same location. The 2007 storm area was much smaller, however, than for the 1972 storm, and severe flooding was restricted to the Hermosa area. In reporting on this event, Driscoll and others (2010) also compiled and examined a history of storm and flood events since 1877 for the Black Hills area (U.S. Geological Survey, 2010a).

In appropriate environments, an efficient means of reducing uncertainties regarding probabilities of flood recurrence is to augment observational and historical peak-flow records by using paleohydrologic techniques (Costa, 1978; Hosking and Wallis, 1986; Stedinger and Baker, 1987; Frances and others, 1994; Webb and others, 2002)—typically using geologic and paleobotanical evidence to determine the age and magnitudes of floods prior to observational records (paleofloods). During 2005–07, the U.S. Geological Survey (USGS) and South Dakota Department of Transportation (SDDOT) cooperated on a reconnaissance-level study (South Dakota Department of Transportation, 2010) confirming that such paleohydrologic techniques could likely improve estimates of the magnitude and frequency of low-probability floods in the Black Hills area (O'Connor and Driscoll, 2007). That study was followed in 2008 by a more comprehensive study in cooperation with the SDDOT, and included additional support from the Federal Emergency Management Agency, city of Rapid City, and West Dakota Water Development District. The primary purpose of this more comprehensive study was to improve flood-frequency

characterization of low-probability floods for major streams in the central Black Hills through paleoflood investigations, which included analyses of stratigraphic evidence, timing, and magnitudes for large floods on Spring Creek, Rapid Creek (two reaches), Boxelder Creek (two sub-reaches), and Elk Creek. The stratigraphic records and resulting long-term flood chronologies, locally extending back more than 2,000 years, were combined with modern (gaged) peak-flow records and historical flood observations to derive flood-frequency estimates for each of the six study reaches. The resulting flood chronologies and flood-frequency estimates show that (1) floods as large and even substantially larger than 1972 have previously affected most of these stream reaches, and (2) incorporation of the paleohydrologic information can substantially reduce uncertainties in estimating recurrence of low-probability floods.

Study Area and Background Information

The study area consists of the Spring, Rapid, Boxelder, and Elk Creek drainage basins within the central part of the Black Hills (Figure 1). The primary evidence for past large and infrequent floods consists of stratigraphic records formed of fine-grained sediment deposits preserved in slack-water environments. These deposits accumulate and can record multiple floods over several thousand years 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.

Geology of the Study Area

The successful paleoflood investigations in the Black Hills owe largely to the geologic and hydrologic environment. The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago during the Laramide orogeny (Redden and Lisenbee, 1996). The dome trends north-northwest and is about 120 mi long and 60 mi wide, with elevations ranging from 7,242 feet (ft) above National Geodetic Vertical Datum of 1929 at Harney Peak to about 3,000 ft in the adjacent plains. Erosion has exposed Precambrian-age igneous and metamorphic rock units in the central Black Hills (Figure 1), flanked by outward-tilted (Figure 2) Paleozoic carbonate and sedimentary rocks that include the Ordovician- and Cambrian-age Deadwood Formation through the Permian-age lower Spearfish Formation. Each of the four study basins heads at least in part within the Precambrian rocks before draining eastward through canyons and steep-sided valleys cut into progressively younger Paleozoic rocks and exiting onto the plains of western South Dakota at approximately the upper extent of the Paleozoic sequence.

Four of the six study reaches (all except the upstream reaches of Rapid and Boxelder Creeks) are where the streams cut through the Mississippian- and Devonian-age Madison Limestone and the Pennsylvanian- and Permian-age Minnelusa Formation (Figure 1). Both formations have local site conditions conducive for flood deposition and preservation of deposits. The Madison Limestone is cavernous, with many small caves

Figure 2. Geologic cross-section A-A' (modified from Strobel and others, 1999). Location of section and abbreviations for stratigraphic units are shown in Figure 1.

and alcoves in canyon walls that flank the modern channels and provide many potential sites for accumulating and sheltering flood slack-water deposits. The Minnelusa Formation is not as cavernous, but erodes and weathers into ledgy outcrops with alcoves and overhangs that locally accumulate and preserve slack-water deposits. The upstream sub-reach of Boxelder Creek is within the Ordovician- and Cambrian-age Deadwood Formation, a sandstone and conglomerate that can erode into ledges and overhangs similar to the Minnelusa Formation. The upstream reach of Rapid Creek is within the Precambrian rocks.

The formation and identification of slack-water deposits is enhanced by the coarse-grained Precambrian metamorphic and igneous rocks within the headwaters of all study basins. Tertiary-age intrusive rock units also are exposed in parts of the Boxelder and Elk Creek Basins (Figure 1). The Tertiary rocks and the Precambrian granitic rocks, gneisses, and schists all weather to produce micaceous quartzofeldspathic sand fine enough to be readily entrained during large floods, and thereby creating high suspended-sediment loads, but sufficiently coarse to settle rapidly in slack-water environments so to produce depositional sequences. Additionally, within the five reaches in the Paleozoic sedimentary rocks, the distinctly micaceous sands derived from the upper parts of the four study basins allow for secure identification of main-stem flood deposits. In particular, the mica-rich sands derived from the Precambrian and Tertiary rocks in the upstream parts of the watershed are unambiguously distinguishable within sediment accumulations

from deposits of local tributaries, slope-wash, or sediment spalling from cave and alcove ceilings and walls, all of which do not contain mica.

Another key geologic aspect of the Black Hills study reaches 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 ancient floods from modern channel geometry. All study reaches are in narrow valleys laterally constrained by steep bedrock slopes. Because of the narrow canyons, flood stages change markedly with flow magnitudes, therefore improving reliability of flow estimates derived from the elevations of flood deposits. Additionally, bedrock crops out locally in the channel thalweg for all study reaches, indicating that the streams are flowing on alluvial deposits that are less than a few tens of feet thick. Thus, potential for lateral erosion and channel scour during floods is limited by bedrock valley margins and thin alluvial cover in valley bottoms, which reduces uncertainty in the hydraulic computations owing to uncertain channel geometry. Photographs illustrating channel conditions along Elk Creek are provided in Figure 3.

Long-term regional rates of downcutting are consistent with the premise of overall channel stability for the last several thousand years. Figure 2 shows that more than 5,000 ft of bedrock presently overlies the Deadwood Formation east of the Black Hills. Uplift of the Black Hills area began about 60 to 65 million years ago (Redden and Lisenbee, 1996), indicating a long-term regional erosion rate of 0.08 ft per thousand years. Recent rates of regional downcutting may be different than long-term averages, but overall downcutting

Figure 3. Photographs showing examples of bedrock outcrops in channels. Both photographs were taken along Elk Creek.

in the last 2,000–3,000 years—the maximum length of the stratigraphic records of flooding considered in this study—is almost certainly less than 1 ft.

Hydrology of the Study Area

The hydrology of the study area relative to general water-resource considerations has been described by many investigators, and a comprehensive summary was provided by Driscoll and others (2002). Driscoll and Carter (2001) identified five hydrogeologic settings for the Black Hills area that distinctively influence general streamflow characteristics. Sando and others (2008) described influences of these hydrogeologic settings on peak-flow characteristics, one of which is a distinctive reduction in peak-flow magnitudes for low-magnitude peaks within “loss zones” that exist within the Paleozoic canyon reaches (Hortness and Driscoll, 1998). Because of this influence, the Spring Creek, lower Boxelder Creek, and Elk Creek reaches frequently are dry and flow may not occur during some years.

Driscoll and others (2010) examined climatological factors affecting generation of heavy rain-producing thunderstorms in the Black Hills area, which were identified as causing most of the measured and historically reported large floods in the area. That study documented a tendency for exceptionally heavy precipitation east of the major axis of the Black Hills uplift, which generally coincides with a north/south trending escarpment along the contact between the Deadwood Formation and the Precambrian rocks about 10 to 15 miles east of the South Dakota/Wyoming border (Figure 1). The heaviest rain-producing thunderstorms generally occur east of this escarpment, with the greatest

rainfall intensities and volumes along the eastern flanks of the Black Hills uplift and coinciding with areas of steepest slopes and greatest orographic uplift. This general area also was identified by Sando and others (2008) as having especially large flood potential owing to (1) rapid flow concentration by the steep topography and (2) limited attenuation of flood peaks within the narrow canyon reaches.

In comparing storms and flooding during 2007 and 1972 in the Hermosa area, Driscoll and others (2010) provided examples of very large and rapid changes in flow, which are typical of hydrographs for flash floods that have been recorded for the Black Hills area. In conjunction with the flashy hydrographs, that study also documented large spatial variability in peak flows within short stream reaches for both floods. Such variability in both spatial and temporal flow characteristics for these recent flows undoubtedly applies to floods recorded by slack-water deposits as well.

Driscoll and others (2010) also identified a gradient of increasing potential (from south to north) for contributions to large-scale floods from antecedent moisture conditions, which can include snowpack, soil moisture, high base flow, and runoff from prior precipitation events. Snowpack can contribute by way of both antecedent runoff (from snowmelt) and potential for melting during relatively warm rainfall events. The south to north gradient is consistent with (1) patterns for average annual precipitation, which increases from about 16 inches (in.) at the southern extent of the Black Hills to almost 30 in. near Lead in the northern Black Hills (Driscoll and others, 2000); and (2) seasonal

precipitation patterns, which typically result in the heaviest snowpack accumulations for the northern Black Hills.

Land use and disturbance, especially from forest fires (for example, Agnew and others, 1997) can affect flood generation in the Black Hills. Driscoll and others (2004) documented increases in peak flows following the 1988 Galena Fire within the Battle Creek watershed. Some individual slack-water deposits investigated during this study contained abundant charcoal, indicating probable deposition shortly after large fires that may have enhanced basin runoff. Historical fire suppression probably has increased timber stand densities in the Black Hills (Progulske, 1974; Grafe and Horsted, 2002; Driscoll and others, 2004) with associated decreases in fire frequency, but increases in fire size and intensity (Brown and Sieg, 1996; Covington and More, 1994). For small urbanized basins, flood magnitudes certainly have increased since European settlement from construction of impervious surface areas. However, overall flood potential prior to European settlement is not known to be substantially different than current flood potential as a consequence of land-cover influences for the largely undeveloped and forested basins of this study.

Methods of Investigation

The primary focus of this study was to 1) establish the late Holocene flood history of the study area; and 2) characterize the frequency of recurrence of low-probability floods for six stream reaches within four basins of the central and eastern Black Hills. The main sources of information used in this study are stratigraphic records of large

prehistoric floods, supplemented by existing peak-flow records and historical flood accounts. The overall approach for each reach 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 includes paleoflood information, observational records, and historical flood accounts.

Development of Long-Term Flood Chronologies

Long-term flood chronologies primarily were derived from stratigraphic and geochronologic analysis of paleoflood deposits. Ensuing flood-frequency analyses also incorporated modern chronologies from gaged peak-flow records and historical flood accounts.

Development of Paleoflood Chronologies

Paleoflood chronologies were derived primarily from stratigraphic analysis and age dating of flood slack-water deposits. This approach has been developed over the last three decades and is now a widely used method for quantifying unrecorded floods (Baker, 1987; Kochel and Baker, 1988; Ely and others, 1993; O'Connor and others, 1994; Sheffer and others, 2008). Flood slack-water deposits are composed of sand and silt suspended in large, high-velocity floods and deposited in channel margin areas where the sediment

falls out of suspension due to reduced flow velocities. Typical sites where slack-water deposits are well preserved can include tributary mouths, rock shelters and alcoves, and bedrock caves (Kochel and Baker, 1982, 1988; Baker, 1987). Stable sites can yield information on numerous floods over thousands of years.

Stratigraphic Analysis

For this study, potential sites for stratigraphic analysis were identified by examining canyon walls and valley margins along most of the lengths of each of the study reaches where streams cut through geologic formations suitable for deposition and preservation of slack-water deposits (chiefly the Madison and Minnelusa Formations). 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 discharge, deposit flotsam (particularly beverage containers, milled wood, and plastic debris), and the degree of weathering of the flood deposits or entrained organic material. For sites where reconnaissance indicated possible sediment accumulations from prehistoric floods, the stratigraphy was exposed by excavations. Pits typically were excavated through all the slack-water deposits to either bedrock or large and immovable rockfall. Where possible, several pits were excavated at each site in search for the most complete record. Where possible, stratigraphic sequences were examined at multiple elevations at individual sites, as well as multiple sites within reaches, in order to more precisely define the frequency of deposition at different stages.

Upon excavation, pit stratigraphy was examined to determine the sequence of flood deposits. Individual main-stem flood deposits typically were separated from each other by evidence of temporal hiatus. Such evidence included layers or isolated clasts of local rockfall, bioturbated cave or alcove floor deposits, slopewash, in situ vegetation, and in some cases evidence of cultural occupation or soil development. Identification of this evidence is key to the stratigraphic interpretations, and errors in inferences regarding breaks between individual flood deposits can lead to under- or over-estimates of the number of floods recorded in a sequence of deposits. Consequently, considerable effort was made to expose as much of the stratigraphy as possible and to carefully evaluate deposit stratigraphy for evidence of individual episodes of flood deposition. All observations and interpretations were recorded in detailed field notes and included measured thicknesses of all stratigraphic units, color, texture, grain size, degree of sorting, moisture content, amount of organic material, type of fluvial structures such as laminations or cross-bedding if present, degree of bioturbation, and the nature of the contact between units.

Geochronology

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 geochronologic approach used was radiocarbon analysis using carbon-14 (^{14}C) (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.

Organic samples were collected during examination and description of site stratigraphy. Samples were collected by hand, metal spatula, trowel, or knife and placed in sealable plastic bags. The nature of the material, its location in the section, and depth below the surface were recorded for each sample. For some flood deposits without visible organic material, bulk sediment samples were collected and later more closely examined to identify datable fragments of organic material. From all collected samples (more than 300), the 99 samples submitted for analysis were selected (1) on the basis of judgments regarding the relative importance of individual deposit sequences to understanding the overall flood history; (2) to obtain ages for the largest floods; and (3) to determine the length of depositional records at key sites, typically by selecting samples from near the base of deposit sequences. Results from basal ages guided selection of additional analyses. Additionally, multiple samples from some individual flood deposits (or intervening layers) were submitted to confirm key ages or to reduce ambiguity for cases where ages from previously analyzed samples were inconsistent with stratigraphy. Submitted samples were converted to graphite (Vogel and others, 1984) at the USGS Radiocarbon Dating laboratory in Reston, VA (U.S. Geological Survey, 2010b), and dated by accelerator mass spectrometry at either the Center for Mass Spectrometry, Lawrence Livermore National Laboratory in Livermore, Calif. (Center for Accelerator Mass Spectrometry, 2011) or at the NSF-Arizona Accelerator Mass Spectrometry Laboratory in

Tucson, Ariz. (Accelerator Mass Spectrometry Laboratory, 2011). Ages were calculated according to the methods of Stuiver and Polach (1977).

Results of radiocarbon analyses can have inherent ambiguity. Plants incorporate atmospheric ^{14}C through photosynthesis, and systematic loss of ^{14}C from the plant tissue occurs by radioactive decay beginning when the plant dies. Thus, radiocarbon dating yields the time of death of the plant. Consequently, an inherent assumption is that time of death of organic material associated with a flood deposit closely approximates the time of the flood. More precisely, however, the radiocarbon age of organic material within a flood deposit is a maximum limiting age for the flood, and organic materials associated with subaerial surfaces that accumulated materials between floods, provide a maximum limiting age for the flood deposit overlying the surface. To reduce potential errors resulting from dating materials substantially older than the associated flood deposits, selected samples for dating typically were those not expected to persist long in open environments, such as small plant fragments, pine needles and leaves. In certain situations, however, the only available datable materials were of types that could have persisted for many years, even centuries, before being entrained into a flood deposit. Charcoal and large wood fragments are particularly susceptible to yielding erroneously old ages because of their potential persistence and reworking by multiple floods (Blong and Gillespie, 1978). For many sites, multiple samples were analyzed for key flood deposits to reduce the possibility of these types of errors affecting the final flood chronologies.

In addition to uncertainty introduced by stratigraphic context of the sample, the ratio of ^{14}C to carbon-12 (^{12}C) in the atmosphere, biosphere, and hydrosphere has varied; consequently, radiocarbon ages based on the historical ratio diverge from true calendar ages. For this reason all radiocarbon ages have been converted to calendar ages. For radiocarbon ages less than about 300 years, the resulting uncertainties in the calendar age are especially large because of the large and varying quantities of ^{12}C released into the atmosphere by anthropogenic burning of fossil fuels (Walker, 2005). Samples of organic materials photosynthesizing after A.D. 1950 have particularly high ^{14}C levels owing to substantial ^{14}C introduction into the atmosphere by above-ground nuclear testing, and such post-1950 ages are simply noted as “modern.” As a consequence of these variations, radiocarbon ages of between 60 and about 300 years before present (2010) cannot typically be distinguished from each other, hindering precise dating of individual flood deposits from this time period (Taylor, 2001).

Radiocarbon results for 99 analyzed samples are reported in Table A.1 in Appendix A. Reported results include the uncalibrated radiocarbon age plus or minus ($\pm$) the analysis error of one standard deviation ($1-\sigma$ or 1-sigma). Also reported are the calibrations in calendar years (and the resulting two standard deviation ($2-\sigma$ or 2-sigma) uncertainties) as determined by the radiocarbon calibration program Oxcal version 4.1 (Bronk Ramsey and others, 2001; Bronk Ramsey, 2009; Reimer and others, 2009). Because of fluctuations in the atmospheric ^{14}C content, some radiocarbon ages equate to multiple

calendar-year periods. A median age derived (using the Oxcal calibration program) from the single or multiple age ranges also is reported.

The radiocarbon dating generally resulted in internally consistent results, with younger ages obtained from deposits stratigraphically above deposits with older ages. However, a few cases of widely divergent ages from the same stratigraphic deposit, and inconsistencies among dates relative to stratigraphic position probably resulted from (1) old charcoal or wood being entrained into a flood deposit; (2) bioturbation by plants or burrowing animals, resulting in movement of organic matter between stratigraphic units; (3) mistakenly sampling roots instead of detrital organic materials; and (4) errors in interpretation of the stratigraphic context of the sample in the overall deposit stratigraphy. Judging from the overall consistency of results, however, such issues were uncommon, and most of the few observed inconsistencies probably are due to old detrital material being incorporated into younger flood deposits.

Optically stimulated luminescence (OSL) was used for dating deposits less than about 300 years old, which cannot be precisely dated by radiocarbon analyses, and for deposits with insufficient organic material for radiocarbon dating. Sediment containing (or proximal to) naturally occurring radioactive isotopes, such as uranium, thorium, and potassium-40 are subject to low levels of radiation (Walker, 2005). OSL dating relies on the accumulation of free electrons derived from the decay of such radioisotopes within structural defects in the crystal lattice of a mineral grain. The longer a mineral grain is exposed to a radiation source, such as being buried in sediment with radioactive isotopes,

the more trapped electrons accumulate (Bradley, 1999; Walker, 2005). When a mineral grain is exposed to light, the electrons are stimulated and released from the crystal lattice. Under laboratory conditions, the number of electrons released can be measured and correlated to the amount of time the crystal has been buried, thus giving a burial age. Flood sediments considered for this study primarily are derived from upstream igneous or metamorphic rocks containing naturally occurring radioactive isotopes. Additionally, the sediment contains abundant quartz grains, which accumulate free electrons from radioactive decay in the structural defects of their crystal lattices. If sediment entrained by a flood is exposed to light (bleached) before or during entrainment, the electron traps will be emptied, only to begin accumulation when buried within a flood deposit. In such cases, the measured age as indicated by subsequent electron accumulation represents the age of the depositing flood.

All OSL samples were collected using 1- or 2-in diameter metal or plastic tubes. The tubes were hammered horizontally into freshly exposed flood sediments in locations chosen to avoid large rocks and post-depositional disturbances such as bioturbation, root penetration, or desiccation cracks. Aluminum foil was packed into the exposed end of the tube in order to minimize sample movement in the tube during transit. Tubes were capped, wrapped in aluminum foil, and sealed with opaque tape to prevent light exposure. When necessary, an opaque cloth was used during sample collection to shield the excavation from light. Bulk sediment samples of 1.3 pounds or larger also were collected in sealable plastic bags for measurement of water content and dose-rate. In all, 20 samples were

collected, with 11 samples analyzed (Duller, 2008) by the USGS Luminescence Dating Laboratory in Lakewood, Colorado (U.S. Geological Survey, 2010c). Dates derived using OSL analyses are provided in Table A1.2 in Appendix 1.

The OSL sample ages generally were consistent with the ^{14}C analyses, where both types of dating were applied, and provided improved resolution for floods within the last 300 years. In a few cases, the OSL samples were older than corresponding ^{14}C ages or than the known age of 1972 flood sediments. These discrepancies probably owe to incomplete bleaching of sediment during flood entrainment and deposition, a plausible scenario for the high turbidities and low-light conditions associated with typical late-afternoon thunderstorm genesis and nighttime flood peaks for the Black Hills area (Driscoll and others, 2010).

Cesium-137 (Cs-137) analyses were used in several cases to determine if uppermost flood deposits were from 1972 flooding. Atmospheric Cs-137 was produced during atmospheric nuclear weapons tests, with smaller amounts from nuclear reactor waste and accidental releases such as Chernobyl (*U.S. Environmental Protection Agency, 2010*). Thus, Cs-137 production and deposition began about 1945 and peaked about 1963 (Holmes, 1998). The Cs-137 that reaches the land surface is strongly fixed to the surface deposits. For the purpose of this study, the Cs-137 analyses did not return actual ages for flood units, but presence or absence of Cs-137 indicates whether or not a deposit pre- or post-dates 1945. If Cs-137 is detected in a deposit, the emplacing flood must have been after 1945; if Cs-137 is not detected, the flood was before 1945. This provided a reliable

and economical means to distinguish 1972 flood sediments from those of slightly older (but pre-1945) floods, such as those of 1907 (Honerkamp, 1978), which likely approached 1972 flow rates in some drainages.

The Cs-137 samples were collected with a metal trowel and stored in sealable plastic bags. Freshly exposed samples were extracted from the middle of the flood units, or if the unit was thick, in 4-in, unit depth intervals. Moist samples were air dried and then sent to the USGS Radioisotope Laboratory (U.S. Geological Survey, 2010d) in St. Petersburg, Florida for analysis. Results of Cs-137 analyses are provided in Table A.3 in Appendix A.

Compiling Reach-Scale Paleoflood Chronologies

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. These interpretations required extracting and combining information from multiple sites within a reach and using judgments and inferences regarding the stratigraphic relations among the sites. This process generally entailed selecting a “benchmark” site for each reach (typically one with a particularly long and complete record) to which all paleoflood information for the reach was compiled. Such compilation primarily was derived from the stratigraphic record at the benchmark site, supplemented by stratigraphic records, dating, and flow-magnitude information from other sites within the reach. Interpretations required correlation of flood evidence among

multiple sites, chiefly on the basis of relative position within stratigraphic sequences, unique textural characteristics, or results of age dating and flow estimation.

The collective approaches used for interpreting flood sequences at individual sites and for correlating among sites within a reach lead to possibly underestimating the number of floods in the stratigraphic record. A fundamental premise is that deposition of flood sediment requires exceedance of the deposit elevation by flood stage; however, it is possible that a flood exceeding a deposit elevation may do so barely, or for some other reason may not leave a recognizable deposit. Because the protocol for stratigraphic analysis requires evidence of temporal hiatus in distinguishing individual flood deposits, multiple deposits from floods separated by short intervals can potentially be counted as a single flood unit if such evidence of hiatus is not observed. Correlations among sites were additionally conservative in that stratigraphic records from sites within a reach were considered to be completely overlapping unless compelling stratigraphic or geochronologic information indicated otherwise, again leading to possibly undercounting the total number of floods because stratigraphic records at some sites may include evidence of floods not preserved at other sites owing to various circumstances. Potential biases were minimized by (1) selecting benchmark sites with relatively complete (as inferred by being in low-energy and passive depositional environments) and long-duration records and (2) focusing ensuing flood-frequency analyses on the largest, rarest, and most recent (generally within the last 1,000 years) floods, for which bias due to closely-spaced or inconsistent deposition patterns are less likely to affect results. For example, it

is unlikely that two very large floods are so closely spaced in time that no evidence of temporal hiatus is preserved. By contrast, it is more likely that smaller floods will fail to leave consistent records from site to site than it is for especially large floods.

Development of Modern Peak-Flow Chronologies

For computation of long-term flood-frequency analyses, the paleoflood records derived from the stratigraphy and geochronology were combined with observational records and historical accounts of peak flows, which were compiled and adjusted so as to be directly comparable to the paleoflood records determined for each study reach.

Modern chronologies for each study reach were developed primarily from available systematic USGS peak-flow records (U.S. Geological Survey, 2010e) for selected streamgages (Table 1) and generally are referred to as gaged records within this study. Historical flood accounts pre-dating gaged records also were incorporated in analyses for Rapid Creek and Elk Creek.

Modern peak-flow chronologies (through water year 2009) for the study reaches are provided in Table 2. Details regarding development of the modern chronologies are described in Appendix B. This section includes Tables B.4 through B.8 that provide peak-flow records and historical information (by stream reach) for all streamgages considered. The modern chronologies for both reaches of Rapid Creek are derived for streamgage locations that were coincident with the study reaches. For all other cases, however, gaged and historical records were adjusted on the basis of drainage area to be comparable with the paleoflood study reaches. Drainage areas for the streamgages and

for selected locations within the study reaches are provided in Table 1. Adjustments relative to drainage area were performed using an equation adapted from Burr and Korkow (1996):

$$Q_t = Q_g (A_t/A_g)^{0.6},$$

where Q_t and A_t are peak-flow values and areas, respectively, for a target location, and Q_g and A_g are peak-flow values and areas for a gaged location. Various approaches can be used for selection of the exponent (Burr and Korkow, 1996; Sando, 1998), and 0.6 is consistent with analyses of Sando and others (2008) in which large peak-flow values for the Black Hills area were normalized relative to drainage area. Many of the derived values in table 2 are reported with unrealistic precision (numbers of significant figures) for use in subsequent flood-frequency analyses, with appropriate rounding reported in the final flood-frequency analyses.

Estimation of Flow Rates

A key aspect of any paleoflood record is estimation of flow magnitudes for floods preserved in the stratigraphic records. Flow estimates derive from the elevations of slack-water deposits or other flood evidence in conjunction with hydraulic calculations based on modern channel and valley geometry.

Assumptions and General Considerations

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). Additionally, the

Table 1. Drainage areas and periods of peak-flow record for selected streamgages. Areas for selected locations within and near stream reaches for detailed paleoflood investigations also are included.
[--, not applicable]

Streamgage number	Streamgage name or location of relevant feature or study reach	Drainage area (square miles) ¹	Period of record considered (water years) ²
Spring Creek drainage basin			
06407000	Spring Creek near Hill City, S. Dak.	151	1938–1940
435915103241200	Spring Creek below Bitter Creek, SD	157	1972
06407500	Spring Creek near Keystone, S. Dak.	163	1946–47, 1987–2009
--	Upstream extent of Spring Creek study reach	170	--
--	Downstream extent of Spring Creek study reach	172	--
06408000	Spring Creek near Rapid City, S. Dak.	175	1904–05, 1946–47, 1972
06408500	Spring Creek near Hermosa, S. Dak.	206	1950–2004
Rapid Creek drainage basin			
06409000	Castle Creek above Deerfield Reservoir near Hill City, S. Dak.	79.3	1949–2009
--	Deerfield Dam	92.4	³ 1945
06410000	Castle Creek below Deerfield Dam near Hill City, S. Dak.	92.5	1947–2009
--	Upstream extent of upper Rapid Creek study reach	290	--
06410500	Rapid Creek above Pactola Reservoir at Silver City, S. Dak.	294	1954–2009
NA	Pactola Dam	321	³ 1956
06411500	Rapid Creek below Pactola Dam, S. Dak.	322	1929–42, 1947–2009,
06412000	Rapid Creek at Big Bend near Rapid City, S. Dak.	339	1915–17, 1932–42, 1998–2009
--	Upstream extent of lower Rapid Creek study reach	367	--
06412500	Rapid Creek above Canyon Lake near Rapid City, S. Dak.	375	1947–2009
--	Downstream extent of lower Rapid Creek study reach	384	--
06414000	Rapid Creek at Rapid City, S. Dak.	414	1905–06, 1943–2009

Table 1. Drainage areas and periods of peak-flow record for selected streamgages. Areas for selected locations within and near stream reaches for detailed paleoflood investigations also are included — Continued.
[—, not applicable]

Streamgage number	Streamgage name or location of relevant feature or study reach	Drainage area (square miles) ¹	Period of record considered (water years) ²
Boxelder Creek drainage basin			
06422500	Boxelder Creek near Nemo, S. Dak.	94.4	1907, 1946–47, 1966–2009
--	Upstream extent of Boxelder Creek study reach	98	--
--	Boxelder Creek between two sub-reaches (sub-reach break is about 0.2 miles downstream from confluence with Bogus Jim Creek)	111	--
--	Downstream extent of Boxelder Creek study reach	112	--
06422650	Boxelder Creek at Doty School near Blackhawk, S. Dak.	116	1972, 1978–80
06423000	Boxelder Creek at Blackhawk, S. Dak.	126	1904–05, 1946–47
06423010	Boxelder Creek near Rapid City, S. Dak.	126	1981–2009
Elk Creek drainage basin			
06424000	Elk Creek near Roubaix, S. Dak.	21.6	1946–47, 1992–2009
--	Elk Creek paleoflood study reach	40	--
06424500	Elk Creek above Piedmont, S. Dak.	47.6	1945–47, 1972
06425100	Elk Creek near Rapid City, S. Dak.	211	1979–2009
06425500	Elk Creek near Elm Springs, S. Dak.	549	1950–2009

¹Includes entire drainage area, regardless of effects of regulating structures.

²Includes entire period of record, regardless of effects of regulating structures.

³Water year of first storage within regulating structure.

highest deposits may closely approximate the peak stage (Webb and others, 2002), although maximum flood stages may exceed the highest deposits in many cases. For purposes of hydraulic calculations, stage evidence is related to modern channel and valley geomorphology, which introduces an additional assumption that changes in geometry have been sufficiently small over 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.

Although overall changes in channel and valley geometry probably are small for the length of the paleoflood records (generally 2,000 years or less), it is likely that minor mass wasting and downed timber locally have affected flow hydraulics. No evidence, however, of large-scale mass wasting was discovered during the reach surveys, so it is unlikely that such events have substantially affected results. Log jams and large boulder bars from 1972 flooding were evident in many study reaches, but resulting blockages were small relative to overall canyon geometry and likely had little influence on reach-scale flood hydraulics within the steep channels of the study reaches.

Hydraulic Modeling

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 entire study reaches along Spring Creek, Boxelder Creek, and the reach of Rapid Creek located downstream from Pactola Reservoir and just west of Rapid City (Figure 1). For Rapid Creek, an existing digital topographic coverage (5-ft contour interval) was provided by the city of Rapid City (Dan Jarvenin, written commun., March 2009). For Spring and Boxelder Creeks, SDDOT provided digital topographic coverages (2-ft contour interval) developed from high-resolution photogrammetry acquired specifically for this study. For these reaches, high-water evidence from 1972 flooding and all sites of stratigraphic analysis were surveyed using a combination of survey-grade Global Positioning System and standard leveling equipment. Elevations were related to a high-resolution topographic network developed for the Rapid City area (City of Rapid City, 2010), with internal checks indicating that most surveyed elevations have errors less than 0.1 ft.

All topographic data were converted to triangular irregular networks (TINs) using the spatial analysis tools in ArcMAP (Environmental Systems Research Institute, 2010). Cross sections for HEC-RAS analyses were digitized in ArcMap and placed and oriented to reflect conveyance during flood stages and thus are not always perpendicular to low-water channels. Cross sections include all areas of inferred down-valley flow conveyance, including overbank areas, but exclude areas likely to be occupied by eddies and stagnant flow during high stages, such as at tributary mouths and behind large rock

protrusions. Cross sections were spaced at intervals of 100 ft or less for all of the study reaches.

The HEC-RAS model uses the step-backwater method for estimating water-surface elevations corresponding to specified flow rates. The method is based on the one-dimensional energy equation to determine energy-balanced water-surface profiles for flows that are steady (in time), gradually varied, and for slopes less than about 0.1 ft/ft (U.S. Army Corps of Engineers, 2008b). Step-backwater models have been used extensively to estimate paleoflood magnitudes in multiple studies globally (O'Connor and Webb, 1988; Enzel and others, 1994; Wohl and others, 1994; Hosman and others, 2003; Sheffer and others, 2008).

Average channel gradients in the three simulated reaches are 0.007, 0.008, and 0.01 ft/ft for Rapid, Spring, and Boxelder Creeks, respectively. Critical-flow conditions were identified in many sections of the simulated reaches, which is consistent with conditions described in a subsequent section titled "Other Approaches for Estimation of Flow Rates."

Results of the HEC-RAS simulations for high flows for all simulated reaches were "calibrated" by checking simulation output against known flow values and high-water evidence associated with 1972 flooding, including tree scars, flotsam lines, flood debris piles, and geomorphic evidence. These data allowed evaluation of values for Manning's roughness coefficient (Manning's n) and provided confidence regarding digital topographic coverages and overall model functionality. High-water marks documented by

the U.S. Army Corps of Engineers (1973) were available for part of the reach of lower Rapid Creek and were supplemented by 1972 high-water accounts obtained from local residents in this reach.

Selection of the final (calibrated) HEC-RAS model for each simulated reach was accomplished by comparing simulation output to a water-surface profile based on 1972 estimated flow rates and high-water marks. Cross sections and model input parameters including Manning's n were adjusted accordingly. Roughness coefficients and channel geometry are inherently subject to change over time; however, these variables were assumed constant in the absence of other information. Water-surface elevations were calculated for a range of Manning's n values (± 25 percent of final values) to determine the sensitivity of the reaches to roughness and to obtain a range of flow values likely associated with each water-surface elevation. Once appropriate water-surface elevations corresponding to specific flow rates were established, rating curves (relation between flow rate and stage) were constructed for each paleoflood site. For all paleoflood sites, uncertainties in simulated flow rates resulting from the ± 25 percent range of Manning's n values were substantially smaller than overall uncertainties assigned to paleoflood flow estimates, as described in a subsequent section "Models for Flood-Frequency Analyses."

Other Approaches for Estimation of Flow Rates

Paleoflood evidence for Elk Creek and the upstream reach of Rapid Creek was sparser than for the other study reaches, and use of the HEC-RAS model (and the required

reach-scale topographic surveys) was not justified. Instead, flow estimates were derived by applying the Manning equation or critical-flow equation for a cross section at each site of stratigraphic analysis. The Manning equation (Barnes, 1967; Benson and Dalrymple, 1967) is an established relation for estimating flow rate; $Q = 1.49n^{-1}AS^{1/2}R^{2/3}$, where Q is flow rate (in cubic feet per second), n is the Manning roughness coefficient (dimensionless), A is the cross section area (in square feet), S is the energy gradient (typically assumed equivalent to channel slope, in feet divided by feet), and R is the hydraulic radius, which is the wetted perimeter divided by area (in feet). The critical-flow equation is based on the observation that flows in high-gradient channels tend toward a state of minimum specific energy, thereby allowing calculation of flow from cross section geometry alone (Grant, 1997). This condition is satisfied for $Q = (gA^3T^{-1})^{1/2}$, where g is the acceleration of gravity (32.174 feet per second squared), and T is flow top width (in feet). Alternatively, velocity (V , in feet per second) can be computed as $V = (gHD)^{0.5}$, where HD (hydraulic depth, in feet) is computed as area divided by top width, which allows computation of flow rate as area times velocity.

The main advantage of the critical-flow equation is that it does not rely on judgments regarding Manning's n , and on the assumption that measured channel slope is equivalent to the energy gradient. There may be uncertainty as to whether flow is indeed close to critical conditions—an uncertainty that can only be addressed completely by more sophisticated hydraulic analysis. However, Jarrett and England (2002) showed that peak flow computed by the critical-flow equation generally was within about ± 15 percent

of flow rates computed using direct current meter measurement methods for 35 stream reaches with slopes exceeding about 0.01 ft/ft, as is the case for the applicable study reaches. Additional confidence in the applicability of the critical-flow equation was obtained by inspection of numerous slope-area measurements (method described by Benson and Dalrymple, 1967) conducted by the USGS for large flows events in the Black Hills area, including many measurements reported by Schwarz and others (1975) for sites with large 1972 flows. These measurements commonly showed Froude numbers approaching or exceeding 1.0 (indicative of critical-flow conditions), with computed flow conditions vacillating between sub- and super-critical conditions for multiple cross sections within computational reaches.

Flood-Frequency Analysis

Paleoflood information provides tangible information on the occurrence and magnitude of large and infrequent floods, which when considered in a statistically appropriate manner, can substantially reduce uncertainties in frequency and magnitude estimates of rare floods (Hosking and Wallis, 1986; Costa, 1978; Stedinger and Baker, 1987; Frances and others, 1994; Webb and others, 2002). The increasingly global application of paleoflood studies has prompted development of new techniques to efficiently consider such information in frequency analyses (Stedinger and Cohn, 1986; Cohn and others, 1997; Levish, 2002; O'Connell and others, 2002).

Models for Flood-Frequency 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 and others, 2002), and (2) the PeakfqSA model (Cohn and others, 1997, 2001; Griffis and others, 2004). Both models allow specification of dates, flow rates, and perception thresholds for peak-flow events. Perception thresholds provide constraining information regarding known (or presumed) exceedances (or non-exceedances) of especially large flood magnitudes within specified timeframes. For example, for several study reaches it is known from historical accounts that the 1972 flood was the largest flood since 1907 even in the absence of complete gaged records dating to 1907. Thus, the 1907 flood can be used as a threshold for the period 1907–2009 based on the fact that the 1907 flow has been exceeded once in the intervening 102 years. Similarly, estimates of timing and magnitude for some of the paleofloods within a reach can be used as perception thresholds—based on the assumption that subsequent larger floods would have left evidence.

For both models and all reaches, flood-frequency analyses were computed assuming log-Pearson Type III frequency distributions and were performed for as many as four flood-record scenarios: (1) analysis of gaged annual peak flows only; (2) gaged peak flows in combination with historical flow information (when available), including historical thresholds; (3) all available data, which may include the gaged peak flows, historical flows and thresholds, and paleoflood events and thresholds; and (4) the same as the third scenario, but “top fitting” the distribution by arbitrarily including only the largest

50 percent of the gaged peak flows (that is, those larger than the median of the gaged flows). The Weibull plotting position (Weibull, 1939) was used for graphical representations of results of flood-frequency analyses for all scenarios.

Scenarios 1 and 2 (using only gaged flows and historical information) were conducted as baseline analyses and provided a basis for comparison of incremental effects of including all available data (scenario 3). The top-fitting analyses (scenario 4) could be conducted only with the PeakfqSA model (due to the complexity of the datasets) and enabled consideration of the general sensitivity of the analytical approach to inclusion of relatively small flows that dominate typical gaged peak-flow records. The small flows may result from flood-generation processes with different statistical properties, and thus may adversely affect fitting of the frequency distribution, especially with respect to low-probability floods. Top-fitting strategies similar to scenario 4 may ultimately provide the most robust flood-frequency analyses for rare floods; however, more rigorous evaluation of potential approaches would first be appropriate.

Consequently, analyses resulting from scenario 3, which include the entire observational, historical, and paleoflood records, are considered to provide the best estimates of flood recurrence (flood-frequency estimates) for low-probability floods. Within this report, flood-frequency estimates are provided only for recurrence intervals of 25 years or larger (annual exceedance probabilities of 0.04 or smaller). Results are not reported for smaller recurrence intervals because several study reaches are within loss-zone settings

described by Sando and others (2008), and accurate characterization would require additional analyses beyond the scope of this study.

The FLDFRQ3 model uses a Bayesian approach (O'Connell and others, 2002) with a maximum likelihood method (Stedinger and Cohn, 1986). The FLDFRQ3 model allows for specification of uncertainties for magnitudes and timing of hydrologic events and for thresholds derived from paleoflood data that arise due to flow-rate, stratigraphic, and chronologic uncertainties. Additionally, the FLDFRQ3 model allows for specification of uncertainties in the gaged record, with uncertainties assigned (Table 2) on the basis of general reliability of the datasets. For this study, uncertainties of ± 10 percent were assigned for the most reliable peak-flow records (recent gaged records from locations near the benchmark sites). Progressively larger uncertainties (as much as 33 percent) were assigned for flow values derived using various methods of estimation as described in the previous section "Development of Modern Peak-Flow Chronologies." Especially large flow values generally were assigned uncertainties of ± 33 or 50 percent, depending on professional judgment regarding factors such as sources of data and extrapolation required for applicability to study reaches.

In the maximum likelihood approach used by the FLDFRQ3 model, especially large flows can be used as constraints, or perception thresholds, on the magnitude and timing of the peak flows. When incorporating perception thresholds for paleofloods, a range of ages can be used. In most analyses, thresholds were based on stratigraphic and geochronologic evidence. In order to be consistent with the input values of the PeakfqSA

Table 2. Modern peak-flow chronologies (gaged records) for paleoflood study reaches.

[Shaded cells indicate special computations for the lower Rapid Creek reach, as noted in text. Blank rows signify a gap in the chronology. %, estimated uncertainty, in percent, for use in selected flood-frequency analyses; (H), historical value; --; no data]

Water year	Spring Creek	Rapid Creek						Boxelder Creek				Elk Creek	
		Lower reach		Upper reach		Upstream sub-reach		Downstream sub-reach					
		Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%
1878	--	--	--	7,060 (H)	50	--	--	--	--	--	--	--	--
1883	--	--	--	7,900 (H)	50	--	--	--	--	--	--	--	--
1904	493	20	--	--	--	533	10	578	15	--	--	--	--
1905	691	20	2,350	15	--	559	10	606	15	--	--	--	--
1906	--	--	922	15	--	--	--	--	--	--	--	--	--
1907	--	--	12,200 (H)	50	--	16,400	33	17,700	33	10,400 (H)	50	--	--
1915	--	--	654	15	566	20	--	--	--	--	--	--	--
1916	--	--	217	15	187	20	--	--	--	--	--	--	--
1917	--	--	287	15	248	20	--	--	--	--	--	--	--
1920	--	--	7,540 (H)	50	--	--	--	--	--	--	--	--	--
1929	--	--	870	15	752	20	--	--	--	--	--	--	--
1930	--	--	213	15	184	20	--	--	--	--	--	--	--
1931	--	--	170	15	147	20	--	--	--	--	--	--	--
1932	--	--	747	15	646	20	--	--	--	--	--	--	--
1933	--	--	1,690	15	1,460	20	--	--	--	--	--	--	--
1934	--	--	128	15	111	20	--	--	--	--	--	--	--
1935	--	--	479	15	414	20	--	--	--	--	--	--	--
1936	--	--	110	15	95	20	--	--	--	--	--	--	--

Table 2 Modern peak-flow chronologies (gaged records) for paleoflood study reaches --- Continued.

Water year	Spring Creek			Rapid Creek			Boxelder Creek			Elk Creek		
	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	Lower reach	%	Annual peak flow (ft ³ /s)	Upper reach	%	Annual peak flow (ft ³ /s)	Upstream sub-reach	%	Annual peak flow (ft ³ /s)
1937	--	--	92	15	80	20	--	--	--	--	--	--
1938	539	20	94	15	81	20	--	--	--	--	--	--
1939	638	20	68	15	59	20	--	--	--	--	--	--
1940	260	20	268	15	232	20	--	--	--	--	--	--
1941	--	--	592	15	511	20	--	--	--	--	--	--
1942	--	--	448	15	387	20	--	--	--	--	--	--
1943	--	--	882	15	--	--	--	--	--	--	--	--
1944	--	--	254	15	--	--	--	--	--	--	--	--
1945	--	--	359	15	--	--	--	--	--	--	--	--
1946	346	20	943	15	--	--	--	--	--	--	--	1,630
1947	690	20	950	15	903	20	1,210	10	1,310	15	1,220	20
1948	--	--	245	15	235	20	380	10	412	15	314	20
1949	--	--	290	15	221	20	--	--	--	--	--	--
1950	100	20	209	15	221	20	--	--	--	--	--	--
1951	30	20	77	15	92	20	--	--	--	--	--	--
1952	627	20	2,600	15	2,460	20	--	--	--	--	--	--
1953	240	20	152	15	152	20	--	--	--	--	--	--
1954	418	20	140	15	106	20	--	--	--	--	--	--
1955	29	20	326	15	1,520	20	--	--	--	--	--	--
1956	33	20	203	15	175	20	--	--	--	--	--	--
1957	340	20	595	15	181	20	--	--	--	--	--	--
1958	33	20	131	15	113	20	--	--	--	--	--	--
1959	30	20	169	15	146	20	--	--	--	--	--	--
1960	33	20	135	15	117	20	--	--	--	--	--	--
1961	29	20	111	15	96	20	--	--	--	--	--	--
1962	544	20	1,700	15	390	20	--	--	--	--	--	--

Table 2. Modern peak-flow chronologies (gaged records) for paleoflood study reaches --- Continued.

Water year	Spring Creek	Rapid Creek				Boxelder Creek				Elk Creek	
		Lower reach		Upper reach		Upstream sub-reach		Downstream sub-reach			
		Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	%
1963	389	20	827	15	715	20	--	--	--	--	--
1964	88	20	735	15	635	20	--	--	--	--	--
1965	390	20	2,380	15	2,060	20	--	--	--	--	--
1966	54	20	174	15	150	20	31	10	33	15	89
1967	825	20	726	15	627	20	972	10	1,050	15	510
1968	49	20	123	15	106	20	63	10	69	15	104
1969	398	20	246	15	213	20	147	10	160	15	141
1970	34	20	1,150	15	995	20	663	10	718	15	372
1971	390	20	353	15	305	20	226	10	245	15	176
1972	21,800	33	31,200	33	252	20	30,800	33	50,500	33	10,400
1973	127	20	196	15	169	20	120	10	130	15	129
1974	33	20	476	15	54	20	24	10	25	15	86
1975	43	20	253	15	219	20	437	10	473	15	271
1976	401	20	1,220	15	614	20	1,490	10	1,620	15	744
1977	379	20	216	15	187	20	174	10	188	15	153
1978	204	20	498	15	430	20	308	10	334	15	213
1979	34	20	200	15	173	20	99	10	107	15	120
1980	418	20	87	15	75	20	36	10	39	15	91
1981	31	20	96	15	83	20	27	10	29	15	87
1982	394	20	384	15	332	20	278	10	301	15	200
1983	223	20	303	15	262	20	182	10	197	15	157
1984	283	20	229	15	198	20	220	10	238	15	174
1985	43	20	87	15	75	20	132	10	143	15	134
1986	42	20	142	15	123	20	84	10	91	15	113
1987	123	20	115	15	99	20	126	10	136	15	132
1988	25	20	80	15	69	20	34	10	37	15	90

Table 2. Modern peak-flow chronologies (gaged records) for paleoflood study reaches --- Continued.

Water year	Spring Creek			Rapid Creek			Boxelder Creek			Elk Creek		
	Spring Creek			Lower reach			Upper reach			Upstream sub-reach		
	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)	Annual peak flow (ft ³ /s)	%	Annual peak flow (ft ³ /s)
1989	32	20	64	15	55	20	31	10	33	15	89	20
1990	96	20	108	15	93	20	30	10	32	15	89	20
1991	299	20	487	15	421	20	410	10	444	15	259	20
1992	32	20	64	15	55	20	54	10	59	15	22	20
1993	294	20	1,000	15	867	20	300	10	325	15	223	20
1994	66	20	227	15	196	20	128	10	139	15	149	20
1995	940	20	1,020	15	879	20	1,170	10	1,260	15	745	20
1996	1,000	20	823	15	711	20	845	10	915	15	255	20
1997	531	20	1,090	15	524	20	474	10	513	15	289	20
1998	315	20	1,490	15	1,290	20	621	10	673	15	285	20
1999	315	20	698	15	603	20	334	10	362	15	192	20
2000	109	20	264	15	228	20	182	10	197	15	178	20
2001	68	20	131	15	113	20	53	10	58	15	56	20
2002	32	20	159	15	137	20	48	10	52	15	224	20
2003	64	20	243	15	210	20	102	10	111	15	145	20
2004	14	20	67	15	58	20	19	10	21	15	41	20
2005	28	20	61	15	53	20	25	10	27	15	65	20
2006	24	20	104	15	90	20	105	10	114	15	221	20
2007	35	20	177	15	153	20	205	10	222	15	191	20
2008	175	20	1,000	15	1,640	20	661	10	716	15	434	20
2009	71	20	277	15	239	20	376	10	408	15	188	20

model, threshold ranges varied only slightly (there is not a substantial difference between the minimum and maximum values), with age ranges corresponding to calibrated radiocarbon or OSL ages, reported in years before present (2010). Ages of all paleofloods also were input as years before present. In most cases, the median age from radiocarbon dating (Table A.1) was used as the most likely age of the paleoflood. When multiple age estimates were associated with a specific flood deposit, the youngest age was used, consistent with the condition that detrital organic materials provide maximum ages for the enclosing flood deposits.

For FLDFRQ3 model input, plausible flow ranges for specific floods generally were specified using three values: (1) a minimum being the flow required to inundate any given flood unit, (2) a maximum assumed to be twice the minimum value, and (3) a most likely value assumed as 1.5 times the minimum value. These specified values are based on a general observation that the known 1972 flow rates (mainly from indirect measurements obtained immediately after 1972 flooding) commonly are about twice the flow rates derived by HEC-RAS simulations for elevations of preserved 1972 flood deposits. To accommodate the structure of the Bayesian approach, the three specified values defining this range were each assigned an equal probability weighting.

The PeakfqSA model (Cohn and others, 1997; Cohn and others, 2001; Griffis and others, 2004) also can accommodate paleoflood information; however, the primary difference from the FLDFRQ3 model is use of the expected moments algorithm (EMA), which has an iterative procedure for computing method-of-moments parameter estimates

(Cohn and others, 1997). The EMA can use interval data (such as paleofloods and thresholds) efficiently (Cohn and others, 1997) and provides a method to compute accurate confidence intervals (Cohn and others, 2001). A primary advantage of the PeakfqSA 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; hereinafter referred to as Bulletin 17B), while using additional components to improve upon known shortcomings such as the inability to properly utilize paleoflood data. Consequently, this approach is most consistent with procedures adopted by most Federal agencies for flood-frequency analysis. For this reason, analyses using the PeakfqSA model are used as the primary basis of comparison among results for the six study reaches. A disadvantage of the PeakfqSA model is that it does not allow specification of flow uncertainties associated with gaged records, perhaps resulting in confidence intervals that incompletely consider all uncertainties in the observations. Flow uncertainties associated with the paleofloods are defined by the minimum and maximum flows used in the FLDFRQ3 model. The slightly different structures of the two models precluded exact comparisons of identical input datasets between the two approaches for both the gaged and gaged-plus-paleoflood records, but the analyses were conducted as similarly as possible.

Outstanding Uncertainty Issues

The PeakfqSA and FLDFRQ3 analytical models both account for standard statistical uncertainties in sampling populations and for additional user-specified

uncertainties in the timing and magnitude of individual paleofloods. The FLDFRQ3 model allows for user-specified characterization of the probability distribution function for flood-frequency analysis and for specifying uncertainty in the observational record. Neither model, however, can explicitly account for other factors or conditions that may affect both the analyses and the future recurrence of low-probability floods. Results of flood-frequency analyses for both models may be affected by biases inherent in the stratigraphic approach as conducted for this study that possibly result in underestimating the number of recognized floods (by requiring positive stratigraphic evidence of individual floods), and their associated magnitudes (by using minimum flow rate required for sediment deposition). Both factors collectively result in flood-frequency analyses possibly biased towards underestimating magnitudes of floods associated with specific recurrence intervals. Such biases are minimized, however, by development of accurate and complete stratigraphic records of floods; a condition enabled in this study by the large number of sites, extensive geochronology, and favorable environmental conditions in the Black Hills area for estimating paleoflood magnitudes.

This frequency study does not address uncertainties related to non-stationary climatic trends or long-term changes in geomorphic and land-cover conditions. Thus, the flood-frequency estimates resulting from this study may not perfectly describe future flood recurrence. Another source of uncertainty meriting investigation is the adequacy of the log Pearson Type III frequency distribution used in both flood-frequency analysis models for reasonably representing the true population of low-probability floods.

Chapter 2

Flood-Frequency Analyses from Paleoflood Investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, South Dakota

Spring Creek

Stratigraphic investigations were conducted at four locations (five individual sites) within a 2-mi reach of Spring Creek (Figure 4). Additional information from the Temple of Doom Alcove located about 2 mi farther upstream supplemented the stratigraphic records of the primary study reach.

The primary study reach is a meandering canyon about 200 to 500 ft wide (Figure 4) flanked by near-vertical walls of Minnelusa Formation, as much as several hundred feet, except at the downstream end where Spring Creek exits the canyon reach after passing through the Minnekahta Limestone (Figure 1) about 0.5 mi upstream from Highway 16 . This reach is entirely within a loss zone where flow occurs only during prolonged wet conditions. The channel substrate (Figure 5) consists of cobble-gravel, sand, and locally bedrock. No large tributaries enter the study reach—the drainage area increases from 170 to 172 square miles (mi²) throughout the reach. The valley bottom is vegetated with grass, shrubs, ponderosa pine, and various deciduous trees. This reach is privately owned and primarily used for pasture. No structures or developed roads are within the study reach. The site that is 2 mi upstream from the primary study reach (Figure 4) is within a much narrower canyon carved into the cavernous Madison Limestone.

Figure 4. Topographic information and selected details of hydraulic analysis for Spring Creek reach.

Figure 5. Photographs showing examples of geomorphic setting along Spring Creek reach. Photographs show A, a flotsom pile and other debris from 1972 flooding and the channel looking B, upstream and C, downstream from a point between the Superscour and Hailstorm alcoves.

The 1972 flood had a peak flow of 21,800 cubic feet per second (ft^3/s), as measured for streamgage 06408000 (Schwarz and others, 1975; U.S. Geological Survey, 2010e), which is located at the downstream extent of the study reach (Figure 1). The 1972 flow is the largest (by more than a factor of 20) in the 67 years of non-contiguous gaged records for Spring Creek that date back to 1904 (Table 2, Figure 6). As for all study reaches, the gaged records (modern chronologies) as applied to the study reach were derived from records for multiple streamgages that were adjusted for the location of the study reach (as described in detail in Appendix 2). The 1972 flood locally deposited boulder and gravel bars along the channel as well as large accumulations of woody debris. Along the canyon margins, the 1972 flood deposited abundant flotsam (which provides high-water evidence along the length of the study reach) and fine-grained slack-water deposits. The sites of stratigraphic analysis are in locations where slack-water sediment from the 1972 flood and previous large floods has accumulated in alcoves and under overhangs formed in the canyon walls.

Hydraulic Analysis and Paleoflood Chronology

Paleoflood magnitudes were derived from simulations using the HEC-RAS model based on a digital (2-ft contour interval) topographic coverage (Figure 4). Calibration of the hydraulic model was based on elevations of 1972 high-water evidence (Figure 7) that were surveyed within the reach and by assuming a 1972 peak flow of 21,800 ft^3/s for the reach (Table 2). Simulations using the calibrated hydraulic model were used for estimating flow magnitudes for elevations of paleoflood evidence at locations of detailed site

Figure 6. Modern peak-flow chronology (gaged records) for Spring Creek. Values are from Table 2.

Figure 7. Results of hydraulic model simulations for Spring Creek reach.

investigations within the reach (Figures 4 and 7). Relations between flow rate and elevation are non-linear because of typical exponential relations between flow rate and stage.

The benchmark site for the Spring Creek reach is the Superscour Alcove (Figure 8), which is located along a channel margin near the center of the reach (Figure 4). This site has the most comprehensive paleoflood record within the reach, but is supplemented by key stratigraphic and geochronologic evidence at three additional sites.

Three separate pits at Superscour Alcove had slightly different elevations and depositional environments and therefore contained different stratigraphic records (Figure 9). Pit A (Figure 8C) is the lowest and contained evidence of five floods since A.D. 1272–1391 (sample ww5976; Table A.1), of which the most recent flood unit was inferred to be from 1972 on the basis of fresh-appearing flotsam within and on top of the deposit. Flow estimates required for inundation for pit A (Figure 9) range from 4,000 ft³/s for the oldest flood unit (V) to 6,600 ft³/s for the uppermost (1972) flood unit (I). These flows estimates are small relative to that of 1972 (21,800 ft³/s) because of the relatively low elevation of the pit. Pit B is just upstream from pit A and provided evidence of three floods within the last several hundred years. Radiocarbon analyses indicate that the oldest flood unit (III) is dated between A.D. 1640 and 1806, consistent with an OSL date of A.D. 1785–1815 (Table A1.2). Minimum flows required for inundation at pit B range from 12,000 ft³/s for the oldest flood unit to 14,200 ft³/s for the most recent (1972) flood unit (I). Pit C (slightly upstream from pit B and higher) provided evidence of two floods. The most recent is the 1972 flood.

Figure 8. Photographs showing setting and examples of stratigraphy for Superscour Alcove, Spring Creek. Photographs show A, a large cliff shielding the site; B, pit B, which exposes three flood units; C, pit A, which exposes five flood units; and D, pit D, which exposes two flood units. Detailed stratigraphy for the pits is shown in Figure 9.

Figure 9. Schematic diagram showing paleoflood information for Superscour Alcove, Spring Creek.

The older flood unit (II) was not dated but presumably correlates to flood units in both pits A and B.

Additional flood sands left by the 1972 flood were found at an elevation more than 2 ft higher than the excavated pits at this site, requiring a flow of about 23,000 ft³/s for deposition. This flow rate is consistent with the estimated 1972 flow rate for this reach and within the simulated flow range of 15,000–30,000 ft³/s from the HEC-RAS analysis for the 1972 high-water evidence in the vicinity of Superscour Alcove (Figure 7). It is interpreted that the three floods at pit B correlate with three of the floods in pit A based on unit age and stratigraphic context. Similarly, the two flood units of pit C probably correlate with two of the flood units in pit A.

Two pits were excavated 0.5 mi upstream from Superscour Alcove at Hailstorm Alcove (Figure 10). Pit A provided evidence of three floods since 382–192 B.C. The middle flood unit (II) was dated to A.D. 1296–1410 and is likely the same flood as described later in this section for the Temple of Doom Alcove. The most recent flood deposit in pit A is from 1972, with its relatively low elevation requiring a flow of 10,000 ft³/s for inundation. Pit B had evidence of two floods, the most recent being from 1972. The oldest flood unit (II) in pit B likely correlates with flood unit II in pit A. Because pit B is lower than pit A, corresponding flow values are smaller for pit B, thus limiting the utility of this pit in developing the overall flood chronology. A thin layer of flood sands that were dated to A.D. 1486–1644 was identified in a small crevice about 3 ft higher than pit A. The

Figure 10. Schematic diagram showing paleoflood information for Hailstorm Alcove, Spring Creek.

corresponding flow for deposition of these sands is about 18,200 ft³/s. This layer of flood sands likely correlates with a flood unit in pit A at Superscour Alcove.

Two pits were excavated in the John Doe Alcove (Figure 11), the most downstream site in the reach. Pit B is slightly higher than pit A and provided evidence of four floods. The flow required for inundation of the oldest flood unit (IV) in pit B is 7,500 ft³/s, and the age of the flood unit, for which a datable sample was not be obtained, is constrained between A.D. 892 and 1253 by ages for the underlying and overlying deposits. The next youngest flood unit (III) in pit B was dated to A.D. 1052–1253 and required a flow of 8,750 ft³/s for inundation. The two most recent floods units (I and II) occurred in the last few hundred years and likely correlate with flood units II and III in pit B at Superscour Alcove. Pit A provided a similar flood history; the oldest flood unit (V) was dated to A.D. 1048–1225 and likely correlates with flood unit III in pit B. The three to four other flood units in pit A likely correspond to flood units in both pit B at John Doe and pit A at Superscour Alcove.

The Temple of Doom Alcove is 2 mi upstream from the main study reach and consists of driftwood and flood sediment deposited in small caves in the Madison Limestone. The channel near this alcove is only about 100 ft wide, resulting in high stages during large floods. Sampled wood from a small driftwood accumulation in a cavern 19.9 ft above the channel thalweg was dated between A.D. 1267 and 1392 (Figure 12). On the basis of this age, this deposit likely correlates with flood unit II in pit A and flood unit II in pit B at Hailstorm Alcove. In an adjacent small cavern 25.9 ft above the thalweg, bedded

Figure 11. Schematic diagram showing paleoflood information for John Doe Alcove, Spring Creek.

Figure 12. Schematic diagram showing paleoflood information for Temple of Doom Alcove, Spring Creek.

slack-water sand indicated an even higher flood stage, although the lack of datable material precludes correlation to floods inferred from stratigraphy at other sites. It is most likely that this sediment was deposited by the same flood that deposited the A.D. 1267–1392 driftwood in the adjacent cavern, or by an earlier and possibly larger flood, because a younger flood presumably would have removed the lower driftwood.

Because the Temple of Doom site was outside the area of high-resolution topographic information for Spring Creek, flows rates for elevations of deposits were determined using a critical-flow computation, which was justified by the steep channel slope of 0.013 ft/ft. Computations were performed after first subdividing the cross section at a topographic break located about 89 ft from the left bank (Figure 13). Computations are summarized in Table 3, and the computed flows were 56,400 and 29,300 ft³/s for elevations 25.9 ft and 19.9 ft above the thalweg, respectively. Therefore, the Temple of Doom stratigraphy and flow computations indicate at least a single A.D. 1267–1392 flood of at least 29,300 ft³/s, and possibly as large as 56,400 ft³/s. Evidence supporting the occurrence of two unique floods at this site was not sufficient (nor corroborated by evidence at other sites) to justify interpretation as separate flood units.

Stratigraphic investigations also were conducted at Olympia Alcove located several hundred yards downstream from Superscour Alcove and at the Near Strike Alcove located a few tens of yards upstream from John Doe Alcove (Figure 4). For these sites, however, all inferred flood units possibly correlate with units for other sites previously described. Consequently, these sites do not unambiguously add additional

Figure 13. Channel cross section and relevant elevations for Temple of Doom Alcove, Spring Creek. Cross section is view looking downstream.

Table 3. Summary of critical-flow computations for Temple of Doom Alcove, Spring Creek.

[--, computation not applicable]

Computational unit	Elevation above thalweg (feet)	Top width (feet)	Area (square feet)	Hydraulic depth (feet)	Velocity (feet per second)	Flow rate (cubic feet per second)
Upper elevation, left bank subdivision	25.93	86.8	394	4.54	12.1	4,800
Upper elevation, left bank subdivision	25.93	108.7	2,080	19.1	24.8	51,600
Total flow rate for both subdivisions	--	--	--	--	--	56,400
Lower elevation, left bank subdivision	19.93	30.4	10.3	.34	3.3	34
Lower elevation, left bank subdivision	19.93	108.7	1,428	13.1	20.5	29,300
Total flow rate for both subdivisions	--	--	--	--	--	29,300

information to the overall flood chronology for Spring Creek. For completeness, schematic diagrams for these sites are included as Figures C.1 and C.2 respectively in Appendix C.

Summarizing interpretations for all of the Spring Creek paleoflood sites (Table 4), a chronology of at least five paleofloods with magnitudes approaching or exceeding that of 1972 was preserved by stratigraphic records extending back about (~) 1,000 years. The 1972 flow of 21,800 ft³/s was exceeded by a paleoflood of ~700 years ago with a flow range of 29,300–58,600 ft³/s (P4 in Table 4), which reflects the uncertainty incorporated into the flood-magnitude estimates, as previously described in the section “Models for Flood-Frequency Analysis.” A paleoflood ~450 years ago had a flow of 18,200–36,400 ft³/s (P3). Three paleofloods (P5, P2, and P1) about 800, 200, and 200 years ago had flows of 8,750–17,500, 12,000–24,000, and 13,900–27,800 ft³/s, respectively.

Flood-Frequency Analysis

For flood-frequency analyses, the gaged and paleoflood information were structured into specific events and perception thresholds as summarized in Figure 14 and Table 4. For these analyses, only the most complete part of the stratigraphic record encompassing about the last 1,000 years was considered, for which the largest flows and their timing, as well as reliable perception thresholds could most confidently be identified. In total, five specific paleofloods were included in the flood-frequency analyses, with flows possibly as large as 58,600 ft³/s, and dates as old as A.D. 1048, which represents the lower end of the age range for the oldest flood unit dated at the John Doe Alcove. Three perception thresholds (based on stratigraphic evidence and geochronology) also were

Table 4. Summary of long-term flood chronology used in flood-frequency analysis for Spring Creek.

[ID, identification; PT, perception threshold; min, minimum; max, maximum; $\pm$, plus or minus; --, not applicable]

ID for Figure 14	Data description	Flow values, in cubic feet per second, for flood-frequency analysis			Flood or perception threshold dates, in calendar years A.D.		
		Min	Max	Most likely	Flood date	PT min	PT max
		Perception thresholds					
PT1	Superscour Alcove, pit B unit III	--	--	12,000	--	2009	1800
PT2	Hailstorm Alcove, highest sands	--	--	18,200	--	1799	1487
PT3	Temple of Doom Alcove/Hailstorm Alcove, pit A unit II and Pit B unit II	--	--	29,300	--	1486	1048
Paleoflood chronology							
P1	Superscour Alcove, pit B unit II	13,900	27,800	20,800	1810	--	--
P2	Superscour Alcove, pit B unit III	12,000	24,000	18,000	1800	--	--
P3	Hailstorm Alcove, highest sands	18,200	36,400	27,300	1563	--	--
P4	Temple of Doom/Hailstorm Alcove, pit A unit II and Pit B unit II	29,300	58,600	44,000	1347	--	--
P5	John Doe Alcove, pit A unit V and pit B unit III	8,750	17,500	13,100	1187	--	--
Gaged records							
1972	1972 flood	14,600	29,000	21,800	--	--	--
Gaged record	1904–05, 1938–40, 1946–47, 1950–2009 (excluding 1972). Uncertainty for flow values is $\pm$ 20 percent (not shown). (Top-fitting analysis excludes values less than 127 cubic feet per second)	14	10,000	--	--	--	--

Figure 14. Long-term flood chronology for Spring Creek. Chronology corresponds with Table 4 and includes the gaged record, date ranges for three perception thresholds (PT1–PT3), and uncertainty ranges for the 1972 flood and five paleofloods (P1–P5). Gaged record excluding 1972 includes 66 peak-flow values (1904–2009) of 1,000 cubic feet per second and smaller.

formulated: (1) flows equal to that of Superscour Alcove pit B unit III have been exceeded only three times in the last approximately ~200 years; (2) flows equal to that which deposited the highest sands at Hailstorm Alcove probably have not been exceeded since A.D. 1487; and (3) only one flood has exceeded 29,300 ft³/s since A.D. 1048. The more than 2,000-year-old flood unit (III) at Hailstorm Alcove pit A (Figure 10) lends confidence that if a large flood occurred after A.D. 1048, it would have left evidence.

Flood-frequency analyses for Spring Creek (Table 5) were performed using the FLDFRQ3 and PeakfqSA flood-frequency models for three scenarios: (1) gaged records only, (2) all available data (including paleoflood chronologies and perception thresholds), and (3) top-fitting analysis (PeakfqSA only). No historical peak-flow data (beyond the gaged records) are available for Spring Creek. The analysis of the gaged records only (Figure 6) provided baseline results from which to compare analyses incorporating the paleoflood information. For the FLDFRQ3 model, which allows specification of uncertainty for gaged records, uncertainties of ± 20 percent were assigned for all gaged peak-flow values except that of 1972, for which ± 33 percent was assigned because of larger uncertainty associated with especially large flows (Table 2). For the top-fitting analysis, only the 33 annual peak flows greater than the median value of 127 ft³/s in the gaged records were included. Flood-frequency analyses provided in Table 5 include (1) computed peak-flow magnitudes (quantile estimates) for selected recurrence intervals ranging from 25 to 500 years (equivalent to annual exceedance probabilities ranging from 0.04 to 0.002); and (2) associated 95-percent confidence limits for all quantile estimates.

Table 5. Flood-frequency analyses for Spring Creek.
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

Peak-flow magnitudes and 95-percent confidence limits and intervals, in cubic feet per second, for associated recurrence interval (annual exceedance probability)					
Data description	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)
PeakfqSA model, gaged records only					
Magnitude	2,010	3,620	6,290	10,700	20,800
Lower limit	1,080	1,710	2,600	3,830	6,150
Upper limit	9,750	35,200	102,000	295,000	1,190,000
Interval	8,670	33,500	99,400	291,000	1,180,000
PeakfqSA model, all available data					
Magnitude	2,480	4,530	7,960	13,600	26,900
Lower limit	1,500	2,550	4,160	6,580	11,600
Upper limit	3,850	7,440	14,500	28,600	71,300
Interval	2,350	4,890	10,300	22,000	59,700
% reduction	72.9	85.4	89.6	92.4	94.9
PeakfqSA model, all data with top fitting					
Magnitude	2,630	4,700	8,070	13,500	25,600
Lower limit	1,430	2,490	4,100	6,640	12,000
Upper limit	4,390	7,740	14,200	29,500	96,000
Interval	2,960	5,250	10,100	22,900	84,000
FLDFRQ3 model, gaged records only					
Magnitude	2,510	5,060	9,950	19,200	45,000
Lower limit	1,150	1,910	3,020	4,600	7,730
Upper limit	8,800	24,800	69,300	190,000	721,000
Interval	7,650	22,900	66,300	185,000	713,000

Table 5. Flood-frequency analyses for Spring Creek.
 [% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

	FLDFRQ3 model, all available data				
Magnitude	2,290	4,360	8,080	14,600	31,200
Lower limit	1,470	2,670	4,630	7,710	14,500
Upper limit	3,590	7,300	14,800	30,200	77,400
Interval	2,120	4,630	10,200	22,500	62,900
% reduction	72.3	79.8	84.6	87.8	91.2

Flood-frequency analyses for all scenarios (Figure 15; Table 5) indicate that the addition of the paleoflood information markedly improves estimates of low-probability floods—most clearly indicated by substantial narrowing (relative to results for the gaged record) of the range of the 95-percent confidence limits (especially for the largest recurrence intervals). Magnitudes from flood-frequency analyses were similar between the FLDFRQ3 and PeakfqSA models when paleoflood data were included with the gaged records. Additionally, the top-fitting analysis (PeakfqSA model only) yielded peak-flow magnitudes that were very similar to those for the analysis with all available data; however, the 95-percent confidence intervals generally were somewhat larger because fewer data points were included.

As described in the previous section “Models for Flood-Frequency Analysis,” the flood-frequency analysis using the PeakfqSA model (accounting for all gaged and paleoflood information without top fitting) is judged to be the most appropriate for general applications where estimates of low-probability peak flows are needed. This assessment primarily is based on the analytical approach of the PeakfqSA model, which adheres more closely than that of the FLDFRQ3 model to guidelines recommended for use by Federal agencies in Bulletin 17B (Interagency Advisory Council on Water Data, 1982). Additionally, the approach adopted for top fitting (including the largest 50 percent of gaged flows) is arbitrary, was mainly applied to determine model sensitivity, had little overall effect, and might be improved by more rigorous statistical evaluation.

Figure 15. Flood-frequency analyses for Spring Creek for A, gaged records only, and B, all available data that incorporate the long-term flood chronology data from Figure 14.

On the basis of this assessment, the following summary comparisons for Spring Creek focus on quantile estimates from the PeakfqSA model derived using all available data without top fitting relative to quantile estimates derived using only gaged records. For the analysis derived using all available data, the 100-year quantile estimate was 7,960 ft³/s, with 95-percent confidence limits of 4,160 and 14,500 ft³/s. By contrast, the analysis of gaged records only produced a smaller 100-year quantile estimate of 6,290 ft³/s, but with a much larger 95-percent confidence interval of 2,600–102,000 ft³/s. The addition of the paleoflood data to the gaged records increased the magnitude of the 100-year flood by about 27 percent and reduced the 95-percent confidence interval by about 90 percent. Similarly, consideration of the paleoflood data increased the magnitude of the 500-year flood by about 29 percent and reduced the 95-percent confidence interval by about 95 percent.

Rapid Creek

The flood history for the reach of Rapid Creek downstream from Pactola Dam (Figure 1) is of particular interest because of proximity to urban populations. However, the available paleoflood chronology for this “lower” reach pre-dates construction of Pactola Dam, which regulates 321 mi² of the drainage area for this reach (367–384 mi²; Table 1). Thus, paleoflood investigations also were conducted in an “upper” reach (upstream from Pactola Reservoir). Implications regarding peak-flow characterization for modern conditions (subsequent to dam construction) are described in a subsequent section on “Implications of Paleoflood Chronologies for Rapid Creek.”

Lower Rapid Creek

Stratigraphic investigations were conducted at seven sites within the lower Rapid Creek study reach. The reach (Figure 1 and 16) extends from just downstream from the confluence of Victoria Creek to near the confluence of Cleghorn Canyon. No major tributaries enter the reach—the largest (7 mi²) is Cleghorn Canyon. The study reach is a narrow canyon about 200 to 800 ft wide flanked by near-vertical walls of the Madison Limestone and Minnelusa Formation (Figure 1), as much as several hundred feet high. The valley bottom widens near the downstream end of the reach where it exits the Minnelusa Limestone. The channel substrate consists of cobble-gravel, sand, and locally bedrock. The valley bottom is vegetated with grass, shrubs, ponderosa pine, and various deciduous trees. Most of this reach is privately owned, and homes flank the channel in several locations. Roads parallel the channel throughout the reach.

The 1972 flood had a peak flow of 31,200 ft³/s at streamgage 06412500 (Schwarz and others, 1975; U.S. Geological Survey, 2010e), which is located near the center of the study reach (unregulated drainage area = 54 mi², Table 1) about 0.5 mi upstream from Cleghorn Canyon (Figure 16). This is the largest flow (by more than a factor of 10) in the 86 years of non-contiguous gaged records for lower Rapid Creek that date back to 1905 (Figure 17, Table 2). The 1972 flow also was substantially larger than four historical floods (1878, 1883, 1907, and 1920; as described in Appendix B) of about 7,000 to 12,000 ft³/s, and is known to be the largest flow since 1878 from accounts of Driscoll and others (2010).

Figure 16. Topographic information and selected details of hydraulic analysis for lower Rapid Creek reach.

Figure 17. Modern peak-flow chronology (gaged records) for lower Rapid Creek reach. Values are from Table 2.

The 1972 flood locally destroyed many houses in the study reach, as marked by foundations in many locations. The flood also left abundant flotsam, tree scars, and fine-grained slack-water deposits along the channel margins. The sites of stratigraphic analysis are in locations where slack-water sediment from the 1972 flood and previous large floods has accumulated in alcoves and shallow caves formed in the canyon walls. One site, Black Socks Alcove, is near the downstream end of the reach and consists of sediment accumulated along an outcrop of the Minnelusa Formation. The other sites within the study reach are in small caves or alcoves formed in the Madison Limestone.

Hydraulic Analysis and Paleoflood Chronology

A HEC-RAS hydraulic model based on a digital (5-ft contour interval) topographic coverage (Figure 16) was used for estimating peak-flow magnitudes for paleofloods along lower Rapid Creek (Figure 18). Calibration of the hydraulic model was accomplished by using surveyed elevations for 1972 high-water evidence (Figure 18) within the reach. Calibration primarily was based on the 1972 peak-flow value of 31,200 ft³/s for streamgage 06412500. The drainage area increases by only 17 mi² throughout the reach, relative to an area of 384 mi² at the downstream extent of the reach (Table 1); thus, most tributaries within this reach are small and flow adjustments for calibration purposes were minor. However, a higher flow value of 40,000–50,000 ft³/s for the 1972 flood was inferred for the short reach downstream from Cleghorn Canyon (Figure 16), which contributed about 12,600 ft³/s to Rapid Creek during the 1972 flood (Schwarz and others, 1975).

Slack-water deposits from paleofloods were investigated at seven different sites along lower Rapid Creek. One pit excavated at the upstream-most site, Outhouse Alcove (Figure 19), provided stratigraphic evidence of four floods. The oldest flood unit (IV) was dated between A.D. 124 and 318, and required a flow of at least 5,250 ft³/s for inundation. The second oldest flood unit (III) was dated to A.D. 1039–1215, with a flow of at least 7,700 ft³/s required for inundation. A thick unit of very fine sand comprised flood unit II, which required a flow of 11,300 ft³/s for inundation. This flood unit provided no datable organics for radiocarbon analysis; however, the age was constrained as younger than about 1,000 years by the underlying flood unit. The age was further constrained as older than about 200 years based on a wood fragment from an overlying colluvium unit that was dated to A.D. 1527–1954. Although of limited use alone, this constraint is useful for correlating flood deposits among different sites. The youngest flood unit (I) at this site is from 1972 the flood, with an associated flow of about 15,100 ft³/s for the elevation.

The Spider and Meister Alcoves are about 0.5 mi farther downstream and are close enough (about 100 ft) to be represented on a single HEC-RAS cross section (Figure 16). Stratigraphic evidence of one flood was found at the Spider Alcove (Figure 20), which is farthest upstream and in a small cave in the Madison Limestone. Two radiocarbon samples were analyzed from colluvium directly below the flood unit. Both samples returned ages within 20 years of each other adding confidence to an age estimate for the flood of A.D. 1016–1180, which spans the range of the two samples. The corresponding flow for this flood unit exceeds 64,000 ft³/s, which is about twice that of the 1972 flood at

Figure 19. Schematic diagram showing paleoflood information for Outhouse Alcove, lower Rapid Creek reach.

Figure 20. Schematic diagram showing paleoflood information for Spider Alcove, lower Rapid Creek reach.

the same location. The Meister Alcove is lower in elevation than the Spider Alcove and provided evidence of four floods (Figure 21). The oldest flood unit (IV) was dated to A.D. 708–947, and required a flow of 7,000 ft³/s for inundation. The contact between the two uppermost flood units (I and II) is unclear because of extensive bioturbation; however, all three overlying flood units (I to III) were deposited within the last several hundred years and have corresponding flow rates between 7,200 and 9,000 ft³/s. Flood unit II or III at Meister Alcove likely correlates to flood unit II at Outhouse Alcove based on the age dating and stratigraphic context. Additional flood evidence at Meister Alcove consisted of a thin silt deposit in the alcove wall about 5 ft above the excavated pit and was presumed to be from 1972 flooding. The associated flow for the elevation of this silt is 27,000 ft³/s, which is consistent with the simulated flow range of 20,000–30,000 ft³/s (Figure 18) and abundant evidence of the approximate 1972 flood elevation in this reach.

The site highest in elevation relative to the channel thalweg along lower Rapid Creek is High Alcove, located in a small limestone cave several hundred feet downstream from Spider and Meister Alcoves. High Alcove contained stratigraphic evidence of one flood that was dated using OSL analysis as A.D. 1545–1595 (Figure 22) and has an associated flow exceeding 128,000 ft³/s. This is the largest known flood in the Rapid Creek paleoflood chronology in the last 2,000 years, and also is the largest known flood within all four drainages in the study area.

One pit was excavated at Church Mug Alcove (Figure C.3) located < 100 ft downstream from High Alcove, but at a much lower elevation. This site contained multiple

Figure 21. Schematic diagram showing paleoflood information for Meister Alcove, lower Rapid Creek reach.

Figure 22. Schematic diagram showing paleoflood information for High Alcove, lower Rapid Creek reach.

flood deposits within the last 400-500 years based on radiocarbon dating of the oldest flood unit. However, these flood units had small corresponding flow rates and correlate with flood units at other sites along lower Rapid Creek. Thus, additional information could not be incorporated in the paleoflood chronology for Rapid Creek from this site without possibly counting single floods more than once.

The Lost Alcove is 0.25 mi farther downstream and provided stratigraphic evidence of 12 to 14 especially large floods, all between about 2,400 and 1,200 years ago (Figure 23). Minimum flows for the associated floods are between 66,000 and 79,000 ft³/s. This exceptional paleoflood record was not used in the flood-frequency analyses because it may represent a period of remarkably high flows distinct from the last ~1,000 years. The reason for this is uncertain but may owe to large fires in the basin (many of the flood deposits contain abundant charcoal) or possibly a period of local aggradation (the flood deposits sit directly on round-cobble channel gravel about 22 ft above the modern channel thalweg). The youngest flood at Lost Alcove (79,000 ft³/s between about A.D. 720 and 944) probably does not correlate with the large flood at Spider Alcove (64,000 ft³/s between about A.D. 1016 and 1180) and almost certainly not the very large flood preserved at High Alcove (128,000 ft³/s between about A.D. 1545 and 1595).

The Black Socks Alcove is farthest downstream along lower Rapid Creek and provided stratigraphic evidence of 9 or 10 floods in the last 600 years (Figure 24). The oldest flood unit (X) was dated to A.D. 1400–1466 (oldest of two samples) and required a flow of at least 5,300 ft³/s for inundation. The youngest flood unit (I) is from 1972 and

Figure 23. Schematic diagram showing paleoflood information for Lost Alcove, lower Rapid Creek reach.

Figure 24. Schematic diagram showing paleoflood information for Black Socks Alcove, lower Rapid Creek reach.

required a flow of 13,800 ft³/s for inundation. Radiocarbon samples indicated dates of A.D. 1665 or younger for underlying flood units II through VII. A charcoal sample from a colluvium unit dated to A.D. 410–558, but its stratigraphic position indicates contamination by older carbon (likely from bioturbation). Some or all of the historical peak flows of 1878, 1883, 1907, and 1920 (Table 2) for lower Rapid Creek (about 7,000 to 12,000 ft³/s) may be represented in the stratigraphy at Black Socks Alcove (and possibly Meister and Church Mug Alcoves).

In summary, lower Rapid Creek has experienced two paleofloods in the last ~1,000 years exceeding the 1972 flow of 31,200 ft³/s (Figure 25, Table 6). The largest paleoflood left deposits in High Alcove about 440 years ago and had a flow of 128,000–256,000 ft³/s. Another large paleoflood (recorded in Spider Alcove) was about 1,000 years ago and had a flow of 64,000–128,000 ft³/s. Five smaller paleofloods (Black Socks Alcove) of 9,500–19,000 ft³/s occurred between about 200 and 400 years ago.

Flood-Frequency Analysis

Flood-frequency analyses for lower Rapid Creek are based on a long-term paleoflood chronology over the last ~1,000 years in conjunction with information on four historical floods of 1878, 1883, 1907, and 1920 (H1–H4, respectively, in Figure 25) and the gaged records (Figure 17). Flow values and associated uncertainties for gaged and historical flows are shown in Table 2. The paleoflood chronology (Table 6) includes the two large floods recorded at High and Spider Alcoves, and five smaller paleofloods recorded at Black Socks Alcove. On the basis of their elevation and flow simulations, the

Figure 25. Graphical representation of the long-term flood chronology for lower Rapid Creek reach. Chronology corresponds with Table 6 and includes the gaged record; date ranges for four perception thresholds (PT1–PT4); and uncertainty ranges for four historical floods (H1–H4), the 1972 gaged flood, and seven paleofloods (P1–P7). Gaged record excluding 1972 includes 85 peak-flow values (1905–2009) of 2,600 cubic feet per second and smaller.

Table 6. Summary of long-term flood chronology used in flood-frequency analysis for lower Rapid Creek reach.
[ID, identification; PT, perception threshold; min, minimum; max, maximum; ±, plus or minus; --, not applicable]

ID for Figure 25	Data description	Flow values, in cubic feet per second, for flood-frequency analysis				Flood or perception threshold dates, in calendar years A.D.			
		Min	Max	Most likely	Flood date	PT min	PT max	PT date	
		Perception thresholds							
PT1	1878 historical flood	--	--	7,090	--	2009	1875	1920	
PT2	Black Socks Alcove (P1–P5)	--	--	9,500	--	1874	1595	1740	
PT3	Spider Alcove	--	--	64,000	--	1594	1016	1300	
PT4	Lost Alcove	--	--	79,000	--	1015	720	900	
Paleoflood chronology									
P1	Black Socks Alcove	9,500	19,000	14,300	1810	--	--	--	
P2	Black Socks Alcove	9,500	19,000	14,300	1760	--	--	--	
P3	Black Socks Alcove	9,500	19,000	14,300	1710	--	--	--	
P4	Black Socks Alcove	9,500	19,000	14,300	1660	--	--	--	
P5	Black Socks Alcove	9,500	19,000	14,300	1610	--	--	--	
P6	High Alcove	128,000	256,000	192,000	1570	--	--	--	
P7	Spider Alcove	64,000	128,000	96,000	1103	--	--	--	
Historical floods									
H1	1920	3,770	11,300	7,540	1920	--	--	--	
H2	1907	6,100	18,300	12,200	1907	--	--	--	
H3	1883	3,950	11,800	7,900	1883	--	--	--	
H4	1878	3,530	10,600	7,060	1878	--	--	--	
Gaged records									
1972	1972 flood	29,900	41,500	31,200	--	--	--	--	
Gaged	1905–06, 1915–17, 1929–2009	61	2,600	--	--	--	--	--	

five young paleofloods at Black Socks Alcove were all inferred to have minimum flows of 9,500 ft³/s. More precise resolution of these paleoflood flows was not possible because of the ambiguous relation between the stratigraphy and historical flood records, which include four peak flows of similar magnitude between 1878 and 1920 (Table 2).

Four perception thresholds were specified for the flood-frequency analyses (Figure 25, Table 6). The 1878 historical flood was treated as a threshold since 1875 (PT1). The five small paleofloods at Black Socks Alcove were incorporated into one threshold (PT2). The third threshold (PT3) was set to the flow for the flood unit preserved at Spider Alcove and the fourth threshold (PT4) was set equal to the flow for the youngest flood unit at Lost Alcove. This threshold begins at A.D. 720 because that is the age of the youngest flood unit, and if a larger flood occurred after this time, it is likely that evidence it would have been preserved. For the top-fitting analysis, only the 43 values greater than the median value of 254 ft³/s in the gaged peak-flow record were included.

As was done for Spring Creek, flood-frequency analyses were performed for multiple scenarios (Table 7), with the analysis of the gaged records only providing a basis for comparison with various longer-term analyses that include historical floods, the paleoflood chronology, and appropriate perception thresholds. The 100-, 200-, and 500-year quantile estimates for the analysis with all available data are substantially larger than the quantile estimates for the analyses of the gaged records only and for the gaged records plus historical data, reflecting the evidence for the paleofloods in this reach. Incorporation of all available data greatly reduced uncertainties for low-probability floods

Table 7. Flood-frequency analyses for lower Rapid Creek reach.

[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

Peak-flow magnitudes and 95-percent confidence limits and intervals, in cubic feet per second, for associated recurrence interval (annual exceedance probability)					
Data description	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)
PeakfqSA model, gaged records only					
Magnitude	2,990	5,160	8,720	14,500	27,900
Lower limit	1,780	2,730	4,070	5,910	9,440
Upper limit	11,800	37,100	104,000	294,000	1,170,000
Interval	10,000	34,400	100,000	288,000	1,160,000
PeakfqSA model, gaged records and historical data					
Magnitude	3,840	6,770	11,600	19,600	38,400
Lower limit	2,330	3,680	5,630	8,390	13,800
Upper limit	9,840	28,000	87,400	262,000	957,000
Interval	7,510	24,300	81,800	254,000	943,000
PeakfqSA model, all available data					
Magnitude	4,410	7,950	14,000	24,100	48,300
Lower limit	3,000	5,110	8,350	13,200	23,400
Upper limit	6,330	12,300	24,600	50,300	133,000
Interval	3,330	7,220	16,200	37,100	110,000
% reduction	66.7	79.0	83.8	87.1	90.5
PeakfqSA model, all data with top fitting					
Magnitude	4,670	8,350	14,400	24,300	46,900
Lower limit	2,880	5,200	8,740	13,800	23,500
Upper limit	6,810	12,700	25,000	54,200	169,000
Interval	3,930	7,500	16,300	40,400	146,000

Table 7. Flood-frequency analyses for lower Rapid Creek reach.
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

FLDFRQ3 model, gaged records only					
Magnitude	3,270	5,850	10,300	17,900	36,400
Lower limit	1,830	2,830	4,250	6,240	10,200
Upper limit	8,010	18,400	41,800	93,800	272,000
Interval	6,180	15,600	37,600	87,600	262,000
FLDFRQ3 model, gaged records and historical data					
Magnitude	3,620	6,570	11,700	20,600	42,200
Lower limit	2,220	3,590	5,610	8,550	14,600
Upper limit	6,930	15,000	32,400	69,000	187,000
Interval	4,710	11,400	26,800	60,400	172,000
FLDFRQ3 model, all available data					
Magnitude	3,580	6,580	12,000	21,600	46,700
Lower limit	2,580	4,490	7,640	12,800	24,500
Upper limit	5,020	9,860	19,500	38,900	97,000
Interval	2,440	5,370	11,900	26,100	72,500
% reduction	60.5	65.6	68.4	70.2	72.3

(Figure 26), with 95-percent confidence intervals for the 100-, 200-, and 500-year Peakf_qSA quantile estimates decreasing by more than 80 percent, relative to analyses for gaged records only (Table 7). The modern peak-flow chronology for the lower Rapid Creek study reach (described in Appendix B) was developed to estimate pre-regulation conditions, which is consistent with the paleoflood chronology obtained for the reach. Thus, the resulting flood-frequency analyses are not consistent with the modern post-regulation conditions.

Upper Rapid Creek

The upper reach of Rapid Creek is entirely within the Precambrian-age metamorphic rock units and includes no major tributaries (Figure 1, Table 1). Suitable sites where slack-water deposits can be preserved are uncommon in this reach because of the general absence of caves and alcoves in the schistose bedrock. Thus, the reach is defined by the only two sites where well-preserved paleoflood evidence was found: (1) two adjacent alcoves (Schist and Blue Ribbon Alcoves) about 1 mi downstream from the confluence of Castle and Rapid Creeks and (2) a site 2 mi farther downstream at streamgage 06410500 (Gage House Alcove). In this reach, the valley bottom ranges from about 100 to 300 ft wide and is bounded by steep, bedrock hillslopes. Thus, similar to the other study reaches that are situated within sedimentary canyons, large flows are well constrained to main channel proximities and large flood stages are sensitive to flow magnitude. The channel substrate consists of cobble-gravel, sand, and locally bedrock. This reach of Rapid Creek is primarily under U.S. Forest Service ownership and is largely

Figure 26. Flood-frequency analyses for lower Rapid Creek for A, gaged records only, and B, all available data that incorporate the long-term flood chronology data from Figure 25.

undeveloped. The valley bottom is vegetated with grass, shrubs, ponderosa pine, and various deciduous trees. The 1972 peak flow was only 252 ft³/s in this reach (Figure 27, Table 2). The largest flow in the 80 years of non-contiguous (1915–2009) gaged records was 2,460 ft³/s in 1952, but this flow did not leave substantial geomorphic evidence.

Hydraulic Analysis and Paleoflood Chronology

Application of the Manning equation provided flow estimates for paleoflood deposits preserved at both sites along upper Rapid Creek. The cross section for the downstream site (Gage House Alcove) was sufficiently close to streamgage 06410500 so that resulting flow estimates could be compared with the rating curve for the streamgage. A peak flow of 1,640 ft³/s was recorded (from the rating curve) on July 7, 2008, at the streamgage. This flow has been exceeded during the period of gaged record only by flows of 2,460 and 2,060 ft³/s in 1952 and 1965, respectively (Figure 27; Table 2). The rating curve for this site was substantiated by a current meter measurement made on July 8, 2008.

A channel cross section (Figure 28) was surveyed on August 11, 2008, and a high-water mark from the July 7, 2008, peak flow was used as a point of reference for the hydraulic analysis. Peak flow derived from a trial critical-depth computation was 2,990 ft³/s, largely exceeding the rated flow of 1,640 ft³/s. Application of the Manning equation for the reach slope of 0.005 ft/ft and a Manning's *n* value of 0.04 yielded a computed flow of 1,670 ft³/s, which is close to the value of 1,640 ft³/s recorded for the streamgage. Two pits were excavated at the Gage House site (pits A and B), and associated flows of 5,620

Figure 27. Modern peak-flow chronology (gaged records) for upper Rapid Creek reach. Values are from Table 2.

Figure 28. Channel cross-section and relevant elevations for Gage House Alcove, upper Rapid Creek reach. Cross-section is view looking downstream.

and 1,050 ft³/s for the highest flood deposits, respectively, were computed using the aforementioned application of the Manning equation (Table 8).

A channel cross section (Figure 29) also was surveyed on August 11, 2008, at the location of the Schist and Blue Ribbon Alcoves at the upstream end of the upper Rapid Creek reach (Figure 1). Similar to the Gage House Alcove, flow estimates were made using the Manning equation (Table 8). In this case, a flow value of 1,850 ft³/s was computed for the 2008 peak flow, which was slightly larger than the 1,670 ft³/s recorded farther downstream at streamgage 06410500. This is a reasonable difference, however, because the primary storm cell was located upstream (Driscoll and others, 2010) and the peak flow probably attenuated in the 2 mi between measurement locations. Flow values for elevations of slack-water deposits also are shown in Table 8.

The benchmark site for the upper Rapid Creek reach consists of the Schist and Blue Ribbon Alcoves (Figure 30). The Schist Alcove is the higher of the two alcoves and provided stratigraphic evidence of two floods. The most recent flood unit (I) was dated to A.D. 895–1021 and required a flow exceeding 12,900 ft³/s for inundation (Table 8). The older flood unit (II) did not contain sufficient datable organic material, and an OSL sample could not be obtained because the flood unit was too thin and contained abundant metamorphic clasts not suitable for OSL analysis. It is likely that the older flood occurred between 100 and 1,000 years before the younger flood at Schist Alcove based on its associated flow rate and the thickness of the colluvium between the two flood deposits. For the purpose of incorporating the most complete paleoflood record at this site, it was assumed that the

Table 8. Summary of Manning equation computations for selected locations along upper Rapid Creek reach.
[--, not computed]

Computational unit	Relative elevation (feet)	Manning <i>n</i> value	Slope (feet per foot)	Area (square feet)	Wetted perimeter (feet)	Hydraulic radius (feet)	Flow rate (cubic feet per second)
Summary of computations for Gage House Alcove							
Uppermost deposits (unit I) at pit A	98.02	0.04	0.005	653	110.5	5.91	5,620
High-water mark for July 7, 2008, peak flow	93.52	.04	.005	275	78.5	3.50	1,670
Uppermost deposits (unit I) at pit B	92.38	.04	.005	196	68.0	2.88	1,050
Summary of computations for Schist and Blue Ribbon Alcoves							
Uppermost deposits (unit I) at Schist Alcove	103.24	0.04	0.005	1,300	178.6	7.28	12,900
Penultimate deposits (unit II) at Schist Alcove	103.00	--	--	--	--	--	¹ 12,000
Uppermost deposits (unit I) at Blue Ribbon Alcove	97.55	.04	.005	398	139	2.86	2,110
High-water mark for July 7, 2008, peak flow	97.32	.04	.005	367	138.5	2.65	1,850

¹Estimated based on computed flow for uppermost deposits.

Figure 29. Channel cross-section and relevant elevations for Schist and Blue Ribbon Alcoves, upper Rapid Creek reach. Cross-section view is looking downstream

Figure 30. Schematic diagram showing paleoflood information for Schist and Blue Ribbon Alcoves, upper Rapid Creek reach

older flood was about 500 years before the younger flood. The lower alcove, Blue Ribbon, provided evidence of one flood that was dated to A.D. 1185–1278, which required a flow of about 2,100 ft³/s for inundation.

Two pits were excavated at the Gage House Alcove (Figure 31) at the downstream end of the reach. The upper pit (A) contained stratigraphic evidence of at least two floods. The most recent flood unit (I) required a minimum flow of 5,620 ft³/s for inundation and had a maximum age of A.D. 722–950 based on the age of the underlying local slopewash. Because this flood unit likely correlates with the most recent flood unit (I) at the Schist Alcove, it was not included as an additional flood in the flood-frequency analysis. The second (and oldest) flood unit (II) in pit A likely had evidence of more than one flood due to its thickness; however, unit contacts were not distinguishable. Radiocarbon dating for this unit returned a modern date, indicating contamination from younger carbon, probably from root penetration. Pit B contained evidence of at least four floods, with a flow of at least 1,050 ft³/s required for inundation of the uppermost flood unit (I; Table 8). This stratigraphic record essentially overlaps with the gaged records for the site, which contain six peak-flow values of 1,290 ft³/s or larger since 1915 (Table 2).

In summary, stratigraphic evidence for two paleofloods (P1 and P2) of about 12,000–13,000 ft³/s about 1,000 and 1,500 (estimated) years ago constitute most of the paleoflood chronology for upper Rapid Creek (Figure 32, Table 9). Both paleofloods are substantially larger than the largest flow in the gaged records of about 2,460 ft³/s in 1952 (Figure 27). Only one additional paleoflood (P3), about 800 years ago and similar in

Figure 31. Schematic diagram showing paleoflood information for Gage House Alcove, upper Rapid Creek reach

Figure 32. Graphical representation of the long-term flood chronology for upper Rapid Creek reach. Chronology corresponds with Table 9 and includes the gaged record, date ranges for two perception thresholds (PT1 and PT2), and uncertainty ranges for the 1952 flood and three paleofloods (P1–P3). Gaged record excluding 1952 includes 79 peak-flow values (1915–2009) of 2,060 cubic feet per second and smaller

Table 9. Summary of long-term flood chronology used in flood-frequency analysis for upper Rapid Creek reach.
 [ID, identification; PT, perception threshold; min, minimum; max, maximum; ±, plus or minus; --, not applicable]

ID for Figure 32	Data description	Range of flow values, in cubic feet per second, for flood-frequency analysis			Flood or perception threshold dates, in calendar years A.D.		
		Min	Max	Most likely	Flood date	PT min	PT max
		Perception thresholds					
PT1	1952 flood	--	--	2,460	--	2009	1914
PT2	Schist Alcove unit II	--	--	12,000	--	1913	450
Paleoflood chronology							
P1	Blue Ribbon Alcove	1,060	3,160	2,110	1232	--	--
P2	Schist Alcove unit I	6,450	19,400	12,900	958	--	--
P3	Schist Alcove unit II	6,000	18,000	12,000	458	--	--
Gaged record							
1952	1952	1,650	3,270	2,460	--	--	--
Gaged record	1915–17, 1929–42, 1947–2009 (excluding 1952). Uncertainty for flow values is ± 20 percent (not shown). (Top-fitting analysis excludes values less than 210 cubic feet per second)	53	2,060	--	--	--	--

magnitude to the 1952 flow rate, could be confidently identified for inclusion in the paleoflood chronology. Compared to lower Rapid Creek and all of the other study reaches, the largest floods along upper Rapid Creek are substantially smaller.

Flood-Frequency Analysis

No historical flood accounts are available for upper Rapid Creek; thus, the long-term flood chronology considered for the flood-frequency analyses (Figure 32, Table 9) includes only gaged records (Figure 27) and three paleofloods. Uncertainties of ± 20 percent are assigned for the gaged records (Table 2) because of minor regulatory effects of Deerfield Dam upstream (described in Appendix B). The largest flow in the gaged record (1952) was used as a perception threshold since 1914 (PT1). An additional perception threshold (PT2) was based on the older of the two paleofloods recorded in the Schist Alcove. For the top-fitting analysis, only the 40 values greater than the median value of $210 \text{ ft}^3/\text{s}$ in the gaged peak-flow records were included.

Results of flood-frequency analyses for several scenarios are summarized in Table 10 with results from analyses of the gaged records only and the analyses of all available data shown in Figure 33. Because of the sparse evidence for large paleofloods, the 100-, 200-, and 500-year quantile estimates resulting from incorporation of paleoflood data into the PeakfqSA model are less than 10 percent larger than the quantile estimates for the analysis of the gaged records only. Because the paleoflood record spans at least 1,000 years, the corresponding 95-percent confidence intervals for the paleoflood analysis using the PeakfqSA model are much smaller than those from the analysis of the gaged

Table 10. Flood-frequency analyses for upper Rapid Creek reach

[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

Peak-flow magnitudes and 95-percent confidence limits and intervals, in cubic feet per second, for associated recurrence interval (annual exceedance probability)					
Data description	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)
PeakfqSA model, gaged records only					
Magnitude	1,500	2,200	3,160	4,450	6,850
Lower limit	1,010	1,380	1,830	2,370	3,230
Upper limit	3,420	7,090	15,000	30,400	70,500
Interval	2,410	5,710	13,200	28,000	67,300
PeakfqSA model, all available data					
Magnitude	1,590	2,350	3,390	4,770	7,340
Lower limit	1,130	1,550	2,080	2,720	3,790
Upper limit	2,160	3,280	4,950	7,450	12,800
Interval	1,030	1,730	2,870	4,730	9,000
% reduction	57.3	69.7	78.3	83.1	86.6
PeakfqSA model, all data with top fitting					
Magnitude	1,810	2,630	3,670	4,990	7,220
Lower limit	1,130	1,650	2,240	2,850	3,820
Upper limit	2,610	3,790	5,300	7,390	12,200
Interval	1,480	2,140	3,060	4,540	8,400
FLDFRQ3 model, gaged records only					
Magnitude	1,830	3,030	4,930	7,910	14,500
Lower limit	1,080	1,550	2,160	2,940	4,290
Upper limit	4,280	8,950	18,700	38,400	99,400
Interval	3,200	7,400	16,500	35,500	95,100

Table 10. Flood-frequency analyses for upper Rapid Creek reach ---Continued
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

	FLDFRQ3 model, all available data					
Magnitude	1,570	2,450	3,740	5,660	9,590	
Lower limit	1,130	1,670	2,380	3,320	4,990	
Upper limit	1,100	2,100	3,960	7,300	62,900	
Interval	1,100	2,100	3,960	7,300	15,900	
% reduction	65.6	71.6	76.0	79.4	83.3

Figure 33. Flood-frequency analyses for upper Rapid Creek for *A*, gaged records only, and *B*, all available data that incorporate the long-term flood chronology data from Figure 32.

records only, with reductions of 78 percent or more for recurrence periods of 100 years and larger (Table 10).

Implications of Paleoflood Chronologies for Rapid Creek

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 postulated by Sando and others (2008), with reinforcement and refinement by Driscoll and others (2010), the Limestone Plateau area (Figure 1) and other parts of the upper Rapid Creek reach probably produce relatively small peak flows because of substantial infiltration into the limestone, relatively gentle topography, extensive floodplain storage, and reduced potential for exceptionally heavy rain-producing thunderstorms, relative to downstream

reaches. Additional perspectives regarding application of flood-frequency results for both reaches of Rapid Creek are provided in Chapter 3.

Boxelder Creek

The Boxelder Creek study reach (Figures 1 and 34) encompasses two distinct sub-reaches separated by Bogus Jim Creek and an un-named tributary entering at Custer Gap about 0.2 mi farther downstream. The two tributaries comprise most of the 14 mi² of intervening drainage area between the upstream and downstream extents of the study reach (Table 1) and can substantially affect peak-flow conditions and characteristics within the reach. The upstream sub-reach is primarily within the locally conglomeratic Deadwood Formation. The downstream sub-reach is primarily within the Madison Limestone.

The upstream sub-reach is in a low canyon about 100–500 ft wide flanked by near-vertical bedrock walls locally separated by gentler colluvial slopes. The bedrock outcrops are about 30–200 ft high. The channel in this reach generally consists of bedrock locally covered by gravels, cobbles, and boulders as large as about 10 ft in diameter. The narrow valley bottom is vegetated with grass, shrubs, and riparian trees, primarily ponderosa pine. Land ownership is a mix of U.S. Forest Service and private land, with only several houses present within this sub-reach. A highway parallels the channel, primarily on the left bank.

The 1972 flood had an estimated peak flow of 30,800 ft³/s (Figure 35, Table 2) in the upstream sub-reach, which was based on the peak flow of 30,100 ft³/s for streamgage

Figure 34. Topographic information and selected details of hydraulic analysis for Boxelder Creek reach.

Figure 35. Modern peak-flow chronology (gaged records) for upstream sub-reach of Boxelder Creek. Values are from Table 2.

06422500 (Schwarz and others, 1975; U.S. Geological Survey, 2010e) located 2 mi upstream from the study reach (Figure 1). This is the largest flow in the 49 years of non-contiguous record for this streamgage, and is nearly twice as large the next highest flow of 16,400 ft³/s recorded in 1907. Remaining evidence of the 1972 flood in the upstream sub-reach includes flotsam, tree scars, and fine-grained slack-water deposits along the channel margins.

The downstream sub-reach is about 100–500 ft wide and flanked in most locations by near-vertical walls of Madison Limestone, as much as several hundred feet high (Figure 34). A Holocene-age terrace locally flanks the channel within the downstream part of the reach. The channel substrate consists of cobble-gravel, sand, bedrock, and large boulder bars. This sub-reach is downstream from the two tributaries that divide the reach, and is located primarily within a loss zone where zero-flow conditions are common. The narrow valley bottom is vegetated with grass, shrubs, and riparian trees, primarily ponderosa pine. The reach is almost entirely undeveloped with road access only at the upstream end.

For the downstream sub-reach, the 1972 peak flow was estimated as 50,500 ft³/s (Figure 36, Table 2), based on a flow estimate for streamgage 06422650 (Table B.7) about 2 mi downstream from the study reach (Figure 1). This flow was much larger than for the upstream sub-reach because of large inflows from the two intervening tributaries. The 1907 flow estimate (17,700 ft³/s) was based on a drainage-area adjustment (Table B.7) for upstream streamgage 06422550 and thus is only slightly larger than the flow estimate of

Figure 36. Modern peak-flow chronology (gaged records) for downstream sub-reach of Boxelder Creek. Values are from Table 2.

16,400 ft³/s for the upstream sub-reach. The 1972 flood locally deposited abundant woody debris, anthropogenic flotsam (metal debris, milled wood), and boulder bars. Tree scars and fine-grained slack-water deposits along the channel margins also persist.

Hydraulic Analysis and Paleoflood Chronology for Upstream Sub-Reach

Peak-flow magnitudes associated with the elevations of paleoflood deposits were determined by HEC-RAS hydraulic simulations based on a digital (2-ft contour interval) topographic coverage (Figure 34). The hydraulic model was calibrated by using surveyed elevations for 1972 high-water evidence (Figure 37) and by assuming 1972 peak-flow values of about 30,800 and 50,500 ft³/s for the upstream and downstream sub-reaches, respectively (Table 2). Hydraulic simulations were complicated by valley-bottom grading associated with highway construction within the upstream sub-reach of Boxelder Creek. For analysis and calibration purposes, the modern (modified) topography was assumed for calibrating the hydraulic model with the 1972 flood conditions, but for simulating the paleofloods, the topographic coverage was adjusted to reflect estimated conditions prior to road construction and grading.

Stratigraphic investigations were conducted at five sites in the upstream sub-reach of Boxelder Creek. The most upstream site was Joan's Alcove, where two pits were excavated (Figure 38). The more complete record in pit B provided evidence of four flood units, the oldest of which (unit IV) was dated to between A.D. 972 and 1149 and required at least 11,300 ft³/s for inundation and emplacement. The next three floods were in the last ~500 years; flood unit III was dated to A.D. 1520–1794, unit II was dated to A.D. 1666–1953,

Figure 37. Results of hydraulic model simulations for Boxelder Creek.

Figure 38. Schematic diagram showing paleoflood information for Joan's Alcove, upstream sub-reach of Boxelder Creek.

followed by the 1972 flood (unit I). A minimum flow of 14,800 ft³/s is associated with the 1972 flood deposit for this pit, and the two older deposits in the last several hundred years required slightly smaller flows of 12,800 ft³/s and 12,000 ft³/s for inundation. Pit A contained evidence of only two floods, the most recent being the 1972 flood (unit I), and the older flood (unit II) likely correlates to a flood unit in pit B.

The next site downstream, Enob Alcove, is the benchmark site for the upstream sub-reach. A single pit provided stratigraphic evidence of two large floods within the last several hundred years (Figure 39). The oldest deposit (flood unit II) was dated to A.D. 1515–1798 and required a minimum flow of 39,000 ft³/s for inundation. The most recent flood unit (I) was dated to A.D. 1668–1891 and required a minimum flow of 40,500 ft³/s. This dark gray deposit contained abundant charcoal and had a distinctive fine blocky texture, enabling correlation to deposits at other sites in this reach. Flood deposits from the 1972 flood were not present at Enob Alcove, which along with the flow rate required for inundation, indicate that both deposits in Enob Alcove required floods larger than that of 1972. Flood units II and III in pit B of Joan's Alcove plausibly correlate with the two flood units at Enob Alcove. This correlation is bolstered by the presence of the similar high charcoal content and distinct fine blocky texture of flood unit II at Joan's Alcove, indicating correlation with flood unit I at Enob Alcove.

Stratigraphic investigations also were conducted at Benchmark, Snap-E-Tom, and Asphalt Alcoves, all of which are located within a few hundred yards of Enob Alcove. Stratigraphic records from these sites did not provide additional information beyond that

Figure 39. Schematic diagram showing paleoflood information for Enob Alcove, upstream sub-reach of Boxelder Creek.

recorded in Joan's and Enob Alcoves. Consequently, records derived from these alcoves were not included in the flood-frequency analyses; however, stratigraphy for these alcoves is shown in Figures C.4–C.6. All three sites, however, contained multiple flood deposits, including deposits of 1972 and the charcoal-rich deposit with the fine blocky texture found at Enob Alcove (flood unit I; A.D. 1668–1891). The oldest dated flood deposit in this reach (400–281 B.C.) was at Snap-E-Tom Alcove (flood unit IV in Figure C.5), although it is unlikely that the stratigraphic record for this low alcove (containing evidence for only four floods) is complete back to that date.

In summary, for a period spanning about the last ~1,000 years, two paleofloods in the upstream sub-reach of Boxelder Creek have exceeded the 1972 peak of 30,800 ft³/s (Table 2), both within the last ~500 years (Figure 40, Table 11). The associated flow estimates for these two paleofloods are 39,000–78,000 ft³/s and 40,500–81,000 ft³/s. One other paleoflood that was comparable to the second largest flow of record (16,400 ft³/s in 1907) was almost 1,000 years ago and had an associated flow of 11,300–22,600 ft³/s.

Flood-Frequency Analysis for Upstream Sub-Reach

The flood-frequency analyses of the gaged records only for the upstream sub-reach of Boxelder Creek include large floods for 1907 and 1972 (Figure 35). Uncertainties of ±33 percent were assigned for the large peak-flow values of 1907 and 1972 and uncertainties of ±10 percent were assigned for the rest of the gaged peak-flow values (Table 2). The flood-frequency analyses that considered all available data (Figure 40, Table 11) also included the gaged records, with additional consideration of the 1907 flood

Figure 40. Graphical representation of the long-term flood chronology for upstream sub-reach of Boxelder Creek. Chronology corresponds with Table 11 and includes the gaged record, date ranges for two perception thresholds (PT1 and PT2), and uncertainty ranges for the 1907 and 1972 floods and three paleofloods (P1–P3). Gaged record excluding 1907 and 1972 includes 47 peak-flow values (1904–2009) of 1,490 cubic feet per second and smaller.

Table 11. Summary of long-term flood chronology used in flood-frequency analysis for upstream sub-reach of Boxelder Creek.

[ID, identification; PT, perception threshold; min, minimum; max, maximum; $\pm$, plus or minus; --, not applicable]

ID for Figure 40	Data description	Range of flow values, in cubic feet per second, for flood- frequency analysis				Flood or perception thresholds date, in calendar years A.D.			
		Min	Max	Most likely	Flood date	PT min	PT max	PT date	
		Perception thresholds							
PT1	1907 flood	--	--	16,400	--	2009	1884	1907	
PT2	Enob Alcove unit II	--	--	39,000	--	1883	972	1610	
Paleoflood chronology									
P1	Enob Alcove unit I	40,000	80,000	60,000	1808	--	--	--	--
P2	Enob Alcove unit II	39,000	78,000	58,500	1633	--	--	--	--
P3	Joan's Alcove pit B unit IV	11,300	22,600	17,000	1013	--	--	--	--
Gaged records									
1907	1907 flood	11,000	21,800	16,400	--	--	--	--	--
1972	1972 flood	20,600	41,000	30,800	--	--	--	--	--
Gaged record	1904–05, 1946–47, 1966–2009 (excluding 1972). Uncertainty for flow values is $\pm$ 10 percent (not shown). (Top-fitting analysis excludes values less than 182 cubic feet per second)	19	1,490	--	--	--	--	--	--

as a perception threshold since 1884 (PT1) on the basis of accounts from Driscoll and others (2010). Three paleofloods from the last ~1,000 years—two large paleofloods recorded at Enob Alcove (flood units I and II) and the oldest flood unit (IV) from Joan’s Alcove—were included in the flood-frequency analyses that incorporated all available data. A second perception threshold (PT2) was based on stratigraphic evidence with the assumption that the second highest flood deposit (unit II) at Enob Alcove and its associated minimum flow of 39,000 ft³/s have been exceeded only once in the last ~1,000 years. Joan’s Alcove provided a stratigraphic record starting about 1,000 years ago and records the same two large floods at Enob, this lends confidence that if a large flood had occurred in the last 1,000 years, evidence of it would have been recorded at Joan’s or Enob Alcoves. For the top-fitting analysis, only the 25 values greater than the median value of 182 ft³/s in the gaged peak-flow record were included.

Incorporation of all available data into the flood-frequency analyses for the upstream sub-reach of Boxelder Creek reduced the 100-, 200-, and 500-year quantile estimates by about 50 to 65 percent as determined using the PeakfqSA model, compared to the similar analysis of the gaged record only (Table 12, Figure 41). Similar to the other study reaches, incorporation of the paleoflood information greatly reduced the uncertainty in the estimates for the low-probability floods, in this case by more than 99 percent.

Table 12. Flood-frequency analyses for upstream sub-reach of Boxelder Creek.
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

Peak-flow magnitudes and 95-percent confidence limits and intervals, in cubic feet per second, for associated recurrence interval (annual exceedance probability)					
Data description	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)
PeakfqSA model, gaged records only					
Magnitude	4,680	9,980	20,600	41,700	103,000
Lower limit	1,930	3,430	5,810	9,510	17,500
Upper limit	81,800	419,000	2,190,000	11,600,000	107,000,000
Interval	79,800	416,000	2,180,000	11,600,000	107,000,000
PeakfqSA model, all available data					
Magnitude	3,350	6,120	10,800	18,500	36,500
Lower limit	1,860	3,160	5,120	8,070	14,200
Upper limit	5,460	10,300	19,700	38,500	95,800
Interval	3,600	7,140	14,600	30,400	81,600
% reduction	95.5	98.3	99.3	99.7	99.9
PeakfqSA model, all data with top fitting					
Magnitude	3,210	5,860	10,400	18,000	36,200
Lower limit	1,480	2,660	4,470	7,380	14,300
Upper limit	5,960	10,600	19,200	39,500	141,000
Interval	4,480	7,940	14,700	32,100	127,000
FLDFRQ3 model, gaged records only					
Magnitude	5,590	12,500	27,100	57,300	151,000
Lower limit	2,020	3,520	5,830	9,280	16,400
Upper limit	37,800	146,000	562,000	2,140,000	12,500,000
Interval	35,800	142,000	556,000	2,130,000	12,500,000

Table 12. Flood-frequency analyses for upstream sub-reach of Boxelder Creek ---Continued.
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

FLDFRQ3 model, all available data					
Magnitude	3,980	7,830	14,900	27,500	60,300
Lower limit	2,270	4,200	7,330	12,300	22,900
Upper limit	7,060	15,400	33,600	73,800	209,000
Interval	4,790	11,200	26,300	61,500	186,000
% reduction	86.6	92.1	95.3	97.1	98.5

Figure 41. Flood-frequency analyses for upstream sub-reach Boxelder Creek for A, gaged records only, and B, all available data that incorporate the long-term flood chronology data from Figure 40.

Hydraulic Analysis and Paleoflood Chronology for Downstream Sub-Reach

Stratigraphic investigations were conducted at five sites in the downstream sub-reach of Boxelder Creek (Figure 34). The Custer Gap Alcove is located about 100 yards from the main channel of Boxelder Creek in an un-named tributary canyon at the upstream extent of the reach and provided evidence of three large floods (Figure 42), the most recent (flood unit I) being from 1972. Charcoal from the flood unit II was dated to A.D. 686–870. The oldest flood unit (III) at this site was slightly younger (A.D. 720–944). The inconsistency in ages of these two flood units likely can be attributed to incorporation of old charcoal into flood unit II. Minimum flows required by the elevations of the three flood units range from 52,500 to 57,500 ft³/s. Because this site is within the tributary, flow estimates may have more uncertainty than for most other paleoflood sites due to backwater effects in the tributary, and complicated mixing hydraulics if the tributary contributed substantial flow during flood events.

About 1 mi downstream from Custer Gap Alcove, stratigraphic investigations were performed at Trail, Second Story, Kitty's Corner, and Snow Shovel Alcoves. All except the Snow Shovel Alcove are within about 50 ft and thus were associated to the same HEC-RAS cross section (Figure 34). One flood deposit was found at Second Story Alcove (Figure 43) that required a flow of 61,300 ft³/s for inundation. A stick fragment at the contact between this unit and the underlying colluvium unit was dated to A.D. 1218–1296. Trail Alcove, located directly below Second Story Alcove provided evidence from three floods, with flows of between 23,300 and 25,000 ft³/s required for inundation (Figure 44).

Figure 42. Schematic diagram showing paleoflood information for Custer Gap Alcove, downstream sub-reach of Boxelder Creek

Figure 43. Schematic diagram showing paleoflood information for Second Story Alcove, downstream sub-reach of Boxelder Creek.

Figure 44. Schematic diagram showing paleoflood information for Trail Alcove, downstream sub-reach of Boxelder Creek

The most recent flood deposit was the 1972 flood based on the presence of Cs-137 (Table A.3). The second youngest flood unit was dated to A.D. 1288–1396, and the oldest flood unit at this site was dated to A.D. 1039–1208. Although imprecision in age dates precludes direct correlations among the sites that had the largest flows (Custer Gap, Trail, and Second Story Alcoves), the most conservative assumption is that the three flood units at Trail Alcove (including the 1972 flow) correspond with the three floods recorded at Custer Gap Alcove. Thus, the middle flood unit at Trail Alcove (A.D. 1288–1396) was assumed to be deposited by the same large flood that deposited the sediment in Second Story Alcove (A.D. 1218–1296) as well as flood unit II at Custer Gap Alcove, for which the associated age is considered unreliable.

Three pits were excavated at Kitty's Corner Alcove (Figure 45), the benchmark site for the downstream sub-reach, located below Trail and Second Story Alcoves. Kitty's Corner Alcove is a small cave in the Madison Limestone that narrows from about 10 ft in diameter at the mouth and to about 3 ft in diameter nearly 100 ft beyond the mouth. Pit A was located near the mouth of the cave, pit B was located about 5 ft farther back along the cave wall, and pit C was located near the back of the cave. Pits A and B provided evidence of 4 and 5 floods, respectively, whereas pit C provided evidence of 10 floods. It is interpreted from stratigraphic correlations and age dating that the flood units in pits A and B also are represented in pit C. Thus, the analysis focused on the stratigraphic record contained in pit C, and schematic diagrams were not constructed for pits A and B.

Figure 45. Schematic diagram showing paleoflood information for pit C in Kitty's Corner Alcove, downstream sub-reach of Boxelder Creek.

Pit C of Kitty's Corner Alcove (Figure 45) contained 10 flood units deposited over the last ~2,000 years, including 7 floods within about the last ~1,000 years. The uppermost flood unit (I) probably is from 1972, based on the associated flow (17,000 ft³/s) and the presence of Cs-137 in three samples from unit I of pit C (Table A1.3). Because the floods recorded at Custer Gap, Trail, and Second Story Alcoves were all within the last ~1,000 years, interpretation of the pit C flood chronology was restricted to the last 1,000 years. Of the seven youngest floods, three likely correlate with the three large floods at Custer Gap, Trail, and Second Story Alcoves, leaving four floods recorded in Pit C that were not recorded at the higher sites and thereby providing additional evidence of large floods during the last ~1,000 years. On the basis of deposit elevations and the hydraulic simulations, these four floods required flows exceeding 14,200 to 16,900 ft³/s. The exact ages of these additional floods are not known because all individual flood deposits cannot be correlated from site to site, but plausible estimates of median dates from the age dating (radiocarbon and OSL) for pit C were estimated to be A.D. 995, 1098, 1,445, and 1563 (Table 13). For the flood-frequency analyses, however, the exact ages are less important than the understanding of the total number of floods over the time period of interest.

Stratigraphic investigations also were conducted at Snow Shovel Alcove (Figure C.7) located about 50 ft downstream from Kitty's Corner Alcove. The flood units at Snow Shovel Alcove, however, likely correlate with deposits at other sites, thereby providing no additional information other than corroborating the records obtained from the other sites.

Table 13. Summary of of long-term flood chronology used in flood-frequency analysis for downstream sub-reach of Boxelder Creek.

ID for Figure 46	Data description	Flow value, in cubic feet per second, for flood- frequency analysis			Flood or perception threshold date, in calendar years A.D.			
		Min	Max	Most likely	Flood date	PT min	PT max date	
		Perception thresholds						
PT1	Kitty's Corner Alcove pit C	--	--	14,200	--	2009	945	1510
Paleoflood chronology								
P1	Kitty's Corner Alcove pit C	16,900	33,800	25,400	1563	--	--	--
P2	Kitty's Corner Alcove pit C	15,900	31,800	23,900	1445	--	--	--
P3	Second Story Alcove	61,300	123,000	92,000	1268	--	--	--
P4	Custer Gap Alcove unit III, Trail Alcove unit III	52,500	105,000	78,800	1111	--	--	--
P5	Kitty's Corner Alcove pit C	15,300	30,600	23,000	1098	--	--	--
P6	Kitty's Corner Alcove pit C	14,200	28,400	21,300	995	--	--	--
Gaged record								
--	1907 flood	11,900	23,500	17,700	--	--	--	--
--	1972 flood	33,800	67,200	50,500	--	--	--	--
Gaged record	1904–05, 1946–47, 1966–2009 (excluding 1972). Uncertainty for flow values is ± 15 percent (not shown). (Top-fitting analysis excludes values less than 197 cubic feet per second)	24	1,620	--	--	--	--	--

In summary, two paleofloods with flows substantially larger than the 1972 flood (50,500 ft³/s) have occurred in the last ~1,000 years in the downstream sub-reach of Boxelder Creek (Figure 46, Table 13). The largest paleoflood was about 700 years ago with a flow of 61,300–123,000 ft³/s (P3 in Table 13 and Figure 46), whereas the second largest paleoflood (P4; ~900 years ago) had a flow of 52,500–105,000 ft³/s. Four additional paleofloods between about 450 and 1,000 years ago had flows between about 14,200 and 33,800 ft³/s.

Flood-Frequency Analysis for Downstream Sub-Reach

Flood-frequency analyses of the gaged records only for the downstream sub-reach of Boxelder Creek include the large floods for 1907 and 1972 (Figure 36), for which uncertainties of ± 33 percent were assigned (Table 2). Uncertainties assigned for the rest of the gaged records were ± 15 percent, which were larger than uncertainties assigned to gaged records for the upstream sub-reach because of the uncertain influence of intervening tributaries and flow diminishment within the loss zone of the downstream sub-reach. Analyses for all available data (Figure 46, Table 13) included the gaged records and six paleofloods, two of which exceeded the 1972 flood magnitude. A perception threshold associated with the smallest paleoflood for Kitty's Corner Alcove (PT1) also was included.

The quantile estimates for the flood-frequency analyses of all available data using the PeakfqSA model for the downstream sub-reach of Boxelder Creek (Table 14, Figure 47) are nearly identical to those independently determined for the upstream sub-reach (Table 12, Figure 41). Similar to the upstream sub-reach, the quantile estimates for all

Figure 46. Long-term flood chronology for downstream sub-reach of Boxelder Creek. Chronology corresponds with Table 13 and includes the gaged record, a date range for one perception threshold (PT1), and uncertainty ranges for the 1907 and 1972 floods and six paleofloods (P1-P6). gaged record excluding 1907 and 1972 includes 47 peak-flow values (1904-2009) or 1,620 cubic feet per second and smaller.

Table 14. Flood-frequency analyses for downstream sub-reach of Boxelder Creek.

[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only; --, data not reported]

Peak-flow magnitudes and 95-percent confidence limits and intervals, in cubic feet per second, for associated recurrence interval (annual exceedance probability)						
Data description	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)	
PeakfqSA model, gaged records only						
Magnitude	5,750	12,800	27,900	59,300	157,000	
Lower limit	2,260	4,140	7,240	12,200	23,500	
Upper limit	124,000	738,000	4,510,000	28,000,000	325,000,000	
Interval	122,000	734,000	4,500,000	27,000,000	325,000,000	
PeakfqSA model, all available data						
Magnitude	3,200	5,920	10,600	18,500	37,400	
Lower limit	1,960	3,590	6,280	10,500	19,500	
Upper limit	4,690	8,980	18,100	38,600	111,000	
Interval	2,730	5,390	11,800	28,100	91,500	
% reduction	97.8	99.3	99.7	99.9	100	
PeakfqSA model, all data with top fitting						
Magnitude	2,980	5,540	10,100	18,200	38,900	
Lower limit	919	2,420	5,400	10,600	--	
Upper limit	4,630	8,510	18,400	84,700	--	
Interval	4,480	7,940	14,700	32,100	--	
FLDFRQ3 model, gaged records only						
Magnitude	6,440	14,700	32,600	71,100	195,000	
Lower limit	2,270	4,040	6,830	11,100	20,500	
Upper limit	44,300	176,000	694,000	2,730,000	16,500,000	
Interval	42,000	172,000	687,000	2,720,000	16,500,000	

Table 14. Flood-frequency analyses for upstream sub-reach of Boxelder Creek ---Continued.
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only]

FLDFRQ3 model, all available data					
Magnitude	4,130	8,270	16,000	30,200	68,300
Lower limit	2,540	4,830	8,680	14,900	28,600
Upper limit	6,800	15,000	33,700	75,700	219,000
Interval	4,260	10,200	25,000	60,800	190,000
% reduction	89.9	94.1	96.4	97.8	98.8

Figure 47. Flood-frequency analyses for downstream sub-reach of Boxelder Creek for A, gaged records only, and B, all available data that incorporate the long-term flood chronology data from Figure 46.

available data for the downstream sub-reach are much smaller than those derived using the gaged records only, with quantile estimates reduced by 60 percent or more for recurrence intervals of 100 years and larger. The 95-percent confidence intervals for these recurrence intervals were reduced by more than 99 percent. The quantile estimates derived using the FLDFRQ3 model are notably larger than those derived using PeakfqSA model for both comparable scenarios (gaged records only and all available data) and both sub-reaches (Tables 12 and 14). Evaluation of the differences in the analytical approaches used in the two statistical models is beyond the scope of this report.

Elk Creek

Sites of paleoflood deposits are sparse along Elk Creek. As a consequence, the paleoflood chronology for Elk Creek was based entirely on a single benchmark site, Dracula's Ledge, located within the outcrop of the Madison Limestone (Figure 1). Stratigraphic investigations also were conducted at the Sand Wall, Flat Rock, and Bird's Nest Alcoves (Figures C.8–C.10); however, information provided by these sites could not be used to expand the chronology. Dracula's Ledge is about 5 mi upstream from streamgage 06424500 where the 1972 flood had a peak flow of 11,600 ft³/s (adjusted to 10,400 ft³/s for the study reach; tables 2 and S8). The 1972 peak-flow value is the largest flow in 47 years of non-contiguous data for Elk Creek (1945–2009; Figure 48), although substantial flooding in 1907 is well documented in historical accounts (Driscoll and others, 2010).

Figure 48. Modern peak-flow chronology (gaged records) for Elk Creek. Values are from Table 2.

Elk Creek in the vicinity of the Dracula's Ledge site is in an incised meandering and very narrow canyon about 100 to 200 ft wide flanked by tall (as much as several hundred feet) and near-vertical walls of Madison Limestone and steep colluvial side-slopes. The channel and valley bottom consist of exposed bedrock, thin alluvial deposits, and boulder fields (Figure 3). Flow is ephemeral in this reach, commonly with no flow for prolonged periods. Fine-grained sediments are less abundant in Elk Creek than in the other drainages in the study area, and large accumulations of slack-water sediments are uncommon within most of the Elk Creek valley bottom. No large tributaries enter the study reach. The 1972 flood deposited boulder and gravel bars along the channel bottom as well as accumulations of woody debris. The canyon bottom is densely vegetated with shrubs and stands of small ponderosa pines that generally post-date 1972. This reach is under U.S. Forest Service management, undeveloped, and without roads. Remnants of a narrow gauge railroad line locally flank the channel, but the line was badly damaged by the large 1907 flood and abandoned at that time.

Hydraulic Analysis and Paleoflood Chronology

Peak flows associated with flood deposits at the Dracula Ledge site along Elk Creek were estimated by critical-flow computations for two cross sections located about 10 ft upstream and downstream from the alcove location (Figure 49; Table 15). The channel slope is about 0.038 ft/ft in this reach, justifying use of the critical-flow method. Both cross sections show the abandoned railroad grade; however, an estimate of pre-grading topography was used for computations. Computations for each cross section

Table 15. Summary of critical-flow computations for Dracula's Ledge, Elk Creek.

[--, computation not applicable]

Computational unit	Elevation above thalweg (feet)	Top width (feet)	Area (square feet)	Hydraulic depth (feet)	Velocity (feet per second)	Flow rate (cubic feet per second)
Highest elevation, upstream section	32.67	151.0	3,164	21.0	26.0	82,260
Highest elevation, downstream section	33.99	161.0	3,254	20.2	25.5	82,980
Average flow rate for two cross sections	--	--	--	--	--	82,620
Intermediate elevation, upstream section	31.27	149.5	2,959	19.8	25.2	74,570
Intermediate elevation, downstream section	32.59	161.0	3,029	18.8	24.6	74,510
Average flow rate for two cross sections	--	--	--	--	--	74,540
Lowest elevation, upstream section	26.47	114.5	2,273	15.7	22.5	51,140
Lowest elevation, downstream section	27.79	149.8	2,270	15.2	22.2	50,170
Average flow rate for two cross sections	--	--	--	--	--	50,660

were performed for three elevations (relative to the thalweg elevation). The computed flow rates for each cross section were within 2 percent of each other for each elevation, so the values were averaged, as shown in Table 15, to form the basis for the flow-rate scale shown on Figure 50.

The Dracula's Ledge site had slack-water deposits from four very large floods (fig. 50). The oldest flood unit (IV) was dated to A.D. 85–238 (younger of two samples) and required a flow exceeding 75,000 ft³/s for inundation. The overlying flood unit (III) was dated to A.D. 242–393 and required a flow of about 77,000 ft³/s. The second youngest flood unit (II) was dated to A.D. 869–1014 and required a flow of 80,000 ft³/s. The youngest flood unit (I) was deposited about 900 years ago (A.D. 1016–1155) and has an associated flow of about 83,000 ft³/s. A large beaver-chewed driftwood log was found in a rock crevice less than 30 yards upstream from the excavated pit. This log was radiocarbon dated to A.D. 1220–1284 (Table A.1), which is distinctively younger than the youngest slack-water deposit at the nearby pit. Given the context of the log's location, the only plausible explanation for placement was that it was carried there by a flood with a flow of about 51,000 ft³/s.

Investigations along Elk Creek included efforts to locate evidence for estimating the magnitude of the historical 1907 flood. No such evidence was found, nor was compelling evidence indicating the magnitude of the 1907 flood relative to that of 1972. Thus, in the absence of other information, the 1907 peak flow was assumed equal to the 1972 flood of 10,400 ft³/s.

Figure 50. Schematic diagram showing paleoflood information for Dracula's Ledge, Elk Creek

In summary, the 1972 flow on Elk Creek (10,400 ft³/s) has been substantially exceeded at least five times in the last 1,900 years (Figure 51; Table 16). The largest of these paleofloods (P2) was ~900 years ago and had a flow of 41,500–124,000 ft³/s (83,000 ft³/s $\pm$ 50 percent). Three other paleofloods (P5, P4, and P3 in Table 16) all between 37,500 and 120,000 ft³/s occurred about 1,800, 1,700, and 1,100 years ago, respectively. The fifth large paleoflood (P1), recorded by the beaver-chewed driftwood log, was ~750 years ago and had a flow of 25,500–76,500 ft³/s. The magnitude of the historical flood of 1907 is unknown, but for purposes of flood-frequency analysis, it is inferred to be similar to that of 1972.

Flood-Frequency Analysis

Flood-frequency analyses of the gaged records only for Elk Creek account for the large flood of 1972 and 46 other years of non-contiguous peak-flow data between 1945 and 2009 (Figure 48, Table 2). The analyses incorporating all available data include the gaged records, five paleofloods (Table 16), and the historical 1907 flood (Figure 51). Three perception thresholds were identified: (1) the 1972 flow rate (10,400 ft³/s) likely has not been otherwise exceeded since A.D. 1907; (2) the flow rate represented by the beaver-chewed log has not been exceeded since A.D. 1155; and (3) the smallest paleoflood recorded at the Dracula's Ledge site (75,000 ft³/s) has been exceeded only four times since A.D. 76, as indicated by the length of the paleoflood chronology (~1,900 years) for the site. For the top-fitting analysis, only the 24 values greater than the median value of 176 ft³/s in the gaged records were included.

Figure 51. Long-term flood chronology for Elk Creek
Chronology corresponds with Table 16 and includes the gaged record; date ranges for three perception thresholds (PT1-PT3); and uncertainty ranges for the 1907 historical flood (H1), the 1972 gaged flood, and five paleofloods (P1-P5). Gaged record excluding 1972 includes 46 peak-flow values (1945-2009) if 1,630 cubic feet per second or smaller.

Table 16. Summary of long-term flood chronology used in flood-frequency analysis for Elk Creek.

[ID, identification; PT, perception threshold; min, minimum; max, maximum; $\pm$, plus or minus; --, not applicable]

ID for Figure 51	Data description	Flow values, in cubic feet per second, for flood- frequency analysis					Flood or perception threshold dates, in calendar years A.D.				
		Min		Max	Most likely	Flood date	PT min	PT max	PT date		
Perception thresholds											
PT1	1907 historical flood	--	--	--	10,400	--	2009	1907	1930		
PT2	Beaver chewed log	--	--	--	51,000	--	1906	1155	1259		
PT3	Dracula's Ledge unit IV	--	--	--	75,000	--	1154	76	260		
Paleoflood chronology											
P1	Beaver-chewed log	25,500	76,500		51,000	1259	--	--	--	--	--
P2	Dracula's Ledge unit I	41,500	124,000		83,000	1090	--	--	--	--	--
P3	Dracula's Ledge unit II	40,000	120,000		80,000	935	--	--	--	--	--
P4	Dracula's Ledge unit III	38,500	115,000		77,000	315	--	--	--	--	--
P5	Dracula's Ledge unit IV	37,500	112,000		75,000	171	--	--	--	--	--
Historical floods											
H1	1907	5,200	15,600		10,400	1907	--	--	--	--	--
Gaged records											
1972	1972 flood	6,970	13,800		10,400	--	--	--	--	--	--
Gaged record	1945–47, 1966–2009 (excluding 1972). Uncertainty for flow values is ± 20 percent (not shown). (Top-fitting analysis excludes values less than 254 cubic feet per second)	22	1,630		--	--	--	--	--	--	--

The quantile estimates derived using all available data for the PeakfqSA model are more than twice as large as those derived using the gaged records only for all recurrence intervals (Table 17, Figure 52). This result reflects the evidence of the five paleofloods of the last ~1,900 years that substantially exceeded the largest gaged and historical flows. Similar to all other study reaches, incorporation of the long-term flood chronology in the PeakfqSA model resulted in substantially reduced uncertainties for the flood-quantile estimates; in this case the 95-percent confidence intervals were reduced by 96 percent or more for the 100-, 200-, and 500-year recurrence intervals (Table 17). For the FLDFRQ3 model, uncertainties for estimates derived using all available data were greater than uncertainties for estimated derived using gaged records only because of the large increases in flow magnitudes.

Table 17. Flood-frequency analyses for Elk Creek.

[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only; a negative value indicates a percent increase in confidence interval]

Peak-flow magnitudes and 95-percent confidence limits and intervals, in cubic feet per second, for associated recurrence interval (annual exceedance probability)					
Data description	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)
PeakfqSA model, gaged records only					
Magnitude	1,650	2,980	5,340	9,480	20,000
Lower limit	835	1,290	1,930	2,850	4,660
Upper limit	18,800	85,600	407,000	1,990,000	16,700,000
Interval	18,000	84,300	405,000	1,990,000	16,700,000
PeakfqSA model, gaged records and historical data					
Magnitude	1,900	3,470	6,230	11,100	23,400
Lower limit	941	1,460	2,220	3,310	6,740
Upper limit	7,010	31,400	159,000	625,000	3,020,000
Interval	6,070	29,900	157,000	622,000	3,010,000
PeakfqSA model, all available data					
Magnitude	3,510	6,670	12,400	22,500	48,300
Lower limit	1,960	3,570	6,150	10,300	19,800
Upper limit	5,680	10,900	21,300	42,700	113,000
Interval	3,720	7,330	15,200	32,400	93,200
% reduction	79.3	91.3	96.2	98.4	99.4
PeakfqSA model, all data with top fitting					
Magnitude	4,450	8,700	15,800	27,200	52,000
Lower limit	1,550	3,040	5,580	9,440	22,600
Upper limit	10,000	17,800	28,300	44,700	133,000
Interval	8,450	14,800	22,700	35,300	110,000

Table 17. Flood-frequency analyses for Elk Creek --- Continued.
[% reduction, percent reduction in confidence interval for analysis with all available data, relative to analysis for gaged records only; a negative value indicates a percent increase in confidence interval]

FLDFRQ3 model, gaged records only				
Magnitude	1,150	1,670	2,370	3,300
Lower limit	700	933	1,210	1,540
Upper limit	2,520	4,330	7,310	12,200
Interval	1,820	3,400	6,100	10,700
FLDFRQ3 model, gaged records and historical data				
Magnitude	1,520	2,340	3,540	5,230
Lower limit	886	1,250	1,710	2,290
Upper limit	3,200	5,800	10,300	18,000
Interval	2,310	4,550	8,590	15,700
FLDFRQ3 model, all available data				
Magnitude	3,410	6,340	11,500	20,400
Lower limit	2,140	3,750	6,360	10,500
Upper limit	5,440	10,700	20,900	40,400
Interval	3,300	6,950	14,500	29,900
% reduction	-81.3	-104	-138	-179
				-255

Figure 52. Flood-frequency analyses for Elk Creek for A, gaged records only, and B, all available data that incorporate the long-term flood chronology data from Figure 51.

Chapter 3

Central Black Hills Flood-Frequency: Synopsis and Implications

The paleoflood investigations, in conjunction with observational and historical records, provide a rich history of large floods locally extending back 2,000 years for Spring, Rapid, Boxelder, and Elk Creeks. In total, the flood-frequency analyses for the six study reaches account for 29 large paleofloods inferred from examination and interpretation of stratigraphic records at 29 sites, including 19 primary sites and 10 supplemental sites. For all study reaches, composited stratigraphic records extend back between about 1,000 and 2,000 years, substantially longer than gaged records (which extend to the early 1900s for some drainages) and historical accounts (which extend to 1878 for lower Rapid Creek and 1907 for Elk Creek).

The results of the paleoflood investigations provide much 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 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.

Synopsis of Results and Regional Assessment

Collective examination of flood-frequency results for all six stream reaches allows comparisons among the reaches and regional-scale assessments regarding low-probability flooding in the central Black Hills. These analyses also provide context relative to national-scale information.

Synopsis of Flood-Frequency Results

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 within this section, although the analyses from FLDFRQ3 model generally are similar for most study reaches. Exceptions are the two sub-reaches of Boxelder Creek (Tables 12 and 14). The 100-year quantile estimates (considering all available data) from the FLDFRQ3 model exceed those from the PeakfqSA model by 38 and 51 percent for the upstream and downstream sub-reaches, respectively, and the 500-year quantile estimates have differentials of 65 and 83 percent. In addition to providing a consistent basis for comparison, analyses from the PeakfqSA model accord most closely to established Federal procedures for flood-frequency analysis (Interagency Advisory Council on Water Data, 1982). The analyses considered herein consist of those from the PeakfqSA model for the short-term analyses (derived using only gaged peak-flow records) and long-term analyses (incorporating all available information including paleoflood, historical, and gaged data—with perception thresholds and without top fitting), which in

the absence of additional analysis, probably provide the best available estimates of low-probability flood recurrence for the study reaches.

The overarching result of incorporating the paleoflood information is substantially narrowed confidence intervals, relative to those for the short-term flood-frequency analyses (Table 18). 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 the much longer records of the large paleofloods provided by the stratigraphic records.

For all study reaches except the two Boxelder Creek sub-reaches, quantile estimates for the long-term flood-frequency analyses are larger than for the short-term analyses (Table 18). 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 ft³/s), and the 500-year quantile estimate increased by 73 percent (from 27,900 to 48,300 ft³/s). For Elk Creek, the 100- and 500-year quantile estimates increased by about 130 and 140 percent, respectively. For Spring Creek and the upstream reach of Rapid Creek, increases in the quantile estimates were smaller. In all of these cases, the increases resulted from incorporation of paleofloods that were substantially larger than the largest gaged flows in the flood-frequency analyses.

Table 18. Summary of flood-frequency analyses and large flows for paleoflood study reaches.

Data description	Peak-flow estimate, in ft ³ /s for associated recurrence interval (annual exceedance probability)					Flow (ft ³ /s) for selected paleofloods			Largest gaged flow (ft ³ /s)
	25 years (0.04)	50 years (0.02)	100 years (0.01)	200 years (0.005)	500 years (0.002)	Largest	Second largest		
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 (drainage area = 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 sub-reach 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 sub-reach 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	--	--	--	--

For both sub-reaches of Boxelder Creek, quantile estimates for the long-term flood-frequency analyses were substantially smaller than for the short-term analyses (Table 18). For the upstream sub-reach, the 100-year quantile estimate decreased by 48 percent, and the 500-year quantile estimate decreased by 65 percent. For the downstream sub-reach, the 100-year quantile estimate decreased by 62 percent, and the 500-year quantile estimate decreased by 76 percent. These decreases largely reflect the influence of the two large floods in the gaged records, 1907 and 1972, on the short-term flood-frequency analyses—the short-term quantile estimates for both sub-reaches of Boxelder Creek are substantially larger than for the other study reaches (Table 18). The paleoflood chronologies for the two sub-reaches of Boxelder Creek were independently determined, and although the stratigraphic records cannot be precisely correlated between the two sub-reaches, the general similarities between results help affirm the overall study approaches.

Regional Assessment

An assessment of the flood-frequency analyses in the context of regional information aids in comparisons among the reaches and evaluation of the results. Envelope curves bounding large observed flood measurements relative to drainage area provide an overall basis to assess the magnitudes of paleofloods and associated flood-frequency analyses (Enzel and others, 1993). In particular, such curves can guide assessment of the reasonableness of flood-magnitude inferences or observations in light of other observed floods at a variety of spatial scales. Flood measurements or

observations that substantially exceed existing measurements and associated envelope curves merit extra scrutiny in regards to measurement procedure and validity, extraordinary watershed conditions, and possibly unusual processes in flood generation, such as floods involving debris flows or failures of natural dams (Wolman and Costa, 1984).

The most-likely values for all paleofloods incorporated in the flood-frequency analyses (Tables 4, 6, 9, 11, 13, 16) are plotted in Figure 53 relative to envelope curves developed by Crippen and Bue (1977) for the United States (national envelope curve) and for region 11 that includes the Black Hills area (regional envelope curve). All of the paleofloods plot within the bounds of the national envelope curve, indicating that the national curve represents exceedingly rare floods for the Black Hills area. Several Black Hills paleofloods plotted above the regional envelope curve, which is not surprising because the curve for region 11 is poorly constrained. Elk Creek, lower Rapid Creek, and the downstream sub-reach of Boxelder Creek all had paleofloods exceeding the regional curve; in the case of Elk Creek, by a factor of nearly two. The Black Hills paleofloods represent some of the largest known floods, relative to drainage area, for the United States. Many of the other largest known United States floods (Figure 53; Costa, 1987; International Association of Hydrological Sciences, 2003; Costa and Jarrett, 2008) are in areas with physiographic and climatologic conditions broadly similar to the Black Hills—semi-arid and rugged landscapes that intercept and focus heavy precipitation from convective storm systems (Costa, 1987; O'Connor and Costa, 2004).

Figure 53. Black Hills paleofloods, relative to national and regional envelope curves.

The two largest paleofloods for each study reach (Table 18) and the largest gaged flow (all of which are from 1972, with the exception of upper Rapid Creek) are shown in figure 54 relative to the low-probability quantile estimates from the long-term flood-frequency analyses and regional envelope curve. The paleoflood flow values (Table 18 and Figure 54) are those that are associated with tops of flood-unit deposits and for some cases differ from the most-likely values that are plotted in Figure 53. The largest gaged flow for lower Boxelder Creek (50,500 ft³/s; Tables 2 and 18) essentially coincides with one of the points (1972 flow of 51,600 ft³/s for streamgage 06422650; Table B.7) used by Crippen and Bue (1977) in developing the regional envelope curve.

Two datasets are plotted for lower Rapid Creek (Figure 54)—one based on the entire drainage area and one based on an “adjusted” area of 81 mi², which is the intervening drainage area (Table 1) between representative streamgages 06410500 and 06412500 for the two Rapid Creek study reaches. A key issue for this study is flood-frequency characterization for modern (regulated) conditions for lower Rapid Creek, as described in a previous section “Implications of Paleoflood Chronologies for Rapid Creek,” and this area (81 mi²) is postulated in ensuing interpretations 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.

Figure 54. Results of peak-flow frequency analyses for selected stream reaches, relative to regional envelope curve.

The area-adjusted quantile estimates for lower Rapid Creek (Figure 54) plot close to those for the two sub-reaches of Boxelder Creek, which are nearly identical, and magnitudes for all of these quantile estimates are very similar to those for Elk Creek, for which the drainage area is less than one-half of that for the other three study reaches. 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

The overall results from the paleoflood investigations and associated flood-frequency analyses, in conjunction with gaged records, historical records, and previous studies, support general observations of flood-generation processes in the Black Hills. Such observations are relevant for assessing general flood hazards and for extrapolating flood-frequency results from discrete study reaches to other appropriate locations in the Black Hills.

Driscoll and others (2010) postulated that potential for heavy rain-producing thunderstorms and associated flooding (storm potential) are smallest on the relatively flat top of the Limestone Plateau (Figure 1), with both 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 substantial infiltration into the limestone, gentle topography, and extensive floodplain 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. 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 and others, 2010; Sando and others, 2008). The upper reach composes about 78 percent of the drainage area of the lower reach, as defined by areas for associated streamgages (294 and 375 mi², 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 ft³/s, which substantially exceed the largest gaged flow of 2,460 ft³/s (Table 18). These floods are small, however, compared to the contributing drainage area and plot much lower than paleofloods recognized from deposits within all of the other study reaches (Figures 53 and 54). Moreover, the largest paleoflood of at least 128,000 ft³/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.

The disparity of the paleoflood chronology for upper Rapid Creek relative to other study reaches is consistent with characteristics of the June 9–10, 1972, storm and flooding (Schwarz and others, 1975). The 1972 flooding along Rapid Creek occurred

exclusively downstream from Pactola Reservoir, with peak flows of 31,200 and 50,000 ft³/s determined for streamgages 06412500 and 06414000, respectively (Figure 1; Table B.5). In contrast, the 1972 peak flow for streamgage 06410500 located above Pactola Reservoir was only 252 ft³/s.

The quantile estimates for Spring Creek are smaller than those for all study reaches except upper Rapid Creek (Figure 54), despite having a relatively large drainage area. The Spring Creek drainage is long and like Rapid Creek has high-elevation headwaters extending close to the eastern extent of the Limestone Plateau (Figure 1). Consequently, it is plausible that the largest flows in Spring Creek are chiefly generated in the eastern part of the watershed. Consistent with this, documentation from Schwarz and others (1975) indicates that the Spring Creek watershed upstream from Hill City was not substantially affected by the 1972 storm.

Perhaps the most compelling evidence of enhanced flood generation in the eastern Black Hills is provided by Elk Creek, which has had four paleofloods exceeding 75,000 ft³/s in the last 2,000 years from a drainage area of only 40 mi². 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.

Enhanced flood generation from the eastern Black Hills also is consistent with paleoflood and observed records for the two Boxelder Creek sub-reaches, which are contiguous but separated by two tributaries that compose most of the intervening drainage area that increases from 98 to 112 mi² across the two sub-reaches (Table 1). The two largest paleofloods for the downstream sub-reach are disproportionately larger (relative to drainage area) than for the upstream sub-reach (Table 18). The 1972 flood peak increased from 30,100 to 51,600 ft³/s between streamgages 06422500 and 06422650, which are located slightly beyond the two ends of the overall study reach (Figure 1, Table B.7). Schwarz and others (1975) documented a 1972 peak flow of only 1,180 ft³/s for another site along Boxelder Creek about 3.5 mi upstream from Nemo (drainage area = 37 mi²). This peak flow indicates that primary contributions to the 1972 runoff came from the steep and dissected terrain in the downstream reach of Boxelder Creek that generally parallels the Paleozoic outcrops along the northeastern flank of the Black Hills and that minimal runoff came from the headwater reaches.

In summary, the 1972 precipitation and runoff patterns (Schwarz and others, 1975), previous analyses of peak-flow records (Sando and others, 2008), and results of paleoflood investigations of this study together indicate distinct differences in flood generation within the central Black Hills study area. The eastern flanks are underlain by dissected Paleozoic and Precambrian rocks and produce very large flood flows, contrasting with substantially less storm runoff in and near the Limestone Plateau region. This distinction results from the combined influence of climatology and physiography on

peak-flow generation and is consistent with postulations of Driscoll and others (2010). Despite the developing understanding of these regional gradients of flood generation in the Black Hills, assessment of local and regional flood-hazard management would be further improved by quantitative studies of the spatial variability of such gradients throughout the Black Hills, the relative importance of climatology compared to physiography, and the complex interactions among many variables that can affect peak-flow generation.

Outstanding Issues and Uncertainties

Several broad issues and uncertainties warrant consideration, beyond those that already have been addressed regarding applicability of results, spatial variability, and regional characterization of low-probability flood recurrence for the Black Hills area. One inherent issue in development of paleoflood chronologies and associated hydraulic analyses is possible underestimation of numbers and magnitudes of floods. As described in the “Methods of Investigation” section, stratigraphic records are not always complete, and elevations of flood deposits securely provide only minimum indications of maximum flood stages. Although the investigation of multiple sites within each study reach in combination with specifying ranges of plausible flood magnitudes helps to minimize the bias of such factors, the actual errors remain unknown.

Another uncertainty owes to choice of statistical treatment, including the appropriateness of the log-Pearson Type III probability distribution as best characterizing the population of extreme floods. While the choice of an appropriate distribution is

important and likely is readily testable, analysis of this factor was beyond the scope of this study. The rich paleoflood data set acquired for the Black Hills area, however, provides an opportunity for further investigation of this question.

Especially germane is the question of how applicable is the paleoflood record, for most reaches spanning the last 1,000 to 2,000 years, to the modern risk of flooding. Broad-scale climate and watershed conditions could systematically affect the frequency of extreme floods. It is plausible that the frequency of mesoscale convective systems, similar to those associated with the largest floods within the historical record for the Black Hills area (Driscoll and others, 2010), has changed over the last ~2,000 years as a consequence of climate cycles of various spatial and temporal characteristics. Watershed conditions, and the consequent relation between precipitation and runoff, also may have changed in systematic, episodic, or cyclic manners over the period of time during which the paleoflood deposits accumulated.

The most likely influential factor is forest fire, which can enhance flood magnitudes (see section "Hydrology of the Study Area"). The abundant charcoal in some flood deposits, for example the numerous charcoal-rich deposits for the Lost Alcove in the lower Rapid Creek reach and the distinctive charcoal-rich deposits in the upper Boxelder Creek sub-reach, is evidence that some of the largest flood magnitudes in the paleoflood record possibly were enhanced by effects of fires. A converse example is the exceptional flooding of 1972, which is known to be independent of substantial fire influence. Without specific knowledge of past basin and climate conditions, it is not yet possible to assess

potential for non-stationarity in the paleoflood records. As is the case for assessing the applicability of statistical models for flood-frequency analysis, however, the rich paleoflood data set acquired for the Black Hills area offers excellent opportunities for further pursuit of these questions. Applicability regarding future watershed conditions, which probably will be subject to both future fire effects and enhanced runoff potential from expanding suburban development, is another important question.

Because of such issues and uncertainties, as is the case for application of all flood-frequency analyses, broad consideration of all factors and information is most likely to result in the most complete assessment of flood hazards. The results of the paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, however, provide much 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 these basins and reducing associated uncertainty.

Summary

The primary focus of this study was to characterize the frequency of recurrence of low-probability floods within four basins of the central Black Hills. 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 applicable study reaches; (2) estimating peak-flow magnitudes associated with elevations of flood evidence; (3) interpreting an overall paleoflood chronology for each reach; and (4) conducting quantitative flood-frequency analyses incorporating all relevant peak-flow

information that included paleoflood information, observational records, and historical flood accounts.

Stratigraphic analysis involved excavating pits through slack-water deposits to either bedrock or immovable rocks. Where possible, stratigraphic sequences were examined at multiple elevations at individual sites, as well as multiple sites within reaches, in order to obtain the most complete and precise stratigraphic records. Upon excavation, pit stratigraphy was examined to determine the sequence of flood deposits, which typically were separated by evidence of temporal hiatus, which is key to the stratigraphic interpretations—errors in inferences can lead to under- or over-estimates of the number of floods recorded in a sequence of deposits. Stratigraphic ages were obtained using standard geochronologic approaches, including (1) radiocarbon analysis of paleobotanical evidence; (2) optically stimulated luminescence; and (3) cesium-137 analysis.

A reach-scale paleoflood chronology was interpreted for each study reach, primarily derived from the stratigraphic record at a benchmark site, supplemented by stratigraphic records, dating, and flow-magnitude information from other sites within the reach. An overall bias of underestimating the number of floods in the stratigraphic record for any reach was maintained by a combination of conservative approaches used for interpreting the chronology. Final flood-frequency analyses also incorporated gaged records and historical flood accounts, which were adjusted to be directly comparable to the paleoflood records determined for each study reach.

The primary method for estimating flow magnitudes was the River Analysis System (HEC-RAS) hydraulic model developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. HEC-RAS simulations were applied for study reaches along Spring Creek, Boxelder Creek, and the downstream of two reaches for Rapid Creek. HEC-RAS models for these reaches were calibrated for high-flow conditions using various information from 1972 flooding. Other approaches (critical-flow or Manning equations) for flow estimation were used for Elk Creek and the upstream of two reaches for Rapid Creek.

Two analytical models (FLDFRQ3 and PeakfqSA) with capabilities for incorporating paleoflood data were applied for flood-frequency analyses. Flood-frequency analyses were computed assuming log-Pearson Type III frequency distributions and were performed for as many as four flood-record scenarios: (1) analysis of gaged records only; (2) gaged records in combination with historical flow information (when available); (3) all available data, which may include gaged records, historical flows, paleofloods, and thresholds; and (4) the same as the third scenario, but “top fitting” the distribution by arbitrarily including only the largest 50 percent of the gaged flows.

For each study reach, paleoflood investigations involved hydraulic analyses, interpretation of paleoflood chronologies from stratigraphic records, and flood-frequency analyses, which together allowed understanding of the history and recurrence of low-probability floods. For Spring Creek, a chronology of at least five paleofloods with magnitudes approaching or exceeding that of 1972 was preserved by stratigraphic records extending back about 1,000 years. The 1972 flow of 21,800 ft³/s was exceeded by a

paleoflood of about (~) 700 years ago with a flow range of 29,300–58,600 ft³/s, which reflects the uncertainty regarding flood-magnitude estimates that was incorporated in the flood-frequency analyses. A paleoflood ~450 years ago had a flow of 18,200–36,400 ft³/s, and three paleofloods had flows of 13,900–27,800 ft³/s or smaller. For the PeakfqSA model, consideration of all available data relative to the gaged records only increased the magnitudes of the 100- and 500-year floods by about 27 and 29 percent, respectively, and reduced the associated 95-percent confidence intervals by about 90 and 95 percent.

The lower reach of Rapid Creek has experienced two paleofloods in the last ~1,000 years that have exceeded the 1972 flow of 31,200 ft³/s. The largest paleoflood occurred ~440 years ago and had a flow of 128,000–256,000 ft³/s. Another large paleoflood occurred ~1,000 years ago and had a flow of 64,000–128,000 ft³/s. Five smaller paleofloods of 9,500–19,000 ft³/s occurred between about 200 and 400 years ago. The 100-, 200-, and 500-year quantile estimates for the analysis with all available data (PeakfqSA model) were substantially larger than the quantile estimates for the analyses of the gaged records only and for the gaged records plus historical data, reflecting the evidence for the paleofloods in this reach. Incorporation of all available data greatly reduced uncertainties for low-probability floods, with 95-percent confidence intervals for the 100-, 200-, and 500-year PeakfqSA quantile estimates decreasing by more than 80 percent, relative to analyses for gaged records only.

Two paleofloods of about 12,900 and 12,000 ft³/s occurred along upper Rapid Creek about 1,000 and 1,500 years ago, respectively. Only one additional paleoflood (about 800

years ago) that was similar in magnitude to the largest gaged flow of 2,460 ft³/s could be confidently identified for inclusion in the paleoflood chronology. Compared to lower Rapid Creek and all other study reaches, the largest floods along upper Rapid Creek are substantially smaller. Because of the sparse evidence for large paleofloods, the 100-, 200-, and 500-year quantile estimates resulting from incorporation of paleoflood data into the PeakfqSA model are less than 10 percent larger than those for the analysis of the gaged records only. Because the paleoflood record spans at least 1,000 years, the corresponding 95-percent confidence intervals for the paleoflood analysis are much smaller than those from the analysis of the gaged records only, with reductions of 78 percent or more for recurrence periods of 100 years and larger.

Boxelder Creek was treated as having two sub-reaches because of two relatively large tributaries that can substantially affect peak-flow conditions. During the last ~1,000 years, two paleofloods in the upstream sub-reach of Boxelder Creek have exceeded the 1972 peak of 30,800 ft³/s—both occurred within the last ~500 years, with associated flow estimates 39,000–78,000 ft³/s and 40,500–81,000 ft³/s. One other paleoflood that was comparable to the second largest flow of record (16,400 ft³/s in 1907) was almost 1,000 years ago and had an associated flow of 11,300–22,600 ft³/s. Incorporation of all available data into the flood-frequency analyses (PeakfqSA model) reduced the 100-, 200-, and 500-year quantile estimates by about 50 to 65 percent, compared to the similar analysis of the gaged record only, and reduced the uncertainty in the estimates by more than 99 percent.

For the downstream sub-reach of Boxelder Creek, two paleofloods have occurred in the last ~1,000 years with flows substantially larger than the 1972 flood in this reach (50,500 ft³/s). The largest was ~700 years ago with a flow of 61,300–123,000 ft³/s and the second largest (~900 years ago) had a flow of 52,500–105,000 ft³/s. Four additional paleofloods between about 450 and 1,000 years ago had flows between about 14,200 and 33,800 ft³/s. The flood-quantile estimates (PeakfqSA model) are nearly identical to those independently determined for the upstream sub-reach and are much smaller than those derived using the gaged records only. The quantile estimates are reduced by 60 percent or more for recurrence intervals of 100 years and larger, and the associated 95-percent confidence intervals are reduced by more than 99 percent.

The 1972 flow on Elk Creek (10,400 ft³/s) has been substantially exceeded at least five times in the last 1,900 years. The largest paleoflood (41,500–124,000 ft³/s) was ~900 years ago. Three other paleofloods all between 37,500 and 120,000 ft³/s occurred about 1,800, 1,700, and 1,100 years ago, respectively. A fifth large paleoflood was ~750 years ago and had a flow of 25,500–76,500 ft³/s. The magnitude of the historical flood of 1907 is unknown, but for purposes of flood-frequency analysis, it is inferred to be similar to that of 1972. Flood-quantile estimates derived using all available data (PeakfqSA) model are more than twice as large as those derived using the gaged records only for all recurrence intervals and the 95-percent confidence intervals were reduced by 96 percent or more for the 100-, 200-, and 500-year recurrence intervals.

Considering analyses for all available data (including paleoflood information) from the PeakfqSA model, which accord most closely to established Federal procedures for flood-frequency analysis—for all six study reaches the 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 were reduced by 99 percent or more. For all study reaches except the two Boxelder Creek sub-reaches, quantile estimates for these long-term analyses were larger than for the short-term analyses. For lower Rapid Creek, the 100- and 500-year quantile estimates increased by 61 and 73 percent, respectively. For Elk Creek, the 100- and 500-year quantile estimates increased by about 130 and 140 percent, respectively. For Spring Creek and the upstream reach of Rapid Creek, increases in the quantile estimates were smaller. For the upstream sub-reach of Boxelder Creek, the 100- and 500-year quantile estimates decreased by 48 and 65 percent, respectively. For the downstream sub-reach, the 100- and 500-year quantile estimates decreased by 62 and 76 percent, respectively. The paleoflood chronologies for the two sub-reaches of Boxelder Creek were independently determined, and although the stratigraphic records cannot be precisely correlated between the two sub-reaches, the general similarities between results help affirm the overall study approaches.

All of the paleofloods plot within the bounds of a national envelope curve, indicating that the national curve represents exceedingly rare floods for the Black Hills area. Several Black Hills paleofloods plotted above a regional envelope curve, which is

poorly constrained. Elk Creek, lower Rapid Creek, and the downstream sub-reach of Boxelder Creek all had paleofloods exceeding the regional curve; in the case of Elk Creek, by a factor of nearly two. The Black Hills paleofloods represent some of the largest known floods, relative to drainage area, for the United States. Many of the other largest known United States floods are in areas with physiographic and climatologic conditions broadly similar to the Black Hills—semi-arid and rugged landscapes that intercept and focus heavy precipitation from convective storm systems.

Previous investigators postulated that 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 is smaller in and near the Limestone Plateau area, and storm runoff is further reduced by substantial infiltration into the limestone, gentle topography, and extensive floodplain storage. The 1972 precipitation and runoff patterns, previous analyses of peak-flow records, and results of the paleoflood investigations of this study together support the hypothesis of distinct differences in flood generation within the central Black Hills study area.

The 1972 flow for the Spring Creek study reach was 21,800 ft³/s, which corresponds with a recurrence interval of about 400 years. Recurrence intervals are about 500 years for the 1972 flood magnitudes along the lower Rapid Creek reach and the upstream sub-reach of Boxelder Creek. For the downstream sub-reach of Boxelder Creek,

the large 1972 flood magnitude (50,500 ft³/s) exceeds the 500-year quantile estimate by about 35 percent. The recurrence interval of about 100 years for 1972 flooding along the Elk Creek study reach is small relative to other study reaches along the eastern margin of the Black Hills.

Several broad issues and uncertainties were examined, including potential biases associated with stratigraphic records that inherently are not always complete, uncertainties regarding statistical approaches, and the unknown applicability of paleoflood records to future watershed conditions. Because of such issues and uncertainties, as is the case for application of all flood-frequency analyses, broad consideration of all factors and information is most likely to result in the most complete assessment of flood hazards. The results of the paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, however, provide much 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 these basins and reducing associated uncertainty.

Chapter 4

Late-Holocene Flood Probabilities in the Black Hills, South Dakota with Emphasis on the Medieval Climate Anomaly

Introduction

A detailed flood chronology of the Black Hills of South Dakota allows for examination of the relationship between short-term climate variations and large-magnitude flood events. Such correlations are difficult because of sparse high resolution climate proxy data for the upper Great Plains region of the US. What is available comes from dune fields (Schmeisser et al., 2010; Nicholson and Swinehart, 2005; Schwalb et al., 2010), lake sediment studies (Shapely et al., 2005; Dean and Schwalb, 2000; Fritz et al., 2000; Laird et al., 1996), tree-ring records (Shapley et al., 2005; Weakly, 1943), and buried soils (Fredlund and Tieszen, 1997). These records indicate that in the Great Plains region, the late-Holocene was a time of alternating wet/dry cycles, large scale shifts in atmospheric circulation patterns, and a reduction in forest vegetation.

Study area

The Black Hills of western South Dakota and eastern Wyoming (Figure 1) is an ellipsoidal dome with the major axis oriented roughly northwest to southeast and most likely formed during the Laramide orogeny about 60-65 million years ago (Redden and Lisenbee, 1996). The average elevation of the Black Hills is about 5,500 ft with the highest peak being Harney Peak at 7,242 ft in elevation in the central Hills (Rothrock, 1943).

Surrounding the Black Hills is rolling prairie that has a maximum elevation of about 3,400 ft.

Most of the major streams that drain the Black Hills area start out as springs in a limestone plateau on the western side of the Hills and gain volume either from precipitation, snowmelt, or additional springs at lower elevations. Most major streams drain eastward into the plains either to the Belle Fourche River north and east of the Hills or the Cheyenne River south and east of the Hills.

This study focuses on 4 major eastward draining streams (Elk, Boxelder, Rapid and Spring Creeks) in the central Black Hills (Figure 1). All four basins have headwaters in the crystalline core where streamflow is very responsive to precipitation events and other climatic variables. As the streams drain eastward the geology is dominated by Paleozoic rocks, mainly limestone, where streamflow is less responsive to precipitation and is heavily influenced by stable groundwater flow. Narrow, steep canyons characterize the basins as they drain through the Paleozoic rocks. All four drainage basins are predominately forested with ponderosa pine and have limited urban development. Total drainage basin areas range in size from 383 sq miles for Rapid Creek at Rapid City to 126 sq miles for Boxelder Creek near Rapid City.

General Climatology

The major moisture source for western South Dakota is the Gulf of Mexico, and the Pacific Ocean becomes a secondary moisture source when a trough forms east of the Rocky Mountains (Karl et al., 1983). The Black Hills has a major orographic effect on

storm patterns and the climate in general (Spuhler et al., 1971). Because the Black Hills rise about 3,000-4,000 ft higher than the surrounding plains, they interrupt moisture flow from the northwest, west, and southwest. The largest gradients in topography lie along the foothills. These factors contribute to the higher precipitation totals the Black Hills receive compared to the surrounding plains (Driscoll et al. 2010).

In the summer, the principle source of precipitation is from convective thunderstorms that generally develop when warm moist air that originated in the Gulf of Mexico comes in contact with eastward moving cold fronts. Thunderstorms that form over the Black Hills are largely terrain-driven (Kuo and Orville, 1973; Banta, 1990) According to Banta (1990) and Hjelmfelt et al. (1992); the Black Hills can provide the lifting effect required for storm initiation through three mechanisms; 1) orographic lifting, 2) thermally enhanced circulation, and 3) obstacle effects.

Modern Peak Streamflow

The Black Hills are very susceptible to large flooding events and these events pose a very real hazard for area communities. For example, 1972 flooding killed 238 people in and around Rapid City and 2007 flooding in Hermosa inundated many parts of the small community and washed several houses off their foundations (Driscoll et al., 2010).

Most peaks flows in rivers that drain the Black Hills occur during the summer months of May, June, July, and August when convective cells build over the foothills during the warm afternoons and can cause exceptionally strong rain-producing thunderstorms (Driscoll et al., 2010). These short-lived but intense convective

precipitation events, including supercell thunderstorms, are common in the Black Hills (Dennis et al., 1973; Holm and Smith, 2008). In addition to large storm events, physical basin characteristics play a role in flooding as well.

Basin orientation can contribute to high peak discharges and severe flooding. When storms track in a down basin direction the storms is essentially moving with the flood peak. This can lead to an increase in peak discharge in the channel. Aside from drainages along the South Dakota/Wyoming border, most of the larger drainages in the Black Hills tend to have an east-west drainage orientation, parallel to primary tracking directions of many storms (Driscoll et al., 2010).

Also contributing to high peak flows during storm events are various soil properties such as soil type and soil thickness as well as vegetation cover. In the Black Hills, soil properties are highly variable, however, soil thickness generally decreases with increasing slope (Westin and Malo, 1978; Westin et al., 1987). Because much of the terrain in the Hills is rather steep, soils tend to be thin. Thinner soils contribute to greater runoff and increased channel flow because the soil has less ability to store water. Vegetation can reduce runoff and peak flows by interception as well as evapotranspiration. Generally, sparser vegetation contributes to greater runoff and thus streamflow.

Strong storm events, basin orientation, soil properties, steep slopes, and vegetation cover all contribute to peak flows in the Black Hills of South Dakota. While it is likely that the basins' orientations and slopes have not changed in the last several

thousand years, it is possible that the frequency and strength of storm events, soils properties, and vegetation cover have changed or varied during this time.

Methods

Thirty-five large floods were identified by stratigraphic studies of 29 sites on 4 reaches in the east central Black Hills (Table 19). The 35 flood units include 5 from Elk Creek, 10 from Boxelder Creek, 15 from Rapid Creek, and 5 from Spring Creek. For this study, a large flood is defined as the 100-year event or larger based on the flood-frequency analyses done in Harden et al. (2011; Table 19). All floods in the last 2,000 years with a return period of 100-years or greater were used in this study. These 35 floods are a subset of a larger population of floods identified in the stratigraphic records in the Black Hills. Although dates extend back as far as ~ 6,500 years, the vast majority of dated floods (>75%) are from the last 2,000 years. Therefore, this study is focused on that time period.

A database of radiocarbon results from either the flood slack-water deposits or intervening colluvial units was created to examine the flood history of the study area. Although 99 samples were submitted for analysis, only 35 were considered individual floods based on compelling stratigraphic, hydraulic, or geochronologic evidence and could not be correlated with another flood in the record. This greatly reduces the likelihood of double counting floods. When a flood unit was dated twice, only the youngest age was used. A few flood deposits were also dated by optically stimulated luminescence (OSL); however, only results from radiocarbon dates were used in this study in order to maintain consistency.

Table 19. Paleofloods used in creating CPDF curves for all 4 study reaches in the Balck Hills.

Spring Creek							
100-year Flood Magnitude = 7,960 ft ³ /s							
Flood #	Lab Code for Radiocarbon Analysis	Alcove(s)	Flood Unit	¹⁴ C Age BP	Cal Age	Median age	Discharge
1	ww6003	Temple of Doom/ Hailstorm	II	599±33	A.D. 1296-1410	A.D. 1347	44,000
2	ww7068	Hailstorm	high sands	625±32	A.D. 1496-1644	A.D. 1563	27,300
3	ww7697	John Doe pit A	V	865±25	A.D. 1048-1084, 1122-1138, 1150-1225	A.D. 1187	13,100
4	ww7069	Superscour pit B	III	225±30	A.D. 1640-1684, 1735-1806	A.D. 1764	18,000
5	ww5999	Superscour pit B	II	138±32	A.D. 1669-1780, 1798-1892, 1908-1944	A.D. 1810	20,800

Table 19. Paleofloods used in creating CPDF curves for all 4 study reaches in the Balck Hills ---Continued.

Rapid Creek						
100-year Flood Range = 3,390 ft ³ /s (upstream), 14,000 ft ³ /s (downstream)						
Flood #	Lab Code for Radiocarbon Analysis	Alcove(s)	Flood Unit	¹⁴ C Age BP	Cal Age	Median age Discharge
1	ww7139	Schist	I	1,070±30	A.D. 895-925, 936-1021	A.D. 958 12,900
2	ww7148	Black Socks	IV	75±35	A.D. 1684-1732, 1807-1928	A.D. 1845 14,300
3	ww7704	Black Socks	X	480±35	A.D. 1400-1466	A.D. 1431 14,300
4	ww7749A	Black Socks	VII	155±35	A.D. 1665-1710, 1716-1785, 1793-1891, 1908-1952	A.D. 1784 14,300
5	ww7146	Black Socks	III	130±30	A.D. 1675-1778, 1798-1894, 1905-1942	A.D. 1822 14,300
6	ww7147	Black Socks	V	125±35	A.D. 1675-1778, 1798-1942	A.D. 1825 14,300
7	ww7077	Church Mug/High	VIII	360±35	A.D. 1450-1530, 1538-1635	A.D. 1540 192,000
8	ww7702	Lost	VII	1,740±30	A.D. 234-389	A.D. 300 73,500
9	ww7580	Lost	V	1,795±25	A.D. 130-260, 284-323	A.D. 224 75,100
10	ww7584	Lost	IV	1,550±25	A.D. 430-566	A.D. 491 76,600
11	ww7579	Lost	III	1,380±25	A.D. 612-674	A.D. 652 77,200
12	ww7694	Lost	I	1,190±30	A.D. 720-742, 769-898, 921-944	A.D. 835 80,000
12	Ww7730	Lost	II	1,665±30	A.D. 258-298, 319-434	A.D. 383 78,100
14	ww7586	Lost	X	1,795±30	A.D. 131-262, 280-326	A.D. 224 70,200
15	ww7141	Spider	I	925±30	A.D. 1026-1180	A.D. 1103 96,000

Table 19. Paleofloods used in creating CPDF curves for all 4 study reaches in the Balck Hills ---Continued.

Boxelder Creek						
100-year Flood Magnitude = 10,800 ft ³ /s (upstream), 10,600 ft ³ /s (downstream)						
Flood #	Lab Code for Radiocarbon Analysis	Alcove(s)	Flood unit	¹⁴ C Age BP	Cal Age	Median Age Discharge
1	ww7058	Enob	II	270±30	A.D. 1515-1598, 1616-1669, 1781-1798	A.D. 1633 60,000
2	ww7693	Enob	II	140±30	A.D. 1668-1780, 1798-1891	A.D. 1808 58,500
3	ww7703	Joan's pit B	IV	1,015±30	A.D. 972-1047, A.D. 1090-1122, A.D. 1139-1149	A.D. 1013 17,000
4	ww7066	2nd Story	I	740±35	A.D. 1218-1296	A.D. 1268 92,000
5	ww7059	Kitty's Corner pit C	X	1,795±30	A.D. 131-262, 280-326	A.D. 224 13,800
6	ww7061	Kitty's Corner pit C	III	440±30	A.D. 1416-1490, 1602-1609	A.D. 1445 23,900
7	ww7062	Kitty's Corner pit C	II	310±25	A.D. 1490-1603, 1611-1645	A.D. 1563 25,400
8	ww7682	Kitty's Corner pit C	VII	920±25	A.D. 1030-1173	A.D. 1099 14,000
9	ww7734	Kitty's Corner pit C	V	930±30	A.D. 1024-1169	A.D. 1098 23,000
10	ww7684	Custer Gap/ Trail	III	905±25	A.D. 1039-1190, 1196-1208	A.D. 1111 78,800

Table 19. Paleofloods used in creating CPDF curves for all 4 study reaches in the Balck Hills ---Continued.

Elk Creek							
100-year Flood Magnitude = 12,400 ft ³ /s							
Flood #	Lab Code for Radiocarbon Analysis	Alcove(s)	Flood unit	¹⁴ C Age BP	Cal Age	Median Age	Discharge
1	ww7073	Dracula's Ledge	I	970±30	A.D. 1016-1155	A.D. 1090	83,000
2	ww7072	Dracula's Ledge	IV	1,845±30	A.D. 85-238	A.D. 171	75,000
3	ww7380	Dracula's Ledge	II	1,115±30	A.D. 869-1014	A.D. 935	80,000
4	ww7700	Dracula's Ledge	III	1,725±30	A.D. 242-393	A.D. 315	77,000
5	ww7074	Beaver Chewed Log	-	760±30	A.D. 1220-1284	A.D. 1259	51,000

In only one instance was a flood unit not radiocarbon dated and could not be correlated to other flood units with known radiocarbon ages. This occurred at the John Doe Alcove on Spring Creek. The age of flood unit IV in Pit B could not be correlated to any other dated flood unit however it was constrained by dated units above and below. Thus the flood must have occurred between these dates. The date of the colluvial unit below was assigned to the undated unit because it represents the most likely estimation of the flood unit.

For this study, the historical period is considered to be after 1877 when the first historical flood is reported in the study area. Four historical floods equal to or exceeding the 100-year flood event occurred on 3 out of the 4 drainages in the study area, 1 in 1907 and 3 in 1972. In order to calculate the cumulative probability of flooding for the historical period, the 4 floods were divided by the total number of years in the historical record, or 135.

All dates were calibrated and individual probability distributions were summed using OxCal version 4.1 (Figure 55; Bronk Ramsey et al., 2001; Bronk Ramsey, 2009). Oxcal uses a probability-based method for determining conventional ages which provides a calibrated date that reflects the probability of its occurrence within a given distribution as reflected by the amplitude of the curve. Thus, all dates have associated probability distributions. Cumulative probability distribution function (CPDF) plots were calculated by combining the individual probability distributions following a method similar to Macklin et al. (2005) and later modified by Hoffman et al. (2008). Therefore, the flood probability for

Figure 55. Cumulative flood probability curve of the central Black Hills during the late Holocene. Grayshaded areas indicate periods of time when the probability of a 100-year even or larger was greater than average.

any one time period is not the actual probability, but the cumulative probability. For example, in Figure 55, the 0.01 cumulative probability value reflects a 1 percent probability that a 100-year flood event or larger occurred on at least 1 of the 4 basins. For this study, a flooding episode is defined as a period of time when the probability that the 100-year plus event occurred is greater than .017 (the mean cumulative probability of large floods in the last 2,000 years).

Results

In the last 2,000 years the east-central Black Hills region has experienced 4 distinct episodes of increased flooding ranging in length from about a few hundred years (~ A.D. 130-400) to several hundred years (A.D. 1410 – present; Figure 55). Eight large floods occurred in the earliest flooding episode from A.D. 130-400 followed by a period of about 240 years of less than average probability that ends with a large flood on Rapid Creek sometime between A.D. 640 and 670. From about A.D. 900 to 1290, 13 floods with a magnitude of the 100-year event or larger occurred in the study area. This high concentration of significantly large floods coincides with the Medieval Climate Anomaly (MCA: ~A.D. 900-1300) and is discussed in more detail in the following sections. A period of few large floods persists for a little over 100 years after the MCA then picks up again after about A.D. 1410 and continues until the present. Thirteen paleofloods occurred during this period as well as the 4 large historical floods in 1972 (Spring, Rapid, and Boxelder Creeks) and 1907 (Boxelder Creek).

Figure 56 shows the distribution of flood probabilities per basin for the last 2,000 years. Spring Creek, the southern-most of the drainages, is the only drainage that has not experienced large flooding events from 2,000 to 1,000 years ago even though the record is ~2,400 years. The cause of this is unclear but is possibly due to lower rainfall totals in the southern Hills. Rapid Creek has experienced multiple floods all throughout the last 2,000 years with a noticeable high probability for flooding from about A.D 600 to A.D 700 all due to one flood that occurred sometime between ~ A.D. 610 and A.D. 670. Boxelder Creek has experienced floods throughout the last 2,000 years as well; however, starting around A.D. 350 there is an obvious lack of flooding until (the start of the MCA) about A.D. 900-1000. Elk Creek varies significantly from the other three drainages in that there are no large flood events recorded in the stratigraphy in the last 700 years. The five large floods that did occur are lumped into two distinct groups centered on about A.D. 250 and A.D. 1100 during the MCA. Floods of considerable size were recorded on Elk Creek in 1907 and 1972 but these were less than the 100-year flood from Elk Creek based on the frequency analyses in Harden et al. (2011).

When looking at the spatial relationship of the largest floods in the study area (Figure 57), the 2 largest floods on both Elk Creek and Boxelder Creek occurred during the MCA in addition to the second largest flood on Rapid, Elk and Boxelder Creeks. Although the number of floods occurring in the last 600 years is greater than those occurring in the 600 years from A.D. 100-700, the older floods are significantly larger.

Figure 56. Cumulative probability distributions of the 100-year or greater floods for each of the 4 reaches in the study area.

Figure 57. Flood magnitude for the 39 largest floods, including 4 historical floods in the Black Hills during the last 2,000 years. The largest floods on both Elk and Boxelder Creeks occurred during the MCA as well as the second largest floods on Rapid, Boxelder, and Elk Creeks.

Discussion

When comparing the late-Holocene flood record in the Black Hills to available climate proxy records, one particular correlation stands out. During the Medieval Climate Anomaly which occurred around A.D. 900-1300, floods in the Black Hills had a greater probability of occurring than the previous ~230 years (Figure 58). The same correlation is not seen in another pronounced short-term late-Holocene climate event, the Little Ice Age (~A.D. 1550-1850; Figure 58). Another prominent climate signal affecting the Great Plains is the ~400 year wet/dry cycle attributed to solar forcing (Figure 58; Yu and Ito, 1999; Stuiver and Braziunas, 1989). Because there is no apparent relationship between flooding and wet or dry periods, this signal does not seem to correlate with Black Hills flooding however further investigation is necessary.

MCA in the Great Plains

There is considerable evidence that the climate during the MCA was overall both warmer and drier than the present in the midcontinent and Upper Great Plains region of the U.S. (Dean, 1997; Dean and Schwalb, 2000; Laird et al. 1996; Yu and Ito, 1999; Nordt et al., 2007; Schwalb et al., 2010). This was likely caused by a change in large-scale atmospheric processes (Diffenbaugh et al., 2006). Much of these drought-like conditions are attributed to stronger than normal westerlies that may have blocked moisture from the Gulf of Mexico from penetrating into the interior of the continent (Booth et al. 2006). Laird et al. (2003) proposed that the shift in moisture regimes from wet to dry during the MCA was caused by changes in the location and shape of the jetstream and therefore storms

Figure 58. The Black Hills CPDF curve (black) compared to Atlantic hurricanes (green curve) in the last 1,500 years and the ~ 400 wet/dry cycle. Peaks in hurricane activity are correlated with an increase in flood events in the Black Hills even during the prolonged MCA drought. No clear correlation can be seen during the Little Ice Age. (Atlantic cyclone graph modified from Mann et al., 2009) Wet episodes are identified from the ~400 year wet/dry cycle attributed to solar forcing (Yu and Ito, 1999).

tracks. However, there is some debate as to the mechanisms that caused this shift in atmospheric circulation.

Today much of the wet/dry cycles in most of the US are closely related to sea surface temperatures (SST) in the Pacific and Atlantic Oceans. Cool SST in the tropical Pacific have been linked to major North American droughts in the last 150 years (Cook et al., 2004; Hoerling and Kuwar, 2003; Seager et al., 2005). Additionally, warm SST anomalies in the North Atlantic have been linked to less than normal precipitation in the interior US (Enfield et al., 2001; McCabe et al. 2004). Still, the role of the SST during the MCA is less certain.

While there is little debate about a warmer than present North Atlantic (Kim et al., 2007; Jiang et al., 2005; Keiwign, 1996) and Gulf of Mexico (Richey et al., 2007; Richey, 2010) during the MCA, SST records in the tropical Pacific are more controversial and seemingly less understood. Evidence supports both a cooler than normal tropical Pacific SST (Graham et al., 2007; Kim et al., 2004; Barron et al., 2003) and warmer than normal SST (Moy et al., 2002; Lachniet et al., 2004).

Not surprising then is the lack of agreement in the scientific community regarding the role of El Nino-Southern Oscillation (ENSO) during the MCA. Tropical Pacific sea surface temperatures as well as pressures define the phase of ENSO (warm or cold) and both phases have global teleconnections. Thus, because there is much debate on the SST in the tropical Pacific during the MCA, there is much debate about which phase of ENSO was dominant. According to a marine record from Peru (Rein et al, 2004)

persistently weak El Ninos were associated with the MCA. Yan et al. (2011) examined precipitation reconstructions for several regions affected by ENSO and concluded more El-Nino dominated conditions prevailed during the MCA. However, evidence supporting more frequent La Nina-like conditions has been described from marine corals (Cobb et al., 2003), $\delta^{18}\text{O}$ values from thermocline-dwelling planctonic foraminifera (Khider et al., 2011), and sediment cores (Langton et al., 2008). Both Seager et al. (2007) and Helama et al. (2009) concluded that not only was the MCA marked by more frequent/stronger La Nina-like conditions, but by a positive North Atlantic Oscillation (NAO) as well and those combined factors are what was responsible for the widespread megadrought.

Feng et al. (2008) used the Community Atmospheric Model (CAM) to investigate the role of both the tropical Pacific and North Atlantic on the MCA drought. Results of that study indicate that a cold tropical Pacific can simulate the intensity of the drought while a warm North Atlantic can simulate the areal extent of the drought. They suggest the two together may explain the intensity and duration of the MCA drought in the Upper Great Plains.

Possible Mechanisms for Increased Flooding During the MCA

According to this study, although there was widespread and intense drought conditions during the MCA, there was also an increase in probability of very large floods. Thirteen large floods, or almost 40% of the paleoflood record, occurred in the 390 years from ~A.D. 900 to 1290, including the largest magnitude floods in 2,000 years on 2 drainages and the second largest floods on 3 drainages. There are several possibilities

that could explain this rise in flood probability during this time: 1) instability of air masses caused by stronger than normal westerlies; 2) larger or more frequent hurricanes in the Gulf of Mexico and Atlantic Ocean; or 3) reduced land covering vegetation and an increase in forest fires caused by the severe drought. Likely, a combination of the three is responsible.

Instability of air masses is in large part due to the fact that because less energy is used for latent heating (evapotranspiration) in arid regions with drier soils such as the Black Hills, more heat is used for sensible heating. This produces stronger thermally induced convergence zones which creates a greater density difference in air masses between the mountains and plains. This, coupled with strong westerly winds, creates a lee-side convergence zone that commonly extends east of the major axis of the Black Hills and encompasses the study area (Driscoll et al., 2010). In addition, obstacle effects can be substantial for the Black Hills in terms of promoting thunderstorm development (Kuo and Oroville, 1973). In fact, according to Hjelmfelt and Farely (1992) this effect was greatest with a westerly wind component. An easterly wind component produced considerably weaker or nonexistent lee-side vortices to the west of the Hills. This suggests that during the MCA if the climate was warmer and the principle wind direction was from the west, lee-side convergence due to the obstacle effect and thermal forcing could produce larger and/or more frequent storms during this time. However, this is only possible if enough moisture is in the air.

Because the principle moisture source for western South Dakota is from the Gulf of Mexico, storm activity in this region would affect precipitation and thus streamflow in the Black Hills. There is evidence that the number of hurricanes in the Atlantic and Gulf of Mexico increased during the MCA (Figure 58; Mann et al, 2009; Lane et al., 2010). Mann et al. (2009) used both a statistical model and an empirical record of landfalling hurricanes from multiple sedimentary records to reach the conclusion that there was a peak in hurricane activity during ~A.D. 900-1100. Additionally, according to Lane et al. (2010), storm frequency in the Gulf of Mexico increased from about A.D. 800-1400. If storms were more frequent or more intense in the Gulf of Mexico during the MCA, then it is likely that some of the larger storms could have penetrated far into the interior continent providing moisture and unstable air masses that could have contributed to heavy precipitation events that led to severe flooding in the Black Hills even during a drought. In fact, according the Kendall's tau coefficient ($\tau = 0.131$), flooding in the Black Hills in the last 1,500 years is positively correlated to an increase in Atlantic cyclone activity. Therefore, the occurrence of large flood events is correlated to an increase in Atlantic cyclone activity.

An increase in hurricane activity has many possible mechanisms, including an increase in SST (Richey et al., 2007), long term changes in the Loop Current which brings warm waters from the Caribbean Sea through the Yucatan Strait into the Gulf of Mexico and affects the depth of warm water ($>26^{\circ}\text{C}$) and thus hurricane strength and frequency in the Gulf (Liu and Fearn, 2000; Poore et al., 2003), and migrations of the Intertropical

Convergence Zone (ITCZ; Poore et al., 2003; Peterson et al., 1991; Richey et al., 2007).

ENSO variability has been shown to impact tropical cyclone activity as well. (Donnelly and Woodruff, 2007; Jagger and Elsner, 2006; Jagger and Elsner, 2009).

Drought conditions may have enhanced flood potential by causing the vegetation cover to decrease in the area especially if fires were more common (Chandler et al, 1983; Agnew et al., 1997; Graham et al. 2007). Runoff after fire events increases dramatically and soil infiltration decreases (Swetnam and Betancourt, 1998; Moody and Martin, 2001a; 2001b; Veehuis, 2002).

After high temperature fires, soils can become hydrophobic. This occurs when organic debris in the upper soil gets vaporized by the fire, then condenses and fills the pores in the soil. This creates a hydrophobic layer that resists the passage of water increasing surface runoff and erosion and decreasing infiltration during storm events. This, of course, can lead to greater magnitude flood peaks than would have occurred with the same size storm pre-fire. Supporting this idea is the fact that many of the radiocarbon dated flood units in the Black Hills database contained abundant charcoal (Harden et al., 2011) indicating possible flood after fire events. Additionally, pine forests may have decreased over the last 1,000 in the Black Hills years in response to increased fire frequency (Fredlund and Tieszen, 1997).

A decrease in forest vegetation regardless of a fire could reduce soil infiltration and increase runoff. Vegetation creates more porous soils by reducing the impact of raindrops (through interception) that can sometimes cause the pore spaces in the upper

layer of soil to fill with fine particles and close. The roots of vegetation act as conduits for water and create and enlarge soil pores allowing for greater infiltration and less runoff. In addition to enhancing infiltration, vegetation reduces runoff by evapotranspiration and can tribute to significant water losses from drainage basins.

Historical record

A natural tendency for a study like this is to compare the paleoflood and related paleoclimate record to the historical record and associated climatic conditions. However, comparing the historical record to the paleoflood record is difficult for several reasons. First, the record of historical floods is very limited. Only four historical floods are equivalent to or greater than the 100 year flood magnitude on their respective drainages. One occurred in 1907 and three occurred in 1972 as a result of the same large meteorological storm. While the MCA spans about 400 years, the post-Euro-American settlement historical record spans a little over 130 years. Another difficulty in comparing paleofloods to the historic flood record is the absence of extremely large floods. Aside from the historical floods mentioned above, no other large floods seemed to have occurred in the study area. Of course other floods would have occurred since the Black Hills were settled by Euro-Americans in the mid- to late- 1800s but they were likely not large enough to merit historical comment or were less than the 100-year event. Because this study is focused on low probability extreme flood events, it is not accurate to compare the mechanisms of extreme floods with those of more common floods because the same atmospheric and ground conditions that create storms and runoff capable of

producing the 100 or 200-year flood are very different from those that produce the 5 to 10-year flood. The modern USGS gaged record has the same pitfalls. Even with a longer record (~80 years) and aside from the large 1972 flood, the flows recorded at the gage stations are a fraction of the discharge as those in the paleoflood record.

Uncertainties and Limitations

Radiocarbon dating has inherent uncertainties especially with samples younger than about 300 years before present because of the increased anthropomorphic burning of fossil fuels has released large and varying quantities of ^{12}C . However, it is less of an issue for this study because for any one flood date the whole probability curve is more important than that actual date of the flood. There is a possibility of older or younger organic material being incorporated into a unit through bioturbation. This would lead to an erroneous age of the deposit; however, this risk was reduced by collecting samples that were from seemingly undisturbed units or section of a unit and by collecting and analyzing a large number of samples from all 4 basins in the study area (Harden et al., 2011). Charcoal and large wood fragments, such as tree limbs can sometimes persist in the environment for many years before being incorporated into a flood deposit. Therefore, dating such material might result in an age that is older than the deposit. In order to reduce this error, samples such as pine needles and twig fragments were chosen for radiocarbon analyses whenever possible because these types of materials do not persist long in an open environment.

In addition to uncertainties related to radiocarbon dating, there exists some uncertainty in what influence, if any, the “wiggles” of the calibration curve have on the probability distributions. Also, flood histories are not available for the southern and northern Black Hills so they were not evaluated. Given their close proximity to the basins in the study area, the Black Hills are only about 120 miles long and 60 miles wide, it seems likely that the rivers would respond to climatic events in a similar way but possibly with different magnitudes. However, until temporal data becomes available, this remains speculation.

Conclusions

Thirty-nine floods, including 4 historical floods, with magnitudes greater than or equal to the 100-yr event as defined for the post A.D. 1000 period occurred in the Black Hills in the last 2,000 years. One third or 13 of these large floods occurred during the MCA from ~A.D. 900-1300 giving that time period an average rate of 3.25 large floods per 100 years. This rate is almost 3 times the average rate of occurrence of the 100-year flood. Of those 13 floods, 5 are either the largest or second largest floods in Elk, Boxelder, and Rapid Creeks. In comparison, the last 600 years from A.D. 1410 to present experienced an average rate of 2.8 floods per 100 years.

Reasons for the high concentration of large floods during the MCA, a period of intense drought in the Great Plains region including the Black Hills, is unclear but likely due to a combination of 1) stronger than normal westerlies contributing to instability or air masses, 2) larger or more frequent hurricanes in the Gulf of Mexico and Atlantic Ocean

bringing moisture to the region, and 3) increased runoff due to decreased infiltration caused by forest fires resulting from severe drought-like conditions. Predicting future flood hazards in the Black Hills is complicated at best and impossible at worst. However, by looking at how the region responded in the past to climate events like the MCA, some conclusions can be made. It seems likely that in a warming climate, if a severe long-term drought is expected for the Great Plains region, flood magnitudes and frequency will likely increase as well.

In addition to assessing the Black Hills future flood hazard susceptibility, establishing a global database of riverine paleoflood events is an important step in characterizing past hydrologic regimes, updating flood frequency analyses, and understanding how river systems respond to climate change. This study will add to the growing global database that includes Spain (Thorndycraft and Benito, 2006), Poland (Starkel et al., 2006), Great Britain (Macklin et al., 2005), Ireland (Turner et al., 2010), Germany (Hoffman et al., 2008) and the southwestern US including southern Nevada, Arizona, southern Utah, New Mexico and western Texas (Harden et al., 2010). Creating such databases and making them available to the public through publication in scientific journals is useful for such applications as flood hazard studies, flood frequency analyses, and paleoclimate reconstructions.

Chapter 5

Black Hills Flooding: Summary

The primary purpose of this study was to derive the flood history, improve flood-frequency characterization of low-probability floods, and understand the timing of the floods and how the timing relates to short-term climate anomalies during the late-Holocene. 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; (4) conducting quantitative flood-frequency analyses incorporating all relevant peak-flow information that includes paleoflood information, observational records, and historical flood accounts; and (5) comparing the timing of large floods events to short-term climate anomalies in the late-Holocene.

The primary evidence for past large and infrequent floods consists of stratigraphic records formed of fine-grained sediment deposits preserved in slack-water environments. These deposits accumulate and can record multiple floods over several thousand years. The geology of the Black Hills proved to be an excellent environment for the deposition and preservation of slackwater deposits due to the numerous caves and alcoves along the channel margins.

The stratigraphy provided information on the number of floods and their relative ages. Ages of individual flood deposits and the total length of record preserved in the stratigraphy were obtained by standard geochronologic techniques including radiocarbon analysis, OSL, and Cs-137. Peak-flow magnitudes were estimated mainly through the use of a one-dimensional hydraulic model and supplemented with the Manning's equation and critical flow computations. For the all 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 to be used in the flood-frequency analyses.

Summarizing interpretations for all of the Spring Creek paleoflood sites, a chronology of at least five paleofloods with magnitudes approaching or exceeding that of 1972 was preserved by stratigraphic records extending back about 1,000 years. The 1972 flow of 21,800 ft³/s was exceeded by a paleoflood of ~700 years ago with a flow range of 29,300–58,600 ft³/s, which reflects the uncertainty incorporated into the flood-magnitude estimates. A paleoflood ~450 years ago had a flow of 18,200–36,400 ft³/s. Three paleofloods about 800, 200, and 200 years ago had flows of 8,750–17,500, 12,000–24,000, and 13,900–27,800 ft³/s, respectively.

Lower Rapid Creek experienced two paleofloods in the last ~1,000 years exceeding the 1972 flow of 31,200 ft³/s. The largest paleoflood occurred about 440 years ago and had a flow of 128,000–256,000 ft³/s. Another large paleoflood was about 1,000

years ago and had a flow of 64,000–128,000 ft³/s. Five smaller paleofloods of 9,500–19,000 ft³/s occurred between about 200 and 400 years ago.

Stratigraphic evidence for two paleofloods of about 12,000–13,000 ft³/s about 1,000 and 1,500 (estimated) years ago constitute most of the paleoflood chronology for upper Rapid Creek. Both paleofloods are substantially larger than the largest flow in the gaged records of about 2,460 ft³/s in 1952. Only one additional paleoflood, about 800 years ago and similar in magnitude to the 1952 flow rate, could be confidently identified for inclusion in the paleoflood chronology. Compared to lower Rapid Creek and all of the other study reaches, upper Rapid Creek has experienced the smallest flood in the last 1,000 years.

For a period spanning about the last ~1,000 years, two paleofloods in the upstream sub-reach of Boxelder Creek have exceeded the 1972 peak of 30,800 ft³/s, both within the last ~500 years. The associated flow estimates for these two paleofloods are 39,000–78,000 ft³/s and 40,500–81,000 ft³/s. One other paleoflood that was comparable to the second largest flow of record (16,400 ft³/s in 1907) was almost 1,000 years ago and had an associated flow of 11,300–22,600 ft³/s.

Two paleofloods with flows substantially larger than the 1972 flood (50,500 ft³/s) have occurred in the last ~1,000 years in the downstream sub-reach of Boxelder Creek. The largest paleoflood was about 700 years ago with a flow of 61,300–123,000 ft³/s, whereas the second largest paleoflood (~900 years ago) had a flow of 52,500–105,000 ft³/s. Four additional paleofloods between about 450 and 1,000 years ago had flows between about 14,200 and 33,800 ft³/s.

The 1972 flow on Elk Creek ($10,400 \text{ ft}^3/\text{s}$) has been substantially exceeded at least five times in the last 1,900 years. The largest of these paleofloods was ~900 years ago and had a flow of $41,500\text{--}124,000 \text{ ft}^3/\text{s}$ ($83,000 \text{ ft}^3/\text{s} \pm 50$ percent). Three other paleofloods all between $37,500$ and $120,000 \text{ ft}^3/\text{s}$ occurred about 1,800, 1,700, and 1,100 years ago, respectively. The fifth large paleoflood was ~750 years ago and had a flow of $25,500\text{--}76,500 \text{ ft}^3/\text{s}$.

For all reaches, incorporation of the paleoflood data into flood-frequency analyses reduces associated uncertainties, expressed by the 95% confidence limits, by a factor of 3 to over 500. The results of the paleoflood investigations provide much 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 central Black Hills and reducing associated uncertainties.

In order to address the nonstationarity of flooding in the Black Hills, thirty-five large paleofloods and 4 large historical floods (100-yr event or larger based on the flood-frequency analyses) were used to examine the relationship between short-term climatic events and large flood events in the study area during the last 2,000 years. The 35 paleofloods include 5 from Elk Creek, 10 from Boxelder Creek, 15 from Rapid Creek, and 5 from Spring Creek. All floods in the last 2,000 years with a return period of 100-years or greater were examined.

The east-central Black Hills region has experienced 4 distinct episodes of increased flooding ranging in length from about a few hundred years (~ A.D. 130-400) to

several hundred years (A.D. 1410 – present). Eight large floods occurred in the earliest flooding episode from A.D. 130-400 followed by a period of about 240 years of less than average probability that ends with a large flood on Rapid Creek sometime between A.D. 640 and 670. From about A.D. 900 to 1290, 13 floods with a magnitude of the 100-year event or larger occurred in the study area. This high concentration of significantly large floods coincides with the Medieval Climate Anomaly (MCA: ~A.D. 900-1300). A period of few large floods persists for a little over 100 years after the MCA then picks up again after about A.D. 1410 and continues until the present. Thirteen paleofloods occurred during this period as well as the 4 large historical floods in 1972 (Spring, Rapid, and Boxelder Creeks) and 1907 (Boxelder Creek).

Reasons for the high concentration of large floods during the MCA, a period of intense drought in the Great Plains region including the Black Hills, is unclear but likely due to a combination of 1) stronger than normal westerlies contributing to instability or air masses, 2) larger or more frequent hurricanes in the Gulf of Mexico and Atlantic Ocean bringing moisture to the region, and 3) increased runoff due to decreased infiltration caused by forest fires resulting from severe drought-like conditions.

Using the geological record of past flood events in addition to the gaged record for flood-frequency analysis essentially extends the flood record to 1,000-2,000 years or more. Because climate is not stationary and typical flood-frequency analyses assume stationarity, extending the record through multiple climate events helps to alleviate some of the related uncertainty due to nonstationarity. Additionally, by examining the spatial

relationship of flood events in the last 2,000 years it can be deduced that if the future climate for the Black Hills is similar to the MCA, including severe drought and stronger than normal westerlies, a high concentration of large flood events can be expected.

References Cited

- Accelerator Mass Spectrometry Laboratory, 2011, Accelerator Mass Spectrometry Laboratory, University of Arizona, Tucson, Ariz., accessed June 2, 2011, at www.physics.arizona.edu/ams.
- Agnew, William, Lahn, R.E., and Harding, M.V., 1997, Buffalo Creek, Colorado, fire and flood of 1996: *Land and Water*, v. 41, p. 27–29.
- Baker, V.R., 1987, Paleoflood hydrology and extraordinary flood events: *Journal of Hydrology*, v. 96, p. 79–99.
- Banta, R.M., 1990, The role of mountain flows in making clouds, *Atmospheric Processes Over Complex Terrain: Meteorological Monographs*, W. Blumen (editor), vol. 23, no. 45, American Meteorological Society, pp. 229–283.
- Barnes, H.H., 1967, Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1849, 213 p.
- Barron, J.A., Heusser, T., Herbert, T., Lyle, M., 2003, High resolution climatic evolution of coastal Northern California during the past 16000 years, *Paleoceanography*, vol. 18, no. 1, pp. 20-1 to 20-14.
- Benson, M.A., and Dalrymple, T., 1967, General field and office procedures for indirect discharge measurements: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A1, 30 p.
- Blong, R.J., and Gillespie, R., 1978, Fluvially transported charcoal gives erroneous ^{14}C ages for recent deposits: *Nature*, v. 271, p. 739–741.
- Booth, R.K., Kutzbach, J.E., Hotchkiss, S.C., Bryson, R.A., 2006, A reanalysis of the relationship between strong westerlies and precipitation in the Great Plains and Midwest regions of North America, *Climate Change*, vol. 76, pp. 427–441.
- Bradley, R.S., 1999, *Paleoclimatology—Reconstructing climates of the Quaternary* (2d ed.): Burlington, Mass., Harcourt Academic Press, p. 80–89.
- Bronk Ramsey, Christopher, 2009, Bayesian analysis of radiocarbon dates: *Radiocarbon*, v. 51, no. 1, p. 337–360.

- Bronk Ramsey, Christopher, van der Plicht, J., and Weninger, B., 2001, "Wiggle matching" radiocarbon dates: *Radiocarbon*, v. 43, no. 2A, p. 381–389.
- Brown, P.M., and Sieg, C.H., 1996, Fire history in interior ponderosa pine communities of the Black Hills, South Dakota, USA: *International Journal of Wildland Fire*, v. 6, no. 3, p. 97–105.
- Burr, M.J., and Korkow, K.L., 1996, Peak-flow frequency estimates through 1994 for gaged streams in South Dakota: U.S. Geological Survey Open-File Report 96–202, 407 p.
- Carter, J.M., Williamson, J.E., and Teller, R.W., 2002, The 1972 Black Hills-Rapid City flood revisited: U.S. Geological Survey Fact Sheet FS–037–02, 6 p. (Also available at <http://pubs.usgs.gov/fs/fs-037-02/>)
- Center for Accelerator Mass Spectrometry, 2011, Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, Calif., accessed June 2, 2011, at <http://cams.llnl.gov>.
- Chandler, C., Cheney, P., Thomas, P., Traubad, L., Williams, D., 1983, *Fire in Forestry, Volume I: Forest Fire Behavior and Effects*, John Wiley and Sons, New York, 450 p.
- City of Rapid City, 2010, Pennington County-Rapid City GIS, accessed March 10, 2010, at <http://www.rcgov-gis.org/imf/sites/RapidMap>.
- Cobb, K.M., Charles, C.D., Cheng, H., Edwards, R.L., 2003, El Niño/ Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, vol. 424, p. 271-276.
- Cohn, T.A., Lane, W.L., and Baier, W.G., 1997, An algorithm for computing moments-based quantile estimates when historical flood information is available: *Water Resources Research*, v. 33, no. 9, p. 2,089–2,096.
- Cohn, T.A., Lane, W.L., Stedinger, J.R., 2001, Confidence intervals for expected moments algorithm flood quantile estimates: *Water Resources Research*, v. 37, no. 6, p. 1,695–1,706.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004, Long term aridity changes in the western United States, *Science*, vol. 306, pp. 1015-1018.
- Costa, J.E., 1978, Holocene stratigraphy in flood frequency analysis: *Water Resources Research*, v. 14, no. 4, p. 626–632.

- Costa, J.E., 1987, A comparison of the largest rainfall-runoff floods in the United States with those of the People's Republic of China and the World: *Journal of Hydrology*, v. 96, p. 101–115.
- Costa, J.E., and Jarrett, R.D., 2008, An evaluation of selected extraordinary floods in the United States reported by the U.S. Geological Survey and implications for future advancement of flood science: U.S. Geological Survey Scientific Investigations Report 2008–5164, 232 p., accessed April 6, 2011, at <http://pubs.usgs.gov/sir/2008/5164/>.
- Covington, W.W., and More, M.M., 1994, Southwestern ponderosa forest structure—Changes since Euro-American settlement: *Journal of Forestry*, v. 92, p. 39–47.
- Crippen, J.R., and Bue, C.D., 1977, Maximum flood flows in the conterminous United States: U.S. Geological Survey Water-Supply Paper 1887, 52 p.
- Dean W.E., 1997, Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: Evidence from varved lake sediments, *Geology*, vol. 25, p. 331–334.
- Dean, W.E., Schwalb, A., 2000, Holocene environmental and climatic change in the northern Great Plains as recorded in the geochemistry of sediments in Pickerel Lake, South Dakota, *Quaternary International*, vol. 67, pp. 5–20.
- Dennis, A.S., Schleusener, R.A., Hirsch, J.H., and Koscielski, A., 1973, Meteorology of the Black Hills flood of 1972: Rapid City, South Dakota School of Mines and Technology, Institute of Atmospheric Science Report 73-4, 41 p.
- Diffenbaugh, N.S., Ashfaq, M., Shuman, B., Williams, J.W., Bartlein, P.J., 2006, Summer aridity in the United States: Response to mid-Holocene changes in insolation and sea surface temperature, *Geophysical Research Letters*, vol. 33, L22712.
- Donnelly, J.P., Woodruff, J.D., 2007, Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African Monsoon, *Nature*, vol. 447, pp. 465–468.
- Driscoll, D.G., and Carter, J.M., 2001, Hydrologic conditions and budgets for the Black Hills of South Dakota, through water year 1998: U.S. Geological Survey Water-Resources Investigations Report 01–4226, 143 p. (Also available at <http://pubs.usgs.gov/wri/wri014226/>)
- Driscoll, D.G., and Norton, P.A., 2009, Hydrologic characterization for Spring Creek and hydrologic budget and model scenarios for Sheridan Lake, South Dakota, 1962–2007:

- U.S. Geological Survey Scientific Investigations Report 2009–5059, 80 p. (Also available at <http://pubs.usgs.gov/sir/2009/5059/>.)
- Driscoll, D.G., Bunkers, M.J., Carter, J.M., Stamm, J.F., and Williamson, J.E., 2010, Thunderstorms and flooding of August 17, 2007, with a context provided by a history of other large storm and flood events in the Black Hills area of South Dakota: U.S. Geological Survey Scientific Investigations Report 2010–5187, 139 p. (Also available at <http://pubs.usgs.gov/sir/2010/5187/>.)
- Driscoll, D.G., Carter, J.M., and Ohlen, D.O., 2004, Hydrologic effects of the 1988 Galena fire, Black Hills area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 03–4323, 67 p. (Also available at <http://pubs.usgs.gov/wri/wri034323/>.)
- Driscoll, D.G., Carter, J.M., Williamson, J.E., and Putnam, L.D., 2002, Hydrology of the Black Hills area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 02–4094, 150 p. (Also available at <http://pubs.usgs.gov/wri/wri024094/>.)
- Driscoll, D.G., Hamade, G.R., and Kenner, S.J., 2000, Summary of precipitation data for the Black Hills area of South Dakota, water years 1931–98: U.S. Geological Survey Open-File Report 00–329, 151 p. (Also available at <http://sd.water.usgs.gov/pubs/reports/ofr00-329.pdf>)
- Duller, G.A.T., 2008, Luminescence dating—Guidelines on using luminescence dating in archeology: Swindon, United Kingdom, English Heritage, 44 p.
- Ely, L.L., Enzel, Y., Baker, V.R., and Cayan, D.R., 1993, A 5000-yr record of extreme floods and climate change in the southwestern United States: *Science*, v. 262, p. 410–412.
- Enfield, D.B., Mestas-Nunez, A.M., Trimble, P.J., 2001, The Atlantic multi decadal oscillation and its relation to rainfall and river flows in the continental U.S., *Geophysical Research Letters*, vol. 28, pp. 2077–2080.
- Environmental Systems Research Institute, 2010, ArcGIS 9.3 software, accessed July 2009 at <http://www.ersi.com/>.
- Enzel, Yehouda, Ely, L.L., House, K.P., Baker, V.R., and Webb, R.H., 1993, Paleoflood evidence for a natural upper bound to flood magnitudes in the Colorado River Basin: *Water Resources Research*, v. 29, no. 7, p. 2,287–2,297.

- Enzel, Yehouda, Ely, L.L., Martinez-Goyre, J., and Vivian, R.G., 1994, Paleofloods and a dam failure flood on the Virgin River, Utah and Arizona: *Journal of Hydrology*, v. 153, p. 291–315.
- Feng, S., Oglesby, R.J., Rowe, C.M., Loope, D.B., Hu, Q., 2008, Atlantic and Pacific SST influences on Medieval drought in North America simulated by the Community Atmospheric Model, *Journal of Geophysical Research*, vol. 113, D11101, 14 p.
- Fredlund, G.G., Tieszen, L.L., 1997, Phytolith and carbon isotope evidence for late Quaternary vegetation and climate change in the southern Black Hills, South Dakota, *Quaternary Research*, 47, 206-214.
- Frances, Felix, Salas, J.D., and Boes, D.C., 1994, Flood frequency analysis with systematic and historical or paleoflood data based on the two-parameter general extreme value models: *Water Resources Research*, v. 30, no. 6, p. 1,653–1,664.
- Fritz, S.C., Ito, E., Yu, Z.C., Laird, K.R., Engstrom, D.R., 2000, Hydrologic variation in the northern Great Plains during the last two millennia, *Quaternary Research*, vol. 53, p. 175-184.
- Grafe, Ernest, and Horsted, Paul, 2002, *Exploring with Custer—The 1874 Black Hills Expedition: Custer, S. Dak.*, Golden Valley Press, 288 p.
- Graham, N.E., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., Xu, T., 2007, Tropical Pacific-mid-latitude teleconnections in medieval times, *Climate Change*, vol. 83, pp. 241-285.
- Grant, G.E., 1997, Critical flow constrains flow hydraulics in mobile-bed streams—A new hypothesis: *Water Resources Research*, v. 33, p. 349–358.
- Griffis, V.W., Stedinger, T.A., and Cohn, T.A., 2004, Log Pearson type 3 quantile estimators with regional skew information and low outlier adjustments: *Water Resources Research*, v. 40, no. 10.
- Harden, T., Macklin, M.G., Baker, V.R., 2010, Holocene flood histories in the south-western USA, *Earth Surface Processes and Landforms*, 35, pp. 707-716.
- Harden, T.M., O'Connor, J.E., Driscoll, D.G., Stamm, J.F., 2011, Flood-frequency analyses from Paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, Western South Dakota, U.G. Geological Survey Scientific Investigations Report 2011-5131, 136 p.

- Helama, S., Meriläinen, J., Toumenvirta, H., 2009, Multicentennial megadrought in northern Europe coincided with a global El Niño-Southern Oscillation drought pattern during the Medieval Climate Anomaly, *Geology*, vol 37, no. 2, p. 175-178.
- Hjemfelt, M.R., Farley, R.D., 1992, Airflow over a mesoscale ellipsoidal hill on sloping terrain – the Black Hills, American Meteorological Society, Preprints, 6th Conference on Mountain Meteorology, September 29 – October 2, Portland, Oregon, p. 12-16.
- Hjemfelt, M.R., Kondrasuk, G., Priegnitz, D., 1992, Effects of the Black Hills on mesoscale airflow and precipitation patterns, American Meteorological Society, Preprints, 6th Conference on Mountain Meteorology, September 29-October 2, Portland, Oregon, p. 566-569.
- Hoerling, M.P., Kumar, A., 2003, The perfect ocean for drought, *Science*, vol. 299, pp. 691-699.
- Hoffman, T., Lang, A., Dikau, R., 2008, Holocene river activity: analyzing ¹⁴C-dated fluvial and colluvial sediments from Germany, *Quaternary Science Reviews*, vol. 27, pp. 2031-2040.
- Holm, M., Smith, M., 2008, Rainfall totals from the Hermosa flash flood of 17 August 2007, National Oceanic and Atmospheric Administration/ National Weather Service, Central Region Technical Attachment 08-03, 34 p.
- Holmes, C.W., 1998, Short lived isotopic chronometers—A means of measuring decadal sedimentary dynamics: U.S. Geological Survey fact sheet FS-073-98.
- Honerkamp, J.R., 1978, At the foot of the mountain: Stickney, South Dakota., Argus Printers, 231 p.
- Hortness, J.E., and Driscoll, D.G., 1998, Streamflow losses in the Black Hills of western South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4116, 99 p. (Also available at <http://pubs.usgs.gov/wri/wri984116/>.)
- Hosking, J.R.M., and Wallis, J.R., 1986, Paleoflood hydrology and flood frequency analysis: *Water Resources Research*, v. 22, no. 4, p. 543-550.

- Hosman, K.J., Ely, L.L., and O'Connor, J.E., 2003, Holocene paleoflood hydrology of the lower Deschutes River, Oregon, *in* O'Connor, J.E., and Grant, G.E., eds., *A peculiar river—Geology, geomorphology and hydrology of the Deschutes River, Oregon: American Geophysical Union Water Science and Application Series 7*, p. 121–146.
- Interagency Advisory Council on Water Data, 1982, Guidelines for determining flood flow frequency: Hydrology Subcommittee, Bulletin 17B, appendixes 1–14, 28 p.
- International Association of Hydrological Sciences, 2003, World catalogue of maximum observed floods, compiled by Reg Herschy: Wallingford, Oxfordshire, U.K., IAHS Press, IAHS-AISH Publication 284, 285 p.
- Jagger, T.H., Elsner, J.B., 2006, Climatology models for extreme hurricane winds near the United States, *Journal of Climate*, vol. 19, pp. 3220–3236.
- Jagger, T.H., Elsner, J.B., 2009, Modeling tropical cyclone intensity with quantile regression, *International Journal of Climatology*, vol. 29, issue 10, pp. 1351–1361.
- Jarrett, R.D., and England, J.F., Jr., 2002, Reliability of paleostage indicators for paleoflood studies, *in* House, P.K., Webb, R.H., Baker, V.R., Levish, D.L., eds., *Ancient floods, modern hazards—Principles and applications of paleoflood hydrology: Washington, D.C., American Geophysical Union's Water Science and Application Series, v. 5*, p. 91–109, plus CD-ROM.
- Jiang, H.J., Eiriksson, J., Schultz, M., Knudsen, K., Seidenkrantz, M., 2005, Evidence for solar forcing of sea-surface temperature on the North Icelandic shelf during the late Holocene, *Geology*, vol. 33, pp. 73–76.
- Karl, T.R., Metcalf, L.K., Nicodemus, M.L., Quayle, R.G., 1983, Statewide Average Climate History, South Dakota, 1890–1982: National Climatic Center Historical Climatology Series 6-1, 37 p.
- Keigwin, L.D., 1996, The Little Ice Age and Medieval Warm Period in the Sargasso Sea, *Science*, vol. 274, pp. 1504–1508.
- Khider, D., Stott, L.D., Emile-Geay, J., Thunell, R., Hammond, D.E., 2011, Assessing El Niño Southern Oscillation Variability during the past millennium, *Paleoceanography*, vol. 26, PA3222, 20 p.

- Kim, J.H., Rimbu, N., Lorenz, S.J., Lohmann, G., Nam, S., Schouten, S., Ruhlemann, C., Schneider, R.R., 2004, North Pacific and North Atlantic sea-surface temperature variability during the Holocene, *Quaternary Science Reviews*, vol. 23, pp. 2141-2154.
- Kim, J.H., Meggers, H., Rimbu, N., Lohmann, G., Freudenthal, T., Muller, P.J., Schneider, R.R., 2007, Impacts of the North Atlantic gyre circulation on Holocene climate off northwest Africa, *Geology*, vol. 35, pp. 387-390.
- Kochel, R.C., and Baker, V.R., 1982, Paleoflood hydrology: *Science*, v. 215, p. 353–361.
- Kochel, R.C., and Baker, V.R., 1988, Paleoflood analysis using slackwater deposits, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., eds., *Flood geomorphology*: New York, John Wiley and Sons, p. 357–376.
- Kuo, J.T., and Orville, H.D., 1973, A radar climatology of summertime convective clouds in the Black Hills, *Journal of Applied Meteorology and Climatology*, vol. 12, pp. 359-368.
- Lachniet, M.S., Burns, S.J., Piperno, D.P., Asmerom, Y., Polyak, V.J., Moy, C.M., Christenson, K., 2004, A 1500-year El Niño/Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite, *Journal of Geophysical Research*, vol. 109.
- Laird, K.R., Fritz, S.C., Maasch, K.A., Cumming, B.F., 1996, Greater drought intensity and frequency before A.D. 1200 in the Northern Great Plains, *Nature*, vol. 384, pp. 552-554.
- Laird, K.R., Cumming, B.F., Wunsam, S., Rusak, J.A., Oglesby, R.J., Fritz, S.C., Leavitt, P.R., 2003, Lake sediments record large scale shift in moisture regimes across the northern prairies of North America during the past two millennia, *Proc. Natl. Acad. Sci. U.S.A.*, vol. 100, pp. 2483-2488.
- Lane, P., Donnelly, J., Woodruff, J., Hawkes, A., 2010, A 4500-year record of hurricane frequency in the Gulf of Mexico archived in a north Florida sinkhole, 29th Conference of Hurricanes and Tropical Meteorology, Tucson, AZ., extended abstract, 15 p.
- Langton, S.J., Linsley, B.K., Robinson, R.S., Rosenthal, Y., Oppo, D.W., Eglinton, T.I., Howe, S.S., Djajadihardja, Y.S., Syamsudin, F., 2008, 3500 yr record of centennial-scale climate variability from the Western Pacific Warm Pool, *Geology*, vol. 26, no. 10., p. 795-798.
- Larimer, O.J., 1973, Flood of June 9–10, 1972, at Rapid City, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA–511, 1 sheet, scale 1:18,000.

- Levish, D.R., 2002, Paleohydrologic bounds—Non-exceedance information for flood hazard assessment, *in* House, P.K., Webb, R.H., Baker, V.R., Levish, D.L., eds., *Ancient floods, modern hazards—Principles and applications of paleoflood hydrology*: Washington, D.C., American Geophysical Union's Water Science and Application Series, v. 5, p. 175–190.
- Liu, K., Fearn, M.L., 2000, Reconstructions of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records, *Quaternary Research*, vol. 54, 238-245.
- Macklin, M.G., Johnstone, E., Lewin, J., 2005, Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change, *The Holocene*, 15,7, pp. 937-943.
- Mann, M.E., Woodruff, J.D., Donnelly, J.P., Zhang, Z., 2009, Atlantic hurricanes and climate over the past 1,500 years, *Nature*, vol. 460, pp. 880-885.
- McCabe, G.J., Palecki, M.A., Betancourt, J.L., 2004, Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U.S.A.*, vol. 101, pp. 4136-4141.
- Miller, L.D., and Driscoll, D.G., 1998, Streamflow characteristics for the Black Hills of South Dakota, through water year 1993: U.S. Geological Survey Water-Resources Investigations Report 97–4288, 322 p.
- Moody, J.A., Martin, D.A., 2001a, Hydrologic and sedimentologic response of two burned watersheds in Colorado, USGS Water Resources Investigation Report 01-4122.
- Moody, J.A., Martin, D.A., 2001b, Post-fire rainfall intensity-peak discharge relations for three mountainous watersheds in the western US, *Hydrological Processes*, vol. 15, pp. 2981-2993.
- Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002, Variability of El Nino/Southern Oscillation activity at millennial timescales during the Holocene epoch, *Nature*, vol. 420, pp. 162-165.
- Nicholson, B.J., Swinehart, J.B., 2005, Evidence of Holocene climate change in a Nebraska sandhills wetland, *Great Plains Research*, vol. 15, pp. 45-67.
- Nordt, L., Fischer, J., Tieszen, L., 2007, Late Quaternary temperature record from buried soils of the North American Great Plains, *Geology*, v.35, no. 2, pp. 159-162.

- O'Connell, D.R.H., 1999, FLDFRQ3 user's guide, release 1.1: U.S. Bureau of Reclamation, 19 p.
- O'Connell, D.R.H., Ostenaa, D.A., Levish, D.R., and Klinger, R.E., 2002, Bayesian flood frequency analysis with paleohydrologic bound data: *Water Resources Research*, v. 35, no. 5.
- O'Connor, J.E., and Costa, J.E., 2004, Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 km² in the United States and Puerto Rico: *Water Resources Research*, v. 40, 11p.
- O'Connor, J.E., and Driscoll, D.G., 2007, Applicability of paleoflood surveys to the Black Hills of Western South Dakota: Completion report SD2005–12 submitted to South Dakota Department of Transportation, Office of Research, 59 p., accessed March 16, 2010, at http://apps.sd.gov/Applications/HR19ResearchProjects/Projects/SD2005-12_Final_Report.pdf.
- O'Connor, J.E., and Webb, R.H., 1988, Hydraulic modeling for paleoflood analysis, in Baker, V.R., Kochel, R.C., and Patton, P.C., eds., *Flood geomorphology*: New York, John Wiley and Sons, p. 393–402.
- O'Connor, J.E., Ely, L.L., and Wohl, E.E., 1994, A 4500-yr record of large floods on the Colorado River in the Grand Canyon: *Journal of Geology*, v. 102, p. 1–9.
- Peterson, L.C., Overpeck, J.T., Kipp, N.G., Imbrie, J., 1991, A high-resolution late Quaternary upwelling record from the anoxic Cariaco Basin, Venezuela, *Paleoceanography*, vol. 6, pp. 99–119.
- Poore, R.Z., Dowsett, H.J., Verardo, S., Quinn, T.M., 2003, Millennial-to-century scale variability in Gulf of Mexico Holocene climate records, *Paleoceanography*, vol. 18, no. 2, 1048.
- Prescott, J.R., and Hutton, J.T., 1994, Cosmic ray contribution to dose rates for luminescence and ESR dating—Large depths and long-term time variations: *Radiation Measurements*, v. 23, no. 2–3, p. 497–500.
- Progulske, D.R., 1974, Yellow ore, yellow hair, yellow pine—A photographic survey of a century of forest ecology: *Brooking, S. Dak., Agricultural Experiment Station, South Dakota State University, Bulletin 616*, 169 p.

- Redden, J.A., and Lisenbee, A.L., 1996, Geologic setting, Black Hills, South Dakota, *in* Paterson, C.J., and Kirchner, J.G., eds., Guidebook to the geology of the Black Hills, South Dakota: Rapid City, S. Dak., South Dakota School of Mines and Technology Bulletin No. 19, p. 1–8.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., and Weyhenmeyer, C.E., 2009, IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP: Radiocarbon, v. 51, no. 4, p. 1,111–1,150.
- Rein, B., Lückge, A., Sirocko, F., 2004, A major Holocene ENSO anomaly during the Medieval period, Geophysical Research Letters, vol. 31, L17211, 4 p.
- Richey, J.N., Poore, R.Z., Flower, B.P., Quinn, T.M., 2007, 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico, Geology, vol. 35, no. 5, pp. 423–426.
- Richey, J.N., 2010, Late Holocene climate variability from northern Gulf of Mexico sediments: Merging inorganic and molecular organic geochemical proxies, University of South Florida Theses and Dissertations, Paper 1748, 120 p.
- Rothrock, E.P., 1943, A Geology of South Dakota, Part I – The Surface, South Dakota Geological Survey Bulletin 13, 88 p.
- Sando, S.K., 1998, Techniques for estimating peak-flow magnitude and frequency relations for South Dakota streams: U.S. Geological Survey Water-Resources Investigations Report 98–4055, 48 p. (Also available at <http://pubs.usgs.gov/wri/wri98-4055/>.)
- Sando, S.K., Driscoll, D.G., and Parrett, Charles, 2008, Peak-flow frequency estimates based on data through water year 2001 for selected streamflow-gaging stations in South Dakota: U.S. Geological Survey Scientific Investigations Report 2008–5104, 367 p., accessed March 13, 2010, at <http://pubs.usgs.gov/sir/2008/5104/>.
- Schmeisser, R.L., Loope, D.B., Mason, J.A., 2010, Modern and late Holocene wind regimes over the Great Plains (Central U.S.A.), Quaternary Science Reviews, vol. 29, no. 3–4, pp. 554–566.

- Schwalb, A., Dean, W.E., Fritz, S.C., Geiss, C.E., Kromer, B., 2010, Centennial eolian cyclicity in the Great Plains, USA: a dominant climate pattern of wind transport over the past 4000 years?, *Quaternary Science Reviews*, vol. 29, pp. 2325-2339.
- Schwarz, F.K., Hughes, L.A., Hansen, E.M., Petersen, M.S., and Kelly, D.B., 1975, The Black Hills-Rapid City Flood of June 9–10, 1972—a description of the storm and flood: U.S. Geological Survey Professional Paper 877, 47 p.
- Seager, R., Kushnir, Y., Herweijer, C., Naik, N., Velez, J., 2005, Modeling of tropical forcing of persistent droughts and pluvial over western North America, *Journal of Climate*, vol. 18, pp. 4065-4088.
- Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., Cook, E., 2007, Blueprints for Medieval hydroclimate, *Quaternary Science Reviews*, vol 26, p. 2322-2336.
- Shapley, M.D., Johnson, W.C., Engstrom, D.R., Osterkamp, W.R., 2005, Late-Holocene flooding and drought in the northern Great Plains, USA, reconstructed from tree rings, lake sediments, and ancient shorelines, *The Holocene*, 15, 1, pp. 29-41.
- Sheffer, N.A., Rico, M., Enzel, Y., Benito, G., and Grodek, T., 2008, The paleoflood record of the Gardon River, France: A comparison with the extreme 2002 flood event: *Geomorphology*, v. 98, p. 71–83.
- South Dakota Department of Transportation, 2010, Application of paleoflood survey techniques in the Black Hills of South Dakota: South Dakota Department of Transportation, Office of Research, Project Synopsis for Project SD2008-01
- Spuhler, W., Lytle, W.F., Moe, D., 1971, Climate of South Dakota, South Dakota State University Agricultural Experiment Station Bulletin 582, 30 p.
- Starkel, L., Soja, R., Michczynska, D.J., 2006, Past hydrological events reflected in Holocene history of Polish rivers, *Catena*, vol. 66, issues 1-2, p. 24-33.
- Stedinger, J.R., and Baker, V.R., 1987, Surface water hydrology—Historical and paleoflood information: *Review of Geophysics*, v. 25, no. 2, p. 119–124.
- Stedinger, J.R., and Cohn, T.A., 1986, Flood frequency analysis with historical and paleoflood information: *Water Resources Research*, v. 22, no. 2, p. 785–793.

- Strobel, M.L., Jarrell, G.J., Sawyer, J.F., Schleicher, J.R., and Fahrenbach, M.D., 1999, Distribution of hydrogeologic units in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-743, 3 sheets, scale 1:100,000.
- Stuiver, M., Braziunas, T.F., 1989, Atmospheric ^{14}C and century scale solar oscillations, *Nature*, vol. 338, pp. 405-408.
- Stuiver, Minze, and Polach, H.A., 1977, Discussion—Reporting of ^{14}C data: *Radiocarbon*, v. 19, no. 3, p. 355–363.
- Swetnam, T.W., Betancourt, J.L., 1998, Mesoscale disturbance and ecological response to decadal climate variability in the arid American Southwest, *Journal of Climate*, vol. 11, pp. 3128-3147.
- Taylor, R.E., 2001, Radiocarbon dating, in D.R. Brothwell, and Pollard, A.M., eds., *Handbook of archaeological sciences*: Chichester and New York, John Wiley, p. 23–24.
- Thorndycraft, V.R., Benito, G., 2006, Late Holocene fluvial chronology of Spain: The role of climatic variability and human impact, *Catena*, vol. 5, issues 1-2, p. 34-41.
- Turner, J.N., Macklin, M.G., Jones, A.F., Lewis, H., 2010, New perspectives on Holocene flooding in Ireland using meta-analysis of fluvial radiocarbon dates, *Catena*, vol. 82, issue 3, pp. 183-190.
- U.S. Army Corps of Engineers, 1973: Flood plain information, Rapid Creek, Rapid City, South Dakota: Department of the Army, Omaha District, 48 p., plus plates.
- U.S. Army Corps of Engineers, 2008a, HEC-RAS River Analysis System user's manual, version 4.0: U.S. Army Corps of Engineers, variously paginated.
- U.S. Army Corps of Engineers, 2008b, HEC-RAS River Analysis System hydraulic reference manual, version 4.0: U.S. Army Corps of Engineers, variously paginated.
- U.S. Environmental Protection Agency, 2010, Radiation Protection—Cesium, accessed March 3, 2010, at <http://www.epa.gov/radiation/radionuclides/cesium.html>.
- U.S. Geological Survey, 2010a, History of flooding in the Black Hills, accessed May 11, 2010, at <http://sd.water.usgs.gov/projects/FloodHistory/floodhistory.html>.
- U.S. Geological Survey, 2010b, Eastern Earth Surface Processes Team, Reston, Virginia, geology.er.usgs.gov/eespteam

U.S. Geological Survey, 2010c, Luminescence Dating Laboratory, Lakewood, Colorado, accessed March 22, 2010, at http://crustal.usgs.gov/laboratories/luminescence_dating/index.html.

U.S. Geological Survey, 2010d, Florida Integrated Science Center, accessed March 22, 2010, at www.usgs.gov/state/state.asp?State=FL.

U.S. Geological Survey, 2010e, National Water Information System (NWISWeb)—Peak streamflow for South Dakota: U.S. Geological Survey database, accessed March 22, 2010 at, <http://nwis.waterdata.usgs.gov/sd/nwis/peak>.

Veehuis, J.E., 2002, Effects of wildfire on the hydrology of Capulin and Rito de Los Frijoles canyons, Bandelier National Monument, New Mexico, USGS Water Resources Investigation Report 02-4152.

Vogel, J.S., Southon, J.R., Nelson, D.E., and Brown, T.A., 1984, Performance of catalytically condensed carbon for use in accelerator mass spectrometry, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 5, issue 2, p. 289-293.

Walker, M., 2005, *Quaternary dating methods*: Chichester, England, John Wiley and Sons, Ltd., 286 p.

Weakly, H.E., 1943, A tree-ring record of precipitation in western Nebraska, *Journal of Forestry*, pp. 816-827

Webb, R.H., Blainey, J.B., and Hyndman, D.W., 2002, Paleoflood hydrology of the Paria River, Southern Utah and Northern Arizona, USA, *in* House, P.K., Webb, R.H., Baker, V.R., Levish, D.L., eds., *Ancient floods, modern hazards—Principles and applications of paleoflood hydrology*: Washington, D.C., American Geophysical Union's Water Science and Application Series, v. 5, p. 295-310.

Wells, J.V.B., 1962, *Floods of 1955*: U.S. Geological Survey Water Supply Paper 1455, 74 p.

Weibull, W., 1939, A statistical theory of the strength of materials: *Handlingar, Ingeniors Ventenskaps Akademian*, v. 151–3, p. 45–55.

Westin, D.L., Lemme, G.D., Evensen, P.D., 1987, Understory herbage production of major soils within the Black Hills of South Dakota, *Journal of Range Management*, vol. 20, no. 2, pp. 166-170.

Westin, F.C. and D.D. Malo, 1978, Soils of South Dakota, Bulletin 656. Plant Science Department, South Dakota Agricultural Experiment Station. SDSU, Brookings, 57007-2141

Wohl, E.E., Webb, R.H., Baker, V.R., and Pickup, G., 1994, Sedimentary flood records in the bedrock canyons of rivers in the monsoonal region of Australia: *Water Resources Papers*, v. 107, 102 p.

Wolman, M.G., and Costa, J.E., 1984, Envelope curves for extreme flood events—discussion: *Journal of Hydraulic Engineering*, v. 110, no. 1, p. 77-78.

Yan, H., Sun, L., Wang, Y., Huang, W., Qiu, S., Yang, C., 2011, A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies, *Nature Geoscience*, vol. 4, p. 611-614.

Yu, Z.C., Ito, E., 1999, Possible solar forcing of century-scale drought frequency in the northern Great Plains, *Geology*, vol. 27, pp. 263-266.

Appendix A - Geochronology

This Appendix contains tables that present age-dating results for radiocarbon samples (Table A.1), optically stimulated luminescence samples (Table A.2), and cesium-137 samples (Table A.3).

Table A.1. Results of laboratory analyses for radiocarbon samples.

[ID, identification number; ^{14}C yr BP, uncalibrated carbon-14 age in years before present (referenced to A.D. 1950) calculated using the Libby half-life of 5,568 years; $^{13}\text{C}/^{12}\text{C}$, ratio of carbon-13 to carbon-12; $\pm$, plus or minus; --, analysis could not be performed; "Modern" results indicate a post A.D. 1950 age and are not calibrated; calibrated age ranges and median ages calculated on the basis of Oxcal 4.1 (Bronk Ramsey and others, 2001; Bronk Ramsey, 2009) using IntCal09 calibration dataset (Reimer and others, 2009)]

ID	Sample date	Field sample number	Laboratory identification number	Site or alcove and pit (if applicable)	Material sampled	^{14}C yr BP ± 1 -sigma error	$^{13}\text{C}/^{12}\text{C}$	Calibrated 2-sigma age ranges (fraction of probability density function)	Median age
Spring Creek study reach									
1	05/31/2006	3A(4)	ww6003	Hailstorm Pit A	Wood	599 $\pm$ 33	--	A.D. 1296–1410 (0.95)	A.D. 1347
2	05/31/2006	3A(6)	ww5983	Hailstorm Pit A	Charcoal	2,205 $\pm$ 34	--	382–192 B.C. (0.95)	284 B.C.
3	05/31/2006	3B(2)	ww6004	Hailstorm Pit B	Wood	625 $\pm$ 32	--	A.D. 1289–1400 (0.95)	A.D. 1350
4	05/28/2008	3(1)	ww7068	Hailstorm	Seed shell	320 $\pm$ 25	-23.31	A.D. 1486–1644 (0.95)	A.D. 1563
5	05/28/2008	3(2)	ww7587	Hailstorm	Driftwood	130 $\pm$ 25	-23.98	A.D. 1678–1765 (0.35); A.D. 1799–1893 (0.45); A.D. 1906–1940 (0.15)	A.D. 1825
6	08/12/2008	2A(4)	ww7697	John Doe Pit A	Charcoal	865 $\pm$ 25	-24.61	A.D. 1048–1084 (0.10); A.D. 1122–1138 (0.03); A.D. 1150–1225 (0.82)	A.D. 1187
7	08/12/2008	2B(1)	ww7399	John Doe Pit B	Charcoal	1,090 $\pm$ 30	-25	A.D. 892–1014 (0.95)	A.D. 953
8	08/12/2008	2B(3)	ww7698	John Doe Pit B	Charcoal	860 $\pm$ 25	-25.35	A.D. 1052–1080 (0.07); A.D. 1152–1253 (0.88)	A.D. 1180
9	08/12/2008	2B(4)	ww7590	John Doe Pit B	Charcoal	260 $\pm$ 25	-27.81	A.D. 1522–1573 (0.20); A.D. 1628–1670 (0.63); A.D. 1780–1800 (0.12)	A.D. 1649
10	08/12/2008	1(1)	ww7070	Near Strike	Wood	60 $\pm$ 25	-24.91	A.D. 1694–1728 (0.23); A.D. 1812–1854 (0.21); A.D. 1866–1919 (0.52)	A.D. 1878
11	06/02/2006	1(2)	ww5981	Olympia	Charcoal	738 $\pm$ 32	--	A.D. 1220–1295 (0.95)	A.D. 1270
12	05/28/2008	4(1)	ww7069	Superscours Pit B	Bark fragment	225 $\pm$ 30	-29.66	A.D. 1640–1684 (0.40); A.D. 1735–1806 (0.42)	A.D. 1764
13	06/01/2006	1A(4)	ww5976	Superscours Pit A	Charcoal	672 $\pm$ 32	--	A.D. 1272–1320 (0.54); A.D. 1350–1391 (0.42)	A.D. 1310
14	06/01/2006	1A(5)	ww6005	Superscours Pit A	Ponderosa pine bark	95 $\pm$ 32	--	A.D. 1682–1736 (0.27); A.D. 1804–1934 (0.68)	A.D. 1840
15	06/01/2006	1B(2)	ww5999	Superscours Pit A	Bark	138 $\pm$ 32	--	A.D. 1669–1780 (0.42); A.D. 1798–1892 (0.38); A.D. 1908–1944 (0.15)	A.D. 1810
16	06/01/2006	1B(6)	ww6000	Superscours Pit A	Organic detritus	Modern	--	Modern	--
17	06/05/2007	2(1)	ww6001	Temple of Doom	Driftwood	680 $\pm$ 34	--	A.D. 1267–1320 (0.58); A.D. 1350–1392 (0.37)	A.D. 1303
Downstream reach of Rapid Creek									
18	09/05/2008	1(1)	ww7145	Black Socks	Charcoal	770 $\pm$ 35	-24.92	A.D. 1209–1287 (0.95)	A.D. 1251
19	09/05/2008	1(14)	ww7148	Black Socks	Wood	75 $\pm$ 35	-25.98	A.D. 1684–1732 (0.26); A.D. 1807–1928 (0.70)	A.D. 1845
20	09/05/2008	1(2)	ww7704	Black Socks	Charcoal	480 $\pm$ 35	-25	A.D. 1400–1466 (0.95)	A.D. 1431
21	09/05/2008	1(3)	ww7735	Black Socks	Charcoal	1580 $\pm$ 35	--	A.D. 410–558 (0.95)	A.D. 484
22	09/05/2008	1(5)	ww7749A	Black Socks	Charcoal	155 $\pm$ 35	--	A.D. 1665–1710 (0.17); A.D. 1716–1785 (0.32); A.D. 1793–1891 (0.30); A.D. 1908–1952 (0.17)	A.D. 1784
23	09/05/2008	1(7)	ww7147	Black Socks	Charcoal	130 $\pm$ 30	-27.87	A.D. 1675–1778 (0.38); A.D. 1798–1894 (0.43); A.D. 1905–1942 (0.15)	A.D. 1822
24	09/05/2008	1(9)	ww7146	Black Socks	Charcoal	125 $\pm$ 35	-26.08	A.D. 1675–1778 (0.37); A.D. 1798–1942 (0.59)	A.D. 1825
25	08/04/2008	1(3)	ww7077	Church Mug	Charcoal	360 $\pm$ 35	-24.38	A.D. 1450–1530 (0.47); A.D. 1538–1635 (0.49)	A.D. 1540
26	06/19/2009	1B(10)	ww7581	Lost	Charcoal	1,800 $\pm$ 25	-23.6	A.D. 130–260 (0.87); A.D. 295–322 (0.09)	A.D. 215
27	06/19/2009	1B(11)	ww7702	Lost	Charcoal	1,740 $\pm$ 30	-25	A.D. 234–389 (0.95)	A.D. 300
28	06/19/2009	1B(15)	ww7580	Lost	Charcoal	1,795 $\pm$ 25	-26.82	A.D. 132–260 (0.82); A.D. 284–323 (0.14)	A.D. 224

Table A.1. Results of laboratory analyses for radiocarbon samples.—Continued

[ID, identification number; ^{14}C yr BP, uncalibrated carbon-14 age in years before present (referenced to A.D. 1950) calculated using the Libby half-life of 5,568 years; $^{13}\text{C}/^{12}\text{C}$, ratio of carbon-13 to carbon-12; $\pm$, plus or minus; —, analysis could not be performed; “Modern” results indicate a post A.D. 1950 age and are not calibrated; calibrated age ranges and median ages calculated on the basis of Oxcal 4.1 (Bronk Ramsey and others, 2001; Bronk Ramsey, 2009) using IntCal09 calibration dataset (Reimer and others, 2009)]

ID	Sample date	Field sample number	Laboratory identification number	Site or alcove and pit (if applicable)	Material sampled	^{14}C yr BP ± 1 -sigma error	$^{13}\text{C}/^{12}\text{C}$	Calibrated 2-sigma age ranges (fraction of probability density function)	Median age
Downstream reach of Rapid Creek—Continued									
29	06/19/2009	1B(16)	ww7584	Lost	Charcoal	1,550 $\pm$ 25	-24.31	A.D. 430–566 (0.95)	A.D. 491
30	06/19/2009	1B(18)	ww7579	Lost	Charcoal	1,380 $\pm$ 25	-26.38	A.D. 612–674 (0.95)	A.D. 652
31	06/19/2009	1B(21)	ww7694	Lost	Charcoal	1,190 $\pm$ 30	-27.18	A.D. 720–742 (0.03); A.D. 769–898 (0.89); A.D. 921–944 (0.04)	A.D. 835
32	06/19/2009	1B(25)	ww7730	Lost	Charcoal	1,665 $\pm$ 30	—	A.D. 258–298 (0.08); A.D. 319–434 (0.86)	A.D. 383
33	06/19/2009	1B(3)	ww7585	Lost	Charcoal	2,175 $\pm$ 25	-24.71	360–272 B.C. (0.55); 262–166 B.C. (0.41)	295 B.C.
34	06/19/2009	1B(4)	ww7582	Lost	Charcoal	2,070 $\pm$ 25	-26.02	172–37 B.C. (0.92); 11–2 B.C. (0.02)	89 B.C.
35	06/19/2009	1B(6)	ww7701	Lost	Charcoal	2,065 $\pm$ 25	-24.86	169–36 B.C. (0.90); 31–19 B.C. (0.03); 12–1 B.C. (0.03)	84 B.C.
36	06/19/2009	1B(7)	ww7586	Lost	Charcoal	1,795 $\pm$ 30	-24.85	A.D. 131–262 (0.79); A.D. 280–326 (0.17)	A.D. 224
37	06/19/2009	1B(9)	ww7583	Lost	Charcoal	2,240 $\pm$ 25	-24.71	389–347 B.C. (0.27); 318–206 B.C. (0.67)	278 B.C.
38	05/29/2008	1(1)	ww7589	Meister	Charcoal from hearth	110 $\pm$ 30	-27.68	A.D. 1680–1763 (0.30); A.D. 1801–1938 (0.66)	A.D. 1836
39	08/15/2008	1(2)	ww7142	Meister	Charcoal	1,195 $\pm$ 35	-25	A.D. 708–748 (0.07); A.D. 766–898 (0.84); A.D. 920–947 (0.04)	A.D. 830
40	08/15/2008	1(3)	ww7379	Meister	Wood	160 $\pm$ 30	-27.54	A.D. 1664–1706 (0.17); A.D. 1720–1826 (0.48); A.D. 1832–1884 (0.13); A.D. 1914–1953 (0.18)	A.D. 1775
41	08/07/2008	2(1)	ww7078	Outhouse	Charcoal	895 $\pm$ 35	-26.11	A.D. 1039–1215 (0.95)	A.D. 1131
42	08/07/2008	2(2)	ww7079	Outhouse	Charcoal	1,820 $\pm$ 30	-23.85	A.D. 124–257 (0.92); A.D. 300–318 (0.02)	A.D. 189
43	08/7/2008	2(6)	ww7686	Outhouse	Wood	245 $\pm$ 25	-27.4	A.D. 1527–1552 (0.04); A.D. 1632–1673 (0.62); A.D. 1777–1800 (0.25); A.D. 1941–1954 (0.05)	A.D. 1659
44	08/13/2008	1(1)	ww7140	Spider	Wood	960 $\pm$ 35	-25.9	A.D. 1016–1160 (0.95)	A.D. 1095
45	08/13/2008	1(6)	ww7141	Spider	Charcoal	925 $\pm$ 30	-24.56	A.D. 1026–1180 (0.95)	A.D. 1103
Upstream reach of Rapid Creek									
46	07/22/2008	1(1)	ww7076 A	Blue Ribbon	Charcoal	795 $\pm$ 30	-22.65	A.D. 1185–1278 (0.95)	A.D. 1232
47	08/22/2008	1A(1)	ww7143	Gage House	Charcoal	1,185 $\pm$ 30	-25.88	A.D. 722–740 (0.02); A.D. 770–900 (0.88); A.D. 918–950 (0.06)	A.D. 839
48	08/22/2008	1A(3)	ww7144	Gage House	Organic detritus	Modern	-25	Modern	—
49	08/11/2008	1(3)	ww7139	Schist	Charcoal	1,070 $\pm$ 30	-25.93	A.D. 895–925 (0.21); A.D. 936–1021 (0.74)	A.D. 958
Upstream sub-reach of Boxelder Creek									
50	05/20/2008	1A(3)	ww7054	Asphalt Pit A	Charcoal	265 $\pm$ 30	-23.55	A.D. 1516–1595 (0.35); A.D. 1617–1670 (0.50); A.D. 1780–1799 (0.09)	A.D. 1642
51	05/20/2008	1B(1)	ww7053	Asphalt Pit B	Charcoal	190 $\pm$ 30	-24.88	A.D. 1648–1694 (0.22); A.D. 1726–1813 (0.54); A.D. 1918–1954 (0.20)	A.D. 1772
52	05/21/2008	2A(5)	ww7056	Benchmark	Wood	95 $\pm$ 40	-25	A.D. 1680–1764 (0.30); A.D. 1800–1939 (0.65)	A.D. 1836
53	05/21/2008	2A(7)	ww7057	Benchmark	Wood	85 $\pm$ 30	-25.26	A.D. 1688–1730 (0.26); A.D. 1808–1926 (0.70)	A.D. 1844
54	05/23/2008	1A(1)	ww7058	Enob	Charcoal	270 $\pm$ 30	-23.9	A.D. 1515–1598 (0.42); A.D. 1616–1669 (0.46); A.D. 1781–1798 (0.06)	A.D. 1633

Table A.1. Results of laboratory analyses for radiocarbon samples.—Continued

[ID, identification number; ¹⁴C yr BP, uncalibrated carbon-14 age in years before present (referenced to A.D. 1950) calculated using the Libby half-life of 5,568 years; ¹³C/¹²C, ratio of carbon-13 to carbon-12; ±, plus or minus; --, analysis could not be performed; "Modern" results indicate a post A.D. 1950 age and are not calibrated; calibrated age ranges and median ages calculated on the basis of Oxcal 4.1 (Bronk Ramsey and others, 2001; Bronk Ramsey, 2009) using IntCal09 calibration dataset (Reimer and others, 2009)]

ID	Sample date	Field sample number	Laboratory identification number	Site or alcove and pit (if applicable)	Material sampled	¹⁴ C yr BP ±1-sigma error	¹³ C/ ¹² C	Calibrated 2-sigma age ranges (fraction of probability density function)	Median age
Upstream sub-reach of Boxelder Creek—Continued									
55	05/23/2008	1A(3)	ww7693	Enob	Charcoal	140±30	-25.86	A.D. 1668–1780 (0.43); A.D. 1798–1891 (0.37)	A.D. 1808
56	08/01/2008	1B(10)	ww7064	Joan's	Wood	1,130±35	-26.4	A.D. 781–790 (0.02); A.D. 808–990 (0.94)	A.D. 923
57	08/01/2008	1B(2)	ww7703	Joan's	Charcoal	1015±30	-25	A.D. 972–1047 (0.86); A.D. 1090–1122 (0.07); A.D. 1139–1149 (0.02)	A.D. 1013
58	08/01/2008	1B(7)	ww7678	Joan's	Ponderosa pine bark	165±20	-25.51	A.D. 1666–1694 (0.17); A.D. 1726–1784 (0.47); A.D. 1795–1814 (0.11); A.D. 1917–1953 (0.19)	A.D. 1765
59	08/01/2008	1B(8)	ww7685	Joan's	Charcoal	275±25	-25.21	A.D. 1520–1592 (0.46); A.D. 1619–1666 (0.48); A.D. 1784–1794 (0.02)	A.D. 1625
60	05/21/2008	1A(4)	ww7696	Snap-E Tom	Charcoal	2,030±35	-25.19	161–132 B.C. (0.05); 116 B.C.–A.D. 54 (0.90)	33 B.C.
61	05/21/2008	1A(4)	ww7706	Snap-E Tom	Charcoal	2,280±25	-24.51	400–353 B.C. (0.64); 291–231 B.C. (0.32)	370 B.C.
62	05/21/2008	1A(6)	ww7055	Snap-E Tom	Charcoal	2,145±30	-23.56	355–290 B.C. (0.25); 232–88 B.C. (0.68); 76–57 B.C. (0.02)	187 B.C.
Downstream sub-reach of Boxelder Creek									
63	09/23/2008	2(1)	ww7076 B	Custer Gap	Charcoal	1,190±30	-22.65	A.D. 720–742 (0.03); A.D. 769–898 (0.89); A.D. 921–944 (0.04)	A.D. 835
64	09/23/2008	2(4)	ww7691	Custer Gap	Charcoal	1,240±25	-24.26	A.D. 686–870 (0.95)	A.D. 763
65	08/14/2008	1(2)	ww7066	2nd Story	Wood	740±35	-26.16	A.D. 1218–1296 (0.95)	A.D. 1268
66	08/14/2008	1(2)	ww7749B	2nd Story	Packrat scat	1,195±35	--	A.D. 708–748 (0.07); A.D. 766–898 (0.84); A.D. 920–947 (0.04)	A.D. 830
67	05/24/2008	1A(5)	ww7745	Kitty's Corner Pit A	Wood	925±30	--	A.D. 1026–1180 (0.95)	A.D. 1100
68	05/24/2008	1B(2)	ww7381	Kitty's Corner Pit B	Charcoal	1,560±30	-24.08	A.D. 424–564 (0.95)	A.D. 488
69	05/24/2008	1C(1)	ww7059	Kitty's Corner Pit C	Charcoal	1,795±30	-25.32	A.D. 131–262 (0.79); A.D. 280–326 (0.17)	A.D. 224
70	05/24/2008	1C(10)	ww7683	Kitty's Corner Pit C	Wood	665±25	-24.58	A.D. 1278–1317 (0.50); A.D. 1354–1390 (0.45)	A.D. 1314
71	05/24/2008	1C(12)	ww7061	Kitty's Corner Pit C	Wood	440±30	-25.3	A.D. 1416–1490 (0.94); A.D. 1602–1609 (0.02)	A.D. 1445
72	05/24/2008	1C(13)	ww7062	Kitty's Corner Pit C	Wood	315±25	-26.06	A.D. 1490–1603 (0.74); A.D. 1611–1645 (0.21)	A.D. 1563
73	05/24/2008	1C(2)	ww7680	Kitty's Corner Pit C	Charcoal	1,980±25	-24.11	40 B.C.–A.D. 70 (0.95)	A.D. 22
74	05/24/2008	1C(3)	ww7681	Kitty's Corner Pit C	Wood	1,250±30	-25	A.D. 676–870 (0.95)	A.D. 745
75	05/24/2008	1C(4)	ww7682	Kitty's Corner Pit C	Wood	920±25	-27.43	A.D. 1030–1173 (0.95)	A.D. 1099
76	05/24/2008	1C(7)	ww7060	Kitty's Corner Pit C	Wood	1,000±45	-25	A.D. 902–914 (0.02); A.D. 968–1158 (0.94)	A.D. 1035
77	05/24/2008	1C(9)	ww7734	Kitty's Corner Pit C	Wood	930±30	--	A.D. 1024–1169 (0.95)	A.D. 1098
78	06/22/2009	1C(1)	ww7744	Kitty's Corner Pit C	Pine needle	190±35	--	A.D. 1646–1696 (0.22); A.D. 1725–1814 (0.50); A.D. 1835–1878 (0.05); A.D. 1916–1954 (0.19)	A.D. 1772
79	06/22/2009	1C(6)	ww7591	Kitty's Corner Pit C	Charcoal	275±25	-24.18	A.D. 1520–1592 (0.46); A.D. 1619–1666 (0.48); A.D. 1784–1794 (0.02)	A.D. 1625
80	05/27/2008	2(1)	ww7063	Trail	Wood	1,325±35	-26.19	A.D. 648–728 (0.72); A.D. 736–772 (0.23)	A.D. 687
81	05/27/2008	2(2)	ww7677	Trail	Bark fragment	630±25	-27.58	A.D. 1288–1330 (0.39); A.D. 1340–1396 (0.57)	A.D. 1353
82	05/27/2008	2(4)	ww7378	Trail	Driftwood	870±30	-26.09	A.D. 1045–1095 (0.18); A.D. 1119–1142 (0.06); A.D. 1146–1227 (0.70); A.D. 1232–1252 (0.02)	A.D. 1176

Table A.1. Results of laboratory analyses for radiocarbon samples.—Continued

[ID, identification number; ¹⁴C yr BP, uncalibrated carbon-14 age in years before present (referenced to A.D. 1950) calculated using the Libby half-life of 5,568 years; ¹³C/¹²C, ratio of carbon-13 to carbon-12; ±, plus or minus; --, analysis could not be performed; “Modern” results indicate a post A.D. 1950 age and are not calibrated; calibrated age ranges and median ages calculated on the basis of Oxcal 4.1 (Bronk Ramsey and others, 2001; Bronk Ramsey, 2009) using IntCal09 calibration dataset (Reimer and others, 2009)]

ID	Sample date	Field sample number	Laboratory identification number	Site or alcove and pit (if applicable)	Material sampled	¹⁴ C yr BP ±1-sigma error	¹³ C/ ¹² C	Calibrated 2-sigma age ranges (fraction of probability density function)	Median age
Downstream sub-reach of Boxelder Creek—Continued									
83	06/22/2009	1(1)	ww7684	Trail	Charcoal	905±25	-25.49	A.D. 1039–1190 (0.92); A.D. 1196–1208 (0.03)	A.D. 1111
84	07/24/2008	1(1)	ww7065	Snow Shovel Pit A	Charcoal	1,970±25	-24.96	40 B.C.–A.D. 79 (0.95)	A.D. 32
85	07/24/2008	1(3)	ww7592	Snow Shovel Pit A	Charcoal	1,025±25	-26.37	A.D. 972–1036 (0.95)	A.D. 1007
86	07/24/2008	1(5)	ww7593	Snow Shovel Pit A	Wood	140±25	-25.74	A.D. 1669–1710 (0.16); A.D. 1716–1780 (0.27); A.D. 1797–1890 (0.37); A.D. 1909–1944 (0.16)	A.D. 1809
87	07/29/2008	1(3)	ww7398	Snow Shovel Pit B	Charcoal	2,525±30	-24.11	795–722 B.C. (0.30); 694–540 B.C. (0.66)	653 B.C.
Elk Creek study reach									
88	09/24/2008	2(1)	ww7073	Dracula's Ledge	Charcoal	970±30	-26.42	A.D. 1016–1155 (0.95)	A.D. 1090
89	09/24/2008	2(11)	ww7072	Dracula's Ledge	Charcoal	1,845±30	-24.94	A.D. 85–238 (0.95)	A.D. 171
90	09/24/2008	2(5)	ww7380	Dracula's Ledge	Charcoal	1,115±30	-24.53	A.D. 869–1014 (0.95)	A.D. 935
91	09/24/2008	2(7)	ww7700	Dracula's Ledge	Charcoal	1,725±30	-25	A.D. 242–393 (0.95)	A.D. 315
92	09/24/2008	2(9)	ww7692	Dracula's Ledge	Charcoal	1,870±25	-25.05	A.D. 76–222 (0.95)	A.D. 134
93	09/24/2008	3(1)	ww7074	Dracula's Ledge, beaver-chewed log	Driftwood	760±30	-24.84	A.D. 1220–1284 (0.95)	A.D. 1259
94	08/25/2008	2(1)	ww7699	Bird's Nest	Charcoal	4,475±30	-23.34	3339–3205 B.C. (0.54); 3196–3084 B.C. (0.34); 3064–3028 B.C. (0.07)	3222 B.C.
95	08/27/2008	2(3)	ww7733	Flat Rock	Charcoal	5,775±30	--	4706–4546 B.C. (0.95)	4630 B.C.
96	08/27/2008	2(4)	ww7710	Flat Rock	Charcoal	5,540±30	-24.4	4450–4341 B.C. (0.95)	4389 B.C.
97	08/27/2008	2(5)	ww7690	Flat Rock	Charcoal	38,180±1,080	-24.95	42616–39384 B.C. (0.95)	--
98	08/27/2008	2(6)	ww7679	Flat Rock	Charcoal	5,255±30	-24.8	4229–4200 B.C. (0.12); 4170–4126 B.C. (0.14); 4121–4090 B.C. (0.7); 4082–3980 B.C. (0.56)	4060 B.C.
99	09/24/2008	1(2)	ww7071	Sand Wall	Wood	90±25	-23.67	A.D. 1690–1730 (0.25); A.D. 1810–1925 (0.70)	A.D. 1843

Table A.2. Results of laboratory analyses for optically stimulated luminescence (OSL) samples.

[K, potassium content, in percent; U, uranium concentration; ppm, parts per million; Th, thorium concentration; Gy/ka, Grays per thousand years; Gy, (Grays) the absorption of 1 joule of ionizing radiation by 1 kilogram of matter; $\pm$, plus or minus]

Sample information	Water content ¹ (percent)	² K (percent)	U (ppm) ²	Th (ppm) ²	Cosmic dose ³ additions (Gy/ka)	Total dose additions (Gy/ka)	Equivalent dose (Gy)	Number ⁴	Age (years) ⁵	Calendar year ⁵
9/17/08-OSL-1(3); High Alcove, Rapid Creek	8 (20)	2.14 $\pm$ 0.12	3.36 $\pm$ 0.17	12.7 $\pm$ 0.32	0.32 $\pm$ 0.02	4.23 $\pm$ 0.08	2.73 $\pm$ 0.06; 1.87 $\pm$ 0.09	14 (15); 1 (15)	645 $\pm$ 20; 440$\pm$25	A.D. 1545–1595
5/29/08-OSL-1; Meister Brau, 1972 flood, Spring Creek	17 (46)	1.73 $\pm$ 0.02	3.04 $\pm$ 0.13	7.82 $\pm$ 0.30	0.31 $\pm$ 0.02	3.23 $\pm$ 0.07	1.06 $\pm$ 0.01; 0.61 $\pm$ 0.03	14 (15); 1 (15)	330 $\pm$ 10; 190$\pm$20	A.D. 1800–1840
5/28/08-OSL-1; Hailstorm Alcove, Spring Creek	22 (42)	2.10 $\pm$ 0.06	2.80 $\pm$ 0.05	13.7 $\pm$ 0.08	0.25 $\pm$ 0.01	3.93 $\pm$ 0.08	15.8 $\pm$ 5.53; 10.9 $\pm$ 0.93	23 (25); 8 (25)	4,015 $\pm$ 1,005; 2,765$\pm$255	1010–500 B.C.
5/28/08-OSL-3; Superscour Alcove, Spring Creek	35 (41)	1.79 $\pm$ 0.02	3.04 $\pm$ 0.13	7.82 $\pm$ 0.30	0.27 $\pm$ 0.02	3.49 $\pm$ 0.21	1.26 $\pm$ 0.03; 0.73 $\pm$ 0.04	10 (15); 1 (15)	360 $\pm$ 25; 210$\pm$15	A.D. 1785–1815
5/27/08-OSL-2; Kitty's Corner, Pit C, Boxelder Creek	3 (30)	1.37 $\pm$ 0.07	2.43 $\pm$ 0.11	6.06 $\pm$ 0.27	0.30 $\pm$ 0.02	2.90 $\pm$ 0.13	4.31 $\pm$ 0.06; 2.94 $\pm$ 0.09	28 (30); 4 (30)	1,485 $\pm$ 70; 1,015$\pm$50	A.D. 945–1045
5/27/08-OSL-3; Kitty's Corner, Pit C, Boxelder Creek	2 (31)	1.55 $\pm$ 0.10	3.26 $\pm$ 0.44	4.26 $\pm$ 0.54	0.30 $\pm$ 0.02	3.01 $\pm$ 0.18	2.17 $\pm$ 0.37; 1.30 $\pm$ 0.10	16 (18); 3 (18)	720 $\pm$ 140; 435$\pm$60	A.D. 1515–1635
5/27/08-OSL-8; Kitty's Corner, Pit B, Boxelder Creek	6 (59)	1.44 $\pm$ 0.02	3.09 $\pm$ 0.24	8.10 $\pm$ 0.72	0.25 $\pm$ 0.01	2.78 $\pm$ 0.13	1.12 $\pm$ 0.02; 0.71 $\pm$ 0.02	24 (35); 3 (35)	400 $\pm$ 20; 255$\pm$15	A.D. 1740–1770
5/27/08-OSL-5; Kitty's Corner, Pit A, Boxelder Creek	3 (33)	1.63 $\pm$ 0.03	3.42 $\pm$ 0.25	8.26 $\pm$ 0.45	0.24 $\pm$ 0.01	3.27 $\pm$ 0.11	3.67 $\pm$ 1.03; 2.02 $\pm$ 0.21	22 (24); 18 (24)	1,120 $\pm$ 340; 620$\pm$80	A.D. 1310–1470
5/27/08-OSL-6; Kitty's Corner, Pit A, Boxelder Creek	12 (46)	1.59 $\pm$ 0.02	3.39 $\pm$ 0.26	9.28 $\pm$ 0.44	0.29 $\pm$ 0.02	3.26 $\pm$ 0.10	1.10 $\pm$ 0.28; 0.79 $\pm$ 0.10	17 (20); 7 (20)	335 $\pm$ 70; 245$\pm$35	A.D. 1730–1800

¹Field moisture, with numbers in parentheses indicating the complete sample saturation percent. Ages calculated using approximately 10 percent of saturation values.

²Analyses obtained using laboratory Gamma Spectrometry (low resolution sodium iodide detector).

³Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).

⁴Number of replicated equivalent dose estimates used to calculate the mean. Figures in parentheses indicate total number of measurements made including failed runs with unusable data. Second set of numbers indicates only those equivalent doses that fit into the lowest 10 to 15 percent of equivalent doses. If the data showed large positive skew, those doses were eliminated because of partial bleaching contamination.

⁵Age for fine-grained (90- to 250-micrometer) quartz sand. Linear plus exponential fit used on age, with errors to one standard deviation (very young samples only have linear fit). Age in **bold font** is age used for flood unit.

Table A.3. Results of laboratory analyses for cesium-137 samples.

[dpm/g, disintegrations per minute per gram; ±, plus or minus; <, less than; ND, not detected; --, not applicable]

Sample identification number	Depth, in inches, below top of unit	Sample weight (grams)	Cesium-137 (dpm/g)		Lead-210 (dpm/g)		Radium-226 (dpm/g)		Potassium-40	
			Activity	Error (±)	Activity	Error (±)	Activity	Error (±)	Activity	Error (±)
Trail Alcove Cs-6-22-09-2(1)	<0.5 below surface	50.00	0.44	0.04	2.28	0.18	1.63	0.06	28.09	1.17
Trail Alcove Cs-6-22-09-2(2)	<1.0 below top of intermediate unit	50.00	ND	--	1.36	.14	1.18	.05	8.46	.69
Kitty's Corner Pit A Cs-6-22-09-1(2)	4.7 below surface	50.00	.06	.03	1.50	.16	1.56	.05	27.28	1.11
Kitty's Corner Pit A Cs-6-22-09-1(3)	9.5 below surface	50.00	ND	--	1.47	.16	1.56	.05	27.78	1.04
Kitty's Corner Pit A Cs-6-22-09-1(4)	16 below surface	50.00	ND	--	1.80	.15	1.49	.06	24.10	.91
Kitty's Corner Pit A Cs-6-22-09-1(5)	21 below surface	50.00	ND	--	1.56	.17	1.56	.06	27.98	1.24
Kitty's Corner Pit C Cs-Sample-2	2.8–3.9 below surface of unit II	50.00	ND	--	1.97	.15	1.67	.05	28.27	1.01
Kitty's Corner Pit C Cs-Sample-4	0.2 below surface of unit I	50.00	.40	.04	2.32	.17	1.88	.08	33.26	1.18
Kitty's Corner Pit C Cs-Sample-5	3.2–4.7 below surface	50.00	.66	.06	2.36	.25	1.70	.08	29.54	1.53
Kitty's Corner Pit C Cs-Sample-6	5.5–7.9 below surface	50.00	.92	.06	2.62	.20	1.72	.07	28.81	1.32

Appendix B – Modern Peak-Flow Chronologies

Details regarding development of modern peak-flow chronologies are presented within this section. Peak-flow records (including historical information) that were used in developing the chronologies are presented in tables B.4 through B.8.

Spring Creek

A modern peak-flow chronology (Table 2 and B.4) was developed for the center of the Spring Creek study reach, which has a drainage area of 171 mi², relative to areas of 170 and 172 mi² at the upstream and downstream extents of the reach. This chronology includes 67 annual peak-flow values from five USGS streamgages (Figure 1, Table B.4), the earliest of which was from 1904.

Streamgage 06407500 is nearest the study reach and is most representative, from the standpoint of peak-flow potential. Peak-flow records for this streamgage are relatively short (Table S4), but were extended to include 1950–2009, based primarily on least-squares regression analysis (Helsel and Hirsch, 1992) using concurrent records for 1987–2004 with downstream streamgage 06408500 (annual peak flow for streamgage 06407500, in cubic feet per second = $27.6 + 1.002$ times annual peak flow for streamgage 06408500, in cubic feet per second; correlation coefficient = 0.85). Regression analysis was used because area-weighted adjustments resulted in unrealistically small values for the upstream streamgage, for cases with small downstream values, which owes to large streamflow losses that occur between the two streamgages (Hortness and Driscoll, 1998). The 1996 values (642 and 6,910 ft³/s for streamgages 06407500 and 06408500, respectively)

were excluded from the regression analysis because of the large differential between the values. The chronology for the center of the study reach for this period was then developed by applying drainage-area adjustments to the extended record, with two exceptions. The 1972 value is based entirely on an un-adjusted flow of 21,800 ft³/s reported by Schwarz and others (1975) for streamgage 06408000. The 1996 value of 1,000 ft³/s was arbitrarily selected as an appropriate value based on detailed knowledge of the storm pattern and radar imagery, as described by Driscoll and others (2010). The modern chronology was further extended using drainage-area adjustments to include 1938–40 (based on annual peak flows for streamgage 06407000) and 1946–47 and 1904–05 (based on annual peak flows for streamgage 06408000).

Table B.4. Selected information used in development of modern peak-flow chronology for the Spring Creek study reach.

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06407000		435915103241200		06407500		06407500		Extended record for Spring Creek near Keystone		Modern peak-flow chronology for Spring Creek study reach		06408000		06408500	
	Spring Creek near Hill City, S.Dak.		Spring Creek below Bitter Creek, S.Dak.		Spring Creek near Keystone, S.Dak.		Spring Creek near Keystone, S.Dak.		Area = 163		Area = 163		Spring Creek near Rapid City, S.Dak.		Spring Creek near Hermosa, S.Dak.	
	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q
1904	--	--	--	--	--	--	--	--	--	--	--	493	07/13/1904	500	--	--
1905	--	--	--	--	--	--	--	--	--	--	--	641	08/01/1905	650	--	--
1938	04/16/1938	500	--	--	--	--	--	--	--	--	--	539	--	--	--	--
1939	08/26/1939	592	--	--	--	--	--	--	--	--	--	638	--	--	--	--
1940	06/22/1940	241	--	--	--	--	--	--	--	--	--	260	--	--	--	--
1946	--	--	--	--	05/03/1946	246	05/03/1946	246	--	--	--	346	06/18/1946	351	--	--
1947	--	--	--	--	06/23/1947	865	06/23/1947	865	--	--	--	690	06/23/1947	700	--	--
1950	--	--	--	--	--	--	--	--	--	--	--	100	--	--	08/12/1950	69
1951	--	--	--	--	--	--	--	--	--	--	--	30	--	--	06/19/1951	2.0
1952	--	--	--	--	--	--	--	--	--	--	--	627	--	--	05/23/1952	580
1953	--	--	--	--	--	--	--	--	--	--	--	240	--	--	06/19/1953	205
1954	--	--	--	--	--	--	--	--	--	--	--	418	--	--	08/12/1954	378
1955	--	--	--	--	--	--	--	--	--	--	--	29	--	--	03/30/1955	1.0
1956	--	--	--	--	--	--	--	--	--	--	--	33	--	--	07/03/1956	4.0
1957	--	--	--	--	--	--	--	--	--	--	--	340	--	--	05/25/1957	302
1958	--	--	--	--	--	--	--	--	--	--	--	33	--	--	06/13/1958	4.0
1959	--	--	--	--	--	--	--	--	--	--	--	30	--	--	05/30/1959	2.0
1960	--	--	--	--	--	--	--	--	--	--	--	33	--	--	03/19/1960	4.0
1961	--	--	--	--	--	--	--	--	--	--	--	29	--	--	07/08/1961	1.0
1962	--	--	--	--	--	--	--	--	--	--	--	544	--	--	07/13/1962	500
1963	--	--	--	--	--	--	--	--	--	--	--	389	--	--	06/15/1963	350
1964	--	--	--	--	--	--	--	--	--	--	--	88	--	--	06/20/1964	58
1965	--	--	--	--	--	--	--	--	--	--	--	390	--	--	06/19/1965	351
1966	--	--	--	--	--	--	--	--	--	--	--	54	--	--	08/19/1966	25
1967	--	--	--	--	--	--	--	--	--	--	--	825	--	--	06/07/1967	772

Table B.4. Selected information used in development of modern peak-flow chronology for the Spring Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06407000		435915103241200		06407500		06407500		06407500		Modern peak-flow chronology for Spring Creek study reach		06408000		06408500	
	Spring Creek near Hill City, S.Dak.		Spring Creek below Bitter Creek, S.Dak.		Spring Creek near Keystone, S.Dak.		Spring Creek near Keystone		Extended record for Spring Creek near Keystone		Area = 163		Spring Creek near Rapid City, S.Dak.		Spring Creek near Hermosa, S.Dak.	
	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q
	Area = 151		Area = 157		Area = 163		Area = 163		Area = 163		Area = 171		Area = 175		Area = 206	
1968	--	--	--	--	--	--	--	48	--	--	--	49	--	--	06/25/1968	20
1969	--	--	--	--	--	--	--	386	--	--	--	398	--	--	07/16/1969	358
1970	--	--	--	--	--	--	--	33	--	--	--	34	--	--	06/13/1970	5.0
1971	--	--	--	--	--	--	--	379	--	--	--	390	--	--	06/02/1971	351
1972	--	--	06/09/1972	14,900	--	--	06/10/1972	E20,000	06/10/1972	21,800	06/10/1972	21,800	06/10/1972	21,800	06/10/1972	13,400
1973	--	--	--	--	--	--	--	124	--	--	--	127	--	--	05/10/1973	96
1974	--	--	--	--	--	--	--	32	--	--	--	33	--	--	08/14/1974	4.0
1975	--	--	--	--	--	--	--	42	--	--	--	43	--	--	06/19/1975	14
1976	--	--	--	--	--	--	--	389	--	--	--	401	--	--	06/16/1976	361
1977	--	--	--	--	--	--	--	368	--	--	--	379	--	--	06/12/1977	340
1978	--	--	--	--	--	--	--	198	--	--	--	204	--	--	05/20/1978	170
1979	--	--	--	--	--	--	--	33	--	--	--	34	--	--	11/16/1978	5.0
1980	--	--	--	--	--	--	--	406	--	--	--	418	--	--	06/14/1980	378
1981	--	--	--	--	--	--	--	31	--	--	--	31	--	--	05/17/1981	2.9
1982	--	--	--	--	--	--	--	383	--	--	--	394	--	--	07/25/1982	355
1983	--	--	--	--	--	--	--	217	--	--	--	223	--	--	05/07/1983	189
1984	--	--	--	--	--	--	--	275	--	--	--	283	--	--	06/15/1984	247
1985	--	--	--	--	--	--	--	42	--	--	--	43	--	--	03/20/1985	14
1986	--	--	--	--	--	--	--	41	--	--	--	42	--	--	04/26/1986	13
1987	--	--	--	--	04/29/1987	120	04/29/1987	120	--	--	--	123	--	--	03/06/1987	17
1988	--	--	--	--	03/29/1988	24	03/29/1988	24	--	--	--	25	--	--	03/21/1988	53
1989	--	--	--	--	05/20/1989	31	05/20/1989	31	--	--	--	32	--	--	03/27/1989	.35
1990	--	--	--	--	06/02/1990	93	06/02/1990	93	--	--	--	96	--	--	--/1990	.00
1991	--	--	--	--	06/07/1991	291	06/07/1991	291	--	--	--	299	--	--	06/08/1991	373
1992	--	--	--	--	06/28/1992	31	06/28/1992	31	--	--	--	32	--	--	11/10/1991	2.4
1993	--	--	--	--	06/08/1993	286	06/08/1993	286	--	--	--	294	--	--	08/06/1993	366
1994	--	--	--	--	05/16/1994	64	05/16/1994	64	--	--	--	66	--	--	03/01/1994	100
1995	--	--	--	--	05/09/1995	913	05/09/1995	913	--	--	--	940	--	--	07/18/1995	540

Table B.4. Selected information used in development of modern peak-flow chronology for the Spring Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06407000		435915103241200		06407500		06407500		Modern peak-flow chronology for Spring Creek study reach		06408000		06408500	
	Spring Creek near Hill City, S.Dak.		Spring Creek below Bitter Creek, S.Dak.		Spring Creek near Keystone, S.Dak.		Extended record for Spring Creek near Keystone		Creek study reach		Spring Creek near Rapid City, S.Dak.		Spring Creek near Hermosa, S.Dak.	
	Area = 151		Area = 157		Area = 163		Area = 163		Area = 171		Area = 175		Area = 206	
	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q
1996	--	--	--	--	05/30/1996	642	05/30/1996	642	--	1,000	--	--	05/30/1996	6,910
1997	--	--	--	--	06/03/1997	516	06/03/1997	516	--	531	--	--	06/03/1997	512
1998	--	--	--	--	06/20/1998	306	06/20/1998	306	--	315	--	--	06/20/1998	292
1999	--	--	--	--	06/19/1999	306	06/19/1999	306	--	315	--	--	06/20/1999	457
2000	--	--	--	--	04/25/2000	106	04/25/2000	106	--	109	--	--	04/24/2000	59
2001	--	--	--	--	07/14/2001	66	07/14/2001	66	--	68	--	--	11/01/2000	5.8
2002	--	--	--	--	04/08/2002	31	04/08/2002	31	--	32	--	--	05/11/2002	5.5
2003	--	--	--	--	05/10/2003	62	05/10/2003	62	--	64	--	--	10/22/2002	1.3
2004	--	--	--	--	03/11/2004	14	03/11/2004	14	--	14	--	--	01/10/2004	2.5
2005	--	--	--	--	05/13/2005	27	05/13/2005	27	--	28	--	--	--	--
2006	--	--	--	--	03/30/2006	23	03/30/2006	23	--	24	--	--	--	--
2007	--	--	--	--	05/07/2007	34	05/07/2007	34	--	35	--	--	--	--
2008	--	--	--	--	05/24/2008	170	05/24/2008	170	--	175	--	--	--	--
2009	--	--	--	--	05/13/2009	69	05/13/2009	69	--	71	--	--	--	--

Rapid Creek

The reach of Rapid Creek downstream from Pactola Dam (Figure 1) is of primary interest for the paleoflood investigations because of its proximity to urban populations. However, the available paleoflood chronology pre-dates regulation from Pactola Dam; thus, detailed investigations also were conducted in a reach upstream from Pactola Reservoir to extract comparable paleoflood information.

The modern peak-flow chronology for the downstream (lower) reach of Rapid Creek (Tables 2 and B.5) was developed to estimate pre-regulation conditions for streamgage 06412500, which has a drainage area of 375 mi², relative to areas of 367 and 384 mi² at the upstream and downstream extents of the study reach. The drainage-area differential between the gage location and the upstream extent of the reach is about 2 percent and is considered inconsequential. About 321 mi² of the area has been regulated by Pactola Dam since August 1956, and about 92.4 mi² of the area has been regulated by Deerfield Dam since December 1945 (Miller and Driscoll, 1998). The modern chronology dates back to 1878 and includes area-adjusted values that are based on historical peak-flow values for 1878, 1883, 1907, and 1920 that were provided by the U.S. Army Corps of Engineers (1973) for the location of streamgage 06414000. The modern chronology also includes area-adjusted values based on annual peak flows for 1905–06 and 1943–46 from streamgage 06414000. The modern chronology was further extended using drainage-area adjustments to include 1915–17 (based on annual peak flows from streamgage 064112000) and 1929–42 (based on annual peak flows from streamgage 06411500). All of these

drainage-area adjustments are for periods pre-dating construction of both dams; thus, unregulated areas were used. No adjustments were performed for 1947–55, which precedes construction of Pactola Dam; minor effects of storage in Deerfield Reservoir were considered inconsequential. Adjustments for 1956–2009 to account for effects of storage in Pactola Reservoir were made after scrutinizing individual annual and daily peak-flow records for (1) streamgages 06410500 and 06411500 to evaluate storage effects and (2) streamgages 06411500 and 06412500 to evaluate inflows downstream from Pactola Dam. Most adjustments were then made by adjusting annual peak-flow values for streamgage 06410500, relative to the unregulated area for streamgage 06412500 (multiplying by $375/295$ raised to the 0.6 power); however, adjustments for shaded cells in table S5 were made through consideration of daily flow values for streamgages 06410500 and 06411500. The largest of all adjustments was an increase of about $1,770 \text{ ft}^3/\text{s}$, relative to the recorded annual peak flow of $614 \text{ ft}^3/\text{s}$ for 1965.

Driscoll and others (2010) concluded from detailed examination of historical flood accounts that (1) the effects of storage in Pactola and Deerfield Reservoirs have essentially been inconsequential relative to large-scale flow events, and (2) with the exception of 1972 flooding, flows approaching the magnitudes of the historical peak-flow values (1878, 1883, 1907, and 1920) would not have occurred along lower Rapid Creek since 1920, regardless of storage effects. Driscoll and others (2010) further concluded that no exceptionally large flows have occurred in the reach of Rapid Creek upstream from Pactola Reservoir since 1929. The largest known peak-flow event in this upstream reach

of Rapid Creek was in 1955, when a flow of 8,500 ft³/s occurred along Castle Creek, upstream from Rapid Creek (Wells, 1962). This flow attenuated quickly in moving downstream, and resulted in a peak flow of only 1,520 ft³/s (table S6) at streamgage 06410500 (above Pactola Reservoir).

Table 2 includes a modern chronology for the reach of Rapid Creek upstream from Pactola Reservoir at the location of streamgage 06410500, which has a drainage area of 294 mi², relative to areas of 290 and 294 mi² at the upstream and downstream extents of the reach. The drainage-area differential is considered inconsequential and no adjustments were made for the upstream extent of the reach. The modern chronology for streamgage 06410500 was extended to include 1929–42 and 1947–51 and 1953 using drainage-area adjustments based on annual peak flows from streamgage 06411500, for which the gaged records pre-date construction of Pactola Dam (Table B.6). The 1952 flow was substantially affected by storage in Deerfield Reservoir, so the 1952 adjustment was based on the annual peak flow from streamgage 06409000, which is located upstream from Deerfield Reservoir. The estimated value for 1952 is slightly larger than the largest recorded flow for streamgage 06410500 (2,060 in 1965) but is consistent with large flows along Rapid Creek, as described by Driscoll and others (2010). Flow adjustments were not made for other years because adjustments would require considerable speculation, and effects of storage were inconsequential relative to large-scale flow events. The extended chronology for streamgage 06410500 also includes pre-regulation values for 1915–17 that were based on drainage-area adjustments for annual peak flows from streamgage

06412000. Extension of the chronology to include the large historical values for streamgage 06414000 (1878, 1883, 1907, and 1920) was considered inappropriate and was not performed.

Table B.5. Selected information used in development of modern peak-flow chronology for the lower Rapid Creek study reach.

[Gray-shaded rows signify a gap in the chronology. (H) indicates historical value obtained from U.S. Army Corps of Engineers (1973). **Bold font** indicates special computations for lower Rapid Creek as noted in text. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

	06410500	06411500	06412000	06412500	06412500	06412500	06414000
	Rapid Creek above Pactola Reservoir at Silver City, S.Dak.	Rapid Creek below Pactola Dam, S.Dak.	Rapid Creek at Big Bend near Rapid City, S.Dak.	Rapid Creek above Canyon Lake near Rapid City, S.Dak.	Rapid Creek above Canyon Lake— extended record	Rapid Creek above Canyon Lake— extended record adjusted for regulation effects (modern chronology)	Rapid Creek at Rapid City, S.Dak.
Water year	Area = 294	Area = 322	Area = 339	Area = 375	Area = 375	Area = 375	Area = 414
	Q	Date	Q	Date	Q	Date	Q
1878	--	--	--	--	7,060	--	7,060
1883	--	--	--	--	7,900	--	7,900
1905	--	--	--	--	2,350	--	2,350
1906	--	--	--	--	922	--	922
1907	--	--	--	--	12,200	--	12,200
1915	--	--	06/26/1915	616	--	--	654
1916	--	--	05/24/1916	204	--	--	217
1917	--	--	06/04/1917	270	--	--	287
1920	--	--	--	--	7,540	--	7,540
1929	--	06/03/1929	794	--	--	--	870
1930	--	04/09/1930	194	--	--	--	213
1931	--	04/08/1931	155	--	--	--	170
1932	--	04/24/1932	682	04/24/1932	694	--	747
1933	--	05/24/1933	1,540	05/24/1933	1,570	--	1,690
1934	--	02/11/1934	117	02/11/1934	119	--	128
1935	--	06/01/1935	437	05/01/1935	446	--	479
1936	--	04/13/1936	100	04/13/1936	102	--	110
1937	--	07/12/1937	84	07/12/1937	86	--	92
1938	--	04/16/1938	86	04/16/1938	88	--	94
1939	--	04/24/1939	62	04/24/1939	63	--	68

Table B.5. Selected information used in development of modern peak-flow chronology for the lower Rapid Creek study reach. —Continued

[Gray-shaded rows signify a gap in the chronology. (H) indicates historical value obtained from U.S. Army Corps of Engineers (1973). **Bold font** indicates special computations for lower Rapid Creek as noted in text. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06410500			06411500			06412000			06412500			06412500			06414000		
	Rapid Creek above Pactola Reservoir at Silver City, S.Dak.			Rapid Creek below Pactola Dam, S.Dak.			Rapid Creek at Big Bend near Rapid City, S.Dak.			Rapid Creek above Canyon Lake near Rapid City, S.Dak.			Rapid Creek above Canyon Lake— extended record adjusted for regulation effects (modern chronology)			Rapid Creek at Rapid City, S.Dak.		
	Area = 294			Area = 322			Area = 339			Area = 375			Area = 375			Area = 414		
Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		
1940	--	--	08/27/1940	245		08/27/1940	250		--	--	--	268	--	268	--	--	--	
1941	--	--	06/11/1941	540		06/11/1941	552		--	--	--	592	--	592	--	--	--	
1942	--	--	05/16/1942	409		05/16/1942	417		--	--	--	448	--	448	--	--	--	
1943	--	--	--	--		--	--		--	--	--	882	--	882	06/13/1943	936		
1944	--	--	--	--		--	--		--	--	--	254	--	254	06/12/1944	270		
1945	--	--	--	--		--	--		--	--	--	359	--	359	08/01/1945	381		
1946	--	--	--	--		--	--		--	--	--	942	--	943	07/18/1946	1,000		
1947	--	--	06/23/1947	954		--	--		06/23/1947	950		06/23/1947	950	06/23/1947	950	06/24/1947	1,170	
1948	--	--	06/22/1948	248		--	--		06/22/1948	245		06/22/1948	245	06/22/1948	245	08/13/1948	472	
1949	--	--	06/02/1949	233		--	--		08/15/1949	290		08/15/1949	290	08/15/1949	290	08/15/1949	563	
1950	--	--	04/15/1950	233		--	--		04/15/1950	209		04/15/1950	209	04/15/1950	209	04/16/1950	246	
1951	--	--	06/14/1951	97		--	--		06/15/1951	77		06/15/1951	77	06/15/1951	77	10/09/1950	143	
1952	--	--	05/22/1952	2,170		--	--		05/23/1952	2,600		05/23/1952	2,600	05/23/1952	2,600	05/23/1952	2,540	
1953	--	--	06/15/1953	160		--	--		06/16/1953	152		06/16/1953	152	06/16/1953	152	06/19/1953	824	
1954	05/23/1954	106	05/23/1954	94		--	--		08/12/1954	140		08/12/1954	140	08/12/1954	140	06/10/1954	172	
1955	07/28/1955	1,520	07/29/1955	378		--	--		07/29/1955	326		07/29/1955	326	07/29/1955	326	08/10/1955	878	
1956	03/24/1956	175	03/25/1956	178		--	--		05/29/1956	130		05/29/1956	130	--	203	10/15/1955	182	
1957	05/25/1957	181	03/14/1957	55		--	--		07/14/1957	433		07/14/1957	433	--	595	07/14/1957	784	
1958	05/31/1958	113	06/02/1958	84		--	--		05/30/1958	81		05/30/1958	81	--	131	07/19/1958	362	
1959	09/25/1959	146	08/21/1959	90		--	--		06/30/1959	82		06/30/1959	82	--	169	12/11/1958	141	
1960	03/23/1960	117	07/20/1960	112		--	--		07/16/1960	82		07/16/1960	82	--	135	06/20/1960	290	
1961	07/07/1961	96	06/11/1961	111		--	--		07/01/1961	100		07/01/1961	100	--	111	06/14/1961	115	
1962	06/15/1962	390	05/18/1962	67		--	--		07/13/1962	1,310		07/13/1962	1,310	--	1,700	07/13/1962	3,300	
1963	06/16/1963	715	06/30/1963	184		--	--		06/06/1963	191		06/06/1963	191	--	827	06/05/1963	418	
1964	06/09/1964	635	06/10/1964	266		--	--		06/11/1964	268		06/11/1964	268	--	735	06/13/1964	426	

Table B.5. Selected information used in development of modern peak-flow chronology for the lower Rapid Creek study reach. —Continued

[Gray-shaded rows signify a gap in the chronology. (H) indicates historical value obtained from U.S. Army Corps of Engineers (1973). **Bold font** indicates special computations for lower Rapid Creek as noted in text. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06410500			06411500			06412000			06412500			06412500			06414000		
	Rapid Creek above Pactola Reservoir at Silver City, S.Dak.			Rapid Creek below Pactola Dam, S.Dak.			Rapid Creek at Big Bend near Rapid City, S.Dak.			Rapid Creek above Canyon Lake near Rapid City, S.Dak.			Rapid Creek above Canyon Lake—extended record adjusted for regulation effects (modern chronology)			Rapid Creek at Rapid City, S.Dak.		
	Area = 294			Area = 322			Area = 339			Area = 375			Area = 375			Area = 414		
	Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q	
1965	05/15/1965	2,060		05/19/1965	547		--	--		05/19/1965	614		--	2,380		06/11/1965	706	
1966	03/16/1966	150		03/20/1966	147		--	--		03/22/1966	140		--	174		07/26/1966	586	
1967	06/16/1967	627		06/22/1967	406		--	--		06/15/1967	439		--	726		06/15/1967	616	
1968	06/09/1968	106		10/04/1967	311		--	--		10/04/1967	198		--	123		06/09/1968	259	
1969	07/20/1969	213		05/20/1969	306		--	--		05/20/1969	139		--	246		07/23/1969	195	
1970	04/19/1970	995		05/12/1970	304		--	--		06/14/1970	245		--	1,150		06/12/1970	350	
1971	04/25/1971	305		04/25/1971	338		--	--		04/26/1971	385		--	353		04/26/1971	498	
1972	07/06/1972	252		10/05/1971	505		--	--		06/09/1972	31,200		06/09/1972	31,200		06/09/1972	50,000	
1973	05/09/1973	169		05/08/1973	168		--	--		05/09/1973	173		--	196		07/08/1973	282	
1974	04/30/1974	54		07/04/1974	113		--	--		08/22/1974	516		--	476		08/22/1974	1,040	
1975	04/26/1975	219		06/07/1975	85		--	--		06/07/1975	92		--	253		06/07/1975	1,500	
1976	06/15/1976	614		06/29/1976	234		--	--		06/15/1976	636		--	1,220		06/14/1976	1,400	
1977	04/25/1977	187		05/05/1977	188		--	--		05/08/1977	194		--	216		04/18/1977	209	
1978	05/11/1978	430		06/01/1978	386		--	--		05/21/1978	433		--	498		05/29/1978	602	
1979	07/23/1979	173		06/16/1979	101		--	--		06/17/1979	150		--	200		08/07/1979	451	
1980	05/11/1980	75		07/15/1980	118		--	--		07/16/1980	119		--	87		06/15/1980	265	
1981	07/26/1981	83		05/02/1981	142		--	--		07/13/1981	132		--	96		07/25/1981	409	
1982	05/20/1982	332		07/03/1982	139		--	--		07/22/1982	264		--	384		07/25/1982	2,000	
1983	05/09/1983	262		05/13/1983	268		--	--		05/11/1983	283		--	303		08/22/1983	411	
1984	08/03/1984	198		05/12/1984	222		--	--		06/15/1984	249		--	229		06/15/1984	414	
1985	04/01/1985	75		05/10/1985	144		--	--		07/15/1985	134		--	87		08/19/1985	300	
1986	05/09/1986	123		06/03/1986	93		--	--		06/04/1986	89		--	142		08/12/1986	919	
1987	04/09/1987	99		07/31/1987	99		--	--		05/29/1987	99		--	115		06/10/1987	388	
1988	05/20/1988	69		08/01/1988	128		--	--		08/03/1988	126		--	80		06/22/1988	201	
1989	03/21/1989	55		07/12/1989	130		--	--		07/12/1989	111		--	64		08/24/1989	1,360	

Table B.5. Selected information used in development of modern peak-flow chronology for the lower Rapid Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. (H) indicates historical value obtained from U.S. Army Corps of Engineers (1973). **Bold font** indicates special computations for lower Rapid Creek as noted in text. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06410500		06411500		06412000		06412500		06412500		06414000	
	Rapid Creek above Pactola Reservoir at Silver City, S.Dak.		Rapid Creek below Pactola Dam, S.Dak.		Rapid Creek at Big Bend near Rapid City, S.Dak.		Rapid Creek above Canyon Lake near Rapid City, S.Dak.		Rapid Creek above Canyon Lake—extended record adjusted for regulation effects (modern chronology)		Rapid Creek at Rapid City, S.Dak.	
	Area = 294		Area = 322		Area = 339		Area = 375		Area = 375		Area = 414	
	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q
1990	04/26/1990	93	07/02/1990	122	—	—	07/07/1990	124	—	108	08/28/1990	231
1991	06/07/1991	421	08/29/1991	78	—	—	05/11/1991	201	—	487	05/11/1991	659
1992	07/13/1992	55	05/21/1992	106	—	—	05/21/1992	105	—	64	05/21/1992	152
1993	05/10/1993	867	06/19/1993	286	—	—	06/20/1993	328	—	1,000	07/21/1993	500
1994	05/06/1994	196	04/27/1994	195	—	—	04/29/1994	198	—	227	05/03/1994	670
1995	05/10/1995	879	05/15/1995	393	—	—	06/09/1995	479	—	1,020	07/18/1995	786
1996	05/31/1996	711	06/07/1996	450	—	—	06/01/1996	652	—	823	05/27/1996	880
1997	05/07/1997	524	06/11/1997	426	—	—	06/02/1997	1,050	—	1,090	06/02/1997	3,190
1998	06/18/1998	1,290	07/02/1998	443	07/02/1998	481	06/24/1998	503	—	1,490	09/13/1998	1,260
1999	06/15/1999	603	06/21/1999	444	06/17/1999	555	06/16/1999	642	—	698	06/17/1999	708
2000	04/24/2000	228	05/18/2000	169	05/18/2000	175	05/20/2000	191	—	264	05/17/2000	332
2001	04/07/2001	113	04/09/2001	101	07/11/2001	130	07/15/2001	107	—	131	06/09/2001	533
2002	04/08/2002	137	07/04/2002	130	07/09/2002	112	07/06/2002	139	—	159	07/20/2002	489
2003	03/15/2003	210	06/18/2003	111	06/19/2003	109	06/21/2003	115	—	243	08/18/2003	166
2004	03/27/2004	58	08/19/2004	94	07/01/2004	102	07/01/2004	100	—	67	07/03/2004	418
2005	05/13/2005	53	07/07/2005	105	07/07/2005	95	07/10/2005	104	—	61	08/11/2005	274
2006	04/23/2006	90	06/30/2006	118	08/07/2006	110	08/07/2006	117	—	104	08/07/2006	482
2007	06/02/2007	153	07/07/2007	107	07/09/2007	112	08/17/2007	159	—	177	08/17/2007	535
2008	07/07/2008	1,640	07/17/2008	68	07/18/2008	80	05/24/2008	285	—	1,000	05/24/2008	487
2009	04/24/2009	239	04/25/2009	220	04/26/2009	248	04/26/2009	243	—	277	05/24/2009	342

Table B.6. Selected information used in development of modern peak-flow chronology for the upper Rapid Creek study reach.

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06409000		06410000		06410500		06410500		06411500		06412000	
	Castle Creek above Deer- field Reservoir near Hill City, S.Dak.		Castle Creek below Deerfield Dam, S.Dak.		Rapid Creek above Pactola Reservoir at Silver City, S.Dak.		Rapid Creek above Pactola Reservoir— extended record (modern chronology)		Rapid Creek below Pactola Dam, S.Dak.		Rapid Creek at Big Bend near Rapid City, S.Dak.	
	Area = 79.3		Area = 92.5		Area = 294		Area = 294		Area = 322		Area = 339	
Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q	Date
1915	--	--	--	--	--	--	566	--	--	06/26/1915	616	
1916	--	--	--	--	--	--	187	--	--	05/24/1916	204	
1917	--	--	--	--	--	--	248	--	--	06/04/1917	270	
1929	--	--	--	--	--	--	752	06/03/1929	794	--	--	--
1930	--	--	--	--	--	--	184	04/09/1930	194	--	--	--
1931	--	--	--	--	--	--	147	04/08/1931	155	--	--	--
1932	--	--	--	--	--	--	646	04/24/1932	682	04/24/1932	694	
1933	--	--	--	--	--	--	1,460	05/24/1933	1,540	05/24/1933	1,570	
1934	--	--	--	--	--	--	111	02/11/1934	117	02/11/1934	119	
1935	--	--	--	--	--	--	414	06/01/1935	437	05/01/1935	446	
1936	--	--	--	--	--	--	95	04/13/1936	100	04/13/1936	102	
1937	--	--	--	--	--	--	80	07/12/1937	84	07/12/1937	86	
1938	--	--	--	--	--	--	81	04/16/1938	86	04/16/1938	88	
1939	--	--	--	--	--	--	59	04/24/1939	62	04/24/1939	63	
1940	--	--	--	--	--	--	232	08/27/1940	245	08/27/1940	250	
1941	--	--	--	--	--	--	511	06/11/1941	540	06/11/1941	552	
1942	--	--	--	--	--	--	387	05/16/1942	409	05/16/1942	417	
1947	--	--	06/24/1947	151	--	--	903	06/23/1947	954	--	--	--
1948	--	--	06/30/1948	67	--	--	235	06/22/1948	248	--	--	--
1949	06/02/1949	48	04/05/1949	41	--	--	221	06/02/1949	233	--	--	--
1950	04/14/1950	108	04/15/1950	47	--	--	221	04/15/1950	233	--	--	--
1951	04/06/1951	55	05/14/1951	22	--	--	92	06/14/1951	97	--	--	--

Table B.6. Selected information used in development of modern peak-flow chronology for the upper Rapid Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06409000			06410000			06410500			06410500			06411500			06412000		
	Castle Creek above Deer- field Reservoir near Hill City, S.Dak.			Castle Creek below Deerfield Dam, S.Dak.			Rapid Creek above Pactola Reservoir at Silver City, S.Dak.			Rapid Creek above Pactola Reservoir— extended record (modern chronology)			Rapid Creek below Pactola Dam, S.Dak.			Rapid Creek at Big Bend near Rapid City, S.Dak.		
	Area = 79.3			Area = 92.5			Area = 294			Area = 294			Area = 322			Area = 339		
	Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q	
1952	05/22/1952	1,120		05/22/1952	200		--	--		--	2,460		05/22/1952	2,170		--	--	
1953	08/15/1953	37		05/22/1953	30		--	--		--	152		06/15/1953	160		--	--	
1954	05/23/1954	27		07/18/1954	65		05/23/1954	106		05/23/1954	106		05/23/1954	94		--	--	
1955	04/16/1955	58		07/09/1955	60		07/28/1955	1,520		07/28/1955	1,520		07/29/1955	378		--	--	
1956	05/28/1956	32		08/03/1956	53		03/24/1956	175		03/24/1956	175		03/25/1956	178		--	--	
1957	08/27/1957	40		08/08/1957	42		05/25/1957	181		05/25/1957	181		03/14/1957	55		--	--	
1958	07/18/1958	20		05/15/1958	69		05/31/1958	113		05/31/1958	113		06/02/1958	84		--	--	
1959	04/16/1959	20		09/22/1959	128		09/25/1959	146		09/25/1959	146		08/21/1959	90		--	--	
1960	03/28/1960	68		10/07/1959	31		03/23/1960	117		03/23/1960	117		07/20/1960	112		--	--	
1961	06/13/1961	25		07/07/1961	90		07/07/1961	96		07/07/1961	96		06/11/1961	111		--	--	
1962	04/15/1962	92		05/24/1962	11		06/15/1962	390		06/15/1962	390		05/18/1962	67		--	--	
1963	06/05/1963	124		06/14/1963	14		06/16/1963	715		06/16/1963	715		06/30/1963	184		--	--	
1964	06/09/1964	114		06/09/1964	64		06/09/1964	635		06/09/1964	635		06/10/1964	266		--	--	
1965	06/17/1965	906		05/15/1965	90		05/15/1965	2,060		05/15/1965	2,060		05/19/1965	547		--	--	
1966	03/31/1966	83		10/23/1965	55		03/16/1966	150		03/16/1966	150		03/20/1966	147		--	--	
1967	03/29/1967	74		06/16/1967	59		06/16/1967	627		06/16/1967	627		06/22/1967	406		--	--	
1968	07/17/1968	32		09/24/1968	39		06/09/1968	106		06/09/1968	106		10/04/1967	311		--	--	
1969	07/17/1969	82		09/16/1969	40		07/20/1969	213		07/20/1969	213		05/20/1969	306		--	--	
1970	04/27/1970	95		05/08/1970	74		04/19/1970	995		04/19/1970	995		05/12/1970	304		--	--	
1971	04/17/1971	70		04/20/1971	61		04/25/1971	305		04/25/1971	305		04/25/1971	338		--	--	
1972	05/10/1972	34		09/26/1972	40		07/06/1972	252		07/06/1972	252		10/05/1971	505		--	--	
1973	05/05/1973	40		10/01/1972	40		05/09/1973	169		05/09/1973	169		05/08/1973	168		--	--	
1974	03/28/1974	37		10/02/1973	26		04/30/1974	54		04/30/1974	54		07/04/1974	113		--	--	
1975	04/23/1975	102		04/25/1975	46		04/26/1975	219		04/26/1975	219		06/07/1975	85		--	--	

Table B.6. Selected information used in development of modern peak-flow chronology for the upper Rapid Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06409000			06410000			06410500			06410500			06411500			06412000		
	Castle Creek above Deer- field Reservoir near Hill City, S.Dak.			Castle Creek below Deerfield Dam, S.Dak.			Rapid Creek above Pactola Reservoir at Silver City, S.Dak.			Rapid Creek above Pactola Reservoir— extended record (modern chronology)			Rapid Creek below Pactola Dam, S.Dak.			Rapid Creek at Big Bend near Rapid City, S.Dak.		
	Area = 79.3			Area = 92.5			Area = 294			Area = 294			Area = 322			Area = 339		
	Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q	
1976	06/15/1976	52		04/07/1976	28		06/15/1976	614		06/15/1976	614		06/29/1976	234		--	--	
1977	04/17/1977	27		10/15/1976	42		04/25/1977	187		04/25/1977	187		05/05/1977	188		--	--	
1978	05/18/1978	64		05/18/1978	83		05/11/1978	430		05/11/1978	430		06/01/1978	386		--	--	
1979	04/17/1979	30		02/09/1979	66		07/23/1979	173		07/23/1979	173		06/16/1979	101		--	--	
1980	08/20/1980	28		09/08/1980	43		05/11/1980	75		05/11/1980	75		07/15/1980	118		--	--	
1981	07/25/1981	20		07/31/1981	60		07/26/1981	83		07/26/1981	83		05/02/1981	142		--	--	
1982	08/04/1982	148		08/04/1982	94		05/20/1982	332		05/20/1982	332		07/03/1982	139		--	--	
1983	08/03/1983	87		05/08/1983	41		05/09/1983	262		05/09/1983	262		05/13/1983	268		--	--	
1984	07/16/1984	122		06/16/1984	44		08/03/1984	198		08/03/1984	198		05/12/1984	222		--	--	
1985	03/25/1985	34		07/25/1985	35		04/01/1985	75		04/01/1985	75		05/10/1985	144		--	--	
1986	04/15/1986	34		09/21/1986	26		05/09/1986	123		05/09/1986	123		06/03/1986	93		--	--	
1987	03/07/1987	31		04/10/1987	34		04/09/1987	99		04/09/1987	99		07/31/1987	99		--	--	
1988	04/07/1988	57		05/18/1988	26		05/20/1988	69		05/20/1988	69		08/01/1988	128		--	--	
1989	03/09/1989	23		08/11/1989	26		03/21/1989	55		03/21/1989	55		07/12/1989	130		--	--	
1990	04/03/1990	33		04/26/1990	34		04/26/1990	93		04/26/1990	93		07/02/1990	122		--	--	
1991	06/03/1991	106		06/06/1991	81		06/07/1991	421		06/07/1991	421		08/29/1991	78		--	--	
1992	05/21/1992	30		03/10/1992	23		07/13/1992	55		07/13/1992	55		05/21/1992	106		--	--	
1993	06/08/1993	113		06/10/1993	53		05/10/1993	867		05/10/1993	867		06/19/1993	286		--	--	
1994	04/22/1994	65		05/13/1994	37		05/06/1994	196		05/06/1994	196		04/27/1994	195		--	--	
1995	05/08/1995	153		06/14/1995	56		05/10/1995	879		05/10/1995	879		05/15/1995	393		--	--	
1996	04/09/1996	271		05/31/1996	54		05/31/1996	711		05/31/1996	711		06/07/1996	450		--	--	
1997	07/24/1997	116		--	--		05/07/1997	524		05/07/1997	524		06/11/1997	426		--	--	
1998	06/18/1998	176		06/24/1998	87		06/18/1998	1,290		06/18/1998	1,290		07/02/1998	443		07/02/1998	481	
1999	03/25/1999	198		--	--		06/15/1999	603		06/15/1999	603		06/21/1999	444		06/17/1999	555	

Table B.6. Selected information used in development of modern peak-flow chronology for the upper Rapid Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; —, not available]

Water year	06409000			06410000			06410500			06410500			06411500			06412000		
	Castle Creek above Deer- field Reservoir near Hill City, S.Dak.			Castle Creek below Deerfield Dam, S.Dak.			Rapid Creek above Pactola Reservoir at Silver City, S.Dak.			Rapid Creek above Pactola Reservoir— extended record (modern chronology)			Rapid Creek below Pactola Dam, S.Dak.			Rapid Creek at Big Bend near Rapid City, S.Dak.		
	Area = 79.3			Area = 92.5			Area = 294			Area = 294			Area = 322			Area = 339		
	Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q	
2000	04/19/2000	291		04/29/2000	38		04/24/2000	228		04/24/2000	228		05/18/2000	169		05/18/2000	175	
2001	07/13/2001	56		07/16/2001	51		04/07/2001	113		04/07/2001	113		04/09/2001	101		07/11/2001	130	
2002	03/09/2002	388		04/21/2002	32		04/08/2002	137		04/08/2002	137		07/04/2002	130		07/09/2002	112	
2003	03/31/2003	288		09/17/2003	47		03/15/2003	210		03/15/2003	210		06/18/2003	111		06/19/2003	109	
2004	03/27/2004	31		09/07/2004	34		03/27/2004	58		03/27/2004	58		08/19/2004	94		07/01/2004	102	
2005	05/12/2005	22		05/18/2005	39		05/13/2005	53		05/13/2005	53		07/07/2005	105		07/07/2005	95	
2006	05/23/2006	35		03/29/2006	43		04/23/2006	90		04/23/2006	90		06/30/2006	118		08/07/2006	110	
2007	03/19/2007	35		08/20/2007	11		06/02/2007	153		06/02/2007	153		07/07/2007	107		07/09/2007	112	
2008	07/06/2008	61		08/10/2008	13		07/07/2008	1,640		07/07/2008	1,640		07/17/2008	68		07/18/2008	80	
2009	04/16/2009	48		04/16/2009	37		04/24/2009	239		04/24/2009	239		04/25/2009	220		04/26/2009	248	

Boxelder Creek

Drainage areas for the Boxelder Creek reach increase from 98 to 112 mi² between the upstream and downstream extents of the reach, and potential exists for substantial differences in peak-flow characteristics from the influence of two relatively large tributaries within the upstream part of the reach. A 1972 peak flow (Table B.7) of 30,100 ft³/s was recorded for streamgage 06422500 (drainage area = 94.4 mi²), which is located just upstream from the reach, and a 1972 flow of 51,600 ft³/s was recorded at streamgage 06422650 (drainage area = 116 mi²), which is located just downstream from the reach. Adjusting the flow for the upstream streamgage to the area for the downstream streamgage yields a predicted flow of 34,060 ft³/s and the opposite adjustment yields a flow for the upstream streamgage of 45,600 ft³/s, which illustrates the effect of the intervening tributaries in 1972. Thus, modern chronologies were developed for two separate sub-reaches of Boxelder Creek (located upstream and downstream from the two tributaries; Tables 2 and S7). Both chronologies were based primarily on gaged records for upstream streamgage 06422500, which were extended (based on drainage-area adjustments) to include 1904–05 values from streamgage 06423000. Subsequent adjustments for the two sub-reaches were primarily based on upstream and downstream areas of 98 and 112 mi². However, the 1972 value for the downstream sub-reach was derived from a drainage-area adjustment using downstream streamgage 06423000.

Table B.7. Selected information used in development of modern peak-flow chronology for the Boxelder Creek study reach.

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06422500		Boxelder Creek upstream sub-reach (modern chronology)		Boxelder Creek downstream sub-reach (modern chronology)		06422650		06423000	
	Boxelder Creek near Nemo, S.Dak.						Boxelder Creek at Doty School near Blackhawk, S.Dak.		Boxelder Creek at Blackhawk, S.Dak.	
	Area = 94.4		Area = 98		Area = 112		Area = 116		Area = 126	
	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q
1904	--	521	--	533	--	578	--	--	06/05/1904	620
1905	--	547	--	559	--	606	--	--	07/02/1905	650
1907	06/12/1907	16,000	--	16,400	--	17,700	--	--	--	--
1946	05/02/1946	1,180	--	1,210	--	1,310			05/02/1946	1,320
1947	05/23/1947	372	--	380	--	412			06/23/1947	395
1966	07/28/1966	30	--	31	--	33	--	--	--	--
1967	06/12/1967	950	--	972	--	1,050	--	--	--	--
1968	06/09/1968	62	--	63	--	69	--	--	--	--
1969	05/04/1969	144	--	147	--	160	--	--	--	--
1970	06/12/1970	648	--	663	--	718	--	--	--	--
1971	04/25/1971	221	--	226	--	245	--	--	--	--
1972	06/09/1972	30,100	--	30,800	--	50,500	06/09/1972	51,600	--	--
1973	04/20/1973	117	--	120	--	130	--	--	--	--
1974	04/19/1974	23	--	24	--	25	--	--	--	--
1975	07/30/1975	427	--	437	--	473	--	--	--	--
1976	06/15/1976	1,460	--	1,490	--	1,620	--	--	--	--
1977	04/17/1977	170	--	174	--	188	--	--	--	--
1978	05/11/1978	301	--	308	--	334	05/18/1978	251	--	--
1979	07/04/1979	97	--	99	--	107	--/--/1979	.00	--	--
1980	03/13/1980	35	--	36	--	39	--/--/1980	.00	--	--
1981	05/18/1981	26	--	27	--	29	--	--	--	--
1982	05/20/1982	272	--	278	--	301	--	--	--	--
1983	05/07/1983	178	--	182	--	197	--	--	--	--
1984	06/15/1984	215	--	220	--	238	--	--	--	--
1985	03/18/1985	129	--	132	--	143	--	--	--	--
1986	05/09/1986	82	--	84	--	91	--	--	--	--
1987	03/06/1987	123	--	126	--	136	--	--	--	--
1988	05/09/1988	33	--	34	--	37	--	--	--	--
1989	03/10/1989	30	--	31	--	33	--	--	--	--
1990	05/05/1990	29	--	30	--	32	--	--	--	--
1991	06/06/1991	401	--	410	--	444	--	--	--	--
1992	06/13/1992	53	--	54	--	59	--	--	--	--
1993	06/07/1993	293	--	300	--	325	--	--	--	--
1994	05/06/1994	125	--	128	--	139	--	--	--	--

Table B.7 Selected information used in development of modern peak-flow chronology for the Boxelder Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, estimated; --, not available]

Water year	06422500		Boxelder Creek upstream sub-reach (modern chronology)		Boxelder Creek downstream sub-reach (modern chronology)		06422650		06423000	
	Boxelder Creek near Nemo, S.Dak.						Boxelder Creek at Doty School near Blackhawk, S.Dak.		Boxelder Creek at Blackhawk, S.Dak.	
	Area = 94.4		Area = 98		Area = 112		Area = 116		Area = 126	
	Date	Q	Date	Q	Date	Q	Date	Q	Date	Q
1995	05/09/1995	1,140	—	1,170	--	1,260	—	--	—	--
1996	05/30/1996	826	—	845	--	915	—	--	—	--
1997	06/02/1997	463	—	474	--	513	—	--	—	--
1998	06/18/1998	607	—	621	--	673	—	--	—	--
1999	06/15/1999	327	--	334	--	362	--	--	--	--
2000	04/25/2000	178	--	182	--	197	--	--	--	--
2001	04/07/2001	52	--	53	--	58	--	--	--	--
2002	04/08/2002	47	--	48	--	52	--	--	--	—
2003	03/13/2003	100	--	102	--	111	--	--	--	—
2004	03/11/2004	19	--	19	--	21	--	--	--	—
2005	05/14/2005	24	--	25	—	27	--	--	--	—
2006	04/23/2006	103	--	105	—	114	--	--	--	—
2007	06/02/2007	200	--	205	—	222	--	--	--	--
2008	07/07/2008	646	--	661	—	716	--	--	--	--
2009	04/16/2009	368	--	376	--	408	--	--	--	--

Elk Creek

Drainage areas for the Elk Creek reach increase from 40 to 41 mi² throughout the reach. Upstream streamgage 06424000 (drainage area = 21.6 mi²) is considered to be most hydrologically representative, relative to peak-flow characteristics, but has only short-term records (Table 1). Downstream streamgages 06425100 and 06425500 have much longer records (Table S8; however, drainage areas are much larger (211 and 549 mi², respectively) and peak-flow values correlate very poorly because of substantial hydrogeologic differences in the intervening drainage areas (Sando and others, 2008; Driscoll and others, 2010). Hydrogeologic influences are well illustrated by the substantial attenuation of the 1972 flow values between streamgages 06424500 and 06425500 (11,600 and 1,880 ft³/s, respectively). Thus, the modern peak-flow chronology for Elk Creek (Tables 2 and B.8) was derived by first extending records for upstream streamgage 06424000, based on least-squares regression analysis (Helsel and Hirsch, 1992) using concurrent records for 1982–2009 with long-term streamgage 06422500 that is located along Boxelder Creek near Nemo (annual peak flow for streamgage 06424000, in cubic feet per second = $52.0 + 0.32$ times annual peak flow for streamgage 06422500, in cubic feet per second; correlation coefficient = 0.87). The chronology for the study reach was then obtained using a drainage-area adjustment. The 1972 value and values for 1945–47 were obtained using a drainage-area adjustment for the 1972 flow at downstream streamgage 06424500 (drainage area = 47.6 mi²). Historical accounts (Driscoll and others, 2010) indicate that a very large flow occurred in 1907 that completely destroyed a railroad line within the Elk

Creek study reach and which may well have been larger than the 1972 flow. One focus of paleoflood investigations within Elk Creek was a concerted effort to attempt to determine whether the 1907 or 1972 flow was larger; however, definitive evidence could not be found. Thus, the 1907 flow was arbitrarily assumed equal to the 1972 flow as a historical value for the modern chronology. Relatively large flows may have occurred within the Elk Creek reach during 1952, 1953, and 1962, based on flows for downstream streamgage 06425500 and historical accounts (Driscoll and others, 2010). However, extension of the modern chronology is considered inappropriate, as illustrated by the 1972 flow comparison, and as further illustrated by large flow differentials between streamgages 06425100 and 06425500 for many years of concurrent record (Table B.8) that include relatively large values.

Table B.8. Selected information used in development of modern peak-flow chronology for the Elk Creek study reach.

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, value estimated on the basis of 1972 peak-flow value; --, not available]

Water year	06422500			06424000			Extended record for Elk Creek near Roubaix (06424000)			Elk Creek study reach (modern chronology)			06424500			06425100			06425500		
	Boxelder Creek near Nemo, S.Dak.	Q	Date	Elk Creek near Roubaix, S.Dak.	Q	Date	Area = 21.6	Date	Q	Area = 40	Date	Q	Elk Creek above Piedmont, S.Dak.	Date	Q	Elk Creek near Rapid City, S.Dak.	Date	Q	Elk Creek near Elm Springs, S.Dak.	Date	Q
	Area = 94.4			Area = 21.6			Area = 21.6			Area = 47.6			Area = 211			Area = 549					
1907	06/12/1907	16,000	--	--	--	--	--	--	--	E10,400	--	--	--	--	--	--	--	--	--	--	--
1945	--	--	--	--	--	--	--	--	--	1,630	08/01/1945	1,810	--	--	--	--	--	--	--	--	--
1946	05/02/1946	1,180	05/02/1946	378	--	--	--	--	--	1,220	05/02/1946	1,350	--	--	--	--	--	--	--	--	--
1947	05/23/1947	372	06/22/1947	218	--	--	--	--	--	314	06/23/1947	348	--	--	--	--	--	--	--	--	--
1950	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	04/15/1950	852
1951	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	09/02/1951	328
1952	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	03/29/1952	8,540
1953	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	06/19/1953	5,250
1954	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	06/10/1954	838
1955	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	09/20/1955	270
1956	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	07/03/1956	48
1957	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	05/26/1957	2,690
1958	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	06/16/1958	616
1959	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	05/29/1959	16
1960	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	06/30/1960	796
1961	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--/1985	.00
1962	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	05/29/1962	7,040
1963	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	06/17/1963	698
1964	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	06/08/1964	3,620
1965	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	05/16/1965	3,250
1966	07/28/1966	30	--	--	--	--	61	--	89	--	--	--	--	--	--	--	--	--	--	03/14/1966	775
1967	06/12/1967	950	--	--	--	--	352	--	510	--	--	--	--	--	--	--	--	--	--	06/16/1967	4,960
1968	06/09/1968	62	--	--	--	--	72	--	104	--	--	--	--	--	--	--	--	--	--	06/07/1968	1,020
1969	05/04/1969	144	--	--	--	--	98	--	141	--	--	--	--	--	--	--	--	--	--	07/17/1969	2,300
1970	06/12/1970	648	--	--	--	--	257	--	372	--	--	--	--	--	--	--	--	--	--	04/26/1970	2,920

Table B.8. Selected information used in development of modern peak-flow chronology for the Elk Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, value estimated on the basis of 1972 peak-flow value; --, not available]

Water year	06422500			06424000			Extended record for Elk Creek near Roubaix (06424000)			Elk Creek study reach (modern chronology)			06424500			06425100			06425500		
	Boxelder Creek near Nemo, S.Dak.			Elk Creek near Roubaix, S.Dak.									Elk Creek above Piedmont, S.Dak.			Elk Creek near Rapid City, S.Dak.			Elk Creek near Elm Springs, S.Dak.		
	Area = 94.4			Area = 21.6			Area = 21.6			Area = 40			Area = 47.6			Area = 211			Area = 549		
	Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q		Date	Q	
1971	04/25/1971	221		--	--	122	--	176	--	--	--	06/09/1972	11,600	--	--	--	--	05/23/1971	3,510		
1972	06/09/1972	30,100		--	--	--	--	10,400	06/09/1972	11,600	--	--	--	--	--	--	--	06/11/1972	1,880		
1973	04/20/1973	117		--	--	89	--	129	--	--	--	--	--	--	--	--	--	04/22/1973	1,440		
1974	04/19/1974	23		--	--	59	--	86	--	--	--	--	--	--	--	--	--	04/09/1974	54		
1975	07/30/1975	427		--	--	187	--	271	--	--	--	--	--	--	--	--	--	04/27/1975	1,210		
1976	06/15/1976	1,460		--	--	514	--	744	--	--	--	--	--	--	--	--	--	06/17/1976	2,230		
1977	04/17/1977	170		--	--	106	--	153	--	--	--	--	--	--	--	--	--	06/14/1977	2,270		
1978	05/11/1978	301		--	--	147	--	213	--	--	--	--	--	--	--	--	--	03/18/1978	2,830		
1979	07/04/1979	97		--	--	83	--	120	--	--	--	--	--	--	--	--	--	03/17/1979	92		
1980	03/13/1980	35		--	--	63	--	91	--	--	--	--	--	--	--	--	--	06/15/1980	437		
1981	05/18/1981	26		--	--	60	--	87	--	--	--	--	--	--	--	--	--	08/13/1981	124		
1982	05/20/1982	272		--	--	138	--	200	--	--	--	--	--	--	--	--	--	05/21/1982	5,300		
1983	05/07/1983	178		--	--	108	--	157	--	--	--	--	--	--	--	--	--	10/10/1983	1,940		
1984	06/15/1984	215		--	--	120	--	174	--	--	--	--	--	--	--	--	--	05/04/1984	890		
1985	03/18/1985	129		--	--	93	--	134	--	--	--	--	--	--	--	--	--	03/20/1985	73		
1986	05/09/1986	82		--	--	78	--	113	--	--	--	--	--	--	--	--	--	02/27/1986	4,960		
1987	03/06/1987	123		--	--	91	--	132	--	--	--	--	--	--	--	--	--	05/27/1987	718		
1988	05/09/1988	33		--	--	62	--	90	--	--	--	--	--	--	--	--	--	03/24/1988	101		
1989	03/10/1989	30		--	--	61	--	89	--	--	--	--	--	--	--	--	--	03/22/1989	11		
1990	05/05/1990	29		--	--	61	--	89	--	--	--	--	--	--	--	--	--	09/02/1990	47		
1991	06/06/1991	401		--	--	179	--	259	--	--	--	--	--	--	--	--	--	05/28/1991	620		
1992	06/13/1992	53		05/10/1992	15	15	--	22	--	--	--	--	--	--	--	--	--	06/21/1992	27		
1993	06/07/1993	293		06/08/1993	154	154	--	223	--	--	--	--	--	--	--	--	--	05/08/1993	3,660		
1994	05/06/1994	125		05/05/1994	103	103	--	149	--	--	--	--	--	--	--	--	--	06/08/1994	5,570		
1995	05/09/1995	1,140		05/08/1995	515	515	--	745	--	--	--	--	--	--	--	--	--	05/10/1995	4,580		
1996	05/30/1996	826		05/30/1996	176	176	--	255	--	--	--	--	--	--	--	--	--	05/28/1996	7,660		
1997	06/02/1997	463		04/07/1997	200	200	--	289	--	--	--	--	--	--	--	--	--	02/18/1997	3,000		

Table B.8. Selected information used in development of modern peak-flow chronology for the Elk Creek study reach.—Continued

[Gray-shaded rows signify a gap in the chronology. Area, drainage area in square miles; Date, dates shown are for systematic peak-flow records, entries without dates are derived values; Q, peak-flow value in cubic feet per second; E, value estimated on the basis of 1972 peak-flow value; --, not available]

Water year	06422500		06424000		Extended record for Elk Creek near Roubaix (06424000)		Elk Creek study reach (modern chronology)		06424500		06425100		06425500	
	Boxelder Creek near Nemo, S.Dak.	Area = 94.4	Elk Creek near Roubaix, S.Dak.	Area = 21.6	Date	Q	Date	Q	Date	Q	Date	Q	Elk Creek near Elm Springs, S.Dak.	Area = 549
1998	06/18/1998	607	06/18/1998	197	--	197	--	285	--	--	06/18/1998	357	06/19/1998	592
1999	06/15/1999	327	04/21/1999	133	--	133	--	192	--	--	04/22/1999	985	10/17/1999	5,150
2000	04/25/2000	178	05/11/2000	123	--	123	--	178	--	--	04/25/2000	881	04/19/2000	3,000
2001	04/07/2001	52	04/23/2001	39	--	39	--	56	--	--	03/04/2001	57	03/07/2001	1,200
2002	04/08/2002	47	04/08/2002	155	--	155	--	224	--	--	04/02/2002	16	04/29/2002	19
2003	03/13/2003	100	03/14/2003	100	--	100	--	145	--	--	05/05/2003	20	03/19/2003	61
2004	03/11/2004	19	03/27/2004	28	--	28	--	41	--	--	03/18/2004	10	05/23/2004	37
2005	05/14/2005	24	05/13/2005	45	--	45	--	65	--	--	--/2005	.00	05/12/2005	28
2006	04/23/2006	103	09/23/2006	153	--	153	--	221	--	--	04/28/2006	10	09/22/2006	2.4
2007	06/02/2007	200	06/07/2007	132	--	132	--	191	--	--	08/18/2007	68	08/24/2007	.58
2008	07/07/2008	646	08/06/2008	300	--	300	--	434	--	--	06/06/2008	2,390	06/06/2008	7,000
2009	04/16/2009	368	04/15/2009	130	--	130	--	188	--	--	04/13/2009	2,400	04/14/2009	5,090

Appendix 3 – Schematic Diagrams

Stratigraphic investigations that were conducted for some sites along several of the stream reaches were not incorporated in flood-frequency analyses. Schematic diagrams for such sites are not included within the main body of this report, but are provided in this section (Figures C.1 through C.10) as documentation for potential future needs that may arise.

Figure C.1. Schematic diagram showing paleoflood information for Olympia Alcove, Spring Creek.

Figure C.2. Schematic diagram showing paleoflood information for Near Strike Alcove, Spring Creek.

Figure C.3. Schematic diagram showing paleoflood information for the Church Mug Alcove, lower Rapid Creek reach.

Figure C.4. Schematic diagram showing paleoflood information for Benchmark Alcove, upstream sub-reach of Boxelder Creek.

Figure C.5. Schematic diagram showing paleoflood information for Snap-E-Tom Alcove, upstream sub-reach of Boxelder Creek.

Figure C.6. Schematic diagram showing paleoflood information for Asphalt Alcove, upstream sub-reach of Boxelder Creek.

Figure C.7. Schematic diagram showing paleoflood information for Snow Shovel Alcove, downstream sub-reach of Boxelder Creek.

Figure C.8. Schematic diagram showing paleoflood information for Sand Wall Alcove, Elk Creek.

Figure C.9. Schematic diagram showing paleoflood information for Flat Rock Alcove, Elk Creek.

Figure C.10. Schematic diagram showing paleoflood information for Bird's Nest Alcove, Elk Creek.