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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

Scientific Investigations Report 2008–5164

U.S. Department of the Interior
U.S. Geological Survey

Cover: View looking upstream at slope-area reach in Meyers Canyon, Oregon, August 1956.

Insets from left to right:
Inset 1: View looking downstream of streamflow-gaging station toward slope-area reach, South Fork Wailua River near Lihue, Hawaii, February 25, 2003.
Inset 2: View looking downstream following flood in 1971, Bronco Creek near Wikieup, Arizona.
Inset 3: Slope-area discharge reach for West Nueces River at Kickapoo Springs, Texas, May 2003. Peak discharge of 580,000 ft^3/s from 402 mi^2 in 1935 is a world-record defining flood discharge.

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Conversion Factors and Datum

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square ft (ft^2)	0.09290	square meter (m^2)
square mile (mi2)	2.590	square kilometer (km^2)
	Flow rate	
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)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Elevation, as used in this report, refers to distance above the vertical datum.

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

By John E. Costa and Robert D. Jarrett

Abstract

Thirty flood peak discharges determine the envelope curve of maximum floods documented in the United States by the U.S. Geological Survey. These floods occurred from 1927 to 1978 and are extraordinary not just in their magnitude, but in their hydraulic and geomorphic characteristics. The reliability of the computed discharge of these extraordinary floods was reviewed and evaluated using current (2007) best practices. Of the 30 flood peak discharges investigated, only 7 were measured at daily streamflow-gaging stations that existed when the flood occurred, and 23 were measured at miscellaneous (ungaged) sites. Methods used to measure these 30 extraordinary flood peak discharges consisted of 21 slope-area measurements, 2 direct current-meter measurements, 1 culvert measurement, 1 rating-curve extension, and 1 interpolation and rating-curve extension. The remaining four peak discharges were measured using combinations of culvert, slope-area, flow-over-road, and contracted-opening measurements. The method of peak discharge determination for one flood is unknown.

Changes to peak discharge or rating are recommended for 20 of the 30 flood peak discharges that were evaluated. Nine floods retained published peak discharges, but their ratings were downgraded. For two floods, both peak discharge and rating were corrected and revised. Peak discharges for five floods that are subject to significant uncertainty due to complex field and hydraulic conditions, were re-rated as estimates. This study resulted in 5 of the 30 peak discharges having revised values greater than about 10 percent different from the original published values. Peak discharges were smaller for three floods (North Fork Hubbard Creek, Texas; El Rancho Arroyo, New Mexico; South Fork Wailua River, Hawaii), and two peak discharges were revised upward (Lahontan Reservoir tributary, Nevada; Bronco Creek, Arizona). Two peak discharges were indeterminate because they were concluded to have been debris flows with peak discharges that were estimated by an inappropriate method (slope-area) (Big Creek near Waynesville, North Carolina; Day Creek near Etiwanda, California). Original field notes and records could not be found for three of the floods, however, some data (copies of original materials, records of reviews) were available for two of these floods. A rating was assigned to each of seven peak discharges that had no rating.

Errors identified in the reviews include misidentified flow processes, incorrect drainage areas for very small basins, incorrect latitude and longitude, improper field methods, arithmetic mistakes in hand calculations, omission of measured high flows when developing rating curves, and typographical errors. Common problems include use of two-section slope-area measurements, poor site selection, uncertainties in Manning's *n*-values, inadequate review, lost data files, and insufficient and inadequately described high-water marks. These floods also highlight the extreme difficulty in making indirect discharge measurements following extraordinary floods. Significantly, none of the indirect measurements are rated better than fair, which indicates the need to improve methodology to estimate peak discharge. Highly unsteady flow and resulting transient hydraulic phenomena, two-dimensional flow patterns, debris flows at streamflow-gaging stations, and the possibility of disconnected flow surfaces are examples of unresolved problems not well handled by current indirect discharge methodology. On the basis of a comprehensive review of 50,000 annual peak discharges and miscellaneous floods in California, problems with individual flood peak discharges would be expected to require a revision of discharge or rating curves at a rate no greater than about 0.10 percent of all floods.

Many extraordinary floods create complex flow patterns and processes that cannot be adequately documented with quasi-steady, uniform one-dimensional analyses. These floods are most accurately described by multidimensional flow analysis.

Within the U.S. Geological Survey, new approaches are needed to collect more accurate data for floods, particularly extraordinary floods. In recent years, significant progress has been made in instrumentation for making direct discharge measurements. During this same period, very little has been accomplished in advancing methods to improve indirect discharge measurements. Greater use of paleoflood hydrology could fill many shortcomings of U.S. Geological Survey flood science today, such as enhanced knowledge of flood frequency. Additional links among flood runoff, storm structure, and storm motion would provide more insight to flood hazards. Significant improvement in understanding flood processes and characteristics could be gained from linking radar rainfall estimation and hydrologic modeling. Additionally, more could be done to provide real-time flood-hazard warnings with linked rainfall/runoff and flow models.

Several important recommendations are made to improve the flood-documentation capability of the U.S. Geological Survey. When very large discharges are measured by current meter or hydroacoustics, water-surface slope should be measured as well. This measurement would allow validation of roughness values that can significantly extend the discharge range of verified Manning's *n* for 1-dimensional and 2-dimensional flow analyses. At least two of the floods investigated may have had flow so unstable that large waves affected the interpretation of high-water marks. Instability criteria should be considered for hydraulic analysis of large flows in high-gradient, smooth channels.

The U.S. Geological Survey needs to modernize its toolbox of field and office practices for making future indirect discharge measurements. These practices could include, first and foremost, a new peak-flow file database that allows greater description and interpretation of flow events, such as stability criteria in high-gradient, smooth channels, debris flow documentation, and details of flood genesis (hurricane, snowmelt, rain-on-snow, dam failure, and the like). Other modernized practices could include (a) establishment of calibrated stream reaches in chronic flash flood basins to expedite indirect computation of flow; (b) development of process-based theoretical rating curves for streamflow-gaging stations; (c) adoption of step-backwater models as the standard surface-water modeling tool for U.S. Geological Survey field offices; (d) development and support for multidimensional flow models capable of describing flood characteristics in complex terrain and high-gradient channels; (e) greater use of the critical-depth method in appropriate locations; (f) deployment of non-contact instruments to directly measure large floods, rather than attempting to reconstruct them; (g) increased use of paleoflood hydrology; and (h) assurance that future collection of hydro-climatic data meets the needs of more robust watershed models.

Introduction

> "I think our overflowing river far handsomer and more abounding in soft beautiful contrasts than a merely broad river would be…."
> Journal of Henry D. Thoreau, v. 4, p. 458, April 16, 1852

Flooding is the most widespread hydrologic hazard in the United States, and about 7 percent of the land area of the United States is subject to flooding (Committee on U.S. Geological Survey Water Resources Research, 1999). Flood data are collected by the U.S. Geological Survey (USGS) at more than 7,200 daily streamflow-gaging stations and about 2,400 partial-record stations nationwide. Many of the partial-record stations measure only water height. Data also may be collected from a smaller number of miscellaneous (ungaged) sites as large floods occur. These flood data are used for a wide variety of purposes and by many public and private organizations. It is critical that these data be as complete and accurate as current technology allows.

The Peak-Flow File is a database within the National Water Information System (NWIS) of the USGS (Lepkin and DeLapp, 1979) and as of 2007, the database contains more than 1 million values of annual peak discharge for more than 10,000 locations across the United States. Values stored in the Peak-Flow File have contributed substantially to decisions made by State and local officials on bridge and culvert design, flood-plain mapping, and design of critical structures such as dams and levees.

The highest peak discharges documented at many streamflow-gaging stations are based on indirect discharge estimates, less accurate estimates of historical floods, or from extrapolation of rating curves from smaller flows. In this study, examination of some of the largest floods documented by the USGS led to the realization that some important floods reported in the NWIS database may be incorrect or inaccurate by 2007 measurement standards (Potter and Walker, 1985; Jarrett, 1987). A selected list of 30 of the largest peak discharges documented by USGS for a wide range of drainage areas was prepared. These floods are extraordinary because many define an envelope curve for the largest rainfall-runoff floods documented by the USGS. Each flood was re-evaluated using best current (2007) practices, including field visits by teams of flood experts. Experts included the three USGS Regional Surface-Water Specialists (K. Michael Nolan, Larry Bohman, and William Bartlett), local flood experts from each of the USGS Water Science Centers where the floods occurred, John England (Bureau of Reclamation), and three retired USGS flood experts (Kenneth Wahl, Vernon Sauer, Gary Gallino).

The purpose of this report is

- to conduct a comprehensive review and describe each of these “extraordinary” peak discharges,
- to assure that published peak discharge values are the most accurate possible,
- to document problems and issues that were found, and
- to use the insight gained from these flood evaluations to provide recommendations to the USGS for improvements in flood science and data collection to guide both quality control and future investigations when documenting extraordinary floods.

Because all original USGS data used in the study were collected in English units, these original units are used throughout this report.

Although this report focuses on the evaluation of 30 extraordinary peak discharges documented by the USGS, results of this evaluation raise several issues about USGS flood science including:

1. Challenges of estimating magnitude of these and other large floods;
2. The need for improving indirect discharge measurements;
3. The need to verify roughness coefficients for very large direct discharge measurements to help estimate roughness for other extraordinary floods;
4. The need for and value of measuring peak discharges at miscellaneous (ungaged) sites; and
5. Recommendations to the USGS of areas where advancements in applied flood science are needed.

Some of the measurement complications that exist with large floods, and that need to be addressed by the USGS include:

- Different kinds of flow processes;
- Sediment transport and its effects on flow roughness and flood magnitude;
- Unstable channels that scour and erode or deposit and fill, which make assumptions of cross-sectional area highly uncertain;
- Unstable flows on high-gradient slopes that create high Froude numbers (Fr), wave instabilities, and uncertain high-water marks;
- Unsafe field conditions for making direct measurements;
- Changing flow roughness as flows move overbank, sediment becomes mobile, and bank vegetation interacts with rapidly moving water;
- Uncertain boundary conditions, changing geometry, and unverified flow conditions; and
- Adequately linking the local hydrometeorology to the individual floods.

Methods used by the USGS for documenting peak discharges have not changed for many years. The introduction of hydroacoustics has helped some USGS offices, who have the technology, make more frequent direct flood measurements (Simpson, 2001), but the largest flows generally are not measured because of problems with debris, inaccessibility issues, and safety considerations. As a result, these floods must be reconstructed from field evidence, primarily stage records from streamflow-gaging stations or high-water marks identified near the streamflow-gaging station or reach of streams where flow data are desired. The USGS extrapolates rating curves to about twice the maximum measured flow. Absent a rating curve from a streamflow-gaging station, indirect measurements based on high-water mark profiles and channel cross sections are used to measure peak discharge (Benson and Dalrymple, 1967). The most common indirect method is the slope-area method (Rantz, 1982), but the slope-area method applied in high-gradient channels (greater than 0.01) is frequently unreliable (uncertainty greater than 25 percent) (Jarrett, 1987), primarily because of uncertainty in estimating flow roughness and unstable channel behavior caused by scour and fill. The field estimation of flow roughness may be the single largest source of error in slope-area computations (see for example, Bathurst, 1986; McCuen and Knight, 2006), and alternative methods to evaluate roughness are needed to improve the accuracy of indirect discharge measurements.

Evaluation of Floods

Floods were selected for a detailed evaluation based on the largest unit peak discharges (cubic feet per second per square mile) in the United States that primarily were obtained from national compilations of floods (Crippen and Bue, 1977) and from a study of the hydraulics of the largest measured floods in the United States (Costa, 1987a, 1987b). Not every flood in these reports was evaluated. The 30 flood peak discharges selected for review represent floods that define an envelope curve of maximum unit runoff in the United States, or flows that were known to have been incorrectly interpreted when originally studied. Reviews consisted of evaluating original field notes, photographs, reports, and documentation, conducting field visits to the flood locations, and conducting discussions among flood experts as to the validity and significance of previous and current information. For each flood in this report, records and data were examined for any technical errors (such as misapplication of methods), errors in process identification (primarily debris flows incorrectly interpreted as water floods), and computational errors (many of the floods were computed prior to wide usage of computer programs). Investigators agreed ahead of time that, barring some obvious and egregious error, the original field-selected or revised roughness coefficients used for the computation of peak discharge would be accepted. The subjectivity of estimating Manning's *n*-values made this assumption necessary. Investigators agreed that flood peak discharges would not be changed unless the updated analysis indicated a difference greater than about 10 percent, which is standard USGS policy (Novak, 1985).

Time and resources did not allow investigators to delve deeply into some flood-science questions that arose from this review. The primary purpose of this evaluation was to conduct a comprehensive review of past extraordinary floods and to document problems and issues to guide future investigations.

Floods that were selected for review are shown in table 1. The data in table 1 are organized geographically with the States having the largest number of floods listed first. The "rating" is a subjective adjective describing the qualitative accuracy rating of indirect discharge measurements (Benson and Dalrymple, 1967). The ratings are defined as "good" (possible error within 10 percent), "fair" (possible error of 15 percent), "poor" (possible error of 25 percent or greater), and "estimate" (possible error of greater than 50 to 100 percent). Direct current-meter measurements are rated "good" if the accuracy is thought to be within 5 percent. The "category" column of table 1 refers to the descriptions given in table 2. Original field photographs from the USGS files for each flood, when found, are included in appendix A, along with current photographs taken as part of field investigations for this report.

Flood locations are shown in figure 1. Nearly 77 percent (23 of 30) of the peak discharge locations are at ungaged sites, and only 7 occurred at regular streamflow-gaging stations that existed at the time of the flood. This is a challenging set of floods because they represent most of the largest unit-runoff flows ever documented by the USGS. Open-channel hydraulic characteristics that were either measured or calculated for 19 of the 30 peak discharges are given in table 3. Eleven peak discharges either have missing records, are computed by multiple methods, one of which did not require open-channel flow, or were measured by single methods that did not rely on open-channel flow (for example, culvert or contracted opening).

Flood locations ranged from the head of Chesapeake Bay, Md., to Kauai, Hawaii (fig. 1), and covered the period from 1927 to 1978. For each flood, the original field notes, photographs, and files were collected from the appropriate USGS office. For flood peak discharges computed by slope-area and culvert methods, the original field data and results were re-analyzed using the slope-area computation (SAC) program (Fulford, 1994) or the culvert analysis program (CAP) (Fulford, 1998).

The study began with 30 flood measurements representing a range of drainage areas from 0.15 to 1,130,600 mi^2. One flood measurement was removed from the list of studied floods (Brawley Wash tributary near Tucson, Ariz., flood of September 26, 1962). The published drainage area of the basin is believed to be in error because of either a misplaced decimal point in publication (Lewis, 1963) or an incorrect site selection for the flood along Brawley Wash. The correct drainage area for this flood is believed to be 0.661 mi^2, not the published value of 0.008 mi^2 reported in Lewis (1963) (Kyle House, University of Nevada at Reno, oral commun., 2003).

One flood measurement was added to the list when a second miscellaneous discharge measurement made for the June 14, 1935, flood on the West Nueces River in Texas was discovered (West Nueces River near Cline; table 1, map no. 6).

Figure 1. Location of 30 peak discharge measurements for 28 extraordinary floods in the United States investigated for this report.

Table 1. Summary characteristics of 30 peak discharges for the 28 extraordinary floods that define the envelope curve in the United States, and changes made as a result of this evaluation.

[Data are organized by States with the largest number of floods listed first. Values in brackets [ ] are original data that are believed to be in error and are revised in this report; revised values are shown in **bold**. Shaded peak discharges represent peak-discharge measurements for one flood. **Rating:** Subjective adjective describing the qualitative accuracy rating of indirect discharge measurements (Benson and Dalrymple, 1967); est, estimate (possible error of greater than 50 to 100 percent); f, fair (possible error of 15 percent); g, good (possible error within 10 percent); nv, no value; p, poor (possible error of 25 percent or greater). **Category**: Description of flood categories is shown in table 2. **Abbreviations:** mi^2, square mile; ft^3/s, cubic feet per second]

Map No. (fig. 1)	Site name	Drainage area (mi^2)	Date of flood	Discharge (ft^3/s)	Unit discharge (ft^3/s)	Type of measurement site	Method of peak-discharge determination	Rating	Category	Comments
TEXAS										
1	Seco Creek near D'Hanis	142	05-31-35	230,000	1,620	Misc.	Slope-area	[nv] **p**	a	–
2	North Fork Hubbard Creek near Albany	39.4	08-04-78	[103,000] **74,000**	1,880	08086150[1]; discontinued	Flow-over-road; culvert; contracted-opening	p	c	Incorrect approach angle; errors in contracted opening computations
3	Mailtrail Creek near Loma Alta	75.3	06-24-48	170,000	2,260	Misc.	Slope-area	[nv] **p**	a	–
4	West Fork Nueces River near Kickapoo Springs	402	06-14-35	580,000	1,440	Misc.	Slope-area	[nv] **p**	a	–
5	West Fork Nueces River near Brackettville	694	06-14-35	550,000	790	08190500[1]	Drainage area interpolation and rating-curve extension	nv	a	Gage did not exist in 1935
6	West Fork Nueces River near Cline	880	06-14-35	536,000	610	Misc.	Slope-area	[nv] **f**	a	–
COLORADO										
7	Jimmy Camp Creek at Fountain	[2]54.3	06-17-65	124,000	2,280	07105900[1]	Slope-area	[f] **p**	b	Gage installed at location downstream of 1965 flood measurement
8	Bijou Creek near Wiggins	1,500	06-18-65	466,000	330	06759000; discontinued	Slope-area	p	a	Gage did not exist in 1965
9	East Bijou Creek at Deer Trail	302	06-17-65	274,000	910	Misc.	Slope-area	f	a	
NEVADA										
10	Lahontan Reservoir tributary no. 3 near Silver Springs	0.22	07-20-71	[1,680] **1,840**	8,360	Misc.	Slope-area	[f] **est**	c	Hand computation error
11	Humboldt River tributary near Rye Patch	0.85	05-31-73	8,870	10,400	10335080[1,3]	Slope-area	[f] **est**	a	
12	Eldorado Canyon at Nelson Landing	22.8	09-14-74	76,000	3,330	Misc.	Slope-area	[p] **est**	a	

Table 1. Summary characteristics of 30 peak discharges for the 28 extraordinary floods that define the envelope curve in the United States, and changes made as a result of this evaluation.—Continued

[Data are organized by States with the largest number of floods listed first. Values in brackets [ ] are original data that are believed to be in error and are revised in this report; revised values are shown in **bold**. Shaded peak discharges represent peak-discharge measurements for one flood. **Rating:** Subjective adjective describing the qualitative accuracy rating of indirect discharge measurements (Benson and Dalrymple, 1967); est, estimate (possible error of greater than 50 to 100 percent); f, fair (possible error of 15 percent); g, good (possible error within 10 percent); nv, no value; p, poor (possible error of 25 percent or greater). **Category**: Description of flood categories is shown in table 2. **Abbreviations:** mi^2, square mile; ft^3/s, cubic feet per second]

Map No. (fig. 1)	Site name	Drainage area (mi^2)	Date of flood	Discharge (ft^3/s)	Unit discharge (ft^3/s)	Type of measurement site	Method of peak-discharge determination	Rating	Category	Comments
NORTH CAROLINA										
13	Big Creek near Waynesville	1.69	08-30-40	[13,000] **Unknown**	Indeterminate[4]	Misc.	Slope-area	nv	f	Debris flow
14	Wilson Creek near Adako	65.5	08-13-40	99,000	1,510	Misc.	Slope-area	[nv] **est**	e	Lost or missing records
NEW MEXICO										
15	El Rancho Arroyo near Pojoaque	6.7	08-22-52	[44,000] **34,800**	5,140	Misc.	Slope-area	p	c	Cross section increased by probing sand
16	Cimarron Creek tributary near Cimarron	[0.05] **0.15**	06-05-58	[337] **340**	2,270	Misc.	Culvert	f	a	
OREGON										
17	Meyers Canyon near Mitchell	12.7	07-13-56	54,500	4,290	Misc.	Slope-area	[f] **est**	d	Possible disconnected flow surfaces
18	Lane Canyon near Nolin	5.04	07-26-65	28,500	5,660	Misc.	Slope-area	[f] **p**	a	
ARIZONA										
19	Bronco Creek near Wikieup[5]	19	08-19-71	[73,500] **96,800**	5,100	Misc.	Slope-area	[p] **est**	d	Transient hydraulic wave peak; significant flow instability. Runoff flood peak would be about 28,300 ft^3/s
CALIFORNIA										
20	Day Creek near Etiwanda	4.56	01-25-69	[9,450] **Unknown**	Indeterminate	[6]11067000 discontinued	Slope-area	nv	f	Debris flow
21	Eel River at Scotia	3,113	12-23-64	752,000	240	[1]11477000	Rating-curve extension	[nv] **p**	b	Omitted highest measured flows
UTAH										
22	Little Pinto Creek tributary near Newcastle	0.30	08-11-64	2,630	8,770	Misc.	Slope-area	p	a	

Table 1. Summary characteristics of 30 peak discharges for the 28 extraordinary floods that define the envelope curve in the United States, and changes made as a result of this evaluation.—Continued

[Data are organized by States with the largest number of floods listed first. Values in brackets [ ] are original data that are believed to be in error and are revised in this report; revised values are shown in **bold**. Shaded peak discharges represent peak-discharge measurements for one flood. **Rating:** Subjective adjective describing the qualitative accuracy rating of indirect discharge measurements (Benson and Dalrymple, 1967); est, estimate (possible error of greater than 50 to 100 percent); f, fair (possible error of 15 percent); g, good (possible error within 10 percent); nv, no value; p, poor (possible error of 25 percent or greater). **Category**: Description of flood categories is shown in table 2. **Abbreviations:** mi^2, square mile; ft^3/s, cubic feet per second]

Map No. (fig. 1)	Site name	Drainage area (mi^2)	Date of flood	Discharge (ft^3/s)	Unit discharge (ft^3/s)	Type of measurement site	Method of peak-discharge determination	Rating	Category	Comments
MISSOURI										
23	Boney Branch at Rock Port	0.708	07-18-65	5,080	7,175	Misc.	Slope-area	f	a	
IOWA										
24	Stratton Creek near Washta	1.9	08-09-61	11,000	5,790	Misc.	Slope-area; culvert; flow-over-road	est	b	
SOUTH DAKOTA										
25	Castle Creek tributary no. 2 near Rochford	0.0192	07-28-55	[98.9] **100**	5,200	Misc.	Culvert; flow-over-road	f	a	
WASHINGTON										
26	Wenatchee River tributary near Monitor	0.15	08-25-56	903	6,000	Misc.	Slope-area (average of two computations)	[f] **p**	b	
HAWAII										
27	South Fork Wailua River near Lihue	22.4	04-15-63	[87,300] **68,800**	3,070	16060000[1]	Slope-area	p	c	Improper cross-section subdivision
MARYLAND										
28	Susquehanna River at Conowingo	27,100	06-24-72	1,130,000	42	01578310[1]	Current meter	g	a	
ILLINOIS										
29	Ohio River at Metropolis	203,000	02-01-37	1,850,000	9	03611500[1]	Current meter	[nv] **g**	a	
ARKANSAS										
30	Mississippi River near Arkansas City	1,130,600	05-01-27	2,470,000	2	07265450 discontinued	Unknown	est	e	Lost or missing records (from U.S. Army Corps of Engineers)

[1]Flow data available from U.S. Geological Survey at http://nwis.waterdata.usgs.gov/nwis/peak.
[2]Gage not installed at same location as 1965 flood measurement. Current gage drainage area is 65.6 mi^2.
[3]Not a streamflow-gaging station; station number assigned to this miscellaneous (ungaged) site; no other peaks measured there.
[4]Conditions are such that it would be incorrect to recompute, or determine a reliable peak discharge using other methods.
[5]Two peaks possible for this flood: transient waves of 3–5 ft high (reported here), and a ‘base flood’ runoff peak of 28,300 ft^3/s (House and Pearthree, 1995).
[6]Discharge indeterminate, but peak stage reported. Additional data available from U.S. Geological Survey, California Water Science Center, Sacramento, California.

Three of the 30 flood measurements (table 1) are from along the West Nueces River in Texas and document the magnitude of the 1935 flood. The 1965 floods in the South Platte and Arkansas River basins produced three floods included in this study, all from the same storm system but on different days and streams. The final list of floods studied here (table 1) consist of 30 peak-discharge measurements made during or following 28 different individual storms.

Overview of Flood Evaluation

Locations of each of the 30 flood peak discharges (table 1) were visited in the field by local flood experts except for the Susquehanna River, Ohio River, and Mississippi River locations. Each of the floods was categorized according to one of six descriptions shown in table 2. Hydraulic characteristics of these floods are summarized in table 3.

Only one-third of the flood peak discharges were determined to require no change (10 of 30). Of the 20 floods where changes are recommended, nine are floods where only the qualitative ranking of the accuracy of the measurement was changed, such as a rating downgraded from fair to poor. Seven of the 30 flood peak discharges (23 percent) require a significant change (generally defined as greater than about 10 percent) in the value of the published flood peak discharge. In spite of careful searching, original records for two of the floods could not be located. This is unfortunate because these are among the most interesting floods in the history of the United States.

Table 2. Descriptions of flood categories used in evaluation of peak discharges from extraordinary floods in the United States.

Category	Description	Action	Number of peak discharges
a	Peak discharge and any accuracy rating are acceptable as published.	Retain peak; retain rating	16
b	Peak discharge is a result of some questionable field or hydraulic measurements or assumptions. Reliability is less than originally thought, but no significant revision (about 10 percent or greater change in discharge) is warranted.	Retain peak; downgrade rating	4
c	Peak discharge is the result of an error, procedure, or adjustment inappropriately applied as identified in this evaluation. The identified error(s) are sufficiently straightforward that peak discharge can be corrected. Corrected peak discharge is about 10 percent or greater difference from what was originally reported and should be corrected in USGS databases.	Correct peak; correct rating	4
d	Peak discharge is debatable based on field conditions, methods, or assumptions made at the time of original field work. Sufficient evidence exists to believe the published discharge could be in significant error. Adjustment of the peak discharge may or may not be warranted. Significant new work would be required to improve discharge estimate, if possible at all. The record should be flagged with qualification code “2” (estimate) to reflect status as an estimate if not already qualified as such.	Peak suspect; rate as estimate	2
e	Original files and data not available (misplaced or lost).	Continue searching for original records	2
f	Peak discharge is believed to be the product of invalid field conditions or interpretations that are not realistic. This could include debris flows misidentified as floods. New evidence documented here is compelling, and the original work equivocal. Improved estimates are not currently possible with newer methods or additional data. Peak discharge is so unreliable or irrelevant as to warrant replacement in databases with a flag or notice.	Remove numerical value of discharge; retain stage or other evidence of flood; retain original field records and data	2

Table 3. Hydraulic characteristics for 19 of 30 peak discharges for the 28 selected extraordinary floods in the United States.

[Floods not listed had peak discharges computed with methods other than open-channel flow conditions. Shaded peak discharges represent peak-discharge measurements for one flood. Values in brackets [ ] are original data that are believed to be in error and are revised in this report; revised values are shown in **bold**. **Abbreviations:** ft, feet; ft/ft, foot per foot; ft^3/s, cubic feet per second; ft/s, feet per second; mi^2, square miles; –, no data]

Map No. (fig. 1)	Site name	Drainage area (mi^2)	Date of flood	Discharge (ft^3/s)	Unit discharge (ft^3/s)	Hydraulic depth (ft)	Hydraulic radius (ft)	*n*-value	Mean velocity (ft/s)	Alpha	Froude No.	Water-surface slope (ft/ft)
1	Seco Creek near D'Hanis	142	05-31-35	230,000	1,620	15.9	15.7	0.045	18.6	1.00	0.82	0.0117
3	Mailtrail Creek near Loma Alta	75.3	06-24-48	170,000	2,260	8.8	8.8	0.035	13.7	1.03–1.04	0.81	0.0063
4	West Fork Nueces River near Kickapoo Springs	402	06-14-35	580,000	1,440	36.1	35.1	0.030	22.6	1.00	0.66	0.0035
6	West Fork Nueces River near Cline	880	06-14-35	536,000	610	19.2	19.1	0.040	15.3	1.00	0.60	0.0032
7	Jimmy Camp Creek at Fountain	54.3	06-17-65	124,000	2,280	4.0	3.9	0.028	11.4	1.13–1.40	1.01	0.0073
8	Bijou Creek near Wiggins	1,500	06-18-65	466,000	330	8.0	8.0	0.020–0.035	15.4	1.40–1.46	0.96	0.0034
9	East Bijou Creek at Deer Trail	302	06-17-65	274,000	910	6.1	6.1	0.025–0.060	11.8	1.56–1.87	0.84	0.0035
10	Lahontan Reservoir tributary no. 3 near Silver Springs[1]	0.22	07-20-71	[1,680] **1,840**	8,360	1.9	1.9	0.035–0.044	21.3	1.00–1.18	2.75	0.0777
11	Humboldt River tributary near Rye Patch	0.85	05-31-73	8,870	10,400	4.9	4.5	0.032	31.2	1.00–1.09	2.49	0.0810
12	Eldorado Canyon at Nelson Landing	22.8	09-14-74	76,000	3,330	7.5	7.2	0.028	32.5	1.00	2.12	0.0545
15	El Rancho Arroyo near Pojoaque	6.7	08-22-52	[44,000] **34,800**	5,140	5.2	5.1	0.025–0.040	20.6	1.21–1.27	1.6	0.0195
17	Meyers Canyon near Mitchell	12.7	07-13-56	54,500	4,290	7.9	7.3	0.048	21.2	1.23–1.37	1.33	0.0389
18	Lane Canyon near Nolin	5.04	07-26-65	28,500	5,660	7.0	6.6	0.032	27.6	1.00	1.84	0.0349
19	Bronco Creek near Wikieup	19	08-18-71	[73,500] **96,800**	5,100	7.2	7.0	0.040	23.1	1.00–1.07	1.52	0.0286
22	Little Pinto Creek tributary near Newcastle	0.30	08-11-64	2,630	8,770	2.7	2.6	0.045	17.8	1.00	1.91	0.0878
23	Boney Branch at Rock Port	0.708	07-18-65	5,080	7,175	5.6	5.3	0.055	6.5	1.11–1.39	0.49	0.0058
26	Wenatchee River tributary near Monitor	0.15	08-25-56	9003	6,000	2.1	1.94	0.047	13.9	1.0–1.19	1.69	0.1369
27	South Fork Wailua River near Lihue	22.4	04-15-63	[87,300] **68,800**	3,070	16	15.2	0.035–0.120	15.3	1.062–1.453	0.68	0.0151
28	Susquehanna River at Conowingo	27,100	06-24-72	1,130,000	42	32.6	–	–	8.1	–	0.25	–

[1]Hydraulic variables differ from those reported in Costa (1987a, 1987b) because of corrections in slope-area computations.

Seven of the 30 peak discharges occurred at USGS streamflow-gaging stations, but three of the stations in operation when the floods occurred have been discontinued; one station was discontinued before the flood (Bijou Creek near Wiggins, Colo., map no. 8 table 1), and one station was established after the flood (flood of 1965 on Jimmy Camp Creek, Colo., map no. 7, table 1) but not at the exact location of the original flood measurement). Three of the seven floods at gaging stations (43 percent) had significant errors that required a change in the peak discharge, and one flood record could not be found at all. The error rate is higher at streamflow-gaging stations than at ungaged miscellaneous sites. Data for all evaluated floods are summarized in table 1.

When large floods occur at locations where there are no streamflow-gaging stations, the flow must be reconstructed by indirect discharge methods (Benson and Dalrymple, 1967). If the flow is sufficiently large, it can overwhelm and destroy a streamflow-gaging station. Today (2007), flood data recorded up to the stage where the gage is destroyed are captured by remote data transmission. Indirect discharge methods must be used in cases where there is no record of flow. All widely used indirect discharge methods in the USGS assume quasi-steady one-dimensional flow, which can be far from reality during large floods on steeper gradient streams. Of the 30 floods evaluated during this study, only 2 floods were directly measured by a current meter during the peak discharge, and both floods were in excess of 1.1 million ft^3/s—the 1937 flood on the Ohio River at Metropolis, Illinois, and the 1972 flood on the Susquehanna River at Conowingo, Maryland, at the head of Chesapeake Bay (map nos. 29 and 28, respectively, table 1). These direct measurements are the best data available for computing flow, but unfortunately direct measurements during outstanding floods are rare. It should be anticipated that there is substantial uncertainty in the values of discharge for all the floods listed in table 1, and none, except one directly measured flood, are rated better than fair.

Of the 30 floods evaluated during this study, 21 were estimated by the slope-area method (Dalrymple and Benson, 1967). Of the remaining floods, two were direct current-meter measurements, one was based on extending the rating curve for the streamflow-gaging station, one was solely a culvert measurement, and four were compilations of multiple methods, including flow-over-road and culvert measurement, interpolation and rating-curve extension, a combination of flow-over-road, culvert, and contracted opening measurement, and a combination of flow-over-road, culvert, and slope-area methods. For extraordinary floods, it is not unusual for multiple methods of flow estimation to be combined into one peak discharge value. The method of computation for one flood peak discharge is unknown because of missing files and data (1927 flood on the Mississippi River at Arkansas City, Ark.; map no. 30, table 1).

Description of Specific Problems and Errors Recognized in the Floods Reviewed

The review of the 30 individual flood peak discharges led to the revision of 7 of the original peak discharge values. No reasonable evidence exists to discount or deny the values for the two floods in the Peak-Flow File for which original data could not be found, so these values are accepted as published in previous USGS reports.

Debris Flows

Two floods have compelling evidence that indicates they were debris flows and not water floods. These debris flows occurred on Day Creek near Etiwanda, Calif. (station 11067000, map no. 20, table 1), and Big Creek near Waynesville, N.C. (ungaged site, map no. 13, table 1). Proper identification of the flow process in small basins is important. For purposes of computation of peak discharge, the standard hydraulic methods developed by the USGS are based on the Newtonian flow of floodwater (Pierson and Costa, 1987; Pierson, 2005). Debris flows, a type of mass movement or landslide, are distinctly non-Newtonian (Johnson, 1970; Pierson and Costa, 1987; Iverson, 2003), and peak discharges computed for debris flows using Newtonian-based relations are known to be unreasonably large (Jarrett, 1994). For example, following a debris flow in an instrumented river in Japan (Name River), peak discharge computed for the debris flow was about 60 times greater than the estimated peak discharge obtained by assuming a rainfall/water flood (Takahashi, 1991). Debris flows typically modify their channels by erosion or deposition to a significant degree during the waning stages of a flood. Post-flood channel geometry may bear little relation to the channel width or depth at the time of peak flow (Costa, 1984). Historically, some debris flows in mountain watersheds have been incorrectly interpreted and analyzed as water floods (Costa and Jarrett, 1981). Engineers and geologists widely recognize that floods and debris flows are distinct processes (Vanoni, 1975; Hungr and others, 2001), and the National Research Council cautions that it is technically incorrect to mix runoff (flood) processes with landslide (debris-flow) processes in risk analysis (Committee on Alluvial Fan Flooding, 1996).

The distinction between debris flows and water floods is important because (1) mitigation procedures for water floods, such as channelization and damming, may not be effective for debris flows; (2) the mechanics of water floods and debris flows are fundamentally different, and as such their magnitudes cannot be estimated in the same manner;

and (3) because of sparse rainfall data in mountainous regions, some may attempt to use indirect discharge estimates to determine the amount of rainfall that occurred during a storm (Miller and others, 1978). This attempt could lead to inaccurate estimates of rainfall and flood discharges that are used in the design of flood-control structures and flood-frequency estimates (Costa and Jarrett, 1981; Jarret, 1987). Costly protective measures and risk areas designed for large water floods could be ineffective for debris flows.

Commonly, it is not difficult to identify the flow process in steep mountain basins because debris flows leave distinctive deposits and landforms (Pierson, 2005). The streamflow-gaging program of the USGS is designed and funded to measure water flow, not mass movements. An entirely different kind of analysis is required to interpret risk from debris flows, including different instrumentation, field methods, vocabulary, theory, and engineering solutions (Jakob and Hungr, 2005).

Day Creek near Etiwanda, California (Station 11067000)

The record flow of January 25, 1969, followed unusually intense rainfall that blanketed the San Gabriel Mountains in Southern California in January 1969 (Singer and Price, 1971). The indirect discharge measurement for the storm of January 25, 1969, at Day Creek near Etiwanda (map no. 20, table 1) stood out as a high outlier compared to other floods from the storm in the same region. Upon examination of the original 1969 Day Creek indirect discharge measurement, significant weaknesses and uncertainties were apparent:

1. The selected four-section slope-area reach was a rapidly expanding section at the head of an alluvial fan.
2. Conveyance ratios limits were exceeded and were significantly different among the cross sections.
3. Reach lengths between sections were too short.
4. Cross-section Froude numbers ranged from 60 to 2
5. Velocity head in section 1 was more than 20 ft, greater than the fall in the reach (Kirby, 1987).
6. The reviewer of the slope-area measurement (L.A. Martens, USGS) wrote “It may be that high-water marks defined both banks at the level indicated, but I very much doubt if it did this at the same time. I believe that the flow meandered back and forth as debris blocked the flow. Probably no section completely describes the true flow area but since No. 1 is the smallest, it comes closest.” [Quote from original review of indirect contained in original files, dated March 3, 1969.]

The original four-section slope-area measurement produced a discharge value of 29,740 ft^3/s but was deemed unreliable upon review. The reviewer (L.A. Martens, USGS) recommended that a slope-conveyance computation be made at the smallest cross section and that the result be rated “poor.” For conveyance (*K*) of 33,047 and an average slope of 0.0821 ft/ft, the slope-conveyance measurement was 9,450 ft^3/s. After additional consultation with flood expert H.F. Matthai (USGS), the decision was made to finalize the peak discharge value at 9,500 ft^3/s and call it a “field estimate.” This implies uncertainty and error that are significantly greater than 25 percent, and could be greater than 100 percent.

Numerous debris flows from this storm near Glendora, Calif., were described by Scott (1971). Day Creek is only about 18 mi east of Glendora and in the same geologic and geomorphic setting. Given this background, debris flows would be considered likely in this setting. The original field notes and field photographs strongly suggest that the peak flow at the streamflow-gaging station in January 1969 was a debris flow, not a water flood (fig. 2). This hypothesis was confirmed during a field visit by several USGS debris-flow experts in September 2002 after examination of the sedimentologic and morphologic characteristics of deposits in the original indirect discharge reach for Day Creek. Existing field evidence is unequivocal that the January 1969 flood at the Day Creek streamflow-gaging station was a debris flow. Sedimentological and morphological evidence of deposits along part of the original indirect discharge measurement reach was compared with deposits left by the January 1969 flow in photographs dated February 7, 1969. The original depositional surface was broadly convex with lobate lateral and frontal margins. Coarse clasts were concentrated on outer margins of the lobes. Deposits were clast-supported, unsorted, unstratified, and randomly oriented (no fabric); voids were packed with sandy matrix material. Most significantly, the upstream sides of the stone-masonry side walls of the weir at the streamflow-gaging station were not chipped or battered by the 1969 flow, and live oaks buried as much as 3 ft by the 1969 deposits showed no abrasion damage on upstream sides of their trunks. This lack of damage to stone walls and fragile vegetation occurred when subjected to a flow that transported clasts as much as 3 ft in diameter (figs. 3 and 4). This evidence is characteristic of debris flows and is not found associated with water floods. This evidence also indicates that the debris flow moved past the streamflow-gaging station at a slow velocity—probably no more than 3–5 ft/s because the weir walls and bridge at the gage were undamaged and because trees were gently surrounded by very coarse debris. The slow velocity of the debris flow at the streamflow-gaging station precludes any possibility that the debris flow in January 1969 could have had an instantaneous peak discharge of 9,500 ft^3/s.

Figure 2. Very coarse lobate boulder deposits and remnants of natural levees, which are characteristic of debris flows, near slope-area reach of Day Creek, California, 2002.

Figure 3. Location and condition of Day Creek near Etiwanda streamflow-gaging station, California, November 1968. View is looking downstream.

Figure 4. Deposits filling weir at Day Creek near Etiwanda streamflow-gaging station, California, February 7, 1969. View is looking upstream.

For at least two decades, the USGS has recognized that slope-area methods for calculating peak discharge were not appropriate for debris-flow processes (Costa and Jarrett, 1981; Cannon and others, 2003). Scientists and engineers active in debris-flow investigations have further realized that peak discharge is not an appropriate measure of debris-flow magnitude, and current research is focused on developing models for characterizing magnitude by measures of volume rather than peak discharge. Failure volume is the primary factor affecting where debris flows will travel once initiated (Iverson and others, 1998).

The original published peak discharge of 9,500 ft^3/s for the January 25, 1969, flow at Day Creek near Etiwanda was deemed unreliable because of the unequivocal evidence that the event was a debris flow. On this basis, the discharge value was removed from the USGS Peak-Flow File, but the gage height (9.90 ft and the highest on record) was retained. The next four largest annual peak discharges are not likely to be any more reliable (table 4). The record for the 1969 annual peak discharge for this site should continue to report the stage (9.90 ft) but with no discharge (indeterminate). There are numerous examples of floods at streamflow-gaging stations in USGS databases for which a gage height was recorded but for which, for various reasons, a peak discharge could not be determined. Examples are shown in the following Web sites for South Fork Toutle River at Toutle, Wash.; Toutle River at Kid Valley, Wash.; Pea River at Elba, Ala.; Root River at Rushford, Minn.).

http://nwis.waterdata.usgs.gov/ca/nwis/peak?site_no=11067000&agency_cd=USGS&format=html

http://nwis.waterdata.usgs.gov/wa/nwis/peak?site_no=14241500&agency_cd=USGS&format=html

http://nwis.waterdata.usgs.gov/al/nwis/peak?site_no=02364000&agency_cd=USGS&format=html

http://nwis.waterdata.usgs.gov/mn/nwis/peak?site_no=05384350&agency_cd=USGS&format=html

Retention of the large gage height associated with the 1969 debris flow at the Day Creek gage site in the Peak-Flow File clearly indicates that a very significant event took place at this streamflow-gaging station on January 25, 1969, and all basic data associated with this event are available to anyone. The basis for discrediting the 1969 peak discharge value is not the uncertainty of the number or the difficulty in

Table 4. Basis for peak discharge values for Day Creek near Etiwanda, California.

[**Abbreviations:** ft^3/s, cubic feet per second]

Water year	Computation method	Discharge (ft^3/s)	Unit discharge (ft^3/s)	Comments
1938	Estimated rainfall-runoff	4,200	921	Published value
	Slope area	14,700	6,390	Invalidated by original party
	Slope area	44,000	8,980	Invalidated by original party
	Slope area	9,100	1,995	Invalidated by original party
	Estimate	8,000	1,754	Invalidated by original party
1943	Estimate	1,500	329	Published value
	Estimate	720	158	Not used
1950	Slope area	580	130	Published value
	Slope area	680	149	Superseded by published value
	Slope area	720	158	Superseded by published value
	Slope area	852	187	Superseded by published value
	Critical depth	820	180	Superseded by published value
	Slope area	600	131	Not used
1966	Gage height and field estimate	1,740	380	Published value
	Critical depth	800		Not considered
	Slope area	970	131	
1969	Slope conveyance	9,450	2,080	Determined to be invalid
	Slope area	29,740	6,500	Invalidated by original party

acquisition of high-flow data in this setting, but the application of an indirect discharge method known to be inappropriate for mass movements such as a debris flow. Local interests are concerned about the significance of reinterpreting the 1969 flood as a debris flow, which places the event outside the scope and measurement capability of a streamflow-gaging station. These concerns are summarized in Berg and Boyarsky (2004). A landslide hazards analysis is needed to address the consequences of debris flows downstream of the Day Creek streamflow-gaging station.

The peak-discharge record for the Day Creek near Etiwanda streamflow-gaging station includes other published peak discharges that are problematic and may be debris flows rather than water floods (table 4). Prior to 1969, the largest documented flood occurred in March 1938. Several slope-area measurements near the gaging station resulted in calculated discharges ranging from 9,100 to 44,000 ft^3/s. A different interpretation of one slope-area measurement resulted in an estimated peak discharge of 8,000 ft^3/s. All slope-area calculations were noted as “doubtful” and invalidated by the original field party. The published peak discharge for 1938 was 4,200 ft^3/s, based on rainfall-runoff estimates, and was coded as an estimate. Original field photographs show coarse lobate deposits and levees that are typical of debris flows. Nevertheless, the evidence for a debris flow in 1938 is not as compelling as that for the larger 1969 flow, and the published 1938 peak discharge was retained in the Peak-Flow File. Documentation for other large flow peak discharges in 1943, 1950, and 1966 also indicated uncertainty about the peak discharge, and published values for 1943 and 1966 were noted as “arbitrary estimate” and “field estimate,” respectively. Several indirect-measurement calculations were made for the peak discharge in 1950, although these values ranged somewhat modestly from only 580 (the published value) to 850 ft^3/s. The 1967 peak discharge of 1,330 ft^3/s was only slightly smaller than the “field estimate” value of 1,740 ft^3/s published in 1966, but no documentation exists describing how that value was determined. Overall, all peak-discharge values at this streamflow-gaging station greater than several hundred cubic feet per second were affected by large sediment loads that may have resulted in debris flows or hyperconcentrated flows with large uncertainties. These peak discharges should be considered no better than estimates.

Big Creek near Waynesville, North Carolina (Ungaged Site)

Big Creek (map no. 13, table 1) is a small tributary of the West Fork Pigeon River near Waynesville, N.C. The creek was near the center of severe summer thunderstorms on August 30, 1940. The storms produced hundreds of debris avalanches and debris slides on steep mountain slopes, some of which continued downstream as debris flows (U.S. Geological Survey, 1949). This flow is interpreted to be a debris flow. The best available evidence is photographs taken by the Tennessee Valley Authority after the storm, and the numerous other landslides from the storms documented in the surrounding area. The channel of Big Creek, about 450 ft upstream of the slope-area measurement site, is shown in figure 5. The channel has the distinctive U-shape morphology of a channel following the passage of a non-deforming rigid plug with finite strength, such as a debris avalanche/debris flow (Johnson, 1970).

The documented debris avalanches associated with the thunderstorms and the distinctive channel morphology in the slope-area reach provide strong evidence that the August 30, 1940, indirect discharge estimate for Big Creek near Waynesville, N.C., was most likely a debris flow. This miscellaneous peak discharge should not be included in the record of flood peak discharges, but the occurrence of a debris flow down the channel is a significant public-safety concern as well as of geomorphic interest and should be documented as part of the original records for this site.

Figure 5. View looking upstream of slope-area measurement site after storm of August 1940, Big Creek, North Carolina. Note person in right-center of photograph for scale and the U-shaped channel cross-section characteristic of some debris-flow channels.

Technical Errors of Interpretation

Three floods were discovered to have technical errors of interpretation that needed to be re-evaluated—North Fork Hubbard Creek near Albany, Tex. (map no. 2), El Rancho Arroyo near Pojoaque, N. Mex. (map no. 15), and South Fork Wailua River near Lihue, Hawaii (map no. 27).

North Fork Hubbard Creek near Albany, Texas (station 08086150, Discontinued)

The documentation for this flood is contained in USGS Professional Paper 1332 (Schroeder and others, 1987). Torrential rainfall from the remnants of Tropical Storm Amelia produced a maximum 72-hour rainfall total of more than 48 in. at a location 11 mi northwest of Medina, Tex., on August 1–4, 1978. This storm set a new extreme point-rainfall record for a 72-hour period in the United States.

The peak discharge of 103,000 ft^3/s from 39.4 mi^2 was based on a combination of flow-over-road, bridge contracted-opening, and culvert flow computations at the gaging station (fig. 6). The three flow components were computed to be:

- Flow over road – 81,500 ft^3/s
- Bridge contracted opening – 20,500 ft^3/s
- Culvert flow – 1,040 ft^3/s

The primary difficulties with the indirect discharge computations were the assumption that flow was perpendicular to the road and several errors in the contracted-opening measurement. Flow perpendicular to the road was likely not the case considering the alignment of the roadway and channel. Another concern was the uncertainty associated with the hydraulic-head losses between upstream high-water marks and the road crest. Upstream high-water marks were about 50 ft from the road, far apart, and sparse. The contracted-opening computations had a number of mistakes and errors that would change the discharge value by about 10 percent. These inaccuracies included a math error in computation of the contraction coefficient, use of net rather than gross area of the submerged bridge (see Matthai, 1967, p. 3), and incorrect computation of the wetted perimeter of the contracted section. Recomputation of peak discharge using the corrections previously noted produces:

- Road overflow: 66,000 ft^3/s
- Bridge contracted opening: 22,500 ft^3/s
- Culvert flow: 1,040 ft^3/s

This recomputation results in a revised computed discharge of 89,500 ft^3/s rather than 103,000 ft^3/s.

A second independent indirect discharge computation using the slope-conveyance method was made during this review. Using several methods to estimate channel slope, a relation with stage was established and used to compute rating-curve plotting points. For a stage of 23.3 ft for the August 1978 flood, the peak discharge from the rating curve would have been 58,600 ft^3/s.

The original peak discharge value of 103,000 ft^3/s is not acceptable primarily because it is based on incorrect assumptions regarding road overflow and errors in the contracted-opening computations. Two independent recomputations of peak discharges produced values of 58,600 and 89,500 ft^3/s. The mean of these two values is 74,000 ft^3/s, which probably is the more accurate estimate of peak discharge for this flood. It is not possible to determine which of the two independent discharge estimates is more correct. Both values were based on flow assumptions and reconstructions of a very large flood and both have significant uncertainty. When this situation arises in the field, USGS protocol is to average the independent calculations and report the mean as the peak discharge. The revised peak discharge is rated “poor,” with a probable error of ±25 percent. The revised peak discharge is 28 percent less than the original published value.

Figure 6. View of right end of bridge across North Fork Hubbard Creek near Albany, Texas, August 1978. Flow was about 2 feet above guardrails.

El Rancho Arroyo near Pojoaque, New Mexico (Ungaged Site)

Flood No. 15 on El Rancho Arroyo near Pojoaque, N. Mex. (map no. 15, table 1) resulted from a severe rainstorm on August 22, 1952. A three-section slope-area discharge measurement was made later that month, but upon review, it was determined that the discharge of 44,500 ft^3/s was too unreliable to publish. The original field data and computations remained in local USGS office files, but the peak discharge was never officially accepted or published. The flood peak discharge acquired legitimacy when Tate Dalrymple (USGS employee) included the flood peak discharge in an article in Chow's Handbook of Applied Hydrology (Chow, 1964) and it appeared again in the USGS Water-Supply Paper on maximum flood flows in the United States (Crippen and Bue, 1977). The file on this flood is extensive with evaluations and comments from many prominent flood experts over the next two decades.

Problems listed for this flood discharge computation include the large traverse (lateral) difference in elevation of between 2.8 and 6.3 ft between left- and right-bank cross-section elevations, large irregularities in right-bank water-surface profiles, high velocities and Froude numbers (1.5–1.6), and inclusion of probed scour depths in cross-sectional area computations. Probing cross sections for probable scour depth was a recommended practice in 1952. For this site, probing increased the flow area by 15–20 percent (fig. 7). Probing is not recommended today (2007) unless there is strong evidence that the channel filled with sediment after the peak discharge. Field notes clearly indicate this was not the case for this flood; rooted vegetation remained in the channel following the flood.

The addition of area to the flood cross sections as a result of probing was not appropriate for this site based on field descriptions. Recomputing the peak discharge using the SAC program (Fulford, 1994) and actual measured cross sections (without inclusion of probed area) produce a revised peak discharge of 34,800 ft^3/s. This recomputation is a decrease of 22 percent from the original flood computation. This revised peak discharge should be included in USGS flood records and rated poor.

Figure 7. View looking upstream of slope-area site at El Rancho Arroyo near Pojoaque, New Mexico, 2003. Probing increased cross-sectional area and produced a larger peak discharge than the revision reported herein.

South Fork Wailua River near Lihue, Kawai, Hawaii (Station 16060000)

Mount Waialeale on the island of Kauai, Hawaii, is considered one of the wettest places on Earth, with annual precipitation of about 460 in. The headwaters of the South Fork Wailua River are on the south slope of Mount Waialeale and a series of storms over the Hawaiian Islands in the spring of 1963 produced devastating flooding. Another storm and associated thundershowers on April 15, 1963, produced rainfall intensities of 15 in. in 24 hours over a saturated Kauai (Vaudrey, 1963) (fig. 8).

A two-section slope-area survey was conducted on May 10, 1963, to determine peak discharge on the South Fork Wailua River near Lihue. The gaging station (16060000) is about 1,500 ft upstream of Wailua Falls, and the reach from the gaging station to Wailua Falls is predominately bedrock with some coarse alluvial deposits on the banks of the channel (fig. 9). High-flow measurements are normally made from a cableway located midway between the gaging station and the top of Wailua Falls. Most high-flow measurements at this site are made using a 75-lb sounding weight, which is inadequate for the depths and velocities experienced at this site. This measurement approach creates doubts about the accuracy of direct measurements from this cableway. The upper end of the rating curve for this site is defined by high-flow measurements at the cableway, and the extreme upper end of the curve is drawn through the slope-area discharge measurement of the 1963 flood. The rate of change of discharge at the upper end of the rating for this site is 2,000 ft^3/s per 0.1 ft change in stage, which is extraordinary for a stream only about 300 ft wide.

Figure 8. View looking downstream of streamflow-gaging station after the 1963 flood at South Fork Wailua River near Lihue, Hawaii.

Figure 9. View looking downstream of streamflow-gaging station toward slope-area reach, South Fork Wailua River near Lihue, Hawaii, February 25, 2003.

The field visit to this site confirmed that the site and conditions made an indirect discharge measurement difficult, and there was the possibility of a road-fill failure just downstream of the gaging station. A very wide cross section measured at section B likely had a significant area of noncontributing flow, possibly even reverse flow in a large eddy that caused the right-bank water-surface profile to be almost flat. A composite Manning's *n*-value for section B of 0.055 may be low, considering that *n*-values computed from the highest measured discharges range from 0.070 to 0.075. According to the stage record and rating curve, flow increased from 470 to nearly 90,000 ft^3/s in 2 hours (fig. 10). The gaging station is just upstream of a tall waterfall (fig. 11), and this presents an excellent opportunity for critical-depth discharge estimates following future extraordinary floods, provided the approach bedrock channel sustains subcritical flow, which is not necessarily certain.

After a field visit in 2003 with personnel from the USGS Hawaii Water Science Center, Richard Fontaine, the Surface-Water Specialist made a thorough analysis of the slope-area measurement. The most likely source of error in estimating the peak discharge for this extraordinary flood is assignment and distribution of roughness coefficients in subdivided cross sections. Using field-estimated *n*-values (listed as "not used" in original field notes) and weighting them by subsection area, the SAC program computed a discharge of 68,800 ft^3/s or a revised flood estimate about 21 percent less than originally computed. This was an operational streamflow-gaging station in 2007. The revision to the peak of record resulted in no changes to daily flow values, revision of about 18 peak discharges above base, and flood-frequency changes of –5.2 percent for the 10-year flood and about –12 percent for the 100-year flood.

Clerical (Arithmetic) Error

One flood was found to have arithmetic errors as a result of hand calculations of a two-section slope-area indirect discharge estimate—Lahontan Reservoir tributary no. 3 near Silver Springs, Nev. (map no. 10, table 1). The real value of total cross-sectional area was mistakenly entered as the area of one of the subsections, which produced a larger cross section than was really the case. A second error was made by entering an extra digit when computing conveyance for this same section. The conveyance error was more significant than the cross-section area error. Even though

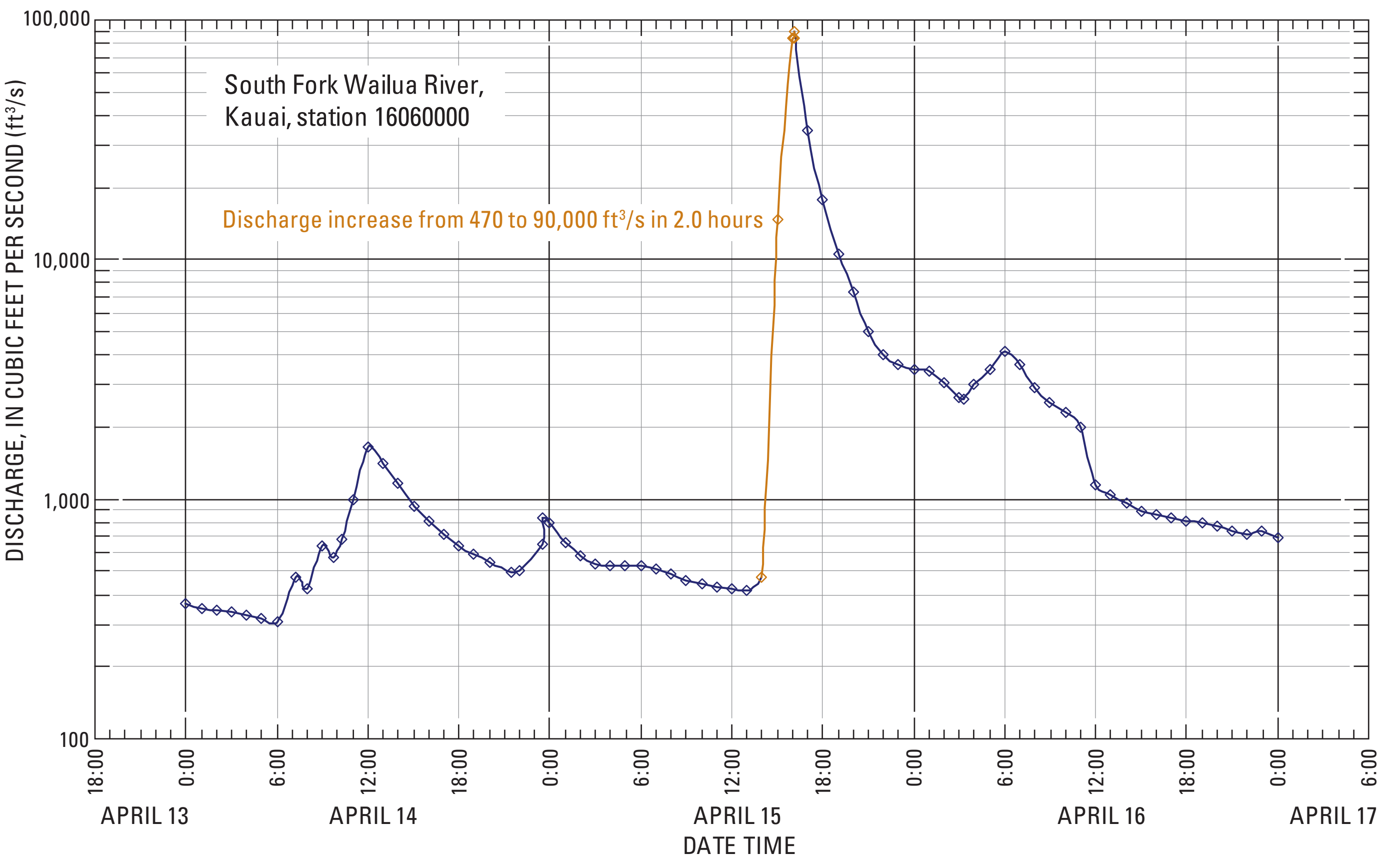

Figure 10. 1963 flood on South Fork Wailua River near Lihue, Hawaii.

Figure 11. View looking just downstream of cableway and streamflow-gaging station, South Fork Wailua River at Wailua Falls, Hawaii, February 25, 2003.

the cross-section area was reduced, the corrected conveyance value resulted in an increase in discharge. When the correct cross-section area and conveyance were used, both the hand-calculation revisions and SAC program produced a peak discharge of 1,840 ft^3/s. This revised peak is about 10 percent larger than the original published value of 1,680 ft^3/s. The revised peak discharge of 1,840 ft^3/s should replace the original discharge measurement of 1,680 ft^3/s. The rating of this measurement is downgraded from fair to estimate primarily because of the unusually large Froude numbers (average of 2.75 for two cross sections).

The revised indirect discharge measurement is one example of many other peak discharges computed in small steep basins that present significant hydraulic challenges—extraordinary values for velocity head and unusually large Froude numbers (greater than 2). Lahontan Reservoir tributary no. 3 has a slope of 0.078 and presents uncertainty in *n*-values, scour, unsteady flow, number of cross sections (minimum of three needed for reliable slope-area measurement; only two used here), and flow instabilities associated with very large Froude numbers (Jarrett, 1987).

Unresolved Problems with Extraordinary Flood Peak Discharges

Six floods presented unique and difficult situations that made resolution of the original published peak discharge impossible or uncertain at best. These flood peak discharges are listed in table 5.

The unresolved problems with peak discharges were discussed previously for Big Creek near Waynesville, N.C.; Wilson Creek near Adako, N.C.; Day Creek near Etiwanda, Calif.; and Mississippi River near Arkansas City, Ark. The flood peak discharges for Bronco Creek near Wikieup, Ariz., and Meyers Canyon near Mitchell, Oreg., were the most difficult to review and interpret. Both are highly controversial and have been the basis of several reports with conflicting conclusions.

Bronco Creek near Wikieup, Arizona (Ungaged Site)

The Bronco Creek site is sufficiently complex and interesting that its study was a major component of a PhD thesis (House and Pearthree, 1995), which itself initiated another paper that analyzed the flood ((Hjalmarson and Phillips, 1997) and produced subsequent discussion and reply (House and others, 1998). On August 19, 1971, an intense thunderstorm deposited about 3 in. of rain in less than 1 hour in the area of Bronco Creek, located about 45 mi southeast of Kingman, Ariz. (map no. 19, fig. 1). The bridge on State Highway 93 was severely damaged. A four-section slope-area indirect discharge measurement was made about 2 weeks later. The original USGS slope-area measurement produced a peak discharge of 96,800 ft^3/s, but during review the field-selected Manning's *n*-values were increased from 0.028–0.032 to 0.040. This change resulted in the published peak discharge of 73,500 ft^3/s, which makes this flood the largest ever documented for a 19-mi^2 basin in the United States as well as the world (Costa, 1987a, 1987b). As expected, this flood attracted significant scrutiny in later years. The most comprehensive examination was the work of House and Pearthree (1995). They conducted a paleoflood study in the bedrock reaches of the three major tributaries to Bronco Creek and corrected for omitted drainage area. The use of bedrock channels avoids the problem of scour and changing geometry in the alluvial reach upstream of the highway bridge where the slope-area measurement was made. Their peak discharge estimate of about 28,000 ft^3/s is much lower than the USGS indirect discharge measurement but is more consistent with the regional envelope curve for flood peak discharges in Arizona (Enzel and others, 1993) and rainfall-runoff modeling (Carmody, 1980). A photograph from the original field surveys is shown in figure 12, and a 2003 view is shown in figure 13.

Figure 12. View looking downstream following flood in 1971, Bronco Creek near Wikieup, Arizona. Note highway bridge in upper right background where waves overtopped the road.

Table 5. Unresolved problems with peak discharges for six extraordinary floods in the United States.

Map No. (fig. 1)	Site name	Unresolved problem
13	Big Creek near Waynesville, N.C.	Debris flow (no meaningful discharge possible)
14	Wilson Creek near Adako, N.C.	Lost or missing records
17	Meyers Canyon near Mitchell, Oreg.	Possible disconnected flow surfaces
19	Bronco Creek near Wikieup, Ariz.	Transient hydraulic waves; highly unsteady flow
20	Day Creek near Etiwanda, Calif.	Debris flow (no meaningful discharge possible)
30	Mississippi River near Arkansas City, Ark.	Lost or missing records

Figure 13. View looking downstream of slope-area reach toward State Highway 93 bridge across Bronco Creek near Wikieup, Arizona.

The authors were not contemplating the kinds of surges that eyewitnesses observed at Bronco Creek. Another later USGS report discusses methods for dealing with surges in streamflow measurements wherein an average discharge is computed by height and length of the waves and the time required for the waves to pass the measuring point. This discharge is significantly less than the peak discharge applied to the crest of the wave (Rantz, 1982, p. 269-270).

House and Pearthree (1995) computed the base discharge from the runoff of the storm into the channel of Bronco Creek upstream of the slope-area reach (about 28,000 ft^3/s). The unsteady wave peak discharge analysis of Hjalmarson and Phillips (1997) was made using original slope-area field data in the reach just upstream of the highway bridge where the waves were fully developed (about 96,700 ft^3/s). The instantaneous peak discharge of 96,700 ft^3/s is a product of channel instability in the steep downstream reach of Bronco Creek. The storm rainfall that generated the flood was likely insufficient to generate such a large peak discharge. Flow instabilities such as roll waves in natural channels can periodically inundate areas much higher than the steady flow discharge of the flood and can greatly reduce carrying capacity of canals (Koloseus and Davidian, 1966). The peak discharge of the August 19, 1971, flood on Bronco Creek, Ariz., should be reported as 96,800 ft^3/s, noting that this peak is likely associated with highly unstable channel conditions and wave surges that set high-water marks above those that would be expected in the absence of the channel instabilities. This peak should not be used in any regionalization or flood-frequency computations because it is a product of channel conditions unique to this location. A hypothetical hydrograph of the Bronco Creek flood is shown in figure 14.

An employee of the Arizona Department of Transportation observed the flow in Bronco Creek during the flood. He reported that about every 4 to 5 minutes, a wave extending bank to bank and 4 to 5 ft in height would sweep over the bridge, and the waves lasted for about 2 hours (Hjalmarson and Phillips, 1997). Hjalmarson and Phillips (1997) analyzed the waves using free-surface instability and celerity relations, which indicated that flow in Bronco Creek would have been highly unstable. They computed that waves may have crashed into the highway bridge at velocities greater than 40 ft/s, and instantaneous peak discharge of the largest translatory waves to be as much as 96,800 ft^3/s. Their model of this flood involves two separate but integral flood processes—a base flood peak controlled by the rainfall-runoff process in the watershed and a larger instantaneous peak discharge from waves caused by highly unstable flow conditions in the channel superimposed on the watershed-runoff flood peak. The analysis by Hjalmarson and Phillips (1997) evokes a significant question about the definition of peak discharge and the occurrence of flow instabilities.

USGS guidance on how to handle wave instability in measurement of peak discharge is ambiguous. Instructions in Benson and Dalrymple (1967, p. 11) specify:

> The effects of surge on the high-water marks found on the banks are an important point to be considered. Observation and photographs of floodflow in natural channels show that, although there may be extensive wave action in the middle of a fast-flowing stream, at the sides, velocities are low and the water surface quiet. Although there undoubtedly is some effect from surge, the high-water marks should be used as found, and no adjustments attempted for surge.

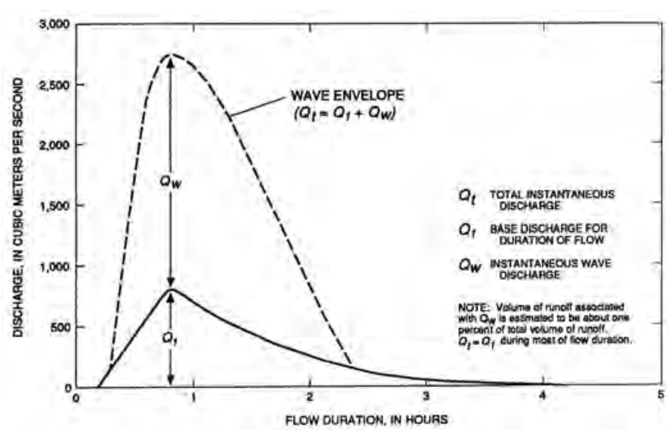

Figure 14. Hypothetical hydrograph of flood discharge for Bronco Creek flood of August 19, 1971 (from Hjalmarson and Phillips, 1997).

Meyers Canyon near Mitchell, Oregon (Ungaged Site)

Late in the afternoon of July 13, 1956, a large convective thunderstorm dumped a tremendous amount of rainfall over the Bridge Creek drainage basin in north-central Oregon, centered on the Meyers Canyon area (fig. 15). The storm and runoff were observed by W.D. Wilkinson, an Oregon State College geology professor, who was camped along the Service Creek Road in the upper Meyer's Canyon basin during the storm. Wilkinson reported rainfall starting about 4:30 p.m. and increasing in intensity until about 5 p.m. The first flood passed his camp at about 5:15 p.m. and had a crest about 7–8 ft high. A second crest passed at about 6:10 p.m. but was much lower, about 4–5 ft high. The most intense part of the storm lasted until about 6 p.m. and diminished until the rain stopped at 7 p.m. The most intense rainfall lasted only about 30 minutes. Wilkinson observed sheet runoff at the base of the hills as deep as 2 in. Velocity of the 2.5-ft-deep overbank flow near Wilkinson's camp was high enough to move his truck 500 ft across a field.

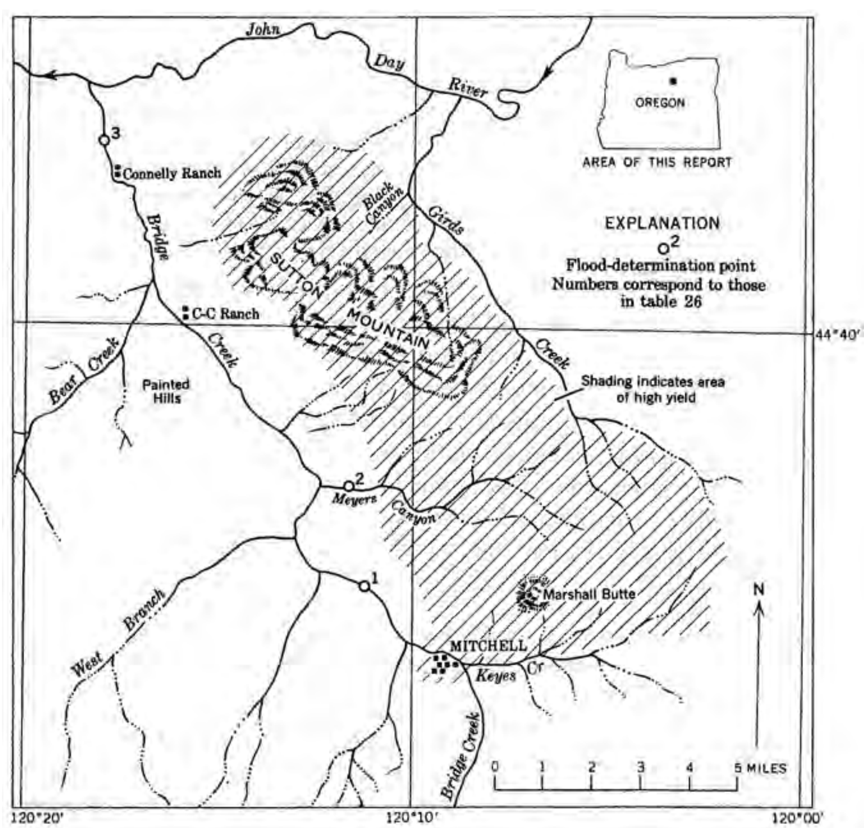

Figure 15. Location of Meyers Canyon and flood area, Oregon. Sites numbered 1 and 3 on the map are slope-area sites on Bridge Creek upstream and downstream of its juncture with Meyers Canyon. Site 2 is the location of the Meyers Canyon indirect discharge measurement discussed herein (from Hendricks, 1964).

USGS made an indirect discharge measurement of this flood shortly after the event (July 22, 1956). A three-section slope-area measurement was attempted, but geometry and hydraulic complications rendered one section unusable, so one cross section was omitted. The initial discharge of 64,000 ft^3/s from 12.7 mi^2 was from a two-section slope-area measurement. Internal review within USGS resulted in a change to the main-channel Manning's *n* roughness values from 0.045 to 0.050, which reduced the peak discharge to 54,500 ft^3/s. This peak discharge was rated fair.

The Meyers Canyon flood was among the largest ever documented from a drainage basin of 12.7 mi^2, and it attracted much attention, primarily from the Bureau of Reclamation, U.S. Department of the Interior, which operates several water-storage projects in the area. Within a month of the original fieldwork, a memorandum from F.C. Hart of the Bureau of Reclamation (August 21, 1956) was sent to USGS (copy in original files of the USGS office in Portland, Oreg.), disagreeing that the peak discharge of 54,500 ft^3/s was far too large a flood based on their field inspection of Meyers Canyon. They argued that little evidence existed downstream for a flood of this size, that the flow surface may have been disconnected between the overbank areas and the canyon, and that the valley mouth could not have held so large a flood. A recent evaluation of this flood by the Bureau of Reclamation was included in a paleoflood study of the Crooked River, Oreg., for dam safety design (Levish and Ostenaa, 1996). Levish and Ostenaa (1996) concluded that it was impossible for a peak discharge of this magnitude to have occurred in Meyers Canyon for the following reasons, most of which were presented by the Bureau of Reclamation in 1956:

- Two slope-area measurements made on Bridge Creek (into which Meyers Canyon flows) about 3 mi upstream of the juncture and about 9 mi downstream of the juncture produced discharge values of 14,400 and 16,300 ft^3/s, respectively.

- No definitive evidence of a discharge as large as 54,000 ft^3/s could be found in the reach of Bridge Creek downstream of Meyers Canyon.

- Step-backwater modeling upstream and downstream of the slope-area reach indicated maximum discharges of only about 7,000–18,000 ft^3/s.

- High-water marks at the indirect discharge measurement site were not directly associated with flow in the main channel of Meyers Canyon.

USGS personnel involved in the field work for this flood in 1956 heard these challenges and made another field visit in October 1956 with USGS Area Engineer and flood expert G.L. Bodhaine. In 1956, USGS hydrologists argued that there was more than sufficient valley storage for attenuation of the flood peak between the mouth of Meyers Canyon and the downstream indirect discharge site on Bridge Creek. Eyewitness accounts of the rainfall and runoff indicated that the hydrograph from Meyers Canyon must have been very flashy and of sufficiently short duration that it might not have produced significant erosion or deposition downstream of the mouth of Meyers Canyon. The step-backwater results (Levish and Ostenaa, 1996) rely on roughness estimates that are 25–46 percent greater than those used in the original slope-area measurement, resulting in significantly smaller discharges. USGS hydrologists did not believe there was sufficient field evidence to support an interpretation of disconnected flow surfaces, and no revision was made to the slope-area measurement. USGS published the peak discharge as 54,500 ft^3/s (Hendricks, 1964).

The uncertainty in peak discharge for this flood rests primarily on the association of high-water marks on the wide overbank valley floor and flow in the main deep arroyo down the middle of Meyers Canyon (figs. 16 and 17). The USGS peak-discharge estimate assumes that flow occupied the entire cross section between left- and right-bank high-water marks at the same time. The flow surface was assumed to be contiguous. Critics of the discharge value argue that flow broke out of the main canyon upstream of the slope-area reach, and part of the flood flowed across the overbank areas to the left and right of the main canyon. Flow in the canyon would have been lower than the top of the main channel banks, creating two disconnected flow surfaces. Near the slope-area reach, flow traveled across the overbank area and poured back into the main canyon.

The basis for this interpretation includes geomorphic evidence of a possible breakout point at the outside of a meander where the canyon depth is less than upstream or downstream (fig. 18). A second line of evidence is the interpretation that upon close inspection the

Figure 16. View looking upstream at slope-area reach in Meyers Canyon, Oregon, August 1956. Upper line represents high-water level with flow filling entire cross section at the same time. Middle line represents perched flow surface on overbank area that is disconnected from main flow in canyon (lowest line in center of figure).

Figure 17. View looking upstream at slope-area reach Meyers Canyon, Oregon, April 2003.

Figure 18. View looking downstream of Meyers Canyon, Oregon, April 2003. Downward-pointing arrow is possible breakout point of flow onto overbank areas. Arrows on flood plain show possible flow paths toward downstream slope-area reach.

photographs of the slope-area reach taken shortly after the flood in 1956 show evidence of overwash from the flood plain back into the canyon, not flow parallel to the canyon (fig. 16, such as at the left bank top of high-water mark in canyon).

New information could be gained about this flood with the use of detailed light detection and ranging (LIDAR) topography and a multidimensional flow model that could capture a hypothetical breakout of flow from the main canyon and routing of that flow down through the slope-area reach. This would be an expensive and time-consuming undertaking and was not done as part of this review. The original field work and analysis for this flood were conducted by experienced flood hydrologists, who were not convinced by arguments from the Bureau of Reclamation hydrologists that the flow measurement was significantly in error. The two-section slope-area measurement of 54,500 ft^3/s should remain as published, but the rating downgraded from “fair” to “estimate.” This flood would be an ideal case study to use with a multidimensional flow model to evaluate the potential breakout of flow from the canyon across the flood plain.

Summary of Remaining Peak Discharges for Extraordinary Floods

None of the remaining peak discharges for the extraordinary floods described in this report were found to require significant revisions. If these floods occurred today, some on larger basins might be documented by hydroacoustic methods, but the indirect discharge measurement sites, especially on smaller streams, would likely produce similar peak discharge values compared to those originally computed. Substantial advancements have been made in the development of tools and equipment for direct discharge measurements (for example, Morlock and others, 2002), but indirect discharge measurements have not evolved or improved significantly for many years. All of the extraordinary floods are individually interesting. Collectively, they define the envelope curve of maximum floods documented in the United States.

Texas Floods

Texas leads the list in the number of extraordinary floods in this investigation, which is not surprising because some of the most prolific flooding in the United States has occurred in this area (O’Connor and Costa, 2004). Six floods from Texas were studied; one (North Fork Hubbard Creek near Albany, Tex., map no. 2, fig. 1) has already been described. Five other floods all occurred in west-central Texas between San Antonio and Del Rio, Tex. (fig. 19) (Asquith and Slade, 1995).

Three floods on the list occurred in June 1935 on the West Nueces River. Sporadic but intense rainfall for 2 weeks in early June produced rain totals of about 20 in. over the entire drainage basin. Storm and rainfall details can be found in Dalrymple and others (1939). Two indirect discharge measurements were made on the West Nueces at Kickapoo Springs (map no. 4, fig. 1) and near Cline (map no. 6, fig. 1). In 1940, a streamflow-gaging station was established near Bracketville, Tex. (map no. 5, fig. 1), midway between Kickapoo Springs and Cline, and the 1935 peak discharge at this site was extrapolated from the calculated discharge upstream and downstream and listed as an historic peak. The peak discharge originally reported at Kickapoo Springs, Tex., was 580,000 ft^3/s from 402 mi^2, at a stage of 36 ft (figs. 20*A* and 20*B*). This indirect discharge measurement defines the largest rainfall-runoff flood ever documented in the world from 402 mi^2 (1,040 km^2) (Herschy, 2003); in fact, the discharge value lies significantly above the world envelope curve for rainfall-runoff floods. The SAC program, using the original two sections, *n*-values, and highest high-water marks, produced a discharge of 522,000 ft^3/s. The reach length is too short using current SAC requirements, but the primary difference between the two indirect discharge computations appears to be in energy slope and velocity head. Although this difference of 58,000 ft^3/s is 10 percent smaller than the original discharge, no change is recommended because of uncertainty in interpretation of high-water marks and water-surface slope. The original discharge value is also compatible with a decrease of peak discharge in

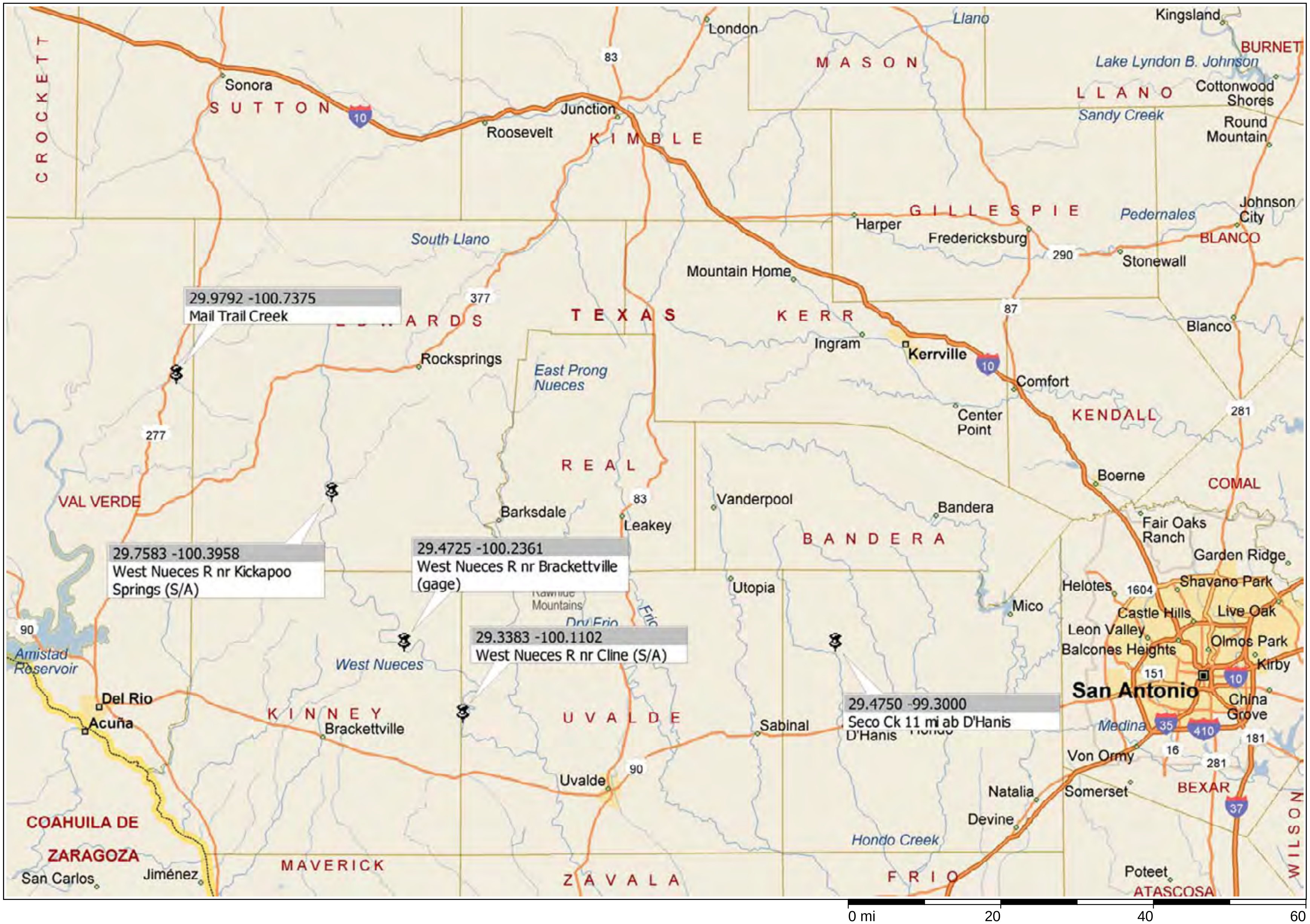

Figure 19. Locations of five of six Texas peak discharges studied in this investigation. Latitude-longitude values are provided below the names for each site.

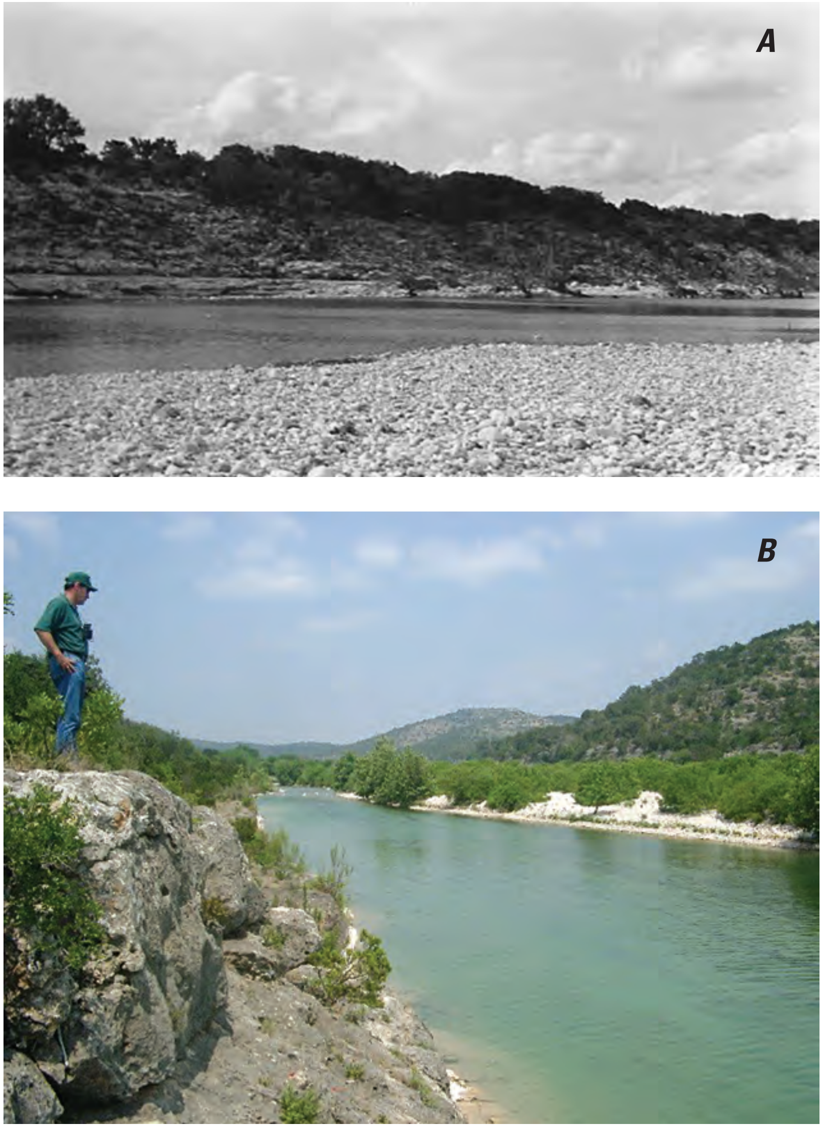

Figure 20. (*A*) View across and upstream of downstream cross section, West Nueces River at Kickapoo Springs, Texas, June 1935. (*B*) Slope-area discharge reach for West Nueces River at Kickapoo Springs, Texas, May 2003. Peak discharge of 580,000 ft^3/s from 402 mi^2 in 1935 is a world-record defining flood discharge.

the downstream direction as measured at a downstream slope-area site (near Cline, see below). These data are consistent with the fact that most of the rain fell primarily north of these sites. The original published discharge of 580,000 ft^3/s should be preserved and rated as poor.

The second indirect discharge measurement on the West Nueces River following the 1935 flood was made near Cline, Tex. (map no. 6, fig. 1), about 57 mi downstream of the first slope-area site near Kickapoo Springs. Flow near Cline was estimated to be 536,000 ft^3/s from a two-section slope-area measurement. The water-surface profile of the right bank was about twice the slope of the left bank, which had a greater number and more consistent high-water marks. The SAC program analysis for this site produced discharges that were about 3–5 percent less, but in light of the variability and uncertainty in the water-surface profile, this difference is not thought to be significant, and the original flow measurement of 536,000 ft^3/s should be retained.

Mailtrail Creek near Loma Alta, Tex. (map no. 3, fig. 1), and Seco Creek near D’Hanis, Tex. (map no. 1, fig. 1) were both extraordinary floods caused by convective thundershowers that produced flash floods following 22 to 24 in. of rain in periods from 3.5 to 12 hours. Some rainfall interpretations for Seco Creek can be found in Smith and others (2000). Both flood sites are ungaged sites, and both peak discharges were computed originally by the slope-area method, which agreed closely with SAC analyses made for this evaluation. Channels at these sites are wide and contain copious amounts of flood-transported cobbles and boulders. Both sites have cross sections that are too closely spaced for current SAC slope-area criterion. At Seco Creek, there is only a left-bank high-water mark profile developed. It is unknown why there is no profile for the right bank. No revisions are required for either flood peak.

Colorado Floods

Three floods investigated in this report occurred in Colorado, and all are associated with the June 1965 storm that caused extensive damage in the Denver Basin area (Matthai, 1969). Two flood sites are ungaged sites (East Bijou Creek at Deer Trail, Colo., map no. 9, fig. 1; and Jimmy Camp Creek at Fountain, Colo., map no. 7, fig. 1), although a streamflow-gaging station was constructed on Jimmy Camp Creek close to the indirect discharge measurement site about 10 years after the 1965 flood. Bijou Creek near Wiggins, Colo. (map no. 8, fig. 1), is a streamflow-gaging station location. At all three sites, the discharge was determined by the slope-area method, and the SAC

Figure 21. Flood plain of East Bijou Creek near Deer Trail, Colorado, June 2003. Flood debris is still present on the flood plain from June 1965 flood. At this location, flow was approximately 6 feet deep.

program confirms that the original discharge values are appropriate. Floods had channel widths from about 3,000 to 4,000 ft (fig. 21). Uncertainties in the discharges for these floods are all associated with selection of flow resistance and unstable channels during flood peaks. Upper flow-regime conditions likely existed for the peak discharge for all locations, except one section at Jimmy Camp Creek. No documentation of the review of these indirect discharge measurements could be found, although it is believed that they were all systematically reviewed at the time.

Jimmy Camp Creek at Fountain, Colo., presents the greatest uncertainty. Data indicate the flow transitioned from sub- to supercritical between the two sections of the slope-area reach in Jimmy Camp Creek. Shallow flow over vegetated flood plains, flow transition within the slope-area reach, a highly irregular left-bank profile, and sharp contraction between sections 1 and 2 add uncertainty to the published discharge for this flood, and the quality rating should be changed from “fair” to “poor” (figs. 22*A* and 22*B*).

Figure 22. (*A*) View upstream at cross section A on Jimmy Camp Creek at Fountain, Colorado, following flood of June 1965. (*B*) View looking downstream of slope-area reach, Jimmy Camp Creek at Fountain, Colorado, June 2003.

Nevada Floods

Three extraordinary floods, all at miscellaneous ungaged sites, were investigated in Nevada. All were documented using the slope-area method. One has already been described (Lahontan Reservoir tributary no. 3 near Silver Springs, Nev., map no. 10, fig. 1) in which a computational error resulted in a correction that increased the flood peak. The second peak is for Humboldt River tributary near Rye Patch, Nev. (map no. 11, fig. 1). The third is the well-known and controversial flood peak in Eldorado Canyon at Nelson Landing (map no. 12, fig. 1), in which nine people perished (Glancy and Harmsen, 1975) (fig. 23). All three floods occurred from thunderstorms over small basins, and all three highlight similar problems faced when trying to document flows in steep channels with movable beds. Froude numbers range from 1.5 to more than 3.0, which indicate the possibility for significant uncertainty (underestimation of total energy loss, channel changes, high sediment concentrations) and deviation from the quasi-steady flow assumptions of the slope-area method.

The flood in Eldorado Canyon is an interesting documentary of the difficulties in interpreting flow characteristics (including peak discharge) from indirect evidence following the event. Based on eyewitness accounts, questions arose as to whether the flow was a debris flow (fig. 24). Extensive examination of the stratigraphy of flood plain and terrace deposits in the slope-area reach in 2003 indicated only stratified to weakly stratified sand and fine gravel, indicative that all recorded previous flows were water flows, not debris flows (fig. 25).

The steep slope and highly mobile bed material at this site implies that flood peaks could be highly unsteady. Using hydraulic data from the slope-area measurement (which used high-water marks that could have resulted from flow instabilities), stability analysis indicates flow would have been highly unstable, similar in nature to the flood that produced translatory waves (Koloseus and Davidian, 1966) in Bronco Creek, Ariz. (Hjalmarson and Phillips, 1997). This stability analyses would indicate that the published peak discharge represents the maximum instantaneous wave discharge and perhaps not the flood discharge associated with rainfall-runoff from the upstream watershed.

Figure 23. Pre–1974 aerial photograph of Nelson Landing at the mouth of Eldorado Canyon, Nevada, showing the potentially dangerous conditions for people and property at the narrow mouth of the canyon.

Figure 24. Upstream view of flow near mouth of Eldorado Canyon at Nelson Landing, Nevada, during the late recession of the flood on September 14, 1974. Photograph by Kenneth E. Beales and reproduced from Glancy and Harmsen (1975).

Hjalmarson and Phillips (1996) cite Eldorado Canyon as a likely site where field conditions and descriptions indicate the likelihood of translatory waves. The unstable channel, highly unsteady flow, and very high Froude numbers render the reliability of the published peak discharge of 76,000 ft^3/s as poor.

Figure 25. Stratigraphy of terrace in slope-area reach of Eldorado Canyon at Nelson Landing, Nevada, showing clear stratification associated with fluvial depositional processes and not originating from debris flows, August 2003.

New Mexico Floods

There is no documentation for the storm that produced a large flood (340 ft^3/s) on Cimarron Creek tributary near Cimarron, N. Mex. (map no. 16, fig. 1). The June 5, 1958, storm was likely the result of a small, intense thunderstorm, characteristic of this part of New Mexico. The flow was measured at a culvert under U.S. Highway 64, about 2 mi west of Cimarron, N. Mex. The indirect discharge measurement was a type 1 culvert flow. The measurement was correctly made, and the original results were confirmed when entered into the USGS culvert analysis program (CAP) program. The only issue with this flood is the drainage area. The original measurement was made by planimeter from a 1:62,500-scale quadrangle sheet with 40-ft contours. The area was reported to be about 0.05 mi^2. For this evaluation, a 30-m digital elevation model and geographic information system (GIS) were used to recompute a revised drainage area of 0.15 mi^2; thus, the unit discharge was reduced from about 6,800 to 2,270 $(ft^3/s)/mi^2$. The August 1952 El Rancho Arroyo, New Mexico flood has been previously discussed.

Oregon Floods

Two floods from northwest and north-central Oregon were studied as part of this investigation. The difficulties and uncertainties involved with the interpretation of the peak discharge at the Meyers Canyon near Mitchell, Oreg. (map no. 17, fig. 1; miscellaneous), site have been previously described. The other Oregon flood was in Lane Canyon near Nolin, Oreg. (map no. 18, fig. 1; ungaged); peak discharge for this flood has also been a topic of debate.

A high-intensity rain and hailstorm began about 5 p.m. on July 26, 1965, in northwestern Oregon, centered over Lane Canyon. A two-section slope-area measurement was made on August 17, 1965, to document the magnitude of the flood from 5.04 mi^2. Supercritical flow existed through the measurement reach (Froude numbers were 1.78–1.90). During investigations for a dam-safety evaluation, Levish and Ostenaa (1996) investigated the flood in Lane Canyon. They concluded the event was a debris flow and that the process documented in the slope-area reach was “…a transient phenomenon such as channel blockage or aggradation” (Levish and Ostenaa, 1996). They ran some step-backwater calculations that indicated the flow was significantly smaller than reported but used roughness values nearly twice those estimated for the original slope-area computations. They cited no hard field evidence for debris flows. The field visit in 2003 confirmed that the deposits from 1965 preserved in the channel bottom are flood, not debris-flow, deposits. The deposits exhibit many features of fluvial boulder deposits, including strong imbrication (fabric) from the unidirectional current flow (fig. 26).

On the basis of preserved sedimentological evidence, original field photographs and notes, and original field-selected roughness values, the peak discharge for the flood in Lane Canyon was likely 28,500 ft^3/s, but the rating should be changed from “fair” to “poor.” Although the channel is steep and appears very smooth (fig. 27), the high Froude numbers for this flood raise concerns about the accuracy of the computed discharge.

Figure 26. Strongly imbricated fluvial boulder deposits in the channel bottom of Lane Canyon near Nolin, Oregon, April 2003. Flow was from right to left. Notebook for scale.

Figure 27. View looking upstream of upstream cross section in Lane Canyon near Nolin, Oregon, April 2003. Person in upper left of photograph located for scale on right-bank high-water mark.

California Floods

Two California flows were included in this investigation, and previously presented evidence documents that the January 1969 event on Day Creek near Etiwanda, Calif. (map no. 20, fig. 1), was a debris flow. The second extraordinary flood in California included in this study is the 1964 flood peak on the Eel River near Scotia, Calif. (station 11477000, map no. 21, fig. 1). One of the most widespread and destructive floods in the history of the West Coast occurred in 1964 (Waananen and others, 1971). The Eel River is the most prodigious flood-producing river in the United States (O'Connor and Costa, 2004). On December 23, 1964, the Eel River at Scotia, Calif. (map no. 21, fig. 1), crested at a stage of 72 ft and a discharge, determined by a rating curve extension, of 752,000 ft^3/s. Peak discharges measured above a threshold at this site use surface velocities measured by optical current meter. The Eel River is one of the few (may be the only) sites in the United States, where optical current meters are routinely used for high-flow discharge measurements.

During this review, the local USGS field office located two discharge measurements made in February 1940. These measurements were the largest and third largest discharge measurements ever made at this site on the Eel River. For unknown reasons, these measurements were not used to document a large flood in 1955, which was determined by rating extension to be 541,000 ft^3/s. If the two 1940 measurements had been used, the 1955 peak discharge would likely have been different. This change would have translated into a change in the peak discharge in 1964, and produced a peak that was substantially less than 752,000 ft^3/s. There is no documentation as to why the 1940 measurements were not used in 1955, but looking at all high-flow measurements since 1940, the 1940 peaks define the left-most points in the cluster of measurements on the rating curve. This observation suggests that the decision to not include those measurements in defining the 1955 rating was not an oversight but was based on comparisons of the data and a conscious decision, albeit undocumented. The published peak discharge of 752,000 ft^3/s appears to be a valid discharge on the basis of the current rating curve. The flood peak discharge for the Eel River at Scotia, Calif., remains unchanged (fig. 28).

Figure 28. Destroyed highway bridge over Eel River at Scotia, California, following 1964 flood.

Utah Flood

On August 11, 1964, a cloudburst storm caused significant flooding along several small streams in the Pine Valley Mountains in southwestern Utah. No rainfall data are available. A two-section slope-area measurement was conducted on Little Pinto Creek tributary near Newcastle, Utah (ungaged; map no. 22, fig. 1). The site is very steep, and there is uncertainty in selection of roughness values for a sand-bed, 9-percent sloping channel (fig. 29). Froude numbers were high (1.84 and 1.99), and because there were apparently no photographs taken, there is some uncertainty in the exact location of the survey. The SAC program produced nearly the identical discharge as originally computed (2,630 ft^3/s and rated "poor"). This measurement had no outside independent review, which is not USGS procedure. In spite of the very high Froude numbers, steep slope, and uncertainty in exact field location, the computations were done correctly, and there is no basis for any revisions.

Figure 29. View looking downstream at section A in Little Pinto Creek tributary near Newcastle, Utah, August 2003. Arms of hydrologists at approximate high-water marks.

Missouri Flood

Torrential rainfalls during July 17–20, 1965, dumped more than 20 in. in northwest Missouri. Thirteen inches were reported by newspapers to have fallen in just 3 hours in the area of Rock Port, and floods from Boney Branch and Rock Creek inundated the entire business district of Rock Port to a depth of about 3 ft (Bowie and Gann, 1967). Rock Port is a small community located in the loess hills that sharply rise 250 ft above the east side of the Missouri River flood plain, which may create an orographic increase in precipitation.

A peak discharge of 5,080 ft^3/s was measured using a three-section, slope-area indirect discharge measurement on Boney Branch at Rock Port, Mo. (ungaged; map no. 23, fig. 1), a small (0.71 mi^2) basin that drains through the small town (figs. 30*A* and 30*B*). The published discharge agrees with the SAC program results, and the only change is drainage area. The original area of this small basin was determined as 0.76 mi^2 from a 1:62,500-scale topographic map. The drainage area measured with GIS from a 1:24,000-scale topographic map (Rock Port quadrangle) is 0.71 mi^2.

Figure 30. (*A*) August 1965 view looking downstream of left bank at cross section 2 following flood of July 18, 1965, Boney Branch at Rock Port, Missouri. (*B*) August 2003 view looking downstream of left bank at cross section 2 following flood of July 18, 1965, Boney Branch at Rock Port, Missouri.

Iowa Flood

On the basis of unofficial reports, more than 11 in. of rain fell in a small area of west-central Iowa in a short period of time on August 8–9, 1961. Two people died, and there was significant damage to roads and bridges. After extensive reconnaissance, a two-section slope-area indirect discharge measurement was made on Stratton Creek near Washta, Iowa (ungaged; map no. 24, fig. 1). The discharge was 13,300 ft^3/s. This measurement was the largest unit runoff ever reported in Iowa and as such received extensive review. The flood specialist who reviewed the measurement (M.S. Petersen) was one of the most knowledgeable and respected flood experts in the USGS. In the original flood file, Petersen's review memorandum is clearly skeptical. He questioned the high-water profiles, the fact that only two sections were used for the slope-area measurement, and questioned whether the drainage area was measured correctly because of the size of the unit discharge [7,000 (ft^3/s)/mi^2].

Petersen sent the flood measurement to Washington, D.C., for further review. The measurement was reviewed by Tate Dalrymple, who had studied the 1935 flood peaks along the West Nueces River in Texas, as previously described. Dalrymple could find no problems with data quality, analysis, or computation but asked for supplemental information to verify the magnitude of the flood. He recommended that a flow-over-road, critical-depth measurement be made.

The new work involved a flow-over-road (6,600 ft^3/s) and culvert flow (3,400 ft^3/s) computation, which gave a new discharge of 10,000 ft^3/s. This new figure was combined with the original slope-area measurement (13,300 ft^3/s), and "by arbitrarily weighing all computations," a peak discharge of 11,000 ft^3/s was determined and was called an estimate (figs. 31*A* and 31*B*). Two new step-backwater computations done by the USGS Iowa Water Science Center for this review resulted in discharge estimates of 11,600 and 9,500 ft^3/s, so no changes are recommended for this flood discharge.

Figure 31. (*A*) view looking toward left bank at road and culvert crossing at Stratton Creek near Washta, Iowa, August 1961. Person on opposite bank is holding survey rod at high-water mark. (*B*) view looking toward left bank at road and culvert crossing at Stratton Creek near Washta, Iowa, May 2003. People standing at approximate high-water mark on right bank. Flow was from left to right.

South Dakota Flood

As much as 5 in. of rain fell in 2 hours on July 28, 1955, in an area of the Black Hills in southwestern South Dakota (Wells, 1962). Several indirect discharge measurements were made in the area of most intense rainfall, and one of these measurements, on a very small basin (Castle Creek tributary #2 near Rochford, S. Dak., ungaged; map no. 25, fig. 1), produced a unit discharge of more than 5,000 $(ft^3/s)/mi^2$ from a culvert and flow-over-road measurement. The drainage basin was measured by transit/stadia survey and planimeter to be 0.0192 mi^2, or about 12 acres. These measurements associated with this storm are an excellent example of the proper way to study and evaluate floods. Although original photographs of this site were lost after the field work in 1955, photographs of the other nearby measurement sites were available. The original discharge of 98.9 ft^3/s was confirmed by the CAP program and verification of flow-over-road computations but should be rounded to 100 ft^3/s when reported (fig. 32).

Figure 32. View looking upstream into basin that produced the 1955 flood, Castle Creek tributary #2 near Rochford, South Dakota, May 2003. Basin perimeter is grassed ridge in near foreground.

Figure 33. View of upstream slope-area site on Wenatchee River tributary near Monitor, Washington, looking downstream following flood in 1956.

Washington Flood

In September 1956, a localized but intense thunderstorm struck the center of Washington and produced prodigious amounts of runoff from the short, steep drainage basins surrounding this reach of the Wenatchee River. Two slope-area indirect discharge measurements were made on Wenatchee River tributary near Monitor, Wash. (miscellaneous; map no. 26, fig. 1) on September 17, 1956. This tributary is very steep and drains only 0.15 mi^2. Two independent two-section slope-area measurements were made near the mouth of the canyon, separated by about 200 ft (fig. 33). The water-surface profile could not be determined between the two reaches, so separate measurements were made (1,010 ft^3/s upstream reach; 796 ft^3/s downstream reach), and the published discharge is the average of these measurements, or 903 ft^3/s. This discharge was rated as fair. No evidence exists that the original flow was a debris flow, although the setting and size of the basin are advantageous to formation of debris flows. There are questions about the channel geometry of the downstream measurement site during the peak, Froude numbers were quite high (1.1–2.4), and roughness values for such a steep site may have been underestimated. In light of these uncertainties, the published discharge of 900 ft^3/s (rounded) should be retained, but the rating downgraded from fair to poor.

Maryland Flood

The June 1972 Hurricane Agnes produced record flooding in the northeastern United States that caused loss of life (117) and significant damage (over $3 billion) (Bailey and others, 1975). The Susquehanna River at Conowingo, Md. (station 01578310; map no. 28, fig. 1) crested on June 24, 1972, at a stage of 36.83 ft. A current-meter measurement, accomplished with the assistance of five USGS hydrologists, was made that day at a stage of 36.76 ft. The flow was measured at 1,130,000 ft^3/s, which was essentially at the peak of the Hurricane Agnes flood. All depths were sounded, and all mean velocities are based on verticals where 0.2- and 0.8-ft depth velocities were measured. The slight extension of 0.06 ft does not change the published peak discharge because of rounding. The USGS Maryland Water Science Center has a Web page that describes this remarkable discharge measurement: http://md.water.usgs.gov/floods/Agnes/Conowingo/index.html

No changes are suggested, and this measured peak is accepted as reported.

Illinois Flood

The 1937 flood in the upper Ohio River Valley was among the most destructive in recorded history. In late January 1937, the Ohio River was above flood stage for its entire 1,000-mi length between Pittsburgh, Pa., and Cairo, Ill. (Hoyt and Langbein, 1955). The discharge on the Ohio River at Metropolis, Ill., was measured from a bridge almost daily by current meter from January 14 to February 18, 1937, which would have been a tremendous work effort.

The most unusual aspect of this flood was the glacial meltwater overflow channel that diverted about 4 percent of the floodflow through a topographic lowland north of the Ohio River for a distance of about 50 mi (fig. 34). The Ohio River broke into this overflow channel about 33 river miles upstream of Metropolis, Ill., and returned to its main channel near Mound City, Ill. The overflow channel was measured by current meter from a boat. Flow in the main channel of the Ohio River was measured from a railroad bridge, where it was not possible to make depth soundings in the deepest part of the flood channel. Cross-section geometry was based on soundings made when flows had receded by about 12 ft. This is the most likely source of uncertainty in the flood measurement. The published discharge of 1,850,000 ft^3/s is the maximum daily average flow. On the basis of 26 current-meter measurements in 35 days over the peak of the flood, the mean daily discharge of 1,850,000 ft^3/s for this flood is close to the instantaneous peak, and no changes are warranted.

Figure 34. Location of overflow channel for 1937 flood on the Ohio River at Metropolis, Illinois. Arrows mark place when the floodwater left the main channel, and the path of the overflow.

Arkansas Flood

The greatest documented flood discharge in the lower Mississippi River Basin is the 1927 flood, described in the book *Rising Tide* (Barry, 1997). The USGS published discharge for this flood is 2,472,000 ft^3/s, at Arkansas City, Ark., and noted to be an estimate and affected by regulation and diversions. This is the largest peak discharge in the USGS Peak-Flow File, and estimates of the 1927 flood peak range from 2.4 to 3.0 million ft^3/s. Apparently there were no direct measurements or indirect measurements of this peak, and no evidence of any flood records for the 1927 peak can be found among the data of the USGS, U.S. Army Corps of Engineers, Mississippi River Commission, or State of Arkansas (Frame, 1930; Mississippi River Commission, 1930; U.S. Army Corps of Engineers, 1997). The peak discharge is impossible to evaluate without any data to review. It is recommended that the peak discharge be rounded to 2.5 million ft^3/s and clearly noted that it is an estimate. The drainage areas reported in the station description and Peak-Flow File do not match, and the correct value should be identified.

U.S. Geological Survey and Flood Science Issues

The floods studied herein are examples of important natural hazards. Two identified weaknesses of the current USGS streamflow-gaging program related to floods are lack of streamflow and water-level data in areas of greatest hydrologic variability, such as steep mountain channels and arid region channels, and the emphasis on measurement of average flows rather than rare, extreme events (Committee on U.S. Geological Survey Water Resources Research, 1999). These extreme and rare events define the limits of maximum floods in the United States. Two questions are raised by these data. The first is how these data are used (specific science and engineering applications), and the second is defining geophysical limits to maximum runoff (Wolman and Costa, 1984). The floods that have raised the envelope curve of the United States since 1965 (Matthai, 1969) are those floods with some of the greatest uncertainty. Within possible error ranges, one can argue that the envelope curve has not changed in more than 40 years. This may be a product of fewer extraordinary floods, less documentation of these floods at ungaged sites, or a true limit to maximum runoff. This report does not resolve this question but does verify that today (2007), USGS documents very few floods at ungaged sites compared to the past. Many extreme floods, especially in smaller mountain or arid region channels, have gone undocumented.

The revisions to the envelope curve of peak discharges documented in the United States by USGS are shown in figure 35. There are some general conclusions and observations that can be made about the detailed evaluations of the 30 extraordinary floods described herein. It is likely that these observations and comments apply to other floods in the USGS Peak-Flow File as well. The following section lists four major issues that impact the quality and reliability of USGS flood measurements and flood data: process recognition, geography accuracy, slope-area methods, and administration of flood data and methods.

Process Recognition Issues

- Proper identification of flow processes in small, steep basins.
- Recognition of when flow instabilities such as translatory waves can affect peak discharge values.
- Limitations of the Peak-Flow File for documenting other than normal flow processes, such as debris flows.

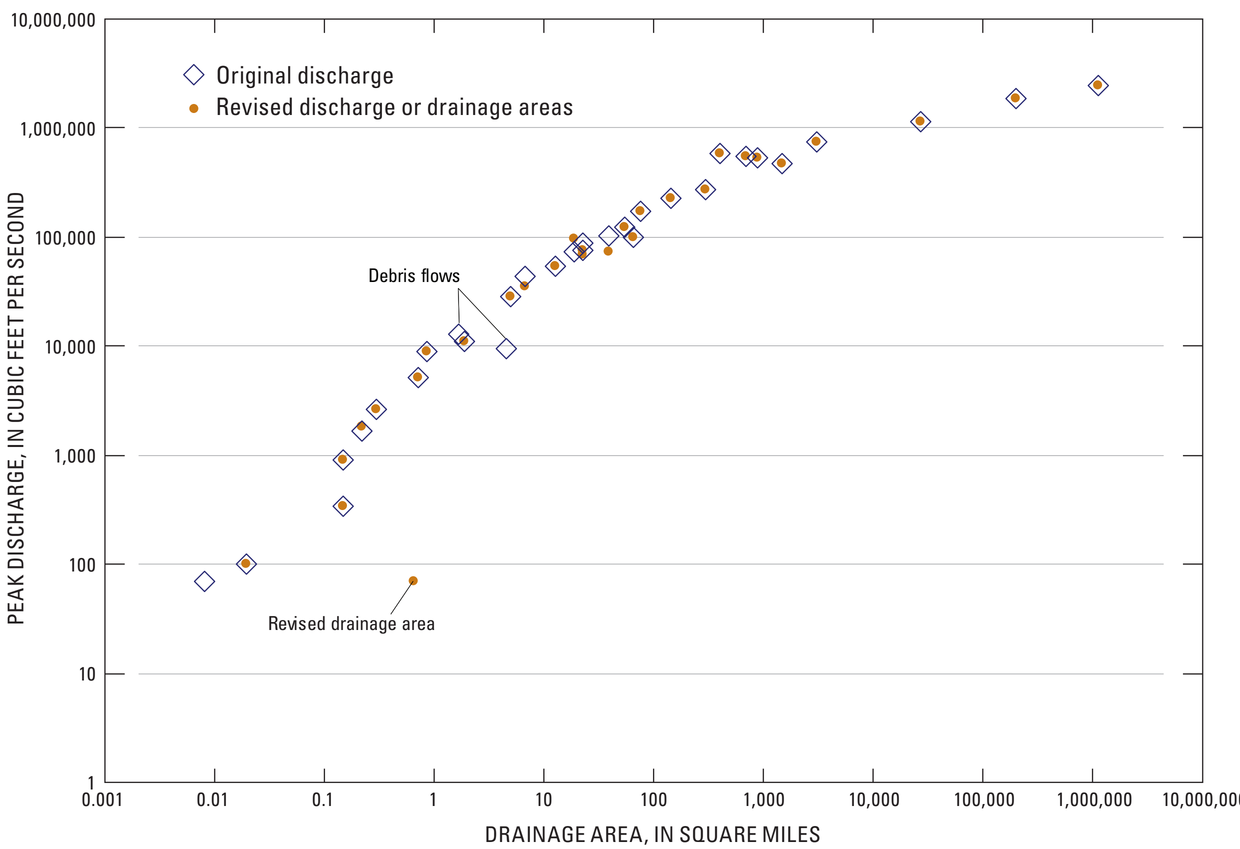

Figure 35. Log-log plot of discharge versus drainage area for the 30 peak discharges in this study.

In steep, small upland basins anywhere in the country, the possibility exists that unusually large flows could be debris flows and not water floods. Descriptions and documentation for these two processes are different, and process identification should be the first task of field people responsible for documenting an event in these settings. Past concern with misidentification of flow process was the basis for two technical memoranda from the USGS Office of Surface Water in 1992: *Guidelines for Identifying and Evaluating Peak Discharge Errors* (Office of Surface Water Technical Memorandum No. 92.10, July 2, 1992) (http://water.usgs.gov/admin/memo/SW/sw92.10.html) and *Flow Process Recognition for Floods in Mountain Streams* (Office of Surface Water Technical Memorandum No. 92.11, July 21, 1992) (http://water.usgs.gov/admin/memo/SW/sw92.11.html).

When indirect discharge measurements indicate unusual hydraulic conditions, such as Froude numbers greater than 1.5, additional analysis and field measurements need to be conducted as soon after the event as possible to evaluate potential flow instabilities such as translatory waves, scour and fill, avulsions of flow into different channels over time, and highly unsteady flow conditions. Flow stability analyses such as that described by Koloseus and Davidian (1966) should be made for any flood that approaches or exceeds the unit runoff in this dataset or has Froude numbers greater than about 1.5.Even when correct process identification is made, the current USGS databases are inadequate to store and describe any flow phenomenon that is not a normal water flow. The USGS databases do not have a place for extended descriptions of storms, flow observations, ancillary field data (hydrologic, hydraulic, or geomorphic) or for photographs.

Geography Issues

- Need for better documentation and accurate data for floods, including adequate location of field sites with global positioning system (GPS). Several older floods have location coordinates that are inaccurate.
- Careful documentation of drainage areas, especially for small basins.
- Collection of related materials such as newspaper articles, use of photographic documentation, and careful preservation of original records and data need to be systematically implemented.

Most recent flood measurements at streamflow-gaging stations and ungaged sites rely on modern tools like GPS and GIS to adequately locate stations and measure watersheds. For older floods documented in USGS files, locations and areas may not be accurate, especially in remote areas where small-scale topographic maps were the only tools available. When using these older data, locations as well as drainage areas need to be carefully checked for accuracy.

Issues with Slope-Area Indirect Discharge Method

- Use of two-section slope-area indirect discharge measurements.
- Inadequate high-water marks.
- Cross sections too close together.
- Subjectivity of estimation of channel/flow roughness values.
- Implications of very high Froude numbers.

A recurring problem identified with the floods whose discharge was determined with the slope-area method was that there were only two cross sections used in the measurements. For the 30 floods investigated for this study, more than one-half (55 percent) of the flood peak discharges measured using the slope-area method relied on just two cross sections. Why is this a problem?

Following a flood, a single cross section, measurement of channel slope, and estimation of flow roughness will provide the information necessary to produce a discharge estimate (usually known as the slope-conveyance method). This is a poor way to estimate peak discharge because (1) one must assume the cross section is representative of all the other possible cross sections in the reach and (2) one must assume that the channel slope, water-surface slope, and energy slope are all parallel, which is unlikely.

Two cross sections allow application of the Bernoulli equation for open-channel flow (Dalrymple and Benson, 1967). With this application, velocity head can be computed at upstream and downstream locations, and more than one discharge can be computed. Advantages of using two cross sections over one cross section are (1) both water-surface and energy slope are known and (2) evaluation of whether uniform, gradually varied, or nonuniform flow conditions existed in the reach is possible. The more unsteady the flow conditions (discharge difference between one cross section and different velocity, depth, width, and slope between cross-sections), the less reliable the indirect discharge measurement. Gradually varied flow conditions generally are considered acceptable with the slope-area method.

Lack of cross sections is not a problem associated with lack of effort. In many small basins, for example, there are limited reaches where indirect discharge measurements can be made, and if the reaches are short, fewer cross sections can be measured. USGS recommends a minimum of three cross sections for slope-area measurements (Dalyrmple and Benson, 1967). Three or more cross sections have the advantage of further documenting the uniformity of flow in multiple locations in the reach. If the various discharges computed by the different combinations of cross sections are similar, one has confidence that relatively uniform flow conditions existed.

As conveyance ratios increase between cross sections, slope-area measurements are less reliable. The floods evaluated herein with two-section slope-area measurements may have been the only option in some cases, but USGS best practice recommends using three or more cross sections.

Several of the older floods had inadequate high-water marks. The high-water marks need to be closely spaced, extended well beyond the end of the upstream- and downstream-most cross sections, and adequately identified as to type and quality. Identification of high-water marks is a learned skill that requires experience and thought. The water-surface profile is determined solely on the basis of the quality of high-water mark data.

The SAC program identified several sites where cross sections were spaced too closely together. Cross sections need to be placed at major breaks in the water-surface profile, although sometimes this problem cannot be avoided.

Estimation of flow roughness remains primarily a visual exercise that is based on experience, tempered with infrequent verification studies. The most ideal situation would be to measure flow directly, but this is unrealistic and often dangerous for large floods. In channels with gradients less than about 0.01 ft/ft, changes in *n*-values of ±25 percent produce a maximum change of about 20 percent in discharge (Wohl, 1998). Quantifying flow resistance and other energy losses remains a point of vulnerability in flood science and an important area in which to invest additional time and resources. Current indirect discharge methods require estimations of coefficients, such as for roughness and for expansion or contraction. These coefficients are critical to the calculations, but they are subject to large uncertainties in the absence of adequate verifications (see discussion in the following paragraphs). Some of the most difficult conditions for estimation of roughness occur during large floods when rivers overflow banks and inundate flood plains.

Several of the ungaged floods investigated for this study resulted in channel-average Froude numbers greater than 2. Large Froude numbers point out the need for additional investigation and a possibility of a different approach. Supercritical flow can occur in smooth bedrock channels, concrete channels, and where flows are fast, shallow, steep, and have substantial quantities of fine-grained sediment, which lessens energy losses (Vanoni, 1946; Jarrett, 1987; Simon and Hardison, 1994). Supercritical flow can occur for short distances and times along channels, and in the main channel of a wide cross section, and in contracted natural cross sections (Wahl, 1993; Grant, 1997), and flow over roads and weir, where flow often is critical. In channels having slopes exceeding about 0.01 (and in some channels, with slopes exceeding about 0.002), Froude number ranges from 0.8 to 1.2. Froude numbers in excess of 2.0 can occur for shallow depths and steep slopes but usually only in a few subsections of a natural channel.

The largest Froude numbers directly measured in natural channels are rarely larger than 1.5 (Simon, 1992; Wahl, 1993). Froude numbers larger than 1.5 measured in natural alluvial channels all have the same characteristics—very shallow flow on steep slopes with an actively moving channel bed. Examples of some of the highest channel-average Froude numbers measured with current meters include the White River, Wash. (Fr = 1.51) (Fahnestock, 1963, table 7), Medano Creek, Colo. (Fr = 1.70) (Schumm and others, 1982), and the North Fork Toutle River above Bear Creek near Kid Valley, Wash. (Fr = 1.95) (data from original discharge measurement field notes at Cascades Volcano Observatory, Vancouver, Wash. (station 14240400) (Dinehart, 1998). This last site, which was a cableway constructed across the North Fork Toutle River in the aftermath of the May 18, 1980, eruption of Mount St. Helens, has the highest magnitude and largest number of high-Froude number flows for natural channels examined in this study. Discharge records from current-meter measurements for this site made between 1984 and 1988 indicate at least 10 channel-wide average Froude numbers greater than 1.5. The largest were 1.95 on February 12, 1987, and 1.91 on November 24, 1986. This cableway was located near the distal end of the gigantic debris avalanche from Mount St. Helens where sediment yields were prolific, hydraulic depth was usually less than 2 ft, and the main channel was actively shifting and dividing in multiple steep and shallow channels. Following large floods, when making an indirect discharge measurement, if the computed flow results have Froude numbers larger than 1.5 and are not steep, shallow flows, then the measurement requires additional investigation and analysis. In this report, if a flood has channel-average Froude numbers larger than 2.0, the measurement is rated as an "estimate."

There are several possibilities for overestimation of flood discharge when using indirect methods that are related to a poor understanding of the role of sediment transport during floods and overbank flow. For floods with larger bed-material sizes (quite common for floods in higher gradient channels), substantial energy is required to transport gravel- to boulder-sized sediment (Jarrett, 1984, 1987, 1992; Grant, 1997). Bagnold (1954) proved that for high bed-load transport, one-third of available energy slope is absorbed by the moving sediment. In effect, only two-thirds of the energy slope is available for transporting water in the channel. Thus, when using the Manning's equation to compute discharge, either the energy slope needs to be reduced to two-thirds of its value or *n*-values should be increased by a factor of 1.22 (Bagnold, 1964). Sellin and others (1990) describe out-of-bank flow conditions for the Rodin River in Britain that had at least 30 percent more energy loss than in-channel floods (for example, *n*-values need to be increased by at least 30 percent) due to flow interactions between main channel and overbank flow.

The following are ways to improve computation of peak discharge from indirect measurements:

- Better site selection for indirect discharge measurements;
- Use of critical depth method;
- Avoid use of one-dimensional flow models in situations that are clearly multidimensional;
- Awareness of the uncertainty of roughness values in sand-bed channels, overbank areas, and for high-gradient and large roughness element channels; and
- Review of conditions in the watershed if peaks are found to be exceptional, such as rainfall distributions, contributing area, sediment loads, and evidence of debris dam failures.

Frequently, selection of adequate field sites at critical locations in order to make indirect discharge measurements is difficult. If an extraordinary flood must be documented, and no adequate site exists, a measurement may be made anyway, but its reliability and quality are diminished. Poor site selection will continue to be a problem in the absence of any new methods or technology to help the dangerous and difficult measurement of extremely large floodflows. Some new ideas and tools are being developed but are not widely used at present, including synthetic ratings that are based on flow models (Kean and Smith, 2005) and noncontact discharge measurements (Costa and others, 2006).

For stream gradients of about 0.002 ft/ft or greater, flood discharge can be estimated using the critical-depth method (Jarrett, 1984; Jarrett and Costa, 1988; Trieste and Jarrett, 1987; Grant, 1997; Jarrett and Tomlinson, 2000; Jarrett and England, 2002). In a comparison of peak discharges determined using critical-depth and current-meter methods at eight streamflow-gaging stations in northwestern Colorado, Jarrett and Tomlinson (2000) noted an average of ±12 percent difference. Jarrett and England (2002) computed peak discharge using the critical-depth method at 35 streamflow-gaging stations where current-meter measurements at or near the peak discharge were available to help validate the critical-depth method (Barnes and Davidian, 1978; Webb and Jarrett, 2002). The range in the difference between the peak discharge computed using the critical-depth method and the peak discharge computed using current-meter measurements was –45 to +43 percent with an average difference of +1 percent. For a 95-percent confidence interval, the average difference was ±15 percent of the gage-measured peak discharge. The primary reason for the large difference at a few sites was that only one critical-depth estimate was made for each site in this study. By averaging three to six critical-depth estimates, results are much more consistent and reliable (Jarrett and England, 2002). The study results of Jarrett and Tomlinson (2002) and Jarrett and England (2002) compare favorably with Grant's (1997) theoretical results that showed that, when using the critical-depth method, the discharge is within ±16 percent of the gage-measured peak discharge.

If cost or resources preclude documentation of flood magnitudes, slope-conveyance methods are fast and provide some estimates of flow peaks that might never be recorded. The basis for suggesting use of this method is the belief that some data (however poor) are better than no data. If nothing else, the channel geometry measurements needed for the computations of flow provide a record of flow cross sections. For this application, flood depth, area, velocity, and discharge must be constant from one cross section to the next. In the slope-conveyance method, a single cross section is surveyed, channel or water-surface slope measured, and flow resistance (n) estimated. Conveyance is computed for the cross section as:

$$K = AR^{0.67}/n, \tag{1}$$

where K is conveyance. Discharge then is computed from continuity as:

$$Q = K(S)^{0.5}, \tag{2}$$

where Q is discharge, in cubic feet per second.

The slope-conveyance method is discouraged because of the assumptions of steady and uniform flow but can be rapidly used when geometry and roughness can be considered uniform along the reach of interest. Proper site availability and selection are the most important limitations on use of this method.

How accurate is the slope-conveyance method? Twenty-eight slope-area measurements from the February 1996 floods in Oregon were used to test the hypothesis that a single cross-section slope-conveyance estimate would give nearly as accurate an estimate of peak discharge as the slope-area method. Using bed slope, selecting one of the surveyed cross sections as a representative section, and using the same *n*-value used in the slope-area estimate, the Oregon data show that the differences between slope-area results and slope-conveyance results for the same stations range from +31 to –38 percent (fig. 36), with a strong mode in the 0–5 percent range, and an overall average difference of 9.8 percent and a small positive bias of +2.2 percent.

These data show only one example of possible results. A full multisection slope-area indirect discharge measurement is always preferred, but if costs or time preclude this kind of analysis, the slope-conveyance approach would give some hard data for the estimation of the magnitude of the flood. For nine different floods since 1996, USGS personnel were able to make 14–25 slope-conveyance estimates per day, so this method is efficient and data-rich.

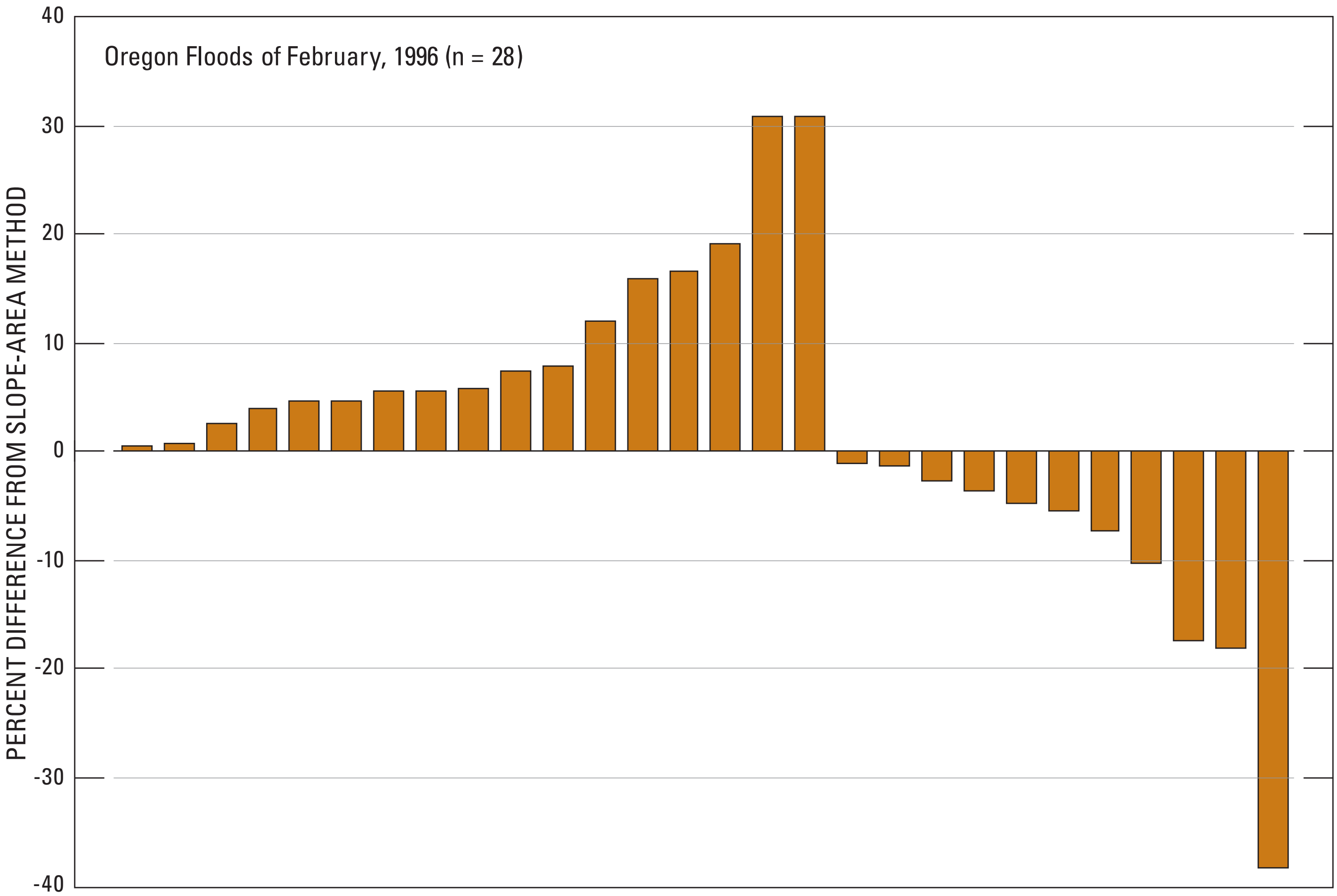

Figure 36. Comparison of results from 28 slope-area indirect discharge measurements from February 1996 floods in Oregon with results from slope-conveyance method.

Several of the 30 extraordinary floods described in this report were clearly multidimensional and inadequately described by one-dimensional flow models. The most widely used method of peak discharge measurement to document the floods investigated in this report is the slope-area method. This method works well when floods are one-dimensional, quasi-steady, uniform, and flow in slightly contracting reaches. Both more simple (slope-conveyance, critical-depth methods) (Webb and Jarrett, 2002) and more complex methods (two-dimensional flood-routing models) (Denlinger and others, 2002; Fulford, 2003) are needed in the appropriate settings. The increasing availability of LIDAR data make use of multidimensional flow models practical in many complex settings. In USGS, a lack of funding to perform flow modeling after a flood and lack of experience in the surface-water data program have resulted in less frequent use of this technology.

Finally, many hydrologists who worked on the 30 floods described in this report recognized that they were recording extraordinary events. When envelope-curve defining floods are found, additional documentation helps verify the unusual event. Examination of the entire watershed upstream of the measurement point can point to unusual circumstances that contributed to the size of the peak downstream, such as temporary landslide dams or recently burned or deforested areas.

Administrative Issues

- Missing or lost data.
- Adequate review of indirect discharge measurements.
- Training needs.
- Reduced interest in making indirect discharge measurements at ungaged sites.
- Databases of floods.
- Of late, most significant floods measured by the USGS are documented by Fact Sheets and Web pages, not comprehensive flood reports.

An unfortunate problem identified in this study is missing data files. For two of the 30 floods described herein, original field notes and documents could not be found. Lost or missing data files are a disappointment. Original field data (such as notes, photographs, computations) are stored in local USGS field offices where the extent of archiving varies. When these small offices relocate, close, or simply clean storage areas, some original data also could be lost or misplaced.

No original USGS records for the 1940 flood on Wilson Creek near Adako, N.C. (map no. 14, fig. 1) were found except for a review of the original indirect discharge measurement and a revised rating curve. The 1927 flood on the lower Mississippi River at Arkansas City, Ark. (map no. 30, fig. 1), is the largest published discharge in the USGS Peak-Flow File (2.47 million ft^3/s), but no records of any flood measurements of the peak discharge or indirect discharge measurements could be located.

Several of the problems identified with floods whose discharge or rating were changed or degraded can be attributed to problems that could have been identified in review. Several floods have no record of review. The June 1965 Colorado floods have no review documents, but Kenneth Wahl of the USGS Central Region Office (now retired) is certain that these floods were reviewed because he participated in the reviews. This is an archival as well as a review problem. Flood measurements, especially indirect discharge measurements, require review outside of the originating office. Outside review used to be standard practice, but today this is no longer the case in the USGS. Numerous examples exist of measurements languishing in a file having been computed and written up but never reviewed (Mark Smith, U.S. Geological Survey, written commun., July 30, 2007). During significant regional flooding, the workload may become onerous, but reviews are required as well as documentation of the review.

The training agenda for USGS surface-water data program needs to be rethought. Qualified and experienced personnel to perform hydraulic modeling has eroded to a point of significant concern. Existing surface-water training classes need to be reviewed and revised. Efforts made to teach slope-area indirect discharge methods should be redirected to new training in step-backwater methods, one-dimensional steady and unsteady flow modeling, and multidimensional watershed and hydraulic modeling. The focus in the data program needs to become more balanced between measurement tools and interpretation skills. In 2007, the program is unbalanced in favor of measurement methods and instruments.

Seventy percent of the floods documented by the USGS in this investigation of the largest unit runoffs occurred at random ungaged locations. Thus, ungaged sites constitute an important element in the maximum runoff events in the United States. However, two serious problems hamper USGS advancements in flood science: (a) the vast majority of the thousands of indirect discharge measurements made by the USGS at miscellaneous sites are not available on NWIS-Web, or in any electronic format; and (b) indirect discharge measurements at ungaged sites are on the decline in USGS, primarily for budgetary reasons.

One example of some extraordinary indirect discharge measurements that are unavailable on-line are the peak discharges computed for small basins in the middle of the Big Thompson, Colorado flood in 1976. These measurements are available only from the USGS in paper reports (McCain and others, 1979; Jarrett and Costa, 2006). At least three of these small tributaries had unit runoff greater than 6,000 $(ft^3/s)/mi^2$. Fewer and fewer indirect discharge measurements are being made, especially at ungaged (miscellaneous) locations. For example in Texas, the foremost State for extraordinary floods (O'Connor and Costa, 2004), there has not been a measurement made at an ungaged site in over a decade (data from field offices of USGS Texas Water Science Center). Without including flood measurements from miscellaneous ungaged sites, the envelope curve of maximum floods for the United States and hydrologically homogeneous regions in the United States would look very different, and could lead to the underdesign for and underestimation of potential maximum floods. As an example, figure 37 shows the annual peak discharge for all the current and historical streamflow-gaging stations in Colorado (black circles).

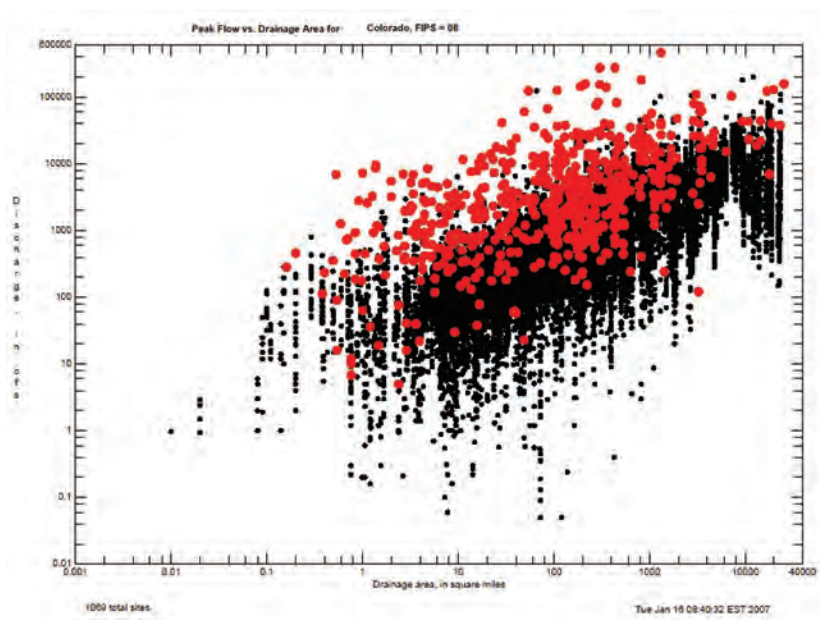

Figure 37. Log-log plot of drainage area versus annual peak discharge measurements for all streamflow-gaging stations in Colorado (current and historic) (black dots), along with indirect discharge measurements from streamflow-gaging stations and ungaged sites prior to 1990 (red dots).

The red circles are all the indirect discharge measurements of floods at both streamflow-gaging stations and ungaged sites, current to only 1990 (U.S. Geological Survey unpub. data). It is apparent that the flood risk in Colorado would be significantly underestimated without the data from indirect measurements from ungaged and discontinued, as well as gaged sites. It is a responsibility of the USGS to collect critical data during and immediately after floods to characterize the events. A commitment to make flood measurements at ungaged sites as well as at gaged sites is essential for advancing flood science hydrology in USGS (Committee on U.S. Geological Survey Water Resources Research, 1999).

The current USGS database for annual flood peaks (Peak-Flow File) is incomplete and the capability to archive essential peak flow data is not available. The National Academy of Sciences Committee on Hydrologic Hazards Science in the U.S. Geological Survey (Committee on U.S. Geological Survey Water Resources Research, 1999) defined the data needs related to floods:

> "Detailed studies of extreme flood events are essential for predicting future events of a similar nature. An adequate database to support such studies requires sufficient site specific information to elucidate the critical hydrologic, hydraulic, geomorphic, and hydroclimate factors that shaped each extreme event. (p. 26)

> "….the agency will need to support integrated database management systems to inventory, store, and make accessible regularly collected meteorological and hydrological information, on a watershed-by-watershed basis, with easy linkages between weather, topography, streamflow, and reservoir management data…." (p. 67)

Currently, the peak-flow file provides no opportunities to enter a debris-flow event, photographs, or a note to indicate that a peak is the result of highly unsteady waves or other unique flood events. The science of flow processes in alluvial channels has lapped the ability of current USGS databases to adequately store and report critical information. It is essential that USGS provide support to enhance the overall electronic database capabilities to accommodate non-water flow events and allow inclusion of details of field observations of unusual flow situations or flow circumstances. A true database structure for preservation of peak flow information and data is needed. The digital world readily permits inclusion of field notes, photographs, sketches, comments, and other readily distributable content about flood peaks for inclusion in annual data reports or archival data files.

Classic publications of flood science, data, interpretation, and documentation, such as Stewart and LaMarche (1967), Matthai (1969), or Williams and Guy (1973) are unusual today. One current example of a comprehensive USGS report on an unusual flood was the study of the upper Potomac and Cheat River floods of 1985 (Jacobson, 1993). Interestingly, unlike the lack of detailed reports on flood hydraulics and hydrology, there have been numerous recent papers with excellent descriptions and interpretations of flood-causing meteorologic situations. These papers utilize Weather Surveillance Radar-1998 Doppler (WSR-88D or NEXRAD) for spatial interpretations of rain intensity, synoptic weather data and observations, and hydrologic models to route water into channels (Smith and others, 2000, 2001; Hicks and others, 2005). Parallel studies and reports of associated floods would have been valuable. Real-time data and increasing costs may have contributed to a declining interest in archival documentation of significant floods. However, many of the most insightful advances in flood science have come from hydrologists who have taken the time to collect sufficient and appropriate data to write comprehensive reports about unusual floods. Flood summary reports, such as Perry and others (2001), are also valuable for synthesis. Insights, thoughts, and hypotheses that lead to new knowledge are fostered when comprehensive reports are prepared. USGS should put renewed emphasis and support on the preparation of in-depth flood reports rather than short summaries presented in Fact Sheets.

Implication for Other Flood Peaks

How serious is the problem of reliability of data in the USGS Peak-Flow File? The dataset described herein includes the largest floods ever documented by USGS and thus would expect to be populated by unusual, extraordinary, and perplexing floods of unusual hydraulic complexity. The USGS California Water Science Center conducted an informal evaluation of 50,000 flood peaks, about 1,500 of which were indirect discharge measurements. Envelope curves representing the maximum experienced discharge at all California streamflow-gaging stations were plotted. About 100 peaks were identified as outliers, and original field data and any other pertinent information were evaluated. About 50 of the 50,000 peak discharge measurements from gaged and ungaged sites were found to be suspect (Robert Meyer, U.S. Geological Survey, unpub. data, various dates). For the gaged sites, six floods were found to have data-entry errors, and those were corrected and the data revised. Fifteen flood peaks were downgraded to "estimates," and 13 were flagged as being so poor (debris flows rather than water floods, for example) that they should be considered for removal from the database.

Because of the diversity of topography and climate of California, flood peaks likely are more varied, complex, and difficult than average. If this is true, then a potential problem rate of 0.10 percent (50 of 50,000) of all flood peaks seems to be a reasonable upper bound for all USGS flood data. This percentage does not seem large, and the actual number of possible problems is 0.1 percent of approximately a million flood peaks in the Peak-Flow File, or about 1,000 floods. Outliers are good candidates for additional investigations (Crippen and Bue, 1977; Enzel and others, 1993).

Recommendations to Improve and Enhance Flood Science Tools within U.S. Geological Survey

The most important needs for flood science in USGS are: (1) a new and robust peak-flow linked database that allows for a richer description of events (including photographs and field notes), documentation of debris flows, interpretation of transient hydraulic processes such as translatory waves, and a much expanded qualification coding that explains the genesis of each flood in the database (that is, hurricane, dam failure, debris jam, rainfall-runoff, wildfire runoff, snowmelt, rain on snow); and (2) renewed commitment to documenting floods at ungaged (miscellaneous) sites. These improvements will greatly facilitate many uses of the flood file such as mixed-population flood-frequency analysis, or the study of high outliers by flow process at many points other than streamflow-gaging stations. As indicated by fig. 37 and the fact that more than 75 percent of the floods documented in this report did not occur at streamflow-gaging stations, there is a critical need for USGS to avoid transfixing on just the 7,000 streamflow-gaging stations in operation today. These streamflow-gaging stations are a very small sample of the millions of other locations where large floods need to be documented. The USGS must begin to make indirect discharge measurements at ungaged sites at a rate that existed half a century ago.

In the last two decades significant progress has been made in the speed and accuracy of direct discharge measurements, primarily through the introduction of hydroacoustic instruments. Enhancement of methods for indirect discharge measurements has been neglected. Some of the most important and significant floods occur at ungaged sites, and the primary basis for estimation of flow at these ungaged sites, if measurements are made at all, is the use of indirect discharge methods predicated on the assumptions of steady, uniform one-dimensional flows. The most common estimating tool is the slope-area method, and this has been true for at least the last 70 years.

The slope-area method depends on identification and interpretation of high-water marks and visual estimation of flow roughness. Estimation of roughness remains the most subjective component in slope-area measurements (Riggs, 1976). Slope-area indirect discharge measurements are time consuming and expensive. In 1996, the approximate cost of making a slope-area measurement was $5,000 (average cost of about 30 slope-area measurements performed in Oregon following 1996 flooding). In 2007, the cost was closer to $12,000 (estimate from USGS Texas Water Science Center).

- In channels where repeated slope-area measurements are being made, calibrated stream reaches could be established with monumented cross sections and multiple pairs of crest-stage gages. This would streamline the slope-area computation and reporting process.

Significant effort has been expended looking for objective surrogates for flow resistance, including slope (Riggs, 1976), particle size (Limerinos, 1970), and regression equations that rely on channel geometry and slope (Jarrett, 1984; 1992). All these methods result in reproducible Manning's *n*-values but with large uncertainties or bias. Verification studies for *n*-values are valuable, but they are limited to flows existing at the time of the work, which are usually not floods.

- The USGS needs a new emphasis on *n*-values verification linked to the direct measurement of large discharges (100-year flows and greater) by current meter and hydroacoustics. Presently, when a large discharge like a 100-year flow is measured, water-surface slope is not required and so is not documented. Back calculations of *n*-values require that water-surface slope be acquired at the time of the discharge measurement. Over time, this will lead to a unique dataset of verified *n*-values for the largest flows measured. This in turn will help guide thinking about flow resistance accompanying large floods at gaged and ungaged sites.

USGS needs to focus on alternatives to conventional indirect discharge methods to document floods where direct measurements are not possible. Several options exist, but they all have several characteristics in common that currently prevent their widespread adoption by USGS. First, these alternative methods are theoretically based, so application requires knowledge of the theory behind the relations, and second, these alternatives are more complex to perform in the field than a culvert or slope-area measurement, thus requiring substantial new training and experience.

One alternative method is the application of theoretical rating curves (Kean and Smith, 2005). This method produces stage/discharge relations for stable channels by using direct measurement of channel shape and physical roughness of the channel bed, banks, and flood plain, including vegetation density. The roughness model quantifies the various contributions to total flow resistance and incorporates results in a one-dimensional flow model that estimates discharge for different stages. This new method shows great promise for improving estimates of discharge for large floods. USGS needs to continue to develop and test theoretical rating curves that rely on direct measurements of roughness factors contributing to flow resistance at high discharges.

Flow models have and continue to offer insight into floods that slope-area measurements cannot provide. Unsteady one-dimensional models can provide exceptional details about hydraulics at individual cross sections but also translate hydrographs downstream and provide data about timing as well as flow magnitudes in multiple locations.

- Step-backwater modeling capability, such as HEC-RAS 3.0 or other software, should become a standard surface-water modeling tool in all USGS Water Science Center data programs.

Ideally for an ungaged site, rainfall data from rain gages or NEXRAD radar would be input into a hydrologic watershed model and that model used to produce hydrographs and discharge (see Giannoni and others, 2003) Alternatively, forecast flood hydrographs from the National Weather Service can be used as starting points for unsteady one-dimensional or multidimensional models, similar to what was used for flooding on the Snoqualmie River, Wash. (Jones and others, 2002).

- Surface-water hydrologists in the USGS Water Science Centers need to become familiar with using robust and stable multidimensional models such as imbedded in the graphical user interface MD_SWMS (McDonald and others, 2006) or UTRIM (Cheng and others, 1993). Widespread use of ground-water modeling in USGS Water Science Centers is evidence that complex modeling can be conducted in an operational program. Ground-water hydrology and hydraulics in the USGS have benefited by a symbiotic and collegial working relationship among the National Research Program of USGS, model developers, and the Office of Ground Water. The positive results of this relationship are clearly shown in the numerous tools used in USGS for ground-water studies and available to the public at: http://water.usgs.gov/software/ground_water.html

Upgrading flood science in USGS Water Science Centers may require surface-water hydrologists with modeling skills to be more closely linked to surface-water data programs, setting of common goals among surface-water researchers, operational, and data people, and a major commitment to upgraded training and hiring of hydrologists with surface-water modeling skills.

- USGS is missing an important opportunity to link flood data collection with meteorological processes applied to flood science such as orographic thunderstorm analysis, supercell thunderstorms, and radar rainfall estimations linked with hydrologic models of runoff. One example of this kind of analysis is presented by Smith and others (2000).

Understanding the largest floods requires insight into the large storm processes that produce record rainfall-runoff flooding. Presently, this link is broken or dysfunctional in USGS. Research on catastrophic storms that generate catastrophic floods has produced important insight into storm science, but this knowledge has not yet enriched USGS flood science. For example, for more than a century all of the greatest floods in western Pennsylvania have occurred in a very small window of time in mid-July. This period coincides with the peak tornado occurrence for the region (Smith and others, 2001). This area has recorded some of the world's largest measured precipitation for short time intervals (Costa, 1987a, 1987b).

Using annual peak discharge data from nearly 15,000 streamflow-gaging stations, O'Connor and Costa (2004) found that areas of the highest unit runoff are clustered in defined regions as a result of regional atmospheric conditions capable of producing large and intense amounts of rain and steep topography, which enhances runoff by convective and orographic processes. Many of the floods described herein were likely caused by orographic thunderstorms or super-cell thunderstorms (Smith and others, 2001; Hicks and others, 2005). Operationally, USGS is focused on post-mortem data collection of large floods if they occur at streamflow-gaging stations. Extraordinary floods at ungaged sites are being increasingly ignored. The capability clearly exists to generate data about flow at ungaged sites using radar rainfall estimations and hydrologic models (for example, Giannoni and others, 2003). USGS needs to build strong links to universities and offices such as NOAA River Forecast Centers, which create, interpret, and use rainfall data for hazard awareness. Interestingly, a model of collaboration between NOAA and USGS is focused on debris-flow warnings (NOAA-USGS Debris Flow Task Force, 2005) but not flood warnings.

- Noncontact methods of measuring cross sections and stream velocity need to be advanced and enhanced.

USGS should accelerate the introduction and piloting of new technologies. This need was identified as part of a review of hydrologic hazards science in USGS:

> Improved methods of streamflow measurement are needed that are less labor intensive and can be carried out quickly without the need to repeatedly physically lower instruments on a cable into the water (Committee on U.S. Geological Survey Water Resources Research, 1999).

By direct measurement of flow and geometry, there is no need for rating curves, extrapolations, models, or roughness estimations. Surface velocity can be measured using Doppler shifts from Bragg scattering, and channel geometry can be measured in real time in low conductivity water using ground-penetrating radar. Surface velocity can be converted into mean velocity with knowledge of the vertical velocity flow structure. This capability to measure discharge directly and with high accuracy using radar has been clearly demonstrated

(Costa and others, 2006). Another method to measure surface velocity involves timing seeded or naturally occurring floating materials. This method is known as particle image velocimetry (PIV) and has produced generally good test results (Creutin and others, 2003). The next step in this research is making radar measurements of cross sections from a single point on the bank of the stream. This work is in progress.

Paleoflood hydrology methods need to be more broadly utilized in the USGS. Just as miscellaneous indirect flood measurements complement the USGS streamflow-gaging station data, paleoflood data can provide important information on large undocumented flood evidence preserved in channels and floodplains. Paleoflood hydrology is the study of recent, past, or ancient floods, although the methodology is applicable to historic or modern floods (Jarrett and England, 2002). Paleoflood hydrology is the science of reconstructing, with here-to-for unavailable data, the magnitude and age of large floods by using flood-sediment deposits and botanical evidence (House and others, 2002). Although the term paleoflood hydrology is fairly recent (about 1970), the use of the methodology has been around for about a century (Costa, 1987c).

Recent paleoflood data and methodologies are used to provide data on extraordinary floods outside streamflow-gaging station records that provide new data to define upper limits of envelope curves, to help provide robust flood frequency estimates with probabilities ranging from 10-1 to 10-4, and to improve flood-hazard assessments (for example, flood forecasting and floodplain management), particularly for dam safety and evaluating other high risk facilities (Jarrett and Tomlinson, 2000; House and others, 2002). Paleoflood techniques also can be used to help provide assessments on the effects of climate change and non-stationarity on flooding. Many paleoflood studies have been conducted throughout the United States providing both information on the largest floods and new tools to advance flood science and societal relevance. House and others (2002) compiled papers on methodology and results using paleoflood hydrology.

USGS has been a leader in the collection of flood data and creation of flood science. Although USGS continues to lead in developing and testing instrumentation for *measurement* of flow, the agency has not made an equal commitment to developing of new *tools* (specifically flow models) or *interpretation* of these measured data. The USGS surface-water data program needs new methods for quantification of floodflows in the absence of direct measurements. These tools exist both within and outside USGS, but they have not been embraced in the data program. USGS continues to teach slope-area classes but the agency should reintroduce step-backwater classes as part of the training program. Use of multidimensional flow models will lead to greater insight into flood hydrology and hydraulics than the quasi-steady flow tools.

Summary and Conclusions

The envelope curve of maximum floods documented in the United States by the U.S. Geological Survey (USGS) was determined using 30 peak discharge measurements from 28 extraordinary floods that occurred from 1927 to 1978. The reliability of the computed discharge of these “extraordinary” floods was reviewed and evaluated using current (2007) best practices. The review and evaluation of the 30 peak discharges indicated that 10 occurred at daily streamflow-gaging stations, and 20 were flood measurements made at miscellaneous (ungaged) sites. Twenty-one measurements were slope-area measurements, two were direct current-meter measurements, one was a culvert measurement, one was a rating-curve extension, one involved interpolation and a rating-curve extension, and the remainder were combinations of culvert, slope-area, flow-over-road, and contracted-opening measurements. The method for determining peak discharge for one flood is unknown.

Changes to peak discharge or rating were required for 15 of the 30 peak discharge measurements that were evaluated. Published peak discharges were retained for six floods, but their ratings were downgraded. Peak discharges and ratings were corrected and revised for two floods. Peak discharges for five floods were subject to significant uncertainty due to difficult field and hydraulic conditions and were re-rated as estimates. The difference in revised peak discharges for 5 of the 30 floods was greater than about 10 percent from the original published values. Peak discharges were smaller than published values for three floods (North Fork Hubbard Creek, Texas; El Rancho Arroyo, New Mexico; South Fork Wailua River, Hawaii), and were larger than published values for two floods (Lahontan Reservoir tributary, Nevada; Bronco Creek, Arizona). Peak discharges for two floods were indeterminate because they were concluded to have been debris flows whose peaks were estimated by using an inappropriate method (slope-area) (Big Creek near Waynesville, North Carolina; Day Creek near Etiwanda, California). Original field notes and records could not be found for three of the floods, but some data (copies of original materials, records of reviews) were available for two of these floods.

Errors identified in the reviews include misidentified flow processes, incorrect drainage areas for very small basins, incorrect latitude and longitude, improper field methods, arithmetic mistakes in hand calculations, omission of measured high flows when developing rating curves, and typographical errors. Common problems include two-section slope-area measurements, poor site selection, uncertainties in Manning’s *n*-values, inadequate review, missing data files, and inadequate high-water marks. These floods also highlight the extreme difficulty in making indirect discharge measurements following extraordinary floods. None of the indirect measurements are rated better than fair, which indicates the need to improve methodology to estimate peak flood discharge. Highly unsteady flow and resulting transient hydraulic phenomena, two-dimensional flow patterns, debris flows at streamflow-gaging stations, and the possibility of disconnected flow surfaces are examples of unresolved problems not handled by current indirect discharge methodology. On the basis of a comprehensive review of 50,000 annual peaks and miscellaneous floods in California, it could be expected that problems with individual flood peaks would require a revision of discharge or rating curves to occur at a rate no greater than about 0.10 percent of all floods.

The envelope curve of extraordinary floods in the United States was determined predominantly by measurements at ungaged sites. Records for only 11 of the 30 floods investigated were available online in the USGS National Water Information System (NWIS) database. Nearly all peaks at ungaged sites were published in compilations of large documented floods such as in USGS Professional Papers or Water-Supply Papers. These peak discharge data were not compiled with other USGS flood data in NWIS. Today (2007), USGS makes few flood measurements at ungaged sites, and most flood reports are 2-page fact sheets. For example, it has been estimated that each year, on average, Colorado experiences at least 150 rainstorms with recurrence intervals of 100 years or larger (Jarrett and Costa, 2006), yet few resulting floods are documented.

Many extraordinary floods create complex flow patterns and processes that can not be adequately documented with quasi-steady one-dimensional analyses. These floods are most accurately described by multidimensional flow analysis. Yet today (2007), the standard practice used by USGS to document the extraordinary floods that have not been directly measured is to apply models, such as the slope-area method, that assume one-dimensional, quasi-steady flow existed at the peak.

New approaches are needed to collect more accurate data for floods, particularly extraordinary floods. In recent years, significant progress has been made in instrumentation for making direct discharge measurements. During this same period, very little has been accomplished in advancing methods to improve indirect discharge measurements. Within USGS, flood meteorology and flood hydrology are frequently considered separately. Additional links among flood runoff, storm structure, and storm motion would provide more insight to flood hazards. Significant improvement in understanding flood processes and characteristics could be gained from linking radar rainfall estimation and hydrologic modeling. Much more could be done to provide real-time flood-hazard warnings with linked rainfall/runoff and flow models.

When large discharges are measured by current meter or hydroacoustics, water-surface slope can be accurately determined. This allows validation of roughness values that can significantly extend the discharge range of verified Manning's *n*-values. With increased use of multidimensional flow models, USGS needs to conduct validation studies of Manning's *n*-values (or more broadly energy losses) for these models because existing *n*-values data are based on one-dimensional flow conditions and likely are not directly applicable for multidimensional flow models. Instability criteria need to be considered for hydraulic analysis of large flows in steep gradient, smooth channels.

USGS needs to modernize its toolbox of field and office practices for making future indirect discharge measurements. First and foremost, a new Peak-Flow File database is needed that incorporates all USGS flood and indirect peak measurements and allows much greater description and interpretation of flows, such as stability criteria in steeper gradient, smooth channels, debris-flow documentation, and details of flood genesis (hurricane, snowmelt, rain-on-snow, dam failure, and the like). Other improvements include:

- Establishment of calibrated stream reaches in chronic flashflood basins to expedite indirect computation of flow;
- Development of process-based theoretical rating curves for streamflow-gaging stations;
- Introduction of step-backwater models as a standard surface-water modeling tool in all USGS Water Science Centers;
- Development and support for multidimensional flow models capable of describing flood characteristics in complex terrain and high-gradient channels;
- Greater use of the critical-depth and slope-conveyence methods in appropriate locations;
- Deployment of noncontact instruments to directly measure large floods rather than trying to reconstruct them; and
- Assurance that future collection of hydroclimatic data meets the needs of more robust watershed models.

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