U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
GRAND CANYON MONITORING AND RESEARCH CENTER

Variations in Sand Storage Measured at Monumented Cross Sections in the Colorado River Between Glen Canyon Dam and Lava Falls Rapid, Northern Arizona, 1992–99

Water-Resources Investigations Report 03—4104

USGS
science for a changing world

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Variations in Sand Storage Measured at Monumented Cross Sections in the Colorado River Between Glen Canyon Dam and Lava Falls Rapid, Northern Arizona, 1992–99

By Marilyn E. Flynn *and* Nancy J. Hornewer

Water-Resources Investigations Report 03—4104

Prepared in cooperation with the

GRAND CANYON MONITORING AND RESEARCH CENTER

Tucson, Arizona
2003

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
520 N. Park Avenue, Suite 221
Tucson, AZ 85719–5035

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
Federal Center
Denver, CO 80225–0046

Information about U.S. Geological Survey programs in Arizona is available online at http://az.water.usgs.gov.

CONTENTS

Page

Abstract 1
Introduction 1
 Background 3
 Purpose and scope 4
 Acknowledgments 4
 Description of the study area 4
 Physical and hydrological conditions 4
 Controlled releases and gaged tributary inputs 5
 Sediment-monitoring network 8
Methods 8
 Data collection 8
 Data processing 19
 Presentation of data 21
Cross-section variability 23
 Spatial variability in changes in cross-sectional area 23
 Temporal variability in cross-sectional area 23
Changes in cross-sectional area 31
Factors affecting sediment storage changes 31
Conclusion 37
Selected references 38

FIGURES

Page

1. Map showing location of areas of monumented cross sections and streamflow-gaging stations 2
2. Graphs showing summary of daily discharge statistics for the streamflow-gaging station Colorado River at Lees Ferry (09380000), Arizona, water years 1992–99 6
3. Graphs showing daily maximum discharge and daily suspended-sediment discharge on tributaries, water years 1992–99.. 9

4–8. Maps showing:
   4. Location of monumented cross sections between Glen Canyon Dam and Lees Ferry, Arizona.. 11
   5. Location of monumented cross sections between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid... 12
   6. Location of monumented cross sections between Badger Creek Rapid and the confluence of the Little Colorado and Colorado Rivers 13
   7. Location of monumented cross sections between the confluence of the Little Colorado and Colorado Rivers and Tanner Rapid 14
   8. Location of monumented cross sections between just above the confluence of Bright Angel Creek and the Colorado River and Lava Falls Rapid.. 15

9. Schematic diagram showing data-collection and processing steps
   A. Steps for collecting and preliminary processing of cross-section elevation data.......................... 18
   B. Procedure for calculating the change in cross-sectional area between two successive measurements 18

10–20. Graphs showing:
   10. Discharge-elevation curves for three water-surface reference points
      A. Sections p01–p15 22
      B. Sections 1a1–1a7... 22
      C. Sections lf1–lf5.. 22
   11. Normalized change-in-area data, excluding 1996 controlled-flood measurements, for cross sections in the primary data set
      A. Sections between the confluences of the Paria and Colorado Rivers, and the Little Colorado and Colorado Rivers 24
      B. Sections between the confluences of the Little Colorado and Colorado Rivers, and Bright Angel Creek and the Colorado River 24
   12. Non-normalized change-in-area data, excluding 1996 controlled-flood measurements, for cross sections in the primary data set
      A. Sections between the confluences of the Paria and Colorado Rivers, and the Little Colorado and Colorado Rivers 25
      B. Sections between the confluences of the Little Colorado and Colorado Rivers, and Bright Angel Creek and the Colorado River 25
   13. Bed-elevation measurements for selected cross sections in the primary data set below the confluence of the Paria and Colorado Rivers.. 26

14. Bed-elevation measurements for selected cross sections in the primary data set below the confluences of the Paria and Colorado Rivers, and the Little Colorado and Colorado Rivers ... 27
15. Bed-elevation measurements for cross section 1a1 in the primary data set below the confluence of the Little Colorado and Colorado Rivers ... 28
16. Discharge and normalized change-in-area data for cross sections in the primary data set between the confluences of the Paria and Colorado Rivers, and Bright Angel Creek and the Colorado River
A. Daily maximum discharge at the streamflow-gaging station at Colorado River at Lees Ferry 29
B. Daily maximum discharge at the streamflow-gaging station at Paria River at Lees Ferry ... 29
C. Sections p01–p32 ... 29
D. Sections h1–h5 and w1–w5 ... 29
E. Daily maximum discharge at the streamflow-gaging station at Colorado River above Little Colorado River ... 30
F. Daily maximum discharge at the streamflow-gaging station at Little Colorado River near Cameron ... 30
G. Sections la1–lf5. ... 30
H. Sections g0–g5 ... 30
17. Net change in area for cross sections in the matching-date data set between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid
A. Sections p01–p08 ... 32
B. Sections p09–p15 ... 32
C. Sections p15a–p20 ... 32
D. Sections p21–p26 ... 33
E. Sections p27–p31 ... 33
18. Net change in area for cross sections in the matching-date data set between the confluence of the Little Colorado and Colorado Rivers and Tanner Rapid
A. Sections la1–la7 ... 34
B. Sections lb1–lb4 ... 34
C. Sections lc1–lc5 ... 34
D. Sections ld1, ld4, and le1–le5 ... 35
E. Sections lf1–lf4 ... 35
19. Associations between average changes in area and five hydrologic conditions for cross sections in the matching-date data set between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid
A. Average of daily mean flows ... 36
B. Average of time-weighted daily mean flows ... 36
C. Average of daily mean range of flows ... 36
D. Average of time-weighted daily mean range of flows ... 36
E. Suspended-sediment discharge from the Paria River ... 36
20. Associations between average changes in area and five hydrologic conditions for cross sections in the matching-date data set between the confluence of the Little Colorado and Colorado Rivers and Tanner Rapid
A. Average of daily mean flows ... 37
B. Average of time-weighted daily mean flows ... 37
C. Average of daily mean range-of-flows ... 37
D. Average of time-weighted daily mean range of flows ... 37
E. Suspended-sediment discharge from the Paria and Little Colorado Rivers ... 37

TABLES

Page

1. Summary statistics for discharge at the streamflow-gaging station Colorado River at Lees Ferry (09380000), Arizona, water years 1992–99 7
2. Summary statistics for discharge and measured suspended-sediment discharge at the streamflow-gaging station Paria River at Lees Ferry (09382000), Arizona, water years 1992–99 10
3. Summary statistics for discharge and measured suspended-sediment discharge at the streamflow-gaging station Little Colorado River near Cameron (09402000), Arizona, water years 1992–99 11
4. Inventory of cross-section measurement dates 16
5. Standard error estimates applied to changes in area 21

CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square meter (m^2)	10.76	square foot (ft^2)
square meter (m^2)	1.1960	square yard (yd^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.3079	cubic yard (yd^3)
cubic meter per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
metric ton (megagram)	1.1023	tons, short (2,000 pounds)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). **Altitude**, as used in this report, refers to distance above or below NGVD 29.

Variations in Sand Storage Measured at Monumented Cross Sections in the Colorado River Between Glen Canyon Dam and Lava Falls Rapid, Northern Arizona, 1992–99

By Marilyn E. Flynn *and* Nancy J. Hornewer

Abstract

Bed elevations were measured at 131 monumented cross sections in the Colorado River between Glen Canyon Dam and Lava Falls Rapid from June 1992 to September 1999 to provide data on channel sand storage. This report documents the location of the 131 monumented cross sections, dates of measurements for all cross sections, methods of data collection and processing, and spatial and temporal variation and variability in changes in cross-sectional area for selected cross sections. Additionally, data were analyzed to determine if changes in sediment storage could be related to main channel flow conditions and tributary sediment inputs. Most of the cross sections showed a limited capacity, both in terms of amount and residence time, to store sediment. Data for 83 of the 131 cross sections were comprehensive and complete, and were used for analyses in this report. This data set is referred to as the primary data set. Of these 83 cross sections, 19 had a net gain in stored sediment, 61 had a net loss of stored sediment, and 3 had no change in stored sediment for the period of data collection, excluding data collected during the high release from Glen Canyon Dam in 1996. A subset of the primary data set consisting of the sections downstream from the Paria and Little Colorado Rivers with measurements made on or nearly on the same day, referred to as the matching-date data set, was used to explore the effects of controlled flows and tributary flows on the changes in cross-sectional area. The matching-date data set consists of data from 57 cross sections. Of these 57 cross sections, 1 had a net gain in stored sediment, 55 had a net loss of stored sediment, and 1 had no change in stored sediment. Results of the analysis did not show that changes in cross-sectional area were strongly related to main channel flow conditions or tributary sediment inputs.

INTRODUCTION

Between 1992 and 1999, the U.S. Geological Survey (USGS), initially in cooperation with Glen Canyon Environmental Studies (GCES) and later in cooperation with the Grand Canyon Monitoring and Research Center (GCMRC), established a network of monumented cross sections along the Colorado River between Glen Canyon Dam and Lava Falls Rapid (fig. 1) to measure changes in cross-sectional area. These changes in cross-sectional area were intended to be an indication of changes in sand stored on the channel bottom.

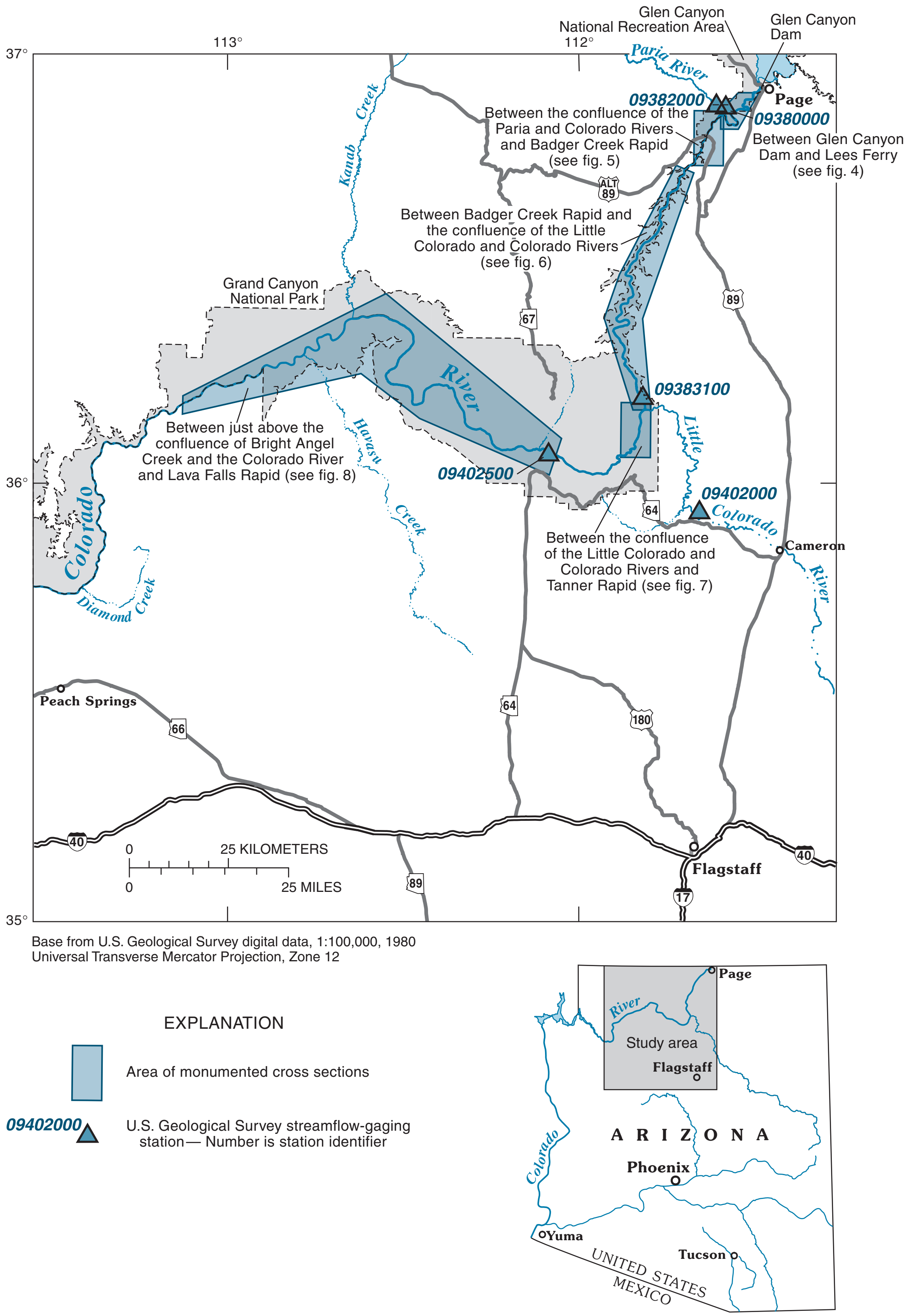


Figure 1. Location of areas of monumented cross sections and streamflow-gaging stations.

Background

In the early 1980s, agencies charged with management of the Colorado River in Grand Canyon, white-water rafters, and anglers became concerned that flow releases from Glen Canyon Dam were eroding sandbars that are critical to the riparian system in Grand Canyon National Park. Concern about sandbars focused on potential degradation by unsteady dam releases for power generation. In 1982, the Bureau of Reclamation (BOR) began coordinating a comprehensive program of investigations—Phase I of GCES—to determine the effects of dam releases on the downstream riverine environment. During Phase I, unexpected high flows prevented adequate study of flows typical of the dam's powerplant operating criteria. After a review of Phase I by the National Academy of Science, the U.S. Department of the Interior directed that further studies be done. Phase II of the GCES was initiated in 1988 to gather additional data on specific dam operational elements and included flow-monitoring and model-development programs.

On July 27, 1989, the Secretary of the Interior directed the BOR to prepare an environmental impact statement (EIS) on the operation of Glen Canyon Dam. To protect the downstream resources until completion of the EIS, interim operating criteria and a monitoring program were implemented in August 1991. The EIS was completed in March 1995, and the Record of Decision (ROD) on the operation of Glen Canyon Dam was signed on October 9, 1996. The ROD stipulated new operating criteria for the dam based on the preferred modified low fluctuating flow (MLFF) alternative presented in the EIS. Under the MLFF alternative, limits were set on maximum and minimum daily flow releases and on the rates of increase (upramp) and decrease (downramp) of releases. Specifically, the maximum flow of 708 m^3/s was imposed in order to conserve sediment in Grand Canyon, especially in the Marble Canyon area. The downramp limit of 42 m^3/s was imposed to reduce beach erosion in the Marble Canyon reach that resulted from rapid leaching of water in the beach sand. Because it was assumed that limiting maximum releases would cause portions of sandbars above the normal peak stage to not be rebuilt; sediment to accumulate at low elevations, including backwaters and camping beaches; and return-current channels to become filled with sediment and eventually overgrown with vegetation, the MLFF also included habitat maintenance flows (high, steady releases within powerplant capacity) to re-form backwaters and maintain sandbars (U.S. Department of the Interior, 1995). The EIS concluded that Glen Canyon Dam reduced the sediment-transport capacity of the river to a greater degree than it reduced the supply of sediment, and thus, sediment would accumulate over time (U.S. Department of the Interior, 1995). Using MLFF operating criteria, the EIS predicted that there would be a 73-percent probability of sand accumulating in the main channel over a 50-year period. Topping, Rubin, and Vierra, 2000; Topping, Rubin, Nelson, and others, 2000; and Rubin and Topping, 2001 have concluded that multiyear sediment accumulation does not occur.

Beginning in 1992, as a part of the GCES Phase II interim-flow monitoring and model-development programs, the USGS established a network of monumented cross sections between the confluence of the Paria and Colorado Rivers and Lava Falls Rapid, with greater emphasis on the reaches downstream from the two largest tributaries—the Paria and Little Colorado Rivers. Measurements were designed around three hydrologic conditions in the year: (1) before the snowmelt runoff in tributaries in early spring, (2) after the snowmelt runoff in late spring or early summer, and (3) after summer rains in the fall. Between 1993 and 1996, additional cross sections were added between Badger Creek Rapid and the confluence of the Colorado and Little Colorado Rivers, and between just upstream from Bright Angel Creek and Lava Falls Rapid. In 1997 the number of cross sections was reduced; sections in reaches that showed little to no change were discontinued, and an index section was chosen for each pool in the remaining reaches. The measurement frequency of these index sites also was reduced from three times per year to twice per year: (1) in April to capture information on deposition of sediment from winter tributary floods, and (2) in September to capture information on deposition of sediment from late summer runoff in tributaries.

One purpose of the cross-section network was to provide data on bed-elevation changes to compare to computations of bed evolution made using multi-dimensional flow, sediment-transport, and bed-evolution models. The network proved useful for this purpose (Wiele and others, 1996). A second purpose of the cross-section network was to provide a direct, empirical method for monitoring the amount of sand stored in the channel to determine if a multiyear accumulation of sediment was occurring. Data indicated that cross sections could be used to provide an assessment of the sand storage in the channel, the storage conditions for possible bar-building high releases, and the effectiveness of those releases in scouring stored sand and rebuilding sandbars.

Purpose and Scope

The purpose of this report is to document locations of the 131 monumented cross sections, the measurement dates during the study period June 1992 to September 1999, and the methods of data collection and processing, and to present a general assessment of the variability in cross-sectional area. A subset of the data, referred to as the primary data set, was used to illustrate the temporal and spatial variability in cross-sectional area. In addition, a subset of the primary data set consisting of data from measurements made on or nearly on the same day at sections downstream from the Paria and Little Colorado Rivers, referred to as the matching-date data set, was used to further explore the effects of hydro-logic conditions on the changes in cross-sectional area. All cross-section measurement data are available electronically as ASCII files from the Arizona District Office of the USGS (address on back of title page).

Acknowledgments

The authors thank the many people who provided assistance throughout the life of this project. In particular, we acknowledge Julia B. Graf, USGS (retired), for her guidance and leadership in establishing the foundations upon which this project was developed. We also thank Dave Anning, Greg Fisk, and Gail Cordy of the USGS for their help in the preparation of this report.

Description of the Study Area

The study area includes the Colorado River between Glen Canyon Dam and Lava Falls Rapid, which is about 195 miles downstream from Glen Canyon Dam in northern Arizona. The study area encompasses parts of Glen Canyon National Recreational Area and Grand Canyon National Park (fig. 1). In this report, distances along the Colorado River are expressed in river miles, and all other measurements are expressed in metric units.

Physical and Hydrological Conditions

For much of its length through the study area, the Colorado River is confined by bedrock, by large blocks of talus, or by alluvial debris fans that are composed of sediment too coarse to be transported except during high flows. Flow depths in the thalweg of the river range from about 1.5 to 32 m at a discharge of 708 m^3/s. Depths can change abruptly, and there are near-vertical drops of as much as 15 m in gorges formed in the metamorphic and igneous rock (Wilson, 1986). Between Lees Ferry (river mile 0) and Diamond Creek (river mile 226), the elevation of the river decreases about 542 m. Much of the decrease in elevation occurs in short, steep reaches, many of which are the well-known rapids of the Colorado River. Although the average gradient between Lees Ferry and Diamond Creek is 0.0015, the gradient of many of the short reaches exceeds 0.01 (Schmidt and Graf, 1990). Many of the reaches between rapids have gradients less than 0.0005 (Birdseye, 1923).

In the study area, tributaries of the Colorado River can be categorized as those having headwaters above the rim and those having headwaters below the rim. The Paria and Colorado Rivers are tributaries having headwaters above the rim; their drainage basins include large plateau areas, and they supply most of the suspended sediment to the Colorado River within the study area. Tributaries having headwaters below the rim have drainage basins largely within the inner canyon and can transport fine sediment as well as large boulders in debris flows (Cooley and others, 1977; Webb and others, 1989). The debris flows from these smaller tributaries define the longitudinal profile and control the geomorphic framework of the Colorado River by forming rapids (Webb, 1996). In addition, the debris fans directly control the formation and stability of most sandbars (Schmidt, 1990; Schmidt and Graf, 1990; Schmidt and Rubin, 1995).

In general, the channel pattern of the Colorado River through the study area is dominated by an alternating rapid-pool sequence (Howard and Dolan, 1981). Flow through the constrictions created by the debris-flow deposits at the mouths of tributaries forms the rapids. Flow through rapids ends in pools (Dolan and others, 1978; Kieffer, 1985). The downstream ends of these pools are controlled by bedrock outcrops or alternating debris bars that are the outwash from the upstream debris fans (Howard and Dolan, 1981; Webb and others, 1989; Melis and Webb, 1993; Melis and others, 1994). Because the debris fans raise the bed elevation (Howard and Dolan, 1981), large pools also form upstream from rapids. The length of the pools is determined by the spacings between debris fans, which are controlled by bedrock geology (Howard and Dolan, 1981). These pools are recirculation zones and may contain one or more eddies and low-velocity areas, thus providing an environment for sediment deposition (Schmidt and Graf, 1990).

Prior to the closure of Glen Canyon Dam in 1963, the Colorado River in Grand Canyon had highly variable discharge and suspended-sediment concentration annually. Between May and July, melting of the snowpack in the headwaters produced mean annual peak discharge of 2,420 m^3/s. Except for brief but occasionally substantial summer tributary flash floods, flow in the Colorado River typically fell to less than 200 m^3/s after the snowmelt flood subsided. Post-dam flow regulation has removed seasonal-flow variations by reducing the frequency of discharges that are greater than powerplant capacity (940 m^3/s) and increasing the overall range and rate of change of discharge during each day.

The average sediment load for the Colorado River at Lees Ferry before the dam was 60 million metric tons per year (Webb, Wegner, and others, 1999). The suspended-sediment load of the post-dam Colorado River has been reduced by 95 percent (Webb, Wegner, and others, 1999) and is primarily supplied by the major tributaries, the Paria and Little Colorado Rivers, and numerous smaller, ungaged tributaries. The mean annual supply of fine sediment was 2.74 million metric tons for 1947–76 from the Paria River and 8.4 million metric tons for 1947–72 from the Little Colorado River (Webb, Wegner, and others, 1999). The smaller tributaries create and maintain the debris fans and rapids on the Colorado River and serve as important sources of fine-grained sediment (Powell, 1895; Hamblin and Rigby, 1968; Dolan and others, 1974; Howard and Dolan, 1981; Keiffer, 1985). Estimating the sediment yield from these smaller tributaries is complicated because sand is contributed by a combination of fluvial and hillslope processes (Webb and others, 2000). Using a sediment-yield model for debris flow, Webb and others (2000) estimate that approximately 2.0 million metric tons of total sediment enters the river from the ungaged tributaries between Glen Canyon Dam and Diamond Creek (river mile -15 to 226).

Controlled Releases and Gaged Tributary Inputs

Changes in area measured at cross sections within the study area are affected by controlled flows from Glen Canyon Dam and sediment input from tributaries. Under the MLFF preferred alternative specified in the EIS, peak releases are limited to 708 m^3/s, minimum releases are limited to 227 m^3/s during the day and 142 m^3/s at night, and the maximum daily fluctuation or range in flow is limited to 227 m^3/s. The preferred alternative also provides for short duration, high-flow releases to accomplish specific management objectives and to simulate some of the dynamics of a natural river (U.S. Department of the Interior, 1995). In March-April 1996, a controlled high-flow release experiment (1996 controlled flood) was conducted. A flow of 1,275 m^3/s was released from Glen Canyon Dam for a period of 7 days to determine the effectiveness with which discharges greatly in excess of the normal powerplant-restricted maximum could renew the riparian environment along the Colorado River. Several papers on the controlled flood are compiled in Webb, Schmidt, and others (1999).

For this study period, the box plots shown in **figure 2** graphically summarize the distribution of maximum, minimum, and range (daily maximum - daily minimum) of daily discharge values for water years 1992–99 at the USGS streamflow-gaging station Colorado River at Lees Ferry (09380000; **fig. 1**), approximately 16 miles downstream from Glen Canyon Dam. The distribution of maximum and minimum daily discharge values is lower during water years 1992–95 than during water years 1996–99. Beginning in water year 1996, there is an increase in the annual median daily maximum and minimum discharge. The annual median daily discharge decreased in water year 1999, but was still larger than medians of the earlier period (1992–95). The maximum daily discharge at this station occurred during the 1996 controlled flood, and the minimum daily discharge occurred in water year 1992. **Table 1** shows annual summary statistics for discharge at Lees Ferry. Suspended-sediment discharge from the Glen Canyon reach, measured at the Lees Ferry gaging station, is negligible and therefore is not included in table 1 or other analyses in this report.

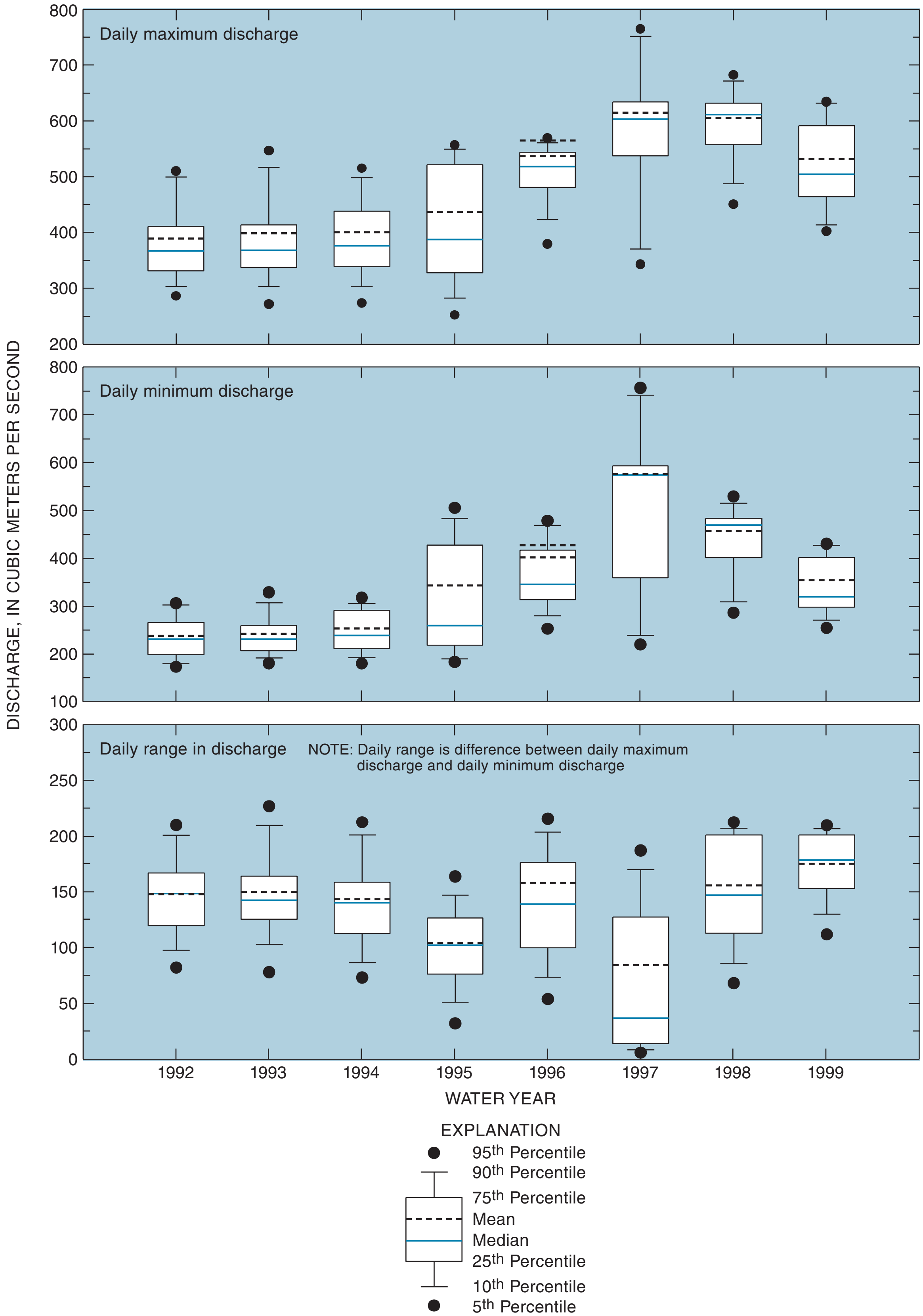


Figure 2. Summary of daily discharge statistics for the streamflow-gaging station Colorado River at Lees Ferry (09380000), Arizona, water years 1992-99

Table 1. Summary statistics for discharge at the streamflow-gaging station Colorado River at Lees Ferry (09380000), Arizona, water years 1992–99

	Water year							
	1992	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Minimum daily discharge summary (values in cubic meters per second)								
Minimum	148	151	160	158	230	187	201	249
Median	232	230	240	259	345	575	470	320
Mean	234	238	250	310	376	504	442	345
Maximum	323	408	345	541	1,290	759	855	702
Standard deviation	42	44	44	113	138	165	76	62
Mean daily discharge summary (values in cubic meters per second)								
Minimum	179	205	206	194	231	220	249	292
Median	303	306	314	328	436	595	547	430
Mean	312	317	324	361	449	542	525	446
Maximum	428	490	447	558	1,290	762	869	708
Standard deviation	54	61	59	107	135	143	78	72
Maximum daily discharge summary (values in cubic meters per second)								
Minimum	228	226	232	221	232	232	281	348
Median	367	368	377	388	518	603	612	504
Mean	379	385	389	410	518	576	592	518
Maximum	530	564	629	569	1,300	767	872	711
Standard deviation	66	76	72	102	133	124	77	78
Daily range (daily maximum - daily minimum) discharge summary (values in cubic meters per second)								
Minimum	39	2.0	2.0	3.1	2.0	2.8	5.7	0.0
Median	148	142	140	102	139	34	147	178
Mean	145	146	139	101	142	72	150	173
Maximum	227	286	331	193	1,050	383	368	261
Standard deviation	36	41	41	37	75	67	50	33

Tributary streamflow and suspended-sediment discharge measured at the USGS streamflow-gaging stations Paria River at Lees Ferry (09382000) and the Little Colorado River near Cameron (09402000; **fig. 1**) are shown in **figure 3**, and annual statistical summaries are shown in tables 2 and 3. Because sediment input from the Paria and Little Colorado Rivers is only significant during storms, suspended-sediment samples were collected only during storms; consequently, annual daily maximums and minimums for suspended-sediment discharge are not available. These samples were collected using automated pump samples or single-stage samplers, or were collected as equal-width-increment or dip samples. On the basis of sediment-discharge rating curves, discharges greater than 30 m^3/s in the Paria River and 60 m^3/s in the Little Colorado River generally can contribute large quantities of sediment to the mainstem of the Colorado River, (G.G. Fisk, U.S. Geological Survey, oral commun., 2000). During the study period, the largest annual suspended-sediment contribution from the Paria River as the result of storms, 4.4 million metric tons, occurred in water year 1997 (**table 2**). The largest annual suspended-sediment contribution from the Little Colorado River as the result of storms, 18.8 million metric tons, occurred in water year 1993 (**table 3**). Most of this sediment was input from a storm in January 1993 that has a 15-year recurrence interval (Smith and others, 1998).

Sediment-Monitoring Network

A total of 131 monumented cross sections were established to measure bed elevation on the Colorado River between Glen Canyon Dam and Lava Falls Rapid (fig. 1) between August 1992 and April 1998. Cross sections were established at locations judged to be favorable for sand storage on the basis of channel geometry, character of bank and visible bed materials, and presence of sand waves on depth-sounder charts (Graf and others, 1995). An emphasis was placed on locating sections immediately downstream from major tributaries, the Paria and Little Colorado Rivers, because of the large sediment inputs from these tributaries and for flow- and sediment-model verification purposes. The four cross sections between Glen Canyon Dam and Lees Ferry (**fig. 4**) were established and first measured in April 1998. Monitoring downstream from the Paria River began in August 1992. Thirty-four cross sections were established between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid at river mile 8 (**fig. 5**). Twenty-six cross sections were established between Badger Creek Rapid and the mouth of the Little Colorado River at river mile 61.3 (**fig. 6**). Most of these cross sections were established and first measured in January 1994. Monitoring downstream from the Little Colorado River (**fig. 7**) began in June and July 1992 when the 15 cross sections at the upstream end were established and first measured. The remaining 17 cross sections at the downstream end were established and first measured in January and February 1993. Thirty-five cross sections were established between river mile 87 (just above Bright Angel Creek) and Lava Falls Rapid at river mile 179.5 (**fig. 8**). A list of all measurement dates by cross-section name in downstream order and the subsets of the data, primary and matching-date data sets, used in this report is given in **table 4**. Location information for the monumented cross sections is available from the Arizona District Office of the USGS.

Beginning with the fall 1997 measurement trip, bed-material samples were collected at the cross sections being measured at the time (table 4). Because of the small number of samples collected, these data are not considered in this report.

METHODS

A sonic-depth sounder was used to measure the depth of the river bed below the water surface, and the graphical record produced by the sounder was digitized to create the digital record used to calculate changes in cross-sectional area. The data-collection and processing steps, and the steps used to calculate the change in area between two measurements for a cross section, are shown in **figure 9** and described below.

Data Collection

For each measurement, a kevlar line with flags at 6.08-m (20-ft.) intervals was strung across the river between the cross-section end points. Where feasible, the zero point on the line was positioned on the left-bank side. The positions of each monument and the edge of water on each bank were noted as distances along the line from the zero point. A boat equipped with a sonic-depth sounder was driven back and forth under the line.

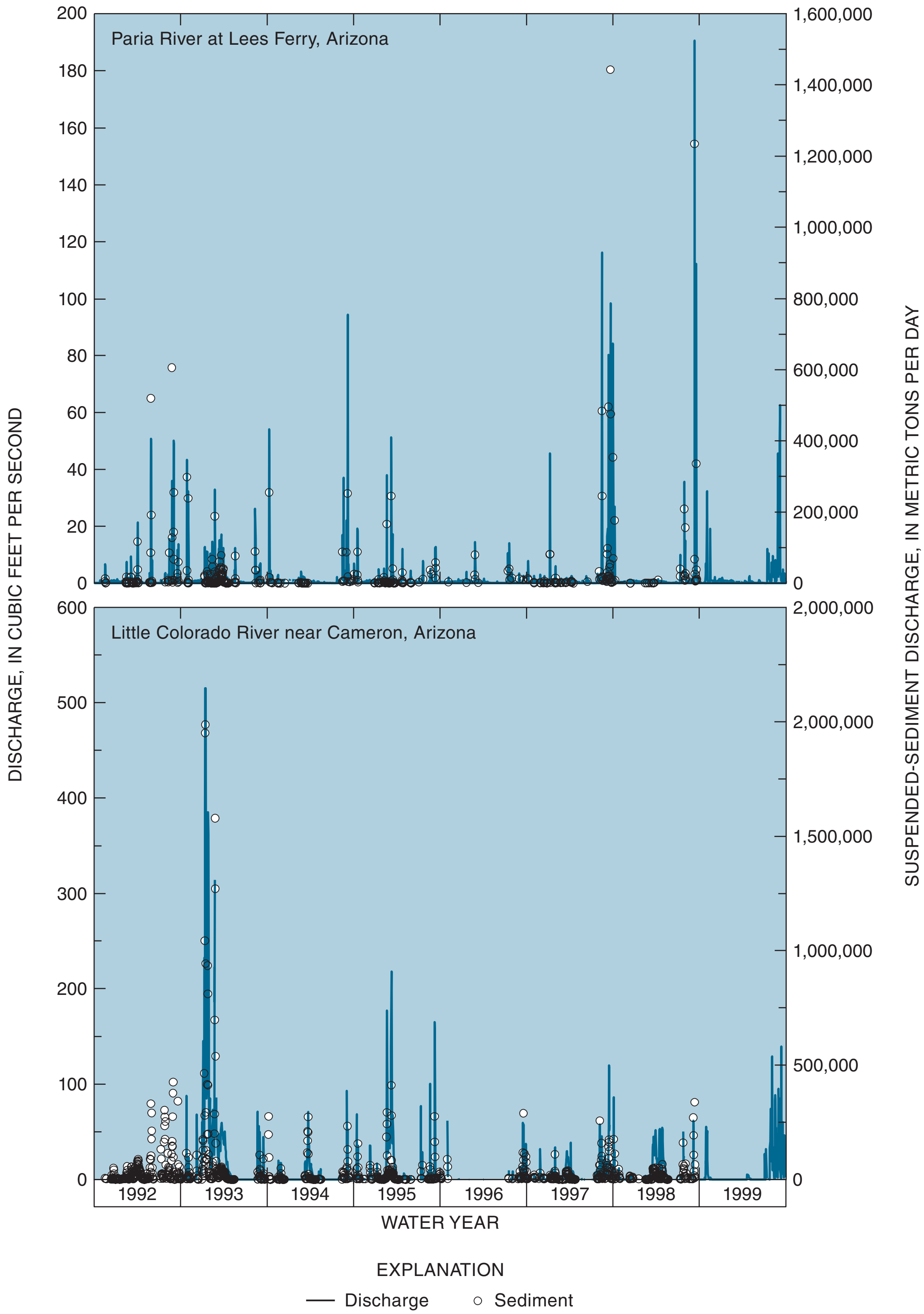


Figure 3. Daily maximum discharge and daily suspended-sediment discharge on tributaries, water years 1992–99.

Table 2. Summary statistics for discharge and measured suspended-sediment discharge at the streamflow-gaging station Paria River at Lees Ferry (09382000), Arizona, water years 1992–99

	Water year							
	1992	1993	1994	1995	1996	1997	1998	1999
Minimum daily discharge summary (values in cubic meters per second)								
Minimum	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0
Median	.3	.4	.3	.4	.3	.4	.4	.4
Mean	.4	.7	.4	.5	.4	.5	.5	.6
Maximum	5.9	9.1	6.8	3.5	3.1	10.5	8.2	25.5
Standard deviation	.7	1.0	.7	.4	.4	.7	.7	1.6
Mean daily discharge summary (values in cubic meters per second)								
Minimum	.1	.1	.1	.1	.1	.1	.1	.1
Median	.4	.4	.4	.5	.4	.5	.5	.5
Mean	.8	1.4	.6	.8	.4	1.1	.8	.9
Maximum	16.0	19.3	17.7	17.6	6.2	56.6	40.8	25.1
Standard deviation	1.8	2.4	1.4	1.4	.4	3.8	2.6	1.8
Maximum daily discharge summary (values in cubic meters per second)								
Minimum	.1	.1	.1	.1	.1	.1	.1	.1
Median	.6	.7	.5	.7	.5	.8	.6	.6
Mean	1.9	2.6	1.6	1.4	0.7	2.9	2.1	1.9
Maximum	50.7	43.3	94.3	51.3	14.4	116	191	62.6
Standard deviation	6.1	4.8	6.8	3.9	1.3	12.1	12.4	5.6
Daily range (daily maximum - daily minimum) discharge summary (values in cubic meters per second)								
Minimum	.0	.0	.0	.0	.0	.0	.0	.0
Median	.3	.3	.1	.2	.1	.2	.1	.2
Mean	1.5	1.8	1.1	.9	.3	2.4	1.6	1.2
Maximum	49.9	42.7	94.2	49.9	13.1	116	190	47.2
Standard deviation	5.7	4.2	6.7	3.8	1.2	11.7	12.2	4.7
Measured suspended sediment discharge (values in millions of metric tons)								
Total from storms during water year	2.5	2.1	.78	.94	.24	4.4	2.3	3.3

Table 3. Summary statistics for discharge and measured suspended-sediment discharge at the streamflow-gaging station Little Colorado River near Cameron (09402000), Arizona, water years 1992–99

	Water year							
	1992	1993	1994	1995	1996	1997	1998	1999
Mean daily discharge summary (values in cubic meters per second)								
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	2.2	.8	0	.3	0	.3	.3	0
Mean	8.4	23.3	3.1	7.1	.7	2.6	5.1	4.2
Maximum	73.6	464	68.2	186	40.8	42.5	51.0	70.8
Standard deviation	12.8	59.7	8.4	21.4	3.1	5.8	10.6	10.9
Measured suspended sediment discharge (values in millions of metric tons)								
Total from storms during water year	8.5	18.8	2.8	4.1	1.4	3.8	4.0	8.6

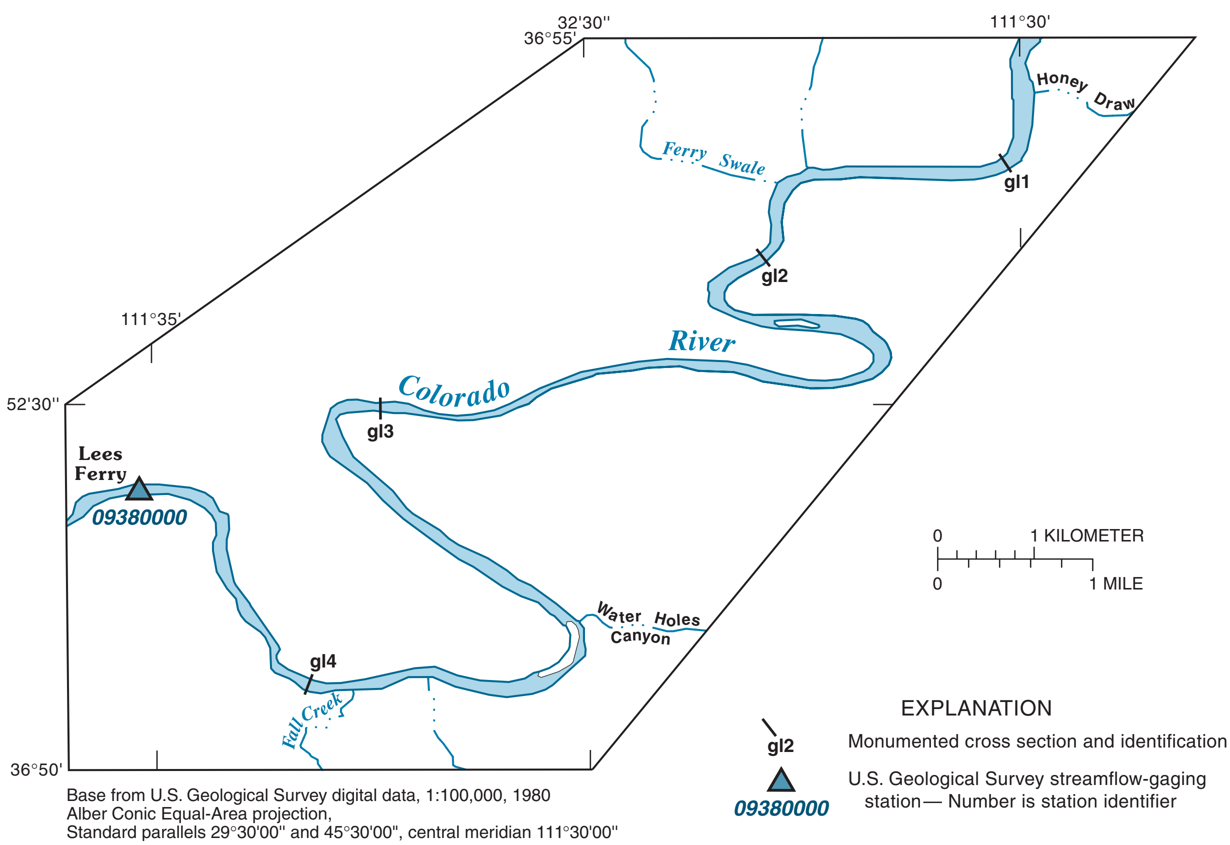
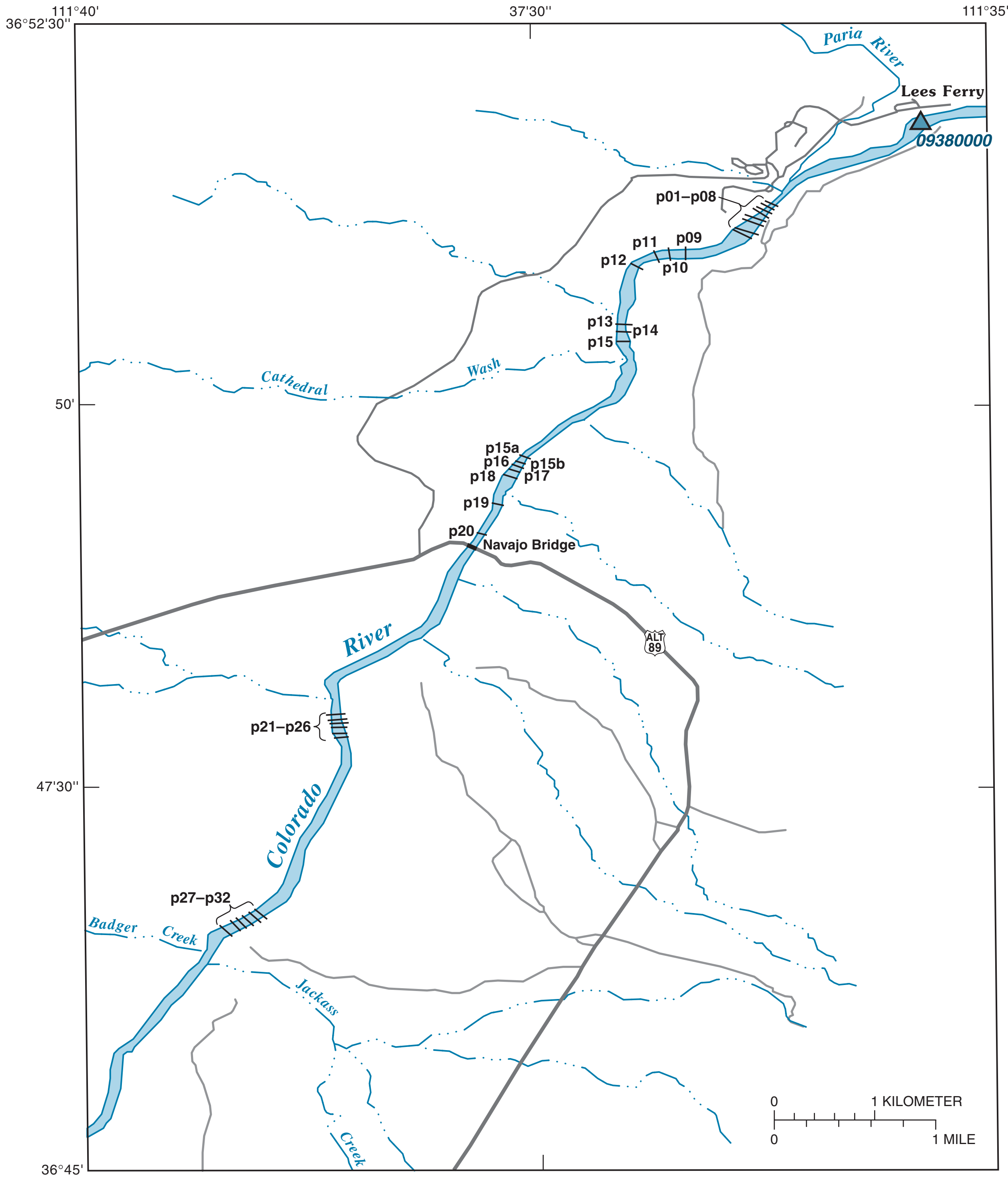


Figure 4. Location of monumented cross sections between Glen Canyon Dam and Lees Ferry, Arizona.



Base from U.S. Geological Survey digital data, 1:100,000, 1980
Alber Conic Equal-Area projection,
Standard parallels 29°30'00'' and 45°30'00'', central meridian 111°30'00''

EXPLANATION

p13 — Monumented cross section and identification

09380000 U.S. Geological Survey streamflow-gaging station— Number is station identifier

Figure 5. Location of monumented cross sections between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid.

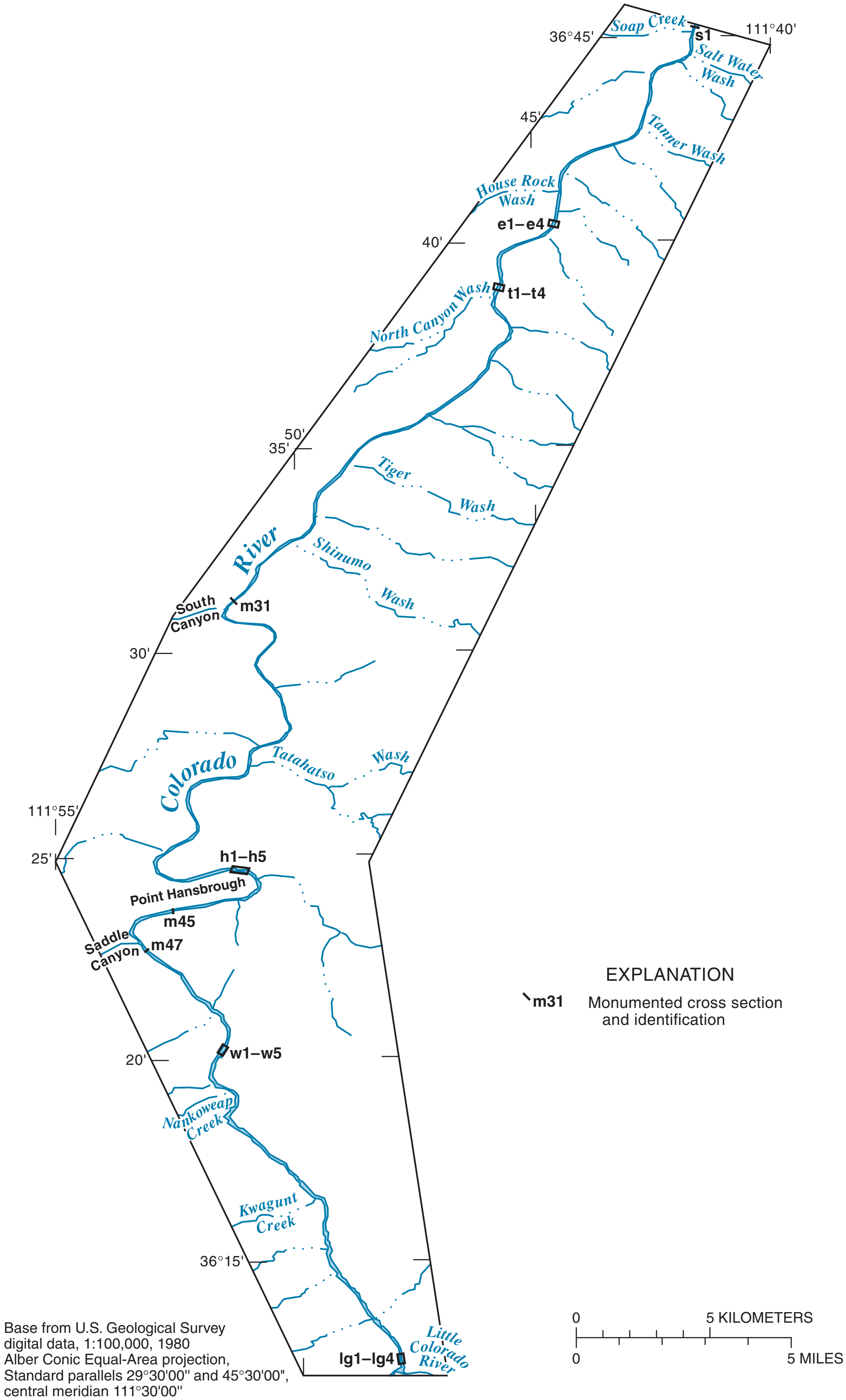


Figure 6. Location of monumented cross sections between Badger Creek Rapid and the confluence of the Little Colorado and Colorado Rivers.

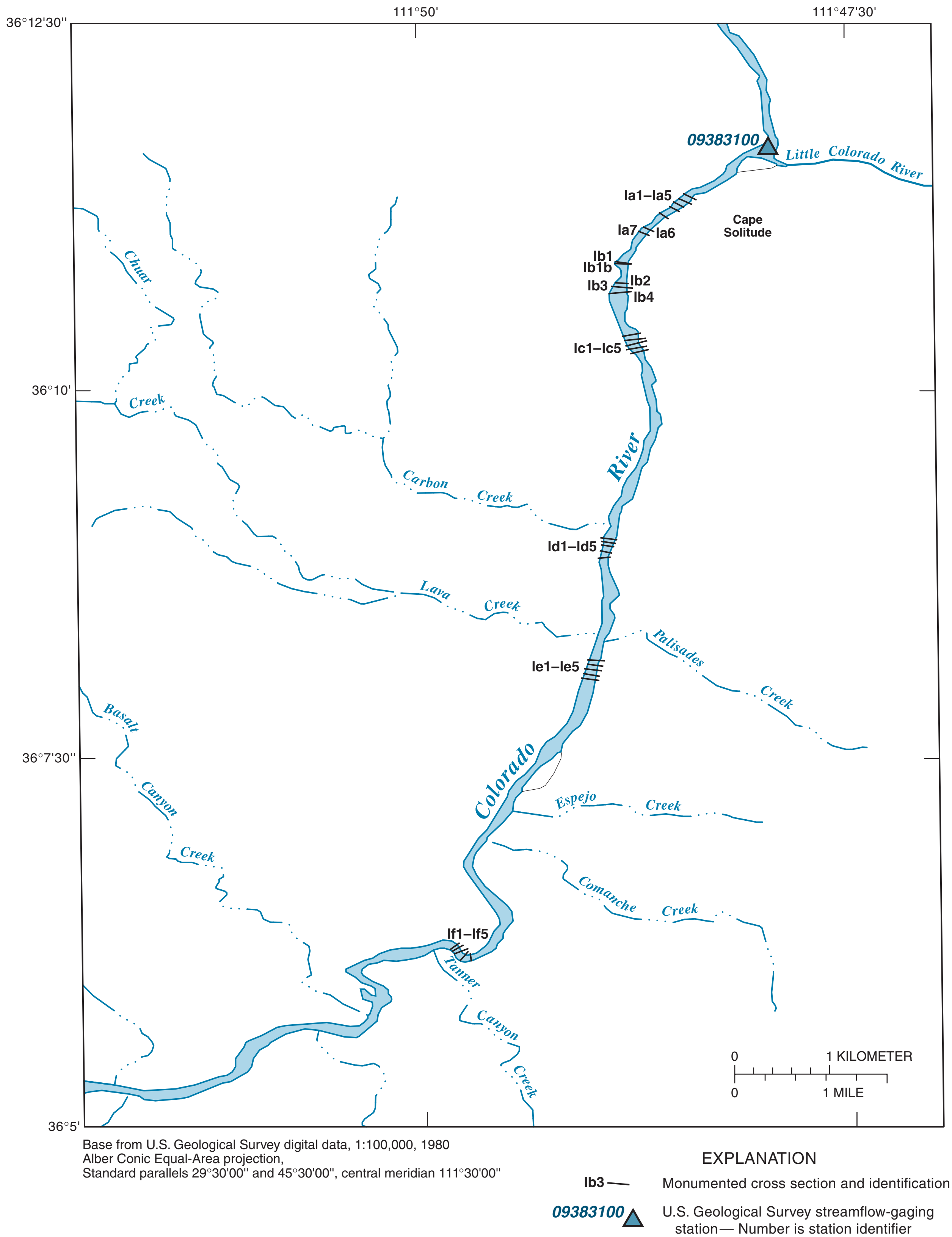


Figure 7. Location of monumented cross sections between the confluence of the Little Colorado and Colorado Rivers and Tanner Rapid.

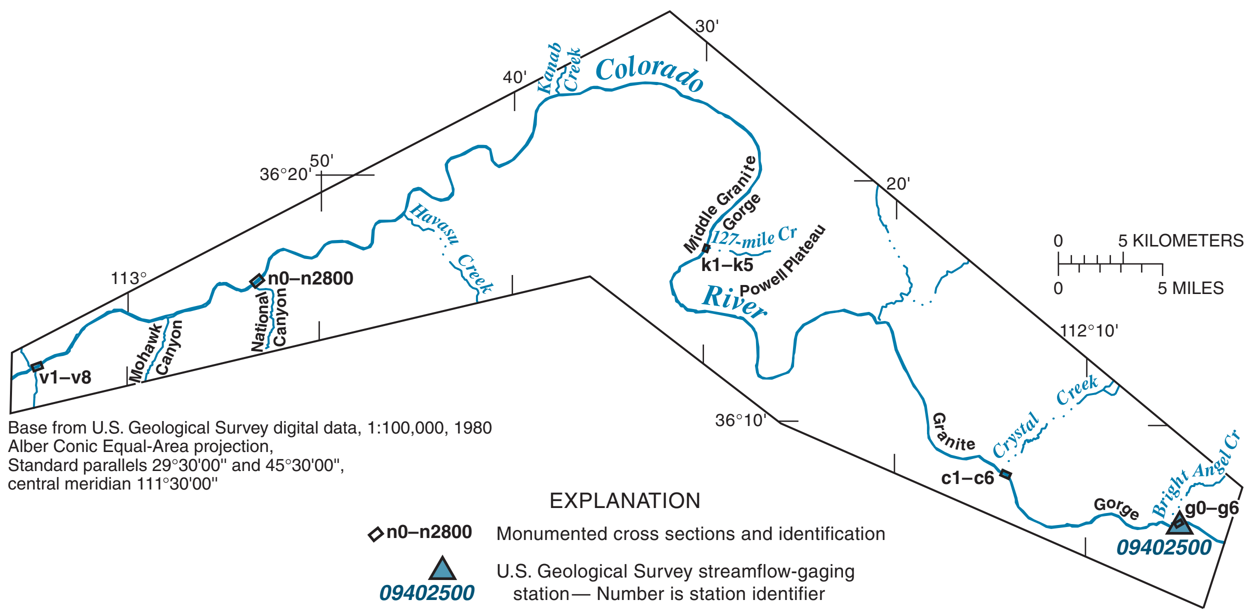


Figure 8. Location of monumented cross sections between just above the confluence of Bright Angel Creek and the Colorado River and Lava Falls Rapid.

Table 4. Inventory of cross-section measurement dates

[Data collected for measurement dates in the nonshaded and gray areas, hereafter referred to as the primary data set, are presented in this report. A subset of the primary data set, shown in the gray areas, will be referred to as the matching-date data set. Data collected for measurement dates in the blue areas are not shown in this report.]

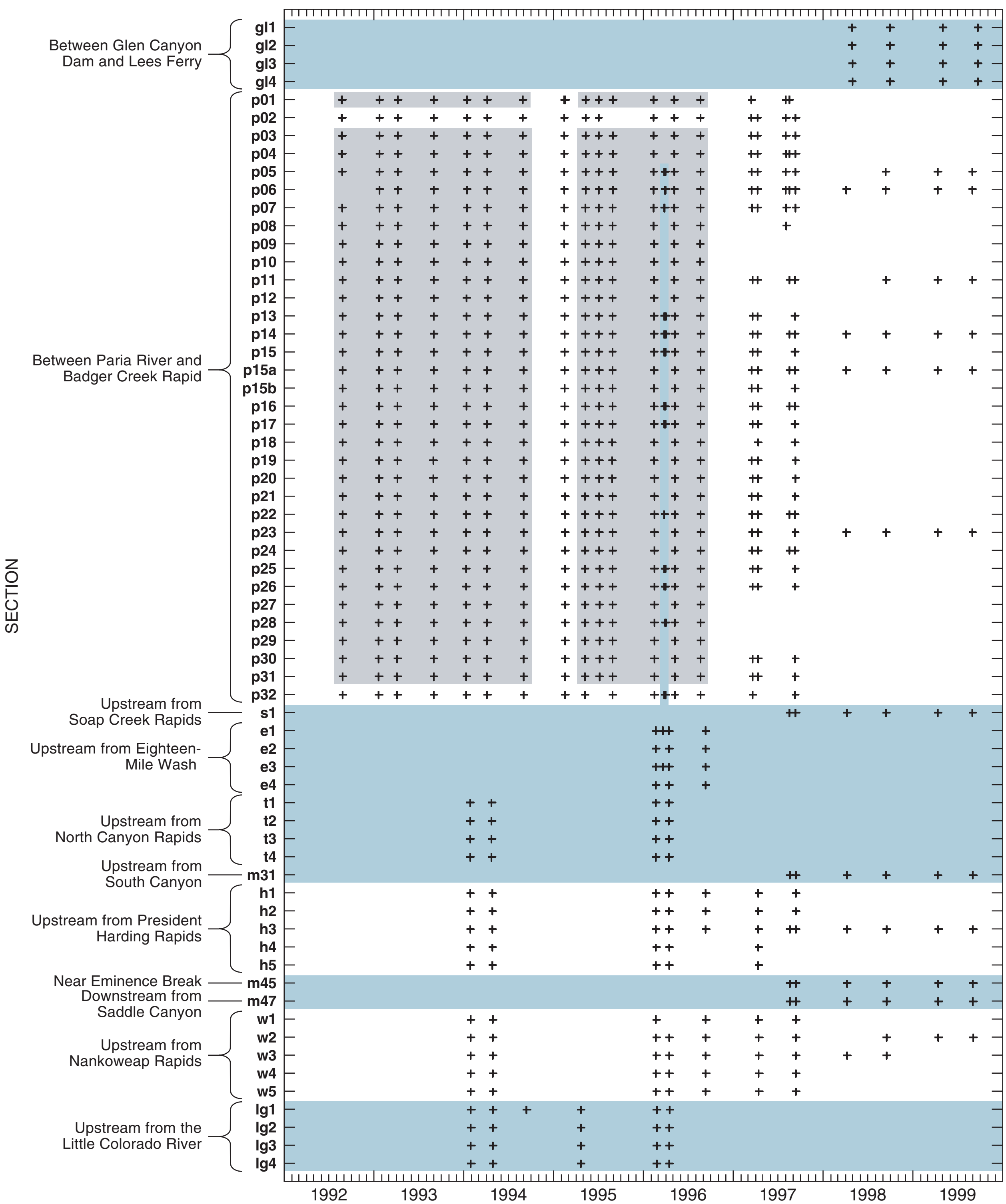
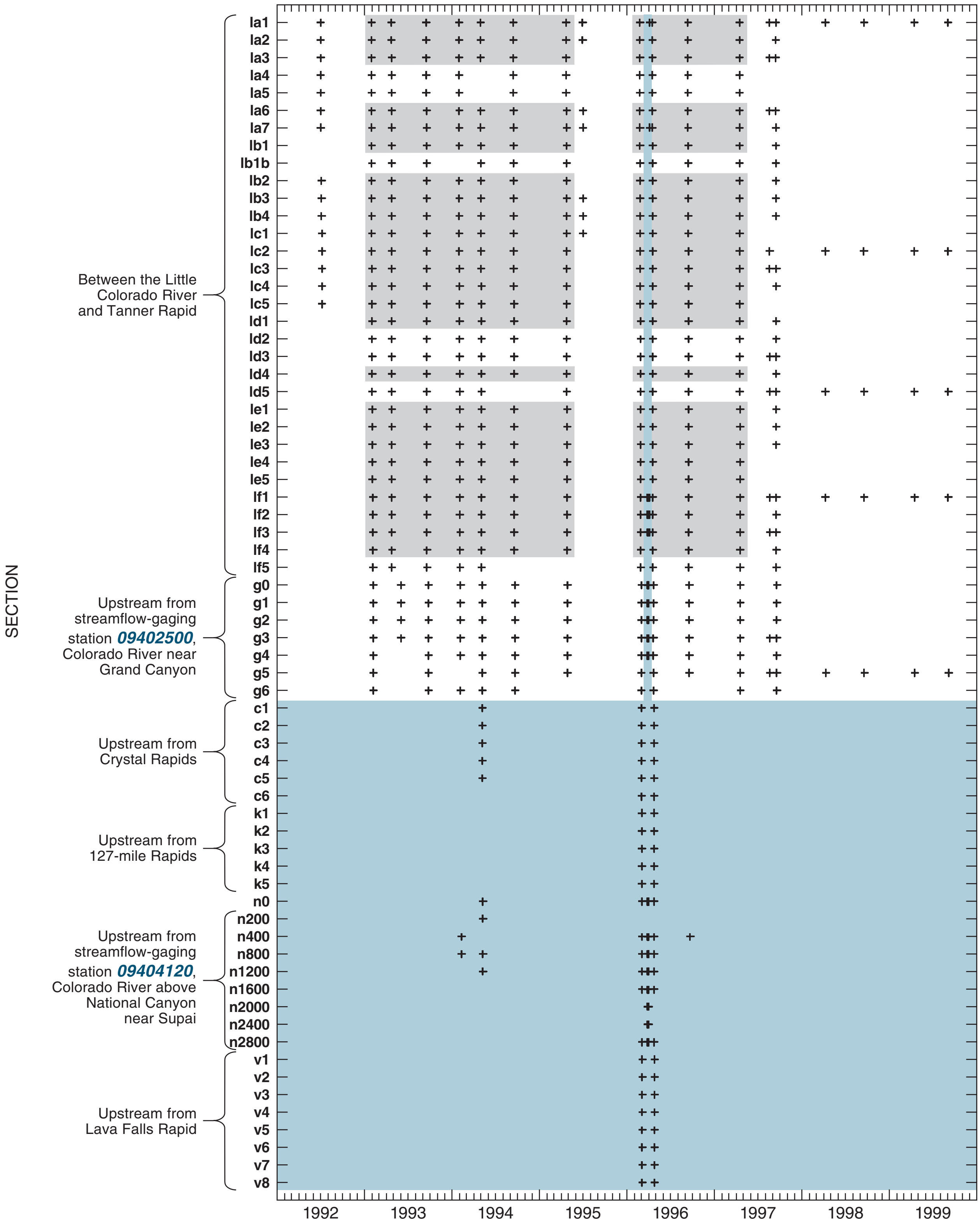


Table 4. Continued.



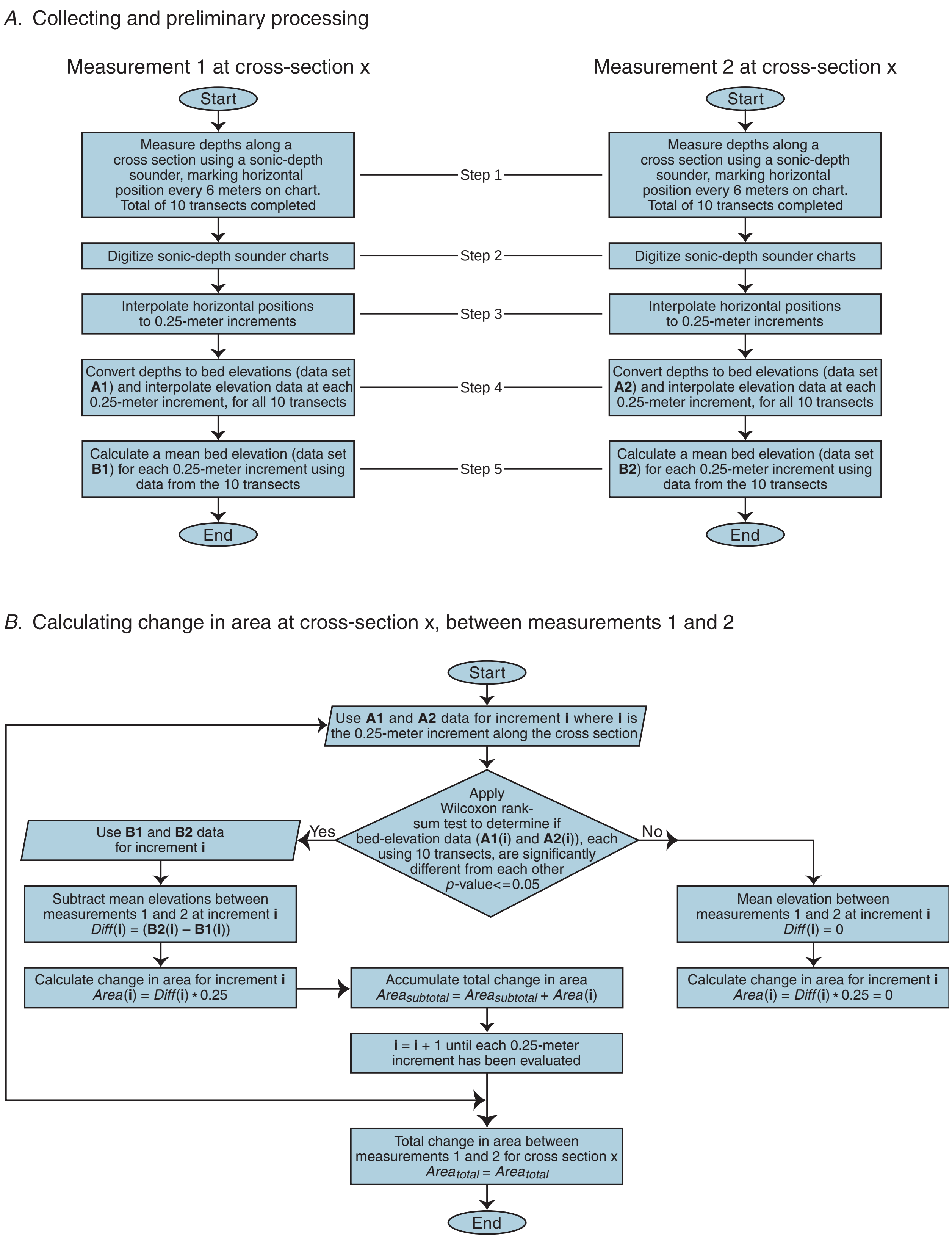


Figure 9. Data-collection and processing steps. *A*, Steps for collecting and preliminary processing of cross-section elevation data. *B*, Procedure for calculating the change in cross-sectional area between two successive measurements.

One pass across the river is referred to as a transect, and 10 transects define a measurement. The pole, mounted directly over the depth-sounder transducer, was used as a reference guide along the kevlar line. One person in the boat watched the line and pole and used a switch attached to the depth sounder to activate a fixed mark on the graphical depth-sounder record when the pole passed under a flag (**fig. 9***A*, step 1). A second person in the boat made notes on the graphical record. Date, time, distance of end points, edges of water, and distance along the line of each fixed mark were noted on the graphical charts.

Variability in the recorded depth at a given location is caused by measurement error of the instrument, changes in boat position, and actual changes in the water-surface elevation during a measurement. Of these, the changes in boat position are by far the largest contributor to depth variability between transects. The depth sounder reported data to 0.03 m and had an accuracy of 0.5 percent of the measured depth according to manufacturer specifications (0.075 m at a depth of 15 m). Changes in boat position occurred because a fixed position under the flagged line could not be maintained in the strong and variable current of the river. Because the river bed is irregular, small changes in boat position could yield large differences in the recorded depth. The method devised to minimize the uncertainty in depth caused by boat position was to measure the cross section 10 times in rapid succession and compute the mean of the 10 transects. The number of transects was selected to provide enough data for statistical analysis and to keep the measurement time short so that changes in water-surface elevation during the measurement would be insignificant. This method resulted in a measurement duration of 10 to 50 minutes, and changes in water-surface elevations during the measurements were typically small.

Changes in river stage were documented by measuring the vertical distance from a water-surface reference point, typically an “x” chiselled into a large boulder, to the water surface before and after a cross-section measurement (10 transects) was completed. The water-surface data were used in processing the cross-sectional measurement data and enabled comparisons of cross-sectional change in area between measurement dates. A water-surface reference point was established for individual reaches, and that reference point was typically used for all cross sections in that reach. In most cases, the reference point was used throughout the data-collection period; however, because of changing flow conditions, some reaches had several water-surface reference points. Relations were established between the original and subsequent water-surface reference points.

Data Processing

The graphical record of each cross-section transect was digitized by recording a point at a preset distance of horizontal cursor movement across the paper (fig. 9*A*, step 2). The interval between digitized points per unit of paper was kept constant and was selected to give about two digitized points for each foot of distance along the river bed. Once the data were digitized, the distance of each point from the left-bank end point (the left-bank monument) in inches of graph paper was converted to ground distance in meters using the known locations of the fixed marks on the graphical record and assuming constant boat speed between marks. To provide depths at equal distances from the end point for the statistical analysis of the data, points were selected or interpolated at 0.25-m intervals across the cross section (fig. 9*A*, step 3).

The sonic-depth sounder recorded depths of the river bed below the water surface. Data were converted to bed elevation by subtracting the measured depth from a water-surface elevation measured at water-surface reference points (fig. 9*A*, step 4). Those water-surface reference points that were not surveyed were assigned an arbitrary elevation of 500 m. Water-surface elevation typically was measured before and after the 10 transects had been completed. If there was a difference between the before and after water-surface elevation measurements, a time-weighted average was used to represent the water-surface elevation. After the depths were converted to bed elevations at each 0.25-m increment for a transect, a mean bed elevation was computed at each increment using data from all 10 transects (fig. 9*A*, step 5). This is referred to as the cross-section measurement. Each cross-section measurement was processed as described above.

To calculate the cross-sectional change in area between two measurements at a cross section, the difference in mean bed elevation was determined for each 0.25-m increment (fig. 9*B*). If the difference was deemed statistically significant, the actual difference value was used in the change-in-area calculation. If the difference was not statistically significant, zero was used in the change-in-area calculation. The Wilcoxon rank-sum test (Devore, 1991; Helsel and Hirsch, 2000) was used to detect statistically significant differences in mean bed elevations. This test was used because it does not require knowledge of the underlying statistical distribution of the bed-elevation recordings. In this application the test has the null hypothesis that, at each increment, the mean bed elevation in one measurement is equal to the mean bed elevation in the next measurement. To evaluate the hypothesis, the test statistic W is computed on the basis of bed-elevation data for the two measurements, and then a two-sided p-value associated with rejecting the null hypothesis is determined on the basis of the value of W and the number of depth recordings for each measurement. For this investigation the null hypothesis was rejected for p-values less than or equal to 0.05, which means that the null hypothesis is rejected with a 5-percent chance of it being true.

Because of differences in water level or in cross-section geometry, or because of missing records as a result of interference of the depth-sounder signal, the depth at some parts of a cross-sectional transect may not have been recorded; therefore, fewer than 10 depth recordings exist for some 0.25-m increments in some cross-section measurements. For increments at which the number of depth recordings equaled or exceeded eight for both measurements, the p-value was computed from the normal approximation for the distribution of W. For increments at which the number of depth recordings for either or both measurements was less than eight but greater than two, the p-value was determined from the exact distribution of W. The test was not applied for increments at which the number of depth recordings for either or both measurements was equal to or less than two. The fraction of the cross section to which the rank-sum test was applied and the fraction of the total cross section for which bed-elevation differences between measurements were significant were also calculated.

Changes in cross-sectional area between measurements were calculated for each incremental distance (0.25 m), using the selected or interpolated point as the center of the increment, by first computing the incremental area as the difference in mean bed elevations multiplied by 0.25 m. The change in area for the entire cross section then was computed by summing those incremental areas for which the p-value was less than or equal to 0.05. Although the original data from the 10 transects recorded for cross section p06 on August 24, 1992, were unrecoverable from the database, the processed mean bed elevations at the 0.25-m increments had been calculated from the original data and stored in the database. Calculations of change in area using these data from this date, therefore, did not consider the p-values. The change in area of the bed elevation represents the change in sediment storage in the cross section. As a consequence of determining changes in cross-sectional area using this method, increases in area indicate sediment deposition and decreases indicate sediment removal.

A standard error that can be applied to the computed cross-sectional change in area was calculated for an averaged cross section. The standard error is a measure of the accuracy with which the computed (mean) change in area estimates the true mean change in area. A range, in which there is a 68.3-percent level of confidence that the true mean change in area lies within this range, can be calculated by subtracting the standard error from the computed mean change in area for the lower end of the range and by adding the standard error to the computed mean change in area for the upper end of the range. For a 95-percent level of confidence, the range is calculated as previously described, but the standard error is first multiplied by 2 (Barford, 1985).

The standard error uses the standard deviation calculated when computing mean bed elevations from the 10 transects collected during a measurement (**fig. 9***A*, step 5), and the number of 0.25-m increments for each transect, which is a function of stream width. The standard error must be propagated through the change-in-area calculations (fig. 9*B*) and accumulated change-in-area calculations (summing changes in area for a cross section across many measurements). A representative standard error was estimated and propagated through the calculations. This representative standard error was calculated using a standard deviation of 0.15 m for the elevations and a stream width of 131 m. These values were calculated from the transect data from all cross sections in the primary data set (**table 4**) and represent an average standard deviation and stream width. **Table 5** shows the estimated standard error that can be applied to changes in area documented in this report. The table shows the standard error for a single change in area calculated between two measurements (1 period) and accumulated changes in area over several measurements (periods), for 68.3-percent and 95-percent levels of confidence. For example, if the change in area between two measurements (1 period) is calculated to be 22 m^2, the standard error is 0.39 m^2, and the range is 22 ±0.39 m^2 with a 68.3-percent level of confidence that the true mean change in area lies within this range. For a 95-percent level of confidence, the standard error is 0.78 m^2, and the range is 22 ±0.78 m^2. If, for example, changes in area are accumulated (summed) between 13 measurements (12 periods) and calculated to be -519 m^2, the standard error is 1.4 m^2, and the range is -519 ±1.4 m^2 with a 68.3-percent level of confidence. For a 95-percent level of confidence, the standard error is 2.8 m^2, and the range is -519 ±2.8 m^2.

Table 5. Standard error estimates applied to changes in area

Number of measurements	Number of period(s)	Standard error (68.3-percent level of confidence; square meters)	Standard error (95-percent level of confidence; square meters)
2	1	0.39	.78
3	2	.55	1.1
4	3	.67	1.4
5	4	.77	1.6
6	5	.86	1.8
7	6	.95	1.9
8	7	1.1	2.2
9	8	1.1	2.2
10	9	1.2	2.4
11	10	1.2	2.6
12	11	1.3	2.6
13	12	1.4	2.8

Bed-elevation corrections from the water-surface reference points enable comparisons between measurements for a given cross section, but do not enable relative comparisons between cross sections because differences in channel geometry are not taken into account. For example, an absolute change in area of 5 m^2 is more significant in a narrower cross section with limited capacity for sediment storage than in a wider cross section with great capacity for sediment storage. To compare relative changes between cross sections without regard to differences in channel geometry, the changes in area were normalized (normalized change in area) for cross sections in the primary data set (**table 4**).

Changes in area from measurement to measurement were normalized by dividing the change in area by the cross-sectional area. The cross-sectional area used for normalization was calculated by estimating the elevation of the water surface at the water-surface reference points at a discharge of 850 m^3/s. A discharge of 850 m^3/s was chosen to maximize the cross-sectional area and because many of the cross sections were measured at discharges near this value. Using the date and time of the measurement and data from the nearest upstream streamflow-gaging station, a discharge value was estimated for each water-surface elevation measurement made at the water-surface reference points. Discharge reference-point elevation curves were plotted for each water-surface reference point and regression equations were fitted to each curve. Using the regression equations, a water-surface elevation was calculated for a discharge of 850 m^3/s for each water-surface reference point. Selected discharge-elevation curves are shown in **figure 10**. Figure 10*A*,*C* illustrate discharge-elevation relations having high R^2 values. Figure 10*B* shows a discharge-elevation relation having a low R^2 value. Possible reasons for the outliers in the discharge-elevation curves include actual changes in the channel that affected the water-surface elevation or inaccurate water-surface measurements. To determine the cross-sectional area for a discharge of 850 m^3/s, the area for each incremental distance then was computed as the difference between the water-surface elevation at a discharge of 850 m^3/s and the lowest measured bed elevation at that distance multiplied by 0.25 m. The normalized area for the cross section was computed by summing the incremental areas.

Presentation of Data

Changes in sediment storage in the Colorado River downstream from the Paria and Little Colorado Rivers are documented from June 1992 to February 1994 (Graf and others, 1995) and April 1994 to August 1995 (Graf and others, 1997). Konieczki and others (1997) documented changes in sediment storage before and after the 1996 controlled flood. All cross-section data collected from June 1992 through September 1999 are available from the USGS as three types of tab-delimited ASCII electronic files. The first file type contains the interpolated data for each measurement. These files contain the transect number; the distance from the left-bank end point, in meters; and the bed elevation for that distance, in meters. The second file type contains the averaged data for each measurement. These files contain the distance from the left-bank end point, in meters; the number of bed-elevation measurements for that distance; the mean, median, minimum, and maximum bed elevations for that distance, in meters; and the standard deviation from the mean bed elevation, in meters. The third file type contains changes in area between measurements for all cross sections. These files contain cross-section name, measurement date 1 and measurement date 2, change in area between the two measurement dates, fraction of tested cross section having differences significant at a *p*-value less than or equal to 0.05, and fraction of cross section for which the rank-sum test was applied. Bed-material sample analyses also are available. Readers who would like to obtain the electronic data should contact the Arizona District Office of the USGS.

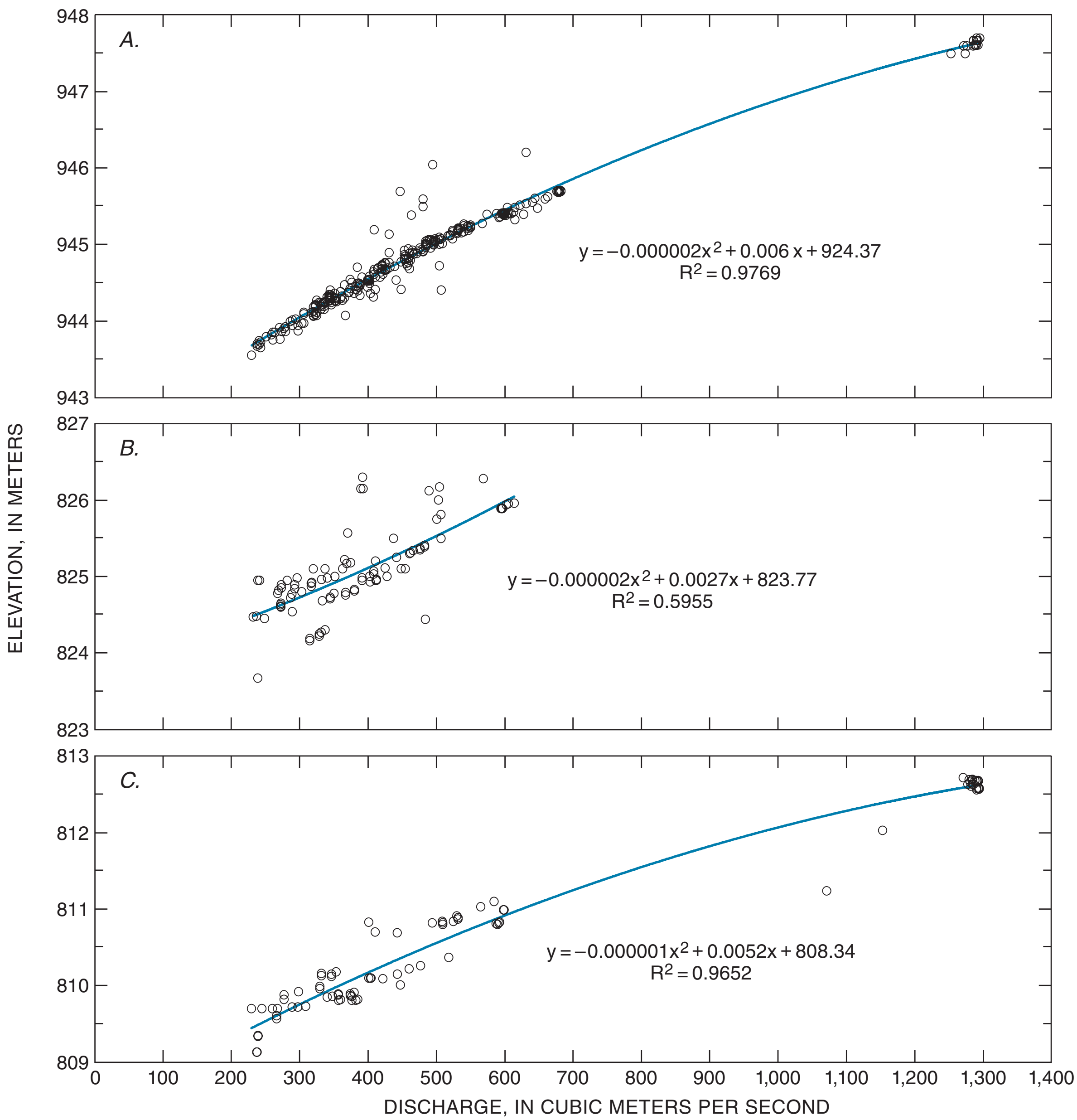


Figure 10. Discharge-elevation curves for three water-surface reference points. *A*, Sections p01–p15. *B*, Sections 1a1–1a7. *C*, Sections lf1–lf5.

CROSS-SECTION VARIABILITY

Because of channel geometry and hydraulics, some cross sections have a larger capacity to store and subsequently lose sediment. This capacity is reflected in the range of change-in-area values.

Spatial Variability in Changes in Cross-Sectional Area

Normalized and non-normalized change in area calculated between successive measurement dates for cross sections in the primary data set (**table 4**) between the Paria River and Bright Angel Creek (**fig. 1**) are shown in **figures 11** and **12**, respectively. All measurements were used in the change-in-area calculations, except for those made during the 1996 controlled flood, and some cross sections were measured more frequently than others. Measurements made during the 1996 controlled flood were not included because flows during the flood were extreme and not representative of normal hydrologic conditions. Some cross sections were more dynamic than others, showing a wider range of sediment deposition and scour. Cross sections p05 and p06 are examples of more dynamic cross sections (**fig. 13**). Both cross sections are immediately below the mouth of the Paria River and are able to store sediment in a large eddy, as well as in the deep main channel, for a limited period of time (fig. 13). For example, the largest increase in sediment was measured for p06 on September 14, 1998 (fig. 13), after significant sediment input from the Paria River (**fig. 3**); however, the next measurement at p06, April 13, 1999 (fig. 13), indicated the largest decrease in sediment. These sections, farthest upstream, also are the first to be exposed to clear water flowing from the dam and thus are more susceptible to winnowing and erosion. Cross sections p12 and ld1 are examples of less dynamic cross sections; unlike sections p05 and p06, they do not have large eddies and thus have a limited capacity to store sediment in the main channel (**fig. 14**).

Although cross section la1 is immediately downstream from the confluence of the Little Colorado and Colorado Rivers and has a channel geometry (**fig. 15**) similar to that of cross sections p05 and p06 (fig. 13), it does not show the same range of deposition and scour (figs. 11 and 12). The largest gain for cross section la1 was measured on January 29, 1993 (fig. 15), immediately following significant inputs of water and sediment from the Little Colorado River (fig. 3); however, only a small loss was measured when cross section la1 was measured on April 22, 1993 (fig. 15). A negative change of comparable magnitude was not measured until the April measurement following the 1996 controlled flood. A possible explanation is that the 1993 flood on the Little Colorado River deposited large-sized sediment immediately downstream from the confluence, armoring the channel at cross section la1 (Anima and others, 1998; Wiele and others, 1999). Releases from Glen Canyon Dam were such that the large-sized sediment was not moved downstream until the controlled flood occurred in 1996.

Temporal Variability in Cross-Sectional Area

The effects of large suspended-sediment inputs from tributaries on changes in the normalized cross sections are evident in the cross-section measurements when viewed chronologically (**fig. 16**). The cross sections downstream from the confluence of the Paria and Colorado Rivers measured in September 1998 show a significant increase in area in the component of the cross section occupied by sediment the day after the storm that produced an input of 1.7 million metric tons of sediment from the Paria River (fig. 3). The subsequent measuring trip in April 1999, which occurred after 7 months of almost no suspended-sediment inputs, reported decreases in cross-sectional area, indicating decreases in sediment, from these same cross sections. Large increases in cross-sectional area also were measured during September 1999 following a storm. The results from this sequence of measurements demonstrate the rapid response of these cross sections to tributary inputs and indicate that because sediment storage in these cross sections is only temporary, the timing of the measurements is critical in terms of capturing the full effect of a tributary input.

Positive changes in cross-sectional area were also measured in the absence of known tributary inputs (fig. 16). For example, around September 1996, there was little sediment input from the Paria River, yet some cross sections in the h1–h5 and the w1–w5 groups (**fig. 6**) showed net positive changes in area (fig. 16*D*). Cross sections in the la1–lf5 group (**fig. 7**) also showed net positive changes in area around March 1999, when there was little sediment input from either the Paria River or the Little Colorado River (fig. 16*G*). The increase in sediment may be the result of a sediment pulse from a previous tributary input.

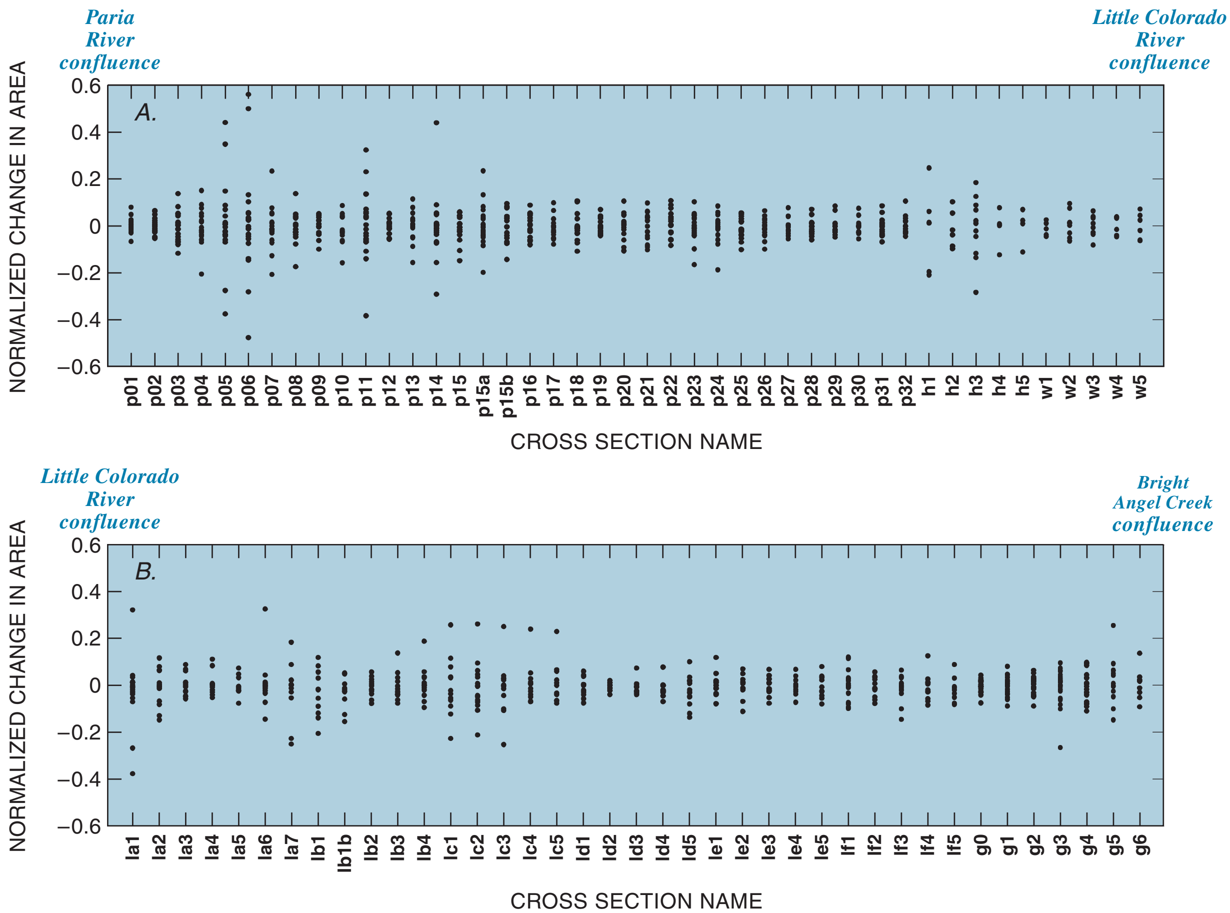


Figure 11. Normalized change-in-area data, excluding 1996 controlled-flood measurements, for cross sections in the primary data set. *A*, Sections between the confluences of the Paria and Colorado Rivers, and the Little Colorado and Colorado Rivers. *B*, Sections between the confluences of the Little Colorado and Colorado Rivers, and Bright Angel Creek and the Colorado River.

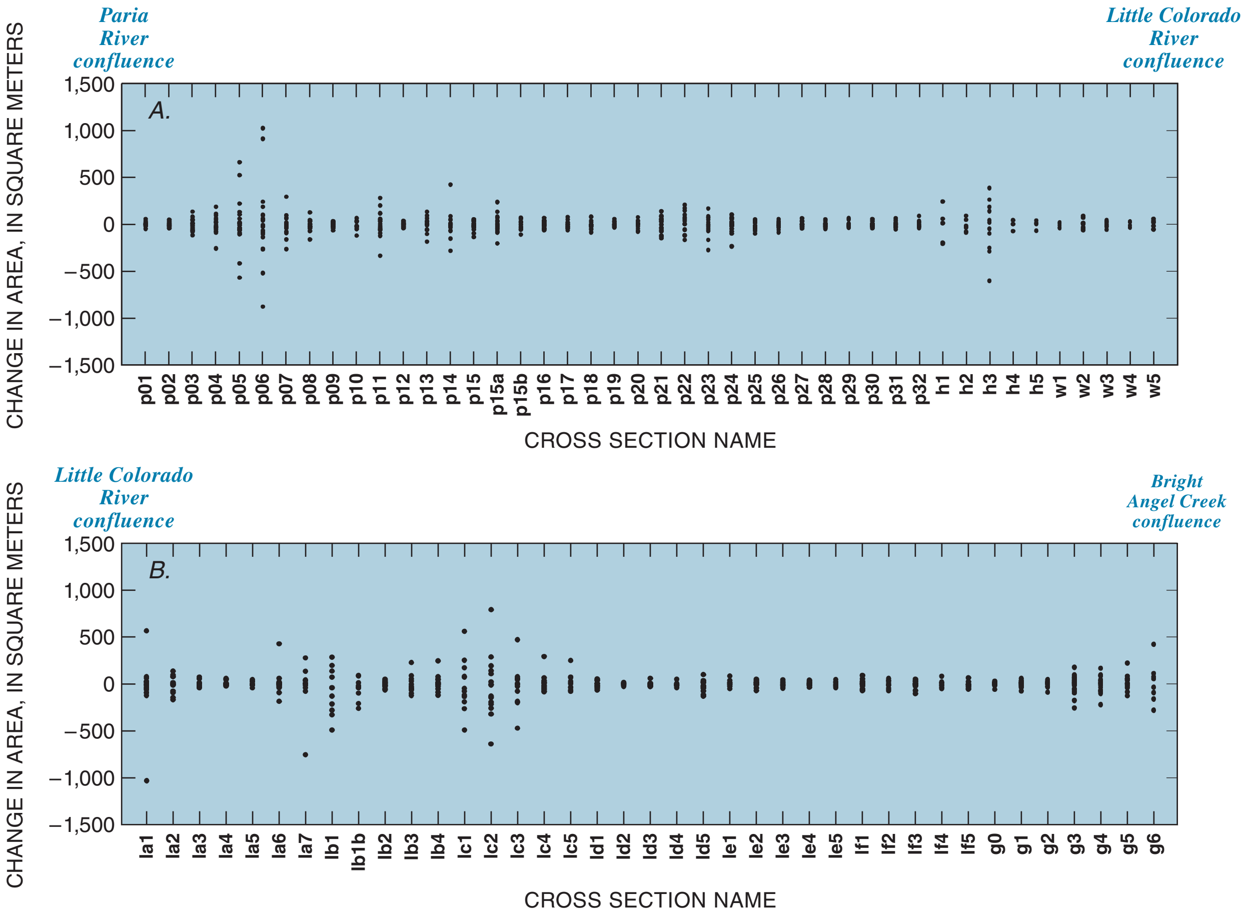


Figure 12. Non-normalized change-in-area data, excluding 1996 controlled-flood measurements, for cross sections in the primary data set. *A*, Sections between the confluences of the Paria and Colorado Rivers, and the Little Colorado and Colorado Rivers. *B*, Sections between the confluences of the Little Colorado and Colorado Rivers, and Bright Angel Creek and the Colorado River.

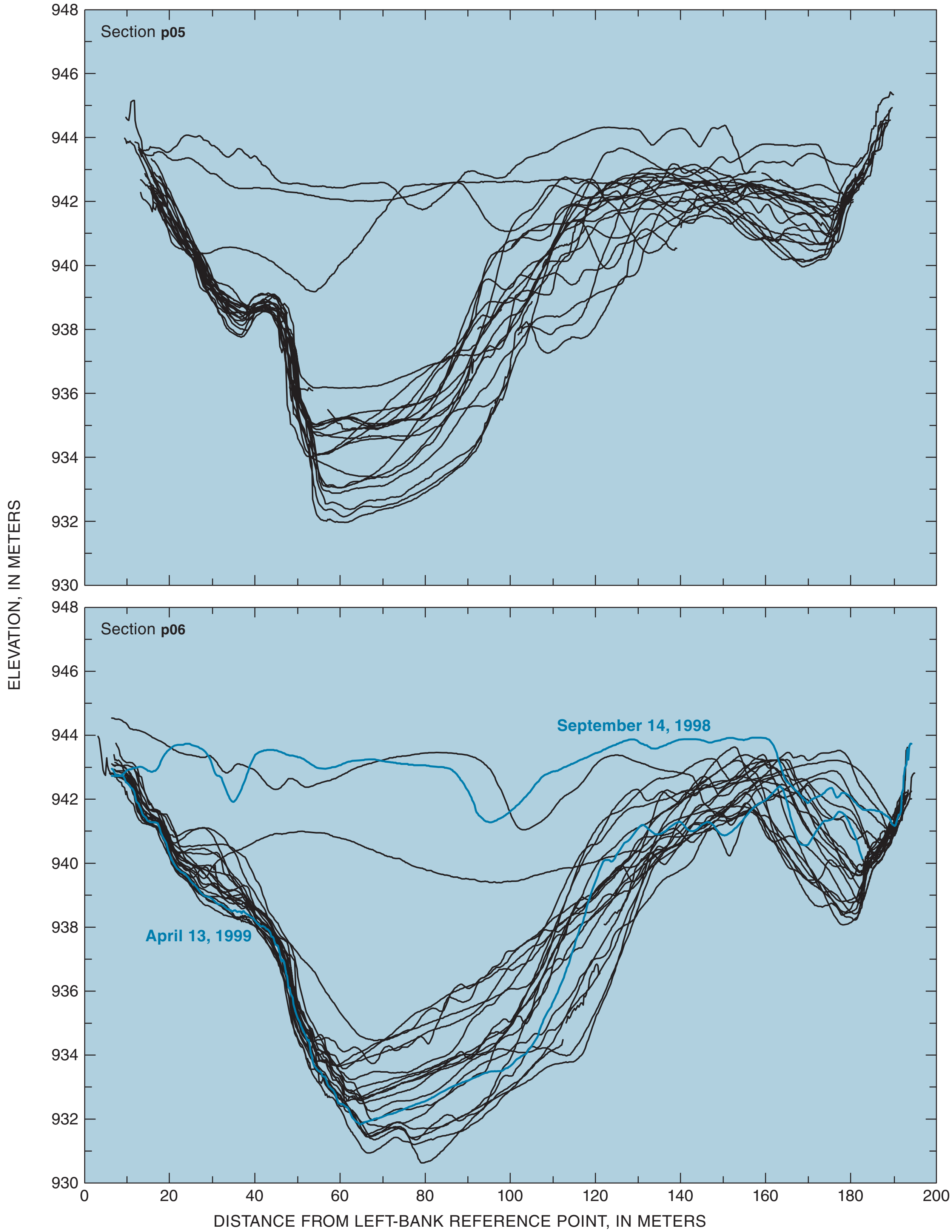


Figure 13. Bed-elevation measurements for selected cross sections in the primary data set below the confluence of the Paria and Colorado Rivers.

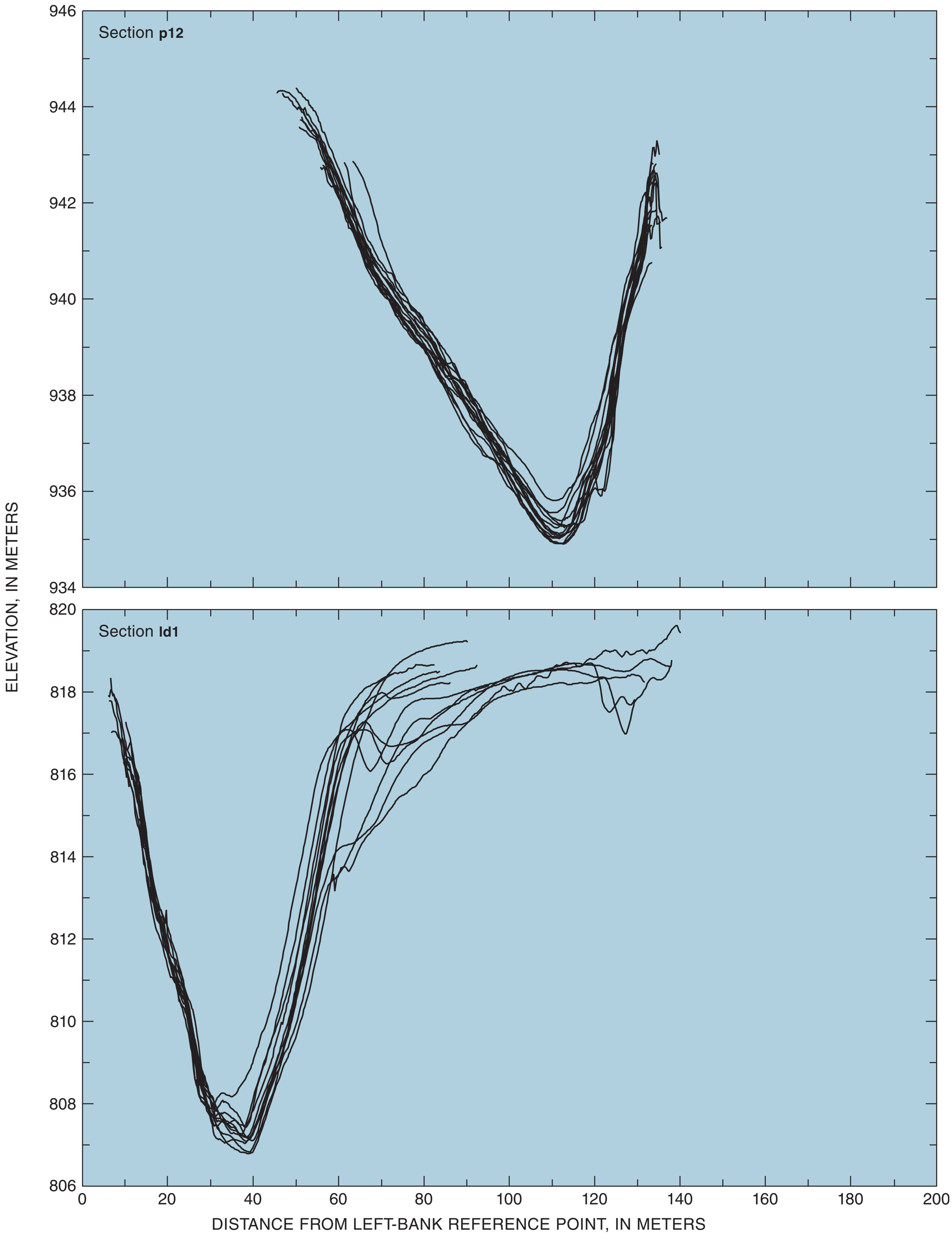


Figure 14. Bed-elevation measurements for selected cross sections in the primary data set below the confluences of the Paria and Colorado Rivers, and the Little Colorado and Colorado Rivers.

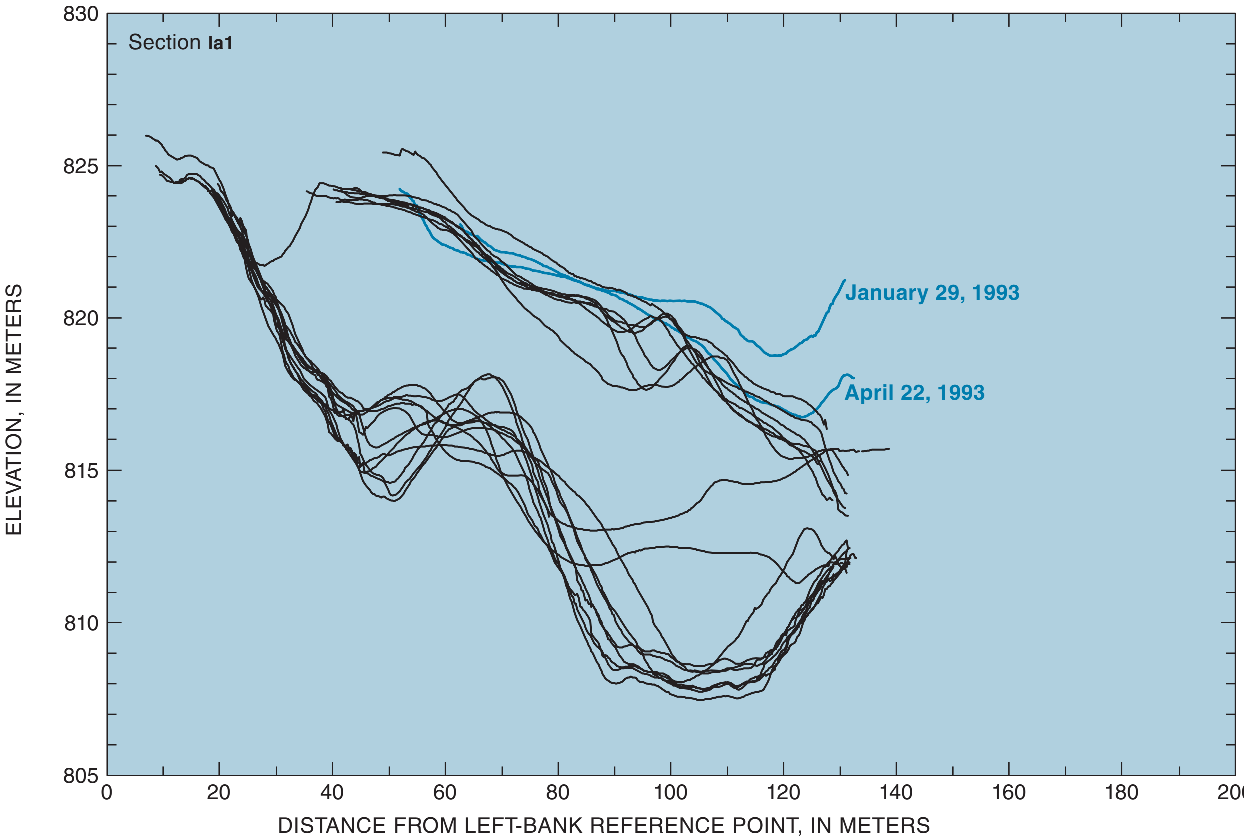


Figure 15. Bed-elevation measurements for cross section 1a1 in the primary data set below the confluence of the Little Colorado and Colorado Rivers.

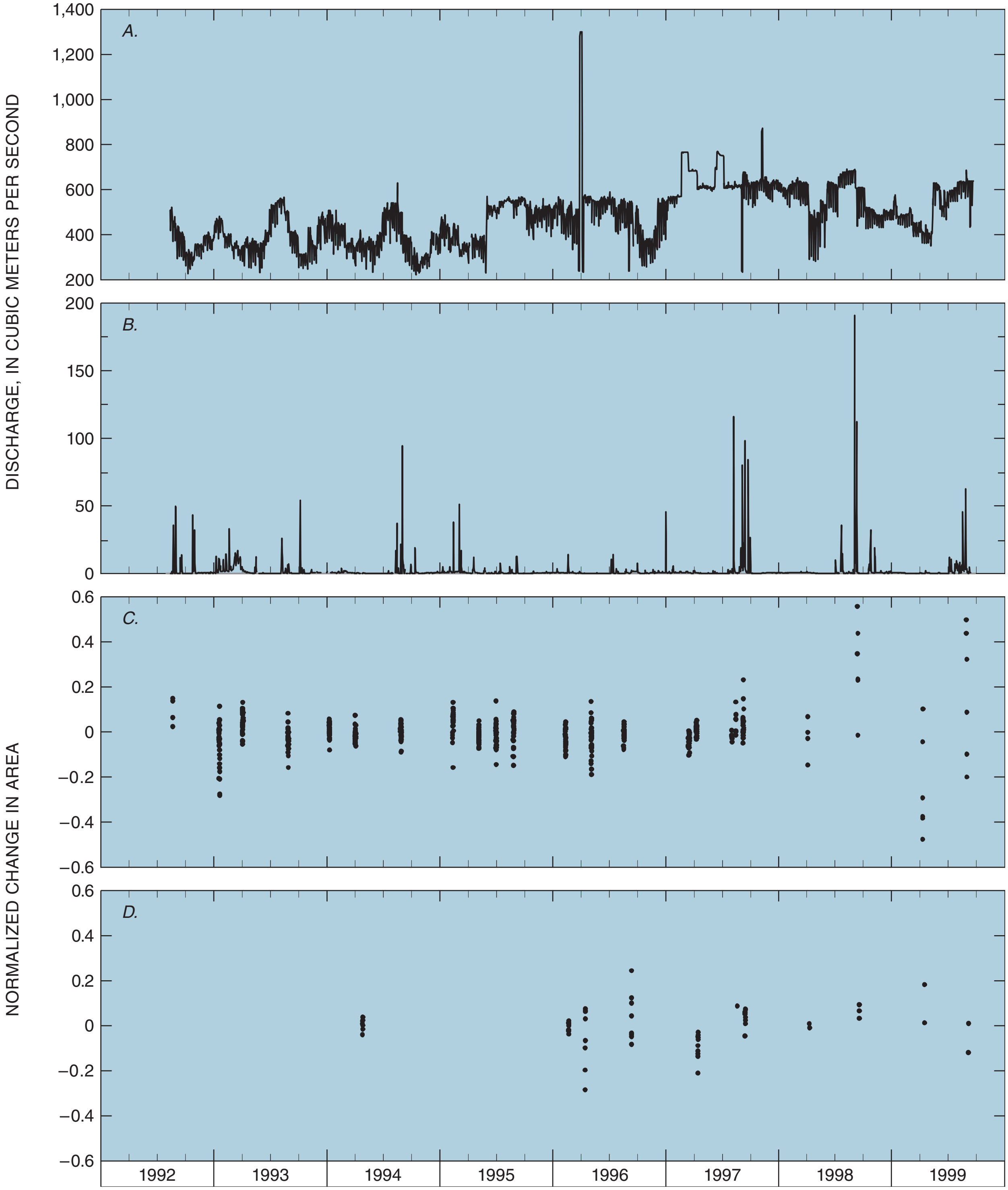


Figure 16. Discharge and normalized change-in-area data for cross sections in the primary data set between the confluences of the Paria and Colorado Rivers, and Bright Angel Creek and the Colorado River. *A*, Daily maximum discharge at the streamflow-gaging station at Colorado River at Lees Ferry. *B*, Daily maximum discharge at the streamflow-gaging station at Paria River at Lees Ferry. *C*, Sections p01–p32. *D*, Sections h1–h5 and w1–w5. *E*, Daily maximum discharge at the streamflow-gaging station at Colorado River above Little Colorado River. *F*, Daily maximum discharge at the streamflow-gaging station at Little Colorado River near Cameron. *G*, Sections la1–lf5. *H*, Sections g0–g5.

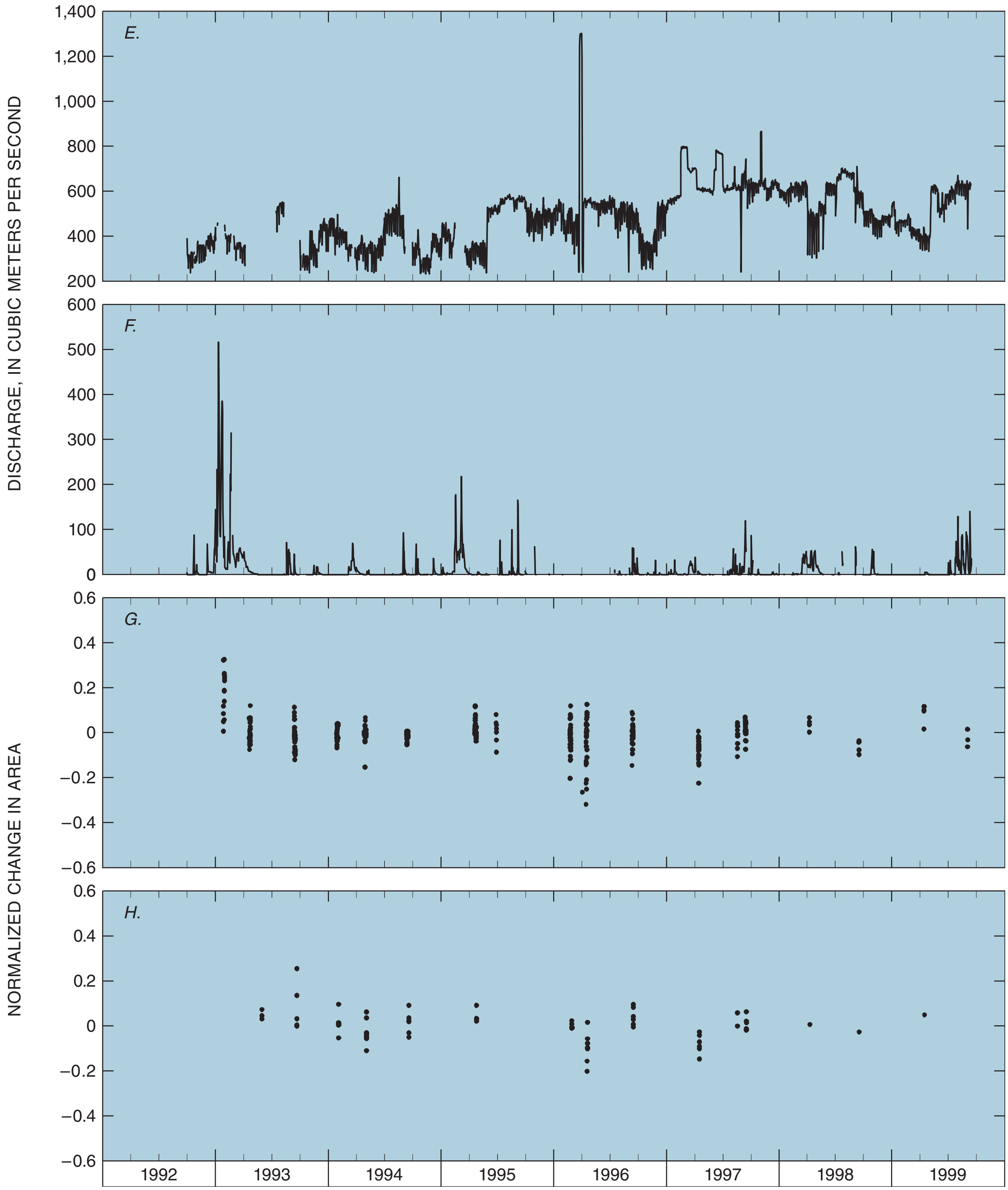


Figure 16. Continued.

Alternatively, because of the changing flow regime from Glen Canyon Dam, sediment in the system is undergoing constant change so that the measurement also may have included existing sediment within the pool or upstream of the pool that was reworked. Sediment also can be supplied by mass failure of sandbars, as documented by Cluer (1991), or from ungaged tributaries.

CHANGES IN CROSS-SECTIONAL AREA

To determine whether cross sections were gaining or losing sediment over time, the net change in area (running total or accumulation) was calculated by summing the non-normalized change in area between measurements for each cross section in the matching-date data set (**table 4**). The first date, considered the initial measurement for these analyses, is assigned to be the baseline with a net area equal to zero. Changes in area then are calculated between subsequent measurements and summed over time to form the net change in area or the running total. Using data from a sequence of dates for which the same cross sections were measured provides a way to observe how individual cross sections respond to similar hydrologic conditions over time. The two study reaches with the longest and most complete time-series data are the reaches below the mouths of the Paria and Little Colorado Rivers.

For the 5 groups of cross sections downstream from the Paria River, there were 13 matching dates or 12 periods (matching-date data set, Paria group) between August 24, 1992, and August 19, 1996, for which the running totals were calculated for all cross sections except p02 and p32 (**fig. 17**). All the cross sections in the first group (p01–p08) had a negative running total, ranging from -22 to -519 m^2, for the first period. This first-period value represents the change in area between the August 24, 1992, and the January 21, 1993, measurement dates. The initial measurement on August 24, 1992, was shortly after large sediment inputs from the Paria River, and it is likely that the cross sections just below the confluence still contained sediment from this tributary input during this measurement. Because the sediment deposited before the August 24, 1992, measurement had scoured from the cross sections before the January 21, 1993, measurement, there is a large decrease in the running total for the first period for these cross sections.

All but two of the cross sections downstream from the Paria showed net losses between August 24, 1992, and August 19, 1996. Cross section p21 had a minimal gain of 70 m^2, and loss or gain could not be determined at p19 because the standard error, ±2.8 m^2 (95-percent level of confidence, **table 5**), added to the net change in area, 2 m^2, is too close to zero. Cross section p06 showed the largest net loss, 562 m^2. Overall there was a wide range of responses among cross sections; cross section p06 showed a large capacity to store and lose sediment, whereas cross sections p27–p31 did not show large net changes.

For the 6 groups of cross sections downstream from the Little Colorado River, there were 11 matching-measurement dates, or 10 periods (matching-date data set, Little Colorado River group), for which all cross sections, except la4, la5, lb1b, ld5, and lf5, were measured between January 29, 1993, and April 16, 1997 (**fig. 18**). Cross sections ld2 and ld3 were excluded because data sets were incomplete. The first measurement in January 1993 was made approximately 2.5 weeks after a large flood (recurrence interval of 15 years) occurred on the Little Colorado River. Unlike cross sections just downstream from the confluence of the Paria River, the cross sections just downstream from the confluence of the Little Colorado River changed little until after the 1996 controlled flood (fig. 18).

All the cross sections just downstream from the Little Colorado River showed net losses for the time between January 31, 1993, and April 16, 1997. Cross section lc2 showed the largest net loss, 1,400 m^2, and cross section 1d1 showed the smallest net loss, 5 m^2. Similar to the cross sections in the Paria reach, the cross sections in the lower portion of the Little Colorado River reach consistently showed less net change than upstream cross sections.

FACTORS AFFECTING SEDIMENT STORAGE CHANGES

An analysis was done to determine if there was a correlation between changes in cross-sectional area and the corresponding hydrologic conditions (factors) that occurred between cross-section measurements. The hydrologic conditions considered included high flow, low flow, mean flow, range of flow, and sediment input from tributaries.

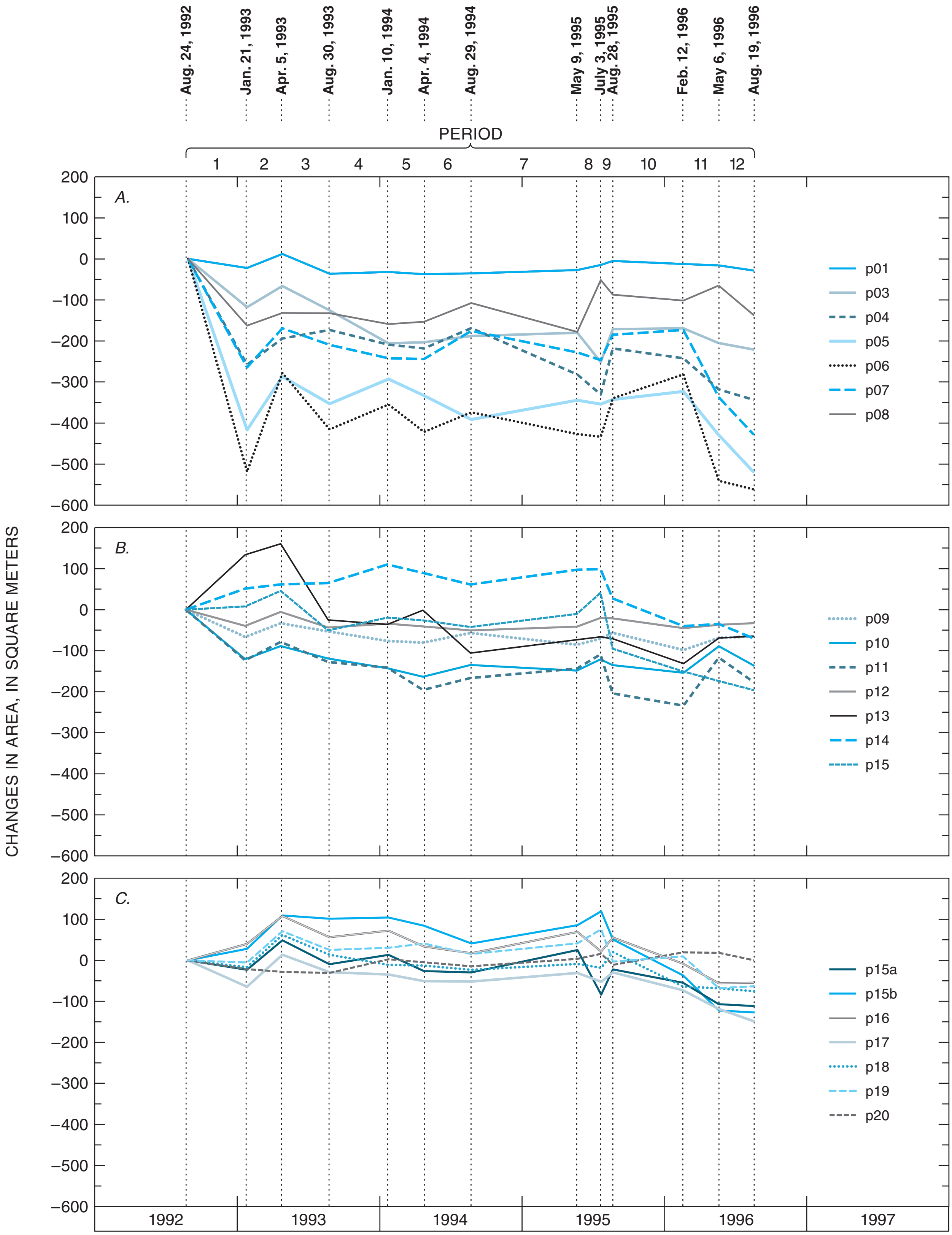


Figure 17. Net change in area for cross sections in the matching-date data set between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid. *A*, Sections p01–p08. *B*, Sections p09–p15. *C*, Sections p15a–p20. *D*, Sections p21–p26. *E*, Sections p27–p31.

Figure 17. Continued.

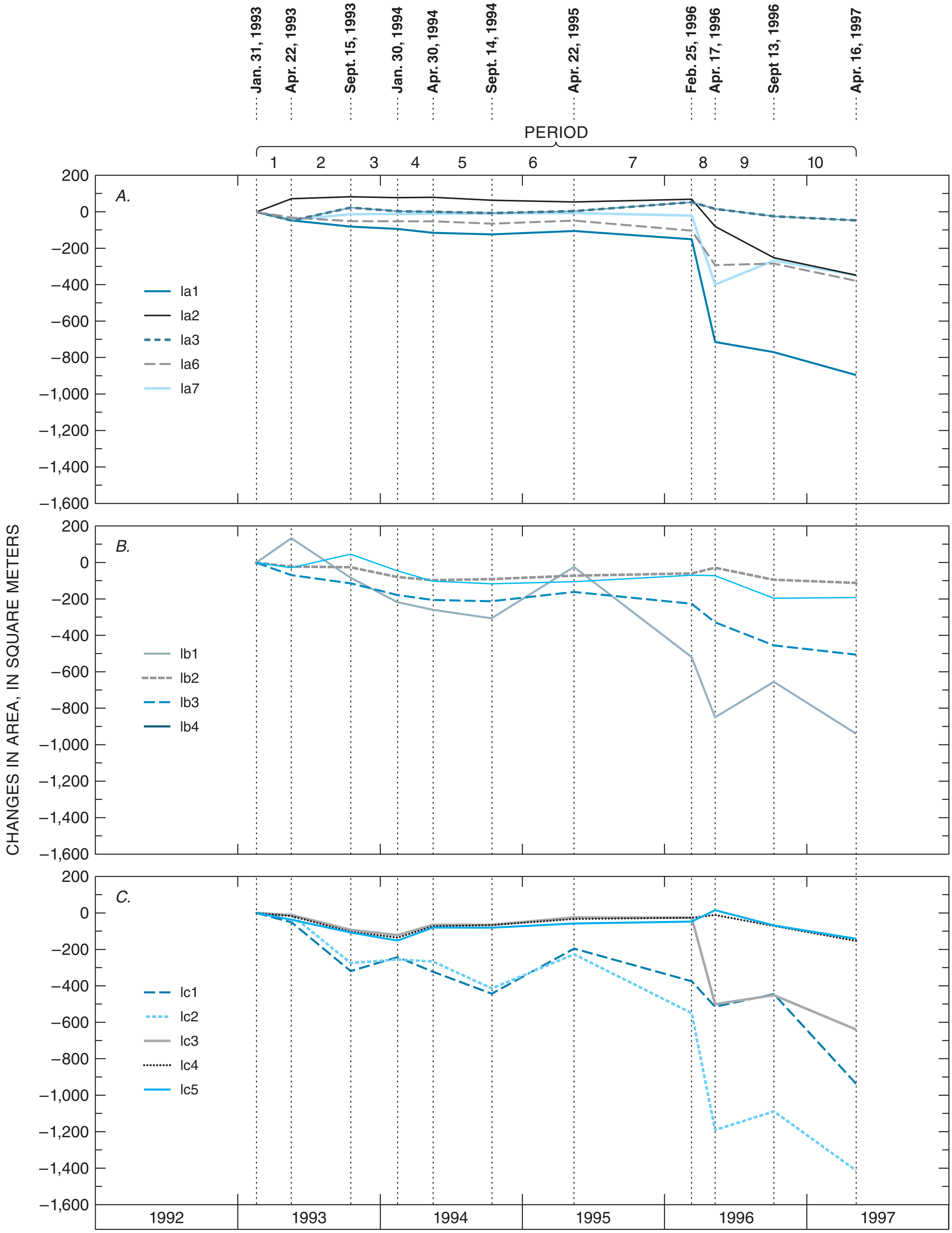


Figure 18. Net change in area for cross sections in the matching-date data set between the confluence of the Little Colorado and Colorado Rivers and Tanner Rapid. *A*, Sections Ia1–Ia7. *B*, Sections Ib1–Ib4. *C*, Sections Ic1–Ic5. *D*, Sections Id1, Id4, and Ie1–Ie5. *E*, Sections If1–If4.

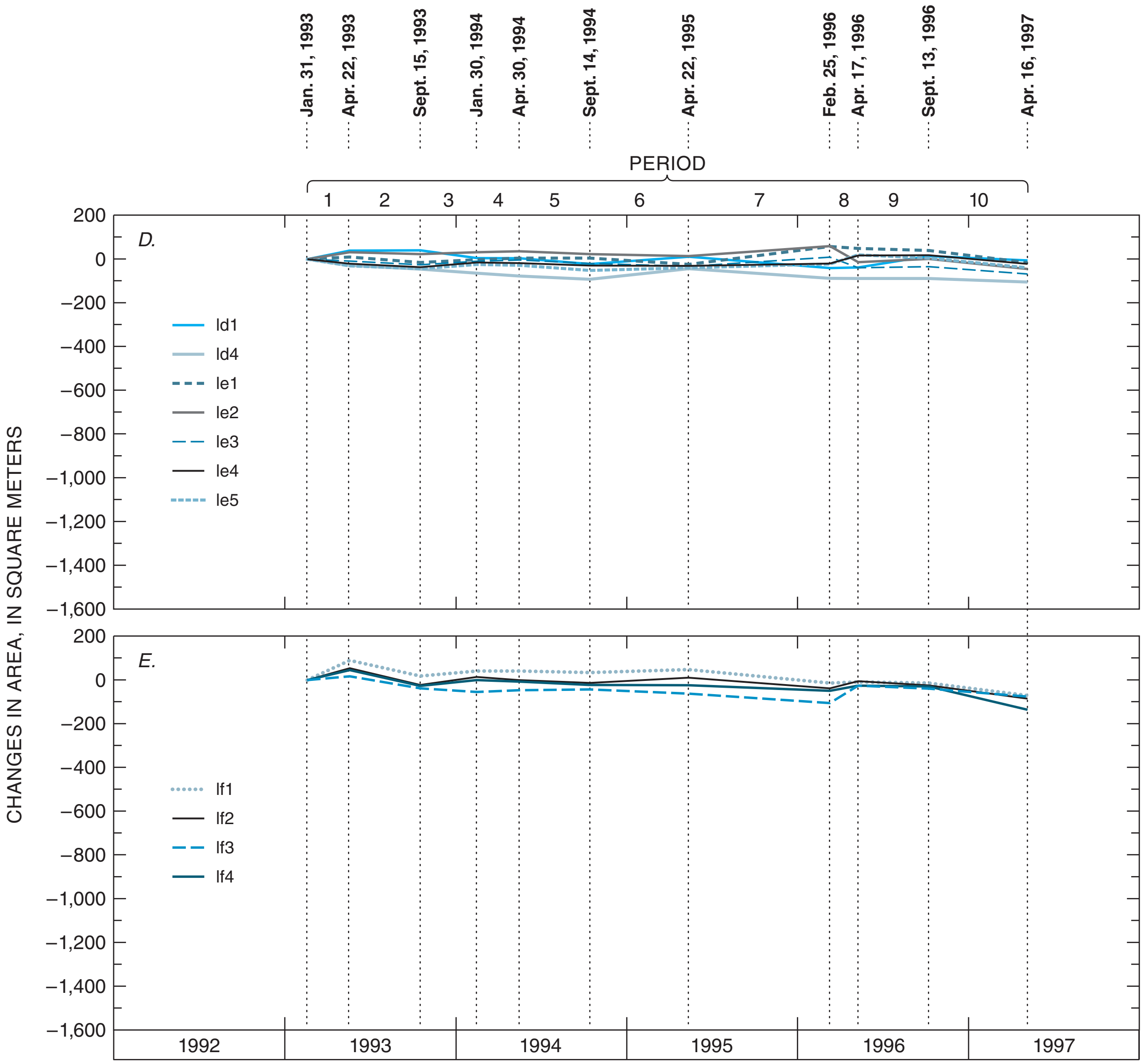


Figure 18. Continued.

Changes in cross-sectional area between measurements were calculated for sections in the matching-date data set (**table 4**) described in the section entitled, "Changes in Cross-Sectional Area." The matching-date data set was chosen because all the cross sections in the same group typically were measured within the same week for a given measurement and thus were exposed to similar hydrologic conditions between measurements.

To generate the values for high flow, low flow, mean flow, and range of flow, daily discharge data from the Colorado River at Lees Ferry were used for the Paria group of cross sections and data from the Colorado River near Grand Canyon were used for the Little Colorado River group of cross sections. The discharge data from the Lees Ferry gaging station, which is upstream from the Paria River, can be used to represent flow conditions for the Paria group of cross sections because the Paria River does not contribute substantial volumes of water to the Colorado River. Because flows from the Little Colorado River can be significant, however, discharge for the Little Colorado River group of cross sections is represented using data from the Grand Canyon gaging station, which is downstream from the Little Colorado River (**fig. 1**).

Additionally, time-weighted values for high flow, low flow, mean flow, and daily range of flow were generated. The weight was obtained by sequentially ordering days between each cross-section measurement and then multiplying the daily flow by the ordered number and dividing by the total number of days between cross-section measurements. This placed greater emphasis on flows that occurred closest to the date that the cross section was measured.

Suspended-sediment discharge data from the Paria River at Lees Ferry gaging station were used to determine tributary inputs to compare to the changes in the Paria group of cross sections. Suspended-sediment discharge data from the Paria River at Lees Ferry and Little Colorado River near Cameron gaging stations were used to determine tributary inputs to compare to the changes in the Little Colorado River group of cross sections. Suspended-sediment input from the Glen Canyon reach of the Colorado River measured at the Lees Ferry gaging station is negligible and, therefore, was assumed to be zero for this analysis. The total suspended-sediment load between cross-section measurements was calculated by summing the loads for those days when flow and suspended-sediment discharge increased in the tributaries because of storms.

Because of the uncertainty in the underlying distributions and relatively small sample sizes, several nonparametric statistical tests using ranked and unranked data were used to determine if any of the factors were more influential than others in explaining the changes in cross-sectional area. Test results showed only a weak relation between changes in cross-sectional area and some of the hydrologic conditions considered—daily mean, daily range of flow, time-weighted daily mean, time-weighted daily range of flow, and sediment inputs from the Paria and Little Colorado Rivers. Scatter plots using the unranked data in figures 19 and 20 illustrate the associations between changes in area and these weakly related hydrologic conditions for the Paria and Little Colorado River groups of sections, respectively. The *p*-values shown on the scatter plots were based on results from Kendall's tau test using unranked data.

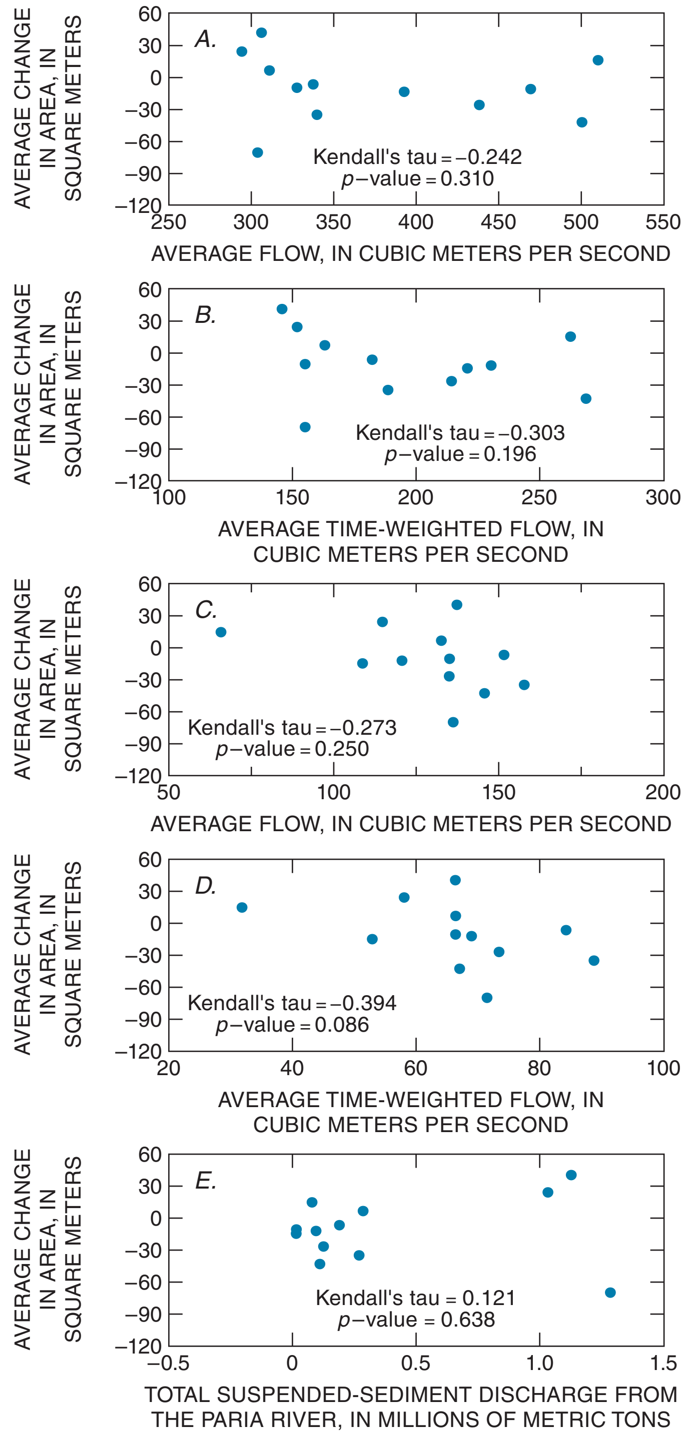


Figure 19. Associations between average changes in area and five hydrologic conditions for cross sections in the matching-date data set between the confluence of the Paria and Colorado Rivers and Badger Creek Rapid. *A*, Average of daily mean flows. *B*, Average of time-weighted daily mean flows. *C*, Average of daily mean range of flows. *D*, Average of time-weighted daily mean range of flows. *E*, Suspended-sediment discharge from the Paria River. All flow data are from the streamflow-gaging station Colorado River at Lees Ferry (09380000).

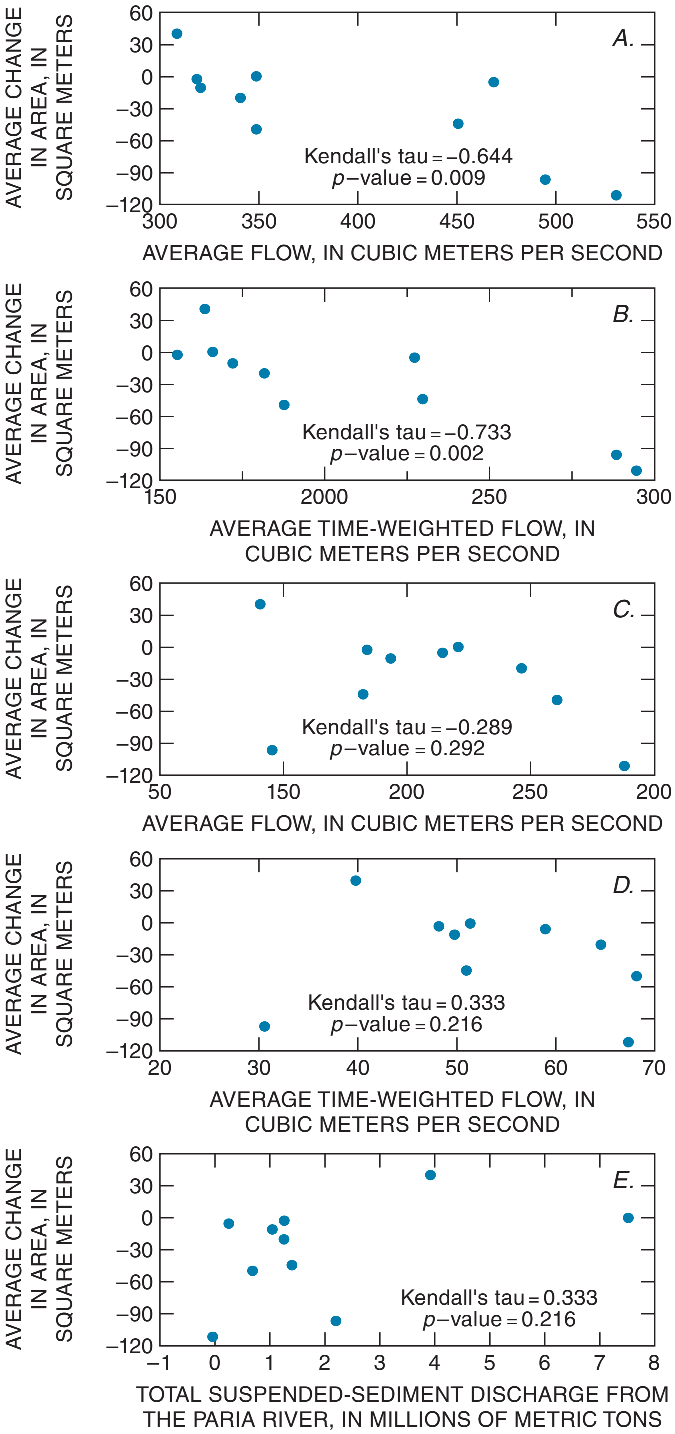


Figure 20. Associations between average changes in area and five hydrologic conditions for cross sections in the matching-date data set between the confluence of the Little Colorado and Colorado Rivers and Tanner Rapid. *A*, Average of daily mean flows. *B*, Average of time-weighted daily mean flows. *C*, Average of daily mean range of flows. *D*, Average of time-weighted daily mean range of flows. *E*, Suspended-sediment discharge from the Paria and Little Colorado Rivers. All flow data are from the streamflow-gaging station Colorado River at Grand Canyon (09402500).

For the Paria group of sections, unranked daily mean range of flow, time weighted (**fig. 19***D*), shows the strongest association with change in area and has a *p*-value of 0.086. For the Little Colorado River group of sections, unranked daily mean flow, both unweighted (fig. 20*A*) and time-weighted (fig. 20*B*), shows the strongest associations with change in area. The corresponding *p*-values are 0.009 for daily mean flows and 0.002 for time-weighted daily mean flows.

The analyses did not strongly indicate that any one of the hydrologic factors considered was more influential in causing changes in area than any other hydrologic factor considered, nor could any causation between factors and changes in area be established. This could indicate that an important governing process was not considered in the analyses, or that the spatial and temporal resolutions of the collected data were inadequate to explain the changes in area.

CONCLUSION

This data-collection effort was successful in providing data to support the development of multidimensional sediment-transport models (Wiele and others, 1996). Because of the highly variable nature of sediment in this system, both temporally and spatially, the data cannot adequately be used to answer questions about the sediment-storage condition of the channel or for tracking the movement of sediment pulses through the system. At the measurement frequency that these data were collected, the data indicate a short residence time for sediment storage in the cross sections. This result is consistent with the conclusion of Topping, Rubin, and Vierra (2000) that multiyear accumulation of sediment has not occurred under the MLFF operating criteria, as was anticipated in the EIS.

The nonparametric statistical tests using ranked and unranked data showed only a weak relation between changes in cross-sectional area and some of the hydrologic conditions considered: daily mean flow, daily range of flow, time-weighted daily mean flow, time-weighted daily range of flow, and sediment inputs from the Paria and Little Colorado Rivers. This lack of correlation indicates that an important governing process was not considered in the analyses, or that the spatial and temporal resolutions of the collected data were inadequate to explain the changes in area.

SELECTED REFERENCES

Anima, R.J., Marlow, M.S., Rubin, D.M., and Hogg, D.J., 1998, Comparison of sand distribution between April 1994 and June 1996 along six reaches of the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Open-File Report 98—141, p. 32.

Barford, N.C., 1985, Experimental measurements: Precision, error and truth: Great Britain, John Wiley and Sons, 159 p.

Birdseye, C.H., 1923, Plan and profile of Colorado River from Lees Ferry, Arizona, to Black Canyon, Arizona-Nevada: U.S. Geological Survey topographic maps, 21 sheets, scale 1:31,680.

Cluer, B.L., 1991, Catastrophic erosion events and rapid deposition of sandbars on the Colorado River, the Grand Canyon, Arizona [abs.], *in* AGU 1991 Fall Meeting Program and Abstracts: American Geophysical Union EOS Transactions, supp. to vol. 72, no. 44, p. 223.

Cooley, M.E., Aldridge, B.N., and Euler, R.C., 1977, Effects of the catastrophic flood of December, 1966, North Rim area, eastern Grand Canyon, Arizona: U.S. Geological Survey Professional Paper 980, 43 p.

Dolan, Robert, Howard, A.D., and Gallenson, A., 1974, Man's impact on the Colorado River in the Grand Canyon: American Scientist, v. 62, no. 4, p. 393–401.

Dolan, Robert, Howard, A.D., and Trimble, D., 1978, Structural control of the rapids and pools of the Colorado River in the Grand Canyon: Science, v. 202, no. 4368, p. 629–631.

Devore, J.L., 1991, Probability and statistics for engineering and the sciences (3rd ed.): Pacific Grove, California, Brooks/Cole Publishing Company, 716 p.

Graf, J.B., Marlow, J.E., Fisk, G.G., and Jansen, S.M.D., 1995, Sand-storage changes in the Colorado River Downstream from the Paria and Little Colorado Rivers, June 1992 to February 1994; U.S. Geological Survey Open-File Report 95—446, 61 p.

Graf, J.B., Marlow, J.E., Rigas, P.D., and Jansen, S.M.D., 1997, Sand-storage changes in the Colorado River downstream from the Paria and Little Colorado Rivers, April 1994 to August 1995; U.S. Geological Survey Open-File Report 97—206, 41 p.

Hamblin, W.K., and Rigby, J.K., 1968, Guidebook to the Colorado River, Part 1—Lees Ferry to Phantom Ranch in Grand Canyon National Park: Provo, Utah, Brigham Young University Geology Studies, v. 15, part 5, 84 p.

Helsel, D.R., and Hirsch, R.M., 2000, Studies in environmental science 49, statistical methods in water resources, 4th impression: Amsterdam, The Netherlands, Elsevier Science, 529 p.

Howard, A.D., and Dolan, Robert, 1981, Geomorphology of the Colorado River in the Grand Canyon: Journal of Geology, v. 89, no. 3, p.269–298.

Inman, R.L., and Conover, W.J., 1983, A modern approach to statistics: New York, John Wiley & Sons, 497 p.

Kieffer, S.W., 1985, The 1983 hydraulic jump in Crystal Rapid—Implications for river running and geomorphic evolution in the Grand Canyon: Journal of Geology, v. 93, no. 4, p. 385–406.

Konieczki, A.D., Graf, J.B., and Carpenter, M.C., 1997, Streamflow and sediment data collected to determine the effects of a controlled flood in March and April 1996 on the Colorado River between Lees Ferry and Diamond Creek, Arizona: U.S. Geological Survey Open-File Report 97—224, 55 p.

Melis, T.S., and Webb, R.H., 1993, Debris flows in Grand Canyon National Park, Arizona: Magnitude, frequency, and effects on the Colorado River, *in* Shen, Hsieh Wen, Su, S.T., and Wen, Feng, eds., Hydraulic engineering,: Proceedings of the National Conference on Hydraulic Engineering, v. 1993, no. 2, p. 1290–1295.

Melis, T.S., Webb, R.H., Griffiths, P.G., and Wise, T.J., 1994, Magnitude and frequency data for historic debris flows in Grand Canyon National Park and vicinity, Arizona: U.S. Geological Survey Water-Resources Investigations Report 94—4214, 285 p.

Powell, J.W., 1895, Canyons of the Colorado River: Meadville, Pennsylvania, Flood and Vincent, The Chataqua-Century Press, 400 p.

Rubin, D.M. and Topping, D.J., 2001, Quantifying the relative importance of flow regulation and grain-size regulation of suspended-sediment transport (α) and tracking changes in grain size on the bed (β): Water Resources Research, v. 37, no. 1, p. 133–146.

Schmidt, J.C., 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona; Journal of Geology, v. 98, p. 709–724.

Schmidt, J.C., and Graf, J.B., 1990, Aggradation and degradation of alluvial sand deposits, 1965 to 1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1493, 74 p.

Schmidt, J.C., and Rubin, D.M., 1995, Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans: Geophysical Monograph, v. 89, p. 177–195.

Smith, C.F., Sherman, K.M., Pope, G.L., and Rigas, P.D., 1998, Summary of floods of 1993; January and February 1993, in Arizona, Perry, C.A., ed., *in* Combs, L.J., ed., Summary of floods in the United States, January 1992 through September 1993: U.S. Geological Survey Water-Supply Paper, w 2499, 1998, p. 185–193.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr., 2000, Colorado River sediment transport 1: Natural sediment supply limitation and the influence of Glen Canyon Dam: Water Resources Research, v. 36, no. 2, p. 515–542.

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J. III, and Corson, I.C., 2000, Colorado River sediment transport 2: Systematic bed-elevation and grain-size effects of sand supply limitation: Water Resources Research, v. 36, no. 2, p. 543–570.

U.S. Department of the Interior, 1995, Operation of Glen Canyon Dam, final environmental impact statement: Salt Lake City, Utah, Bureau of Reclamation, 337 p.

Webb, R.H., 1996, Grand Canyon, a century of change; rephotography of the 1889–1890 Stanton expedition: Tucson, University of Arizona Press, 290 p.

Webb, R.H., Griffiths, P.G., Melis, T.S., and Hartley, D.R., 2000, Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon, Arizona: U.S. Geological Survey Water-Resources Investigations Report 00—4055, 67 p.

Webb, R.H., Pringle, P.T., and Rink, G.R., 1989, Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona: U.S. Geological Survey Professional Paper 1492, 39 p.

Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., 1999, The controlled flood in Grand Canyon: Geophysical Monograph, v. 110, 367 p.

Webb, R.H., Wegner, D.L., Andrews, E.D., Valdez, R.A., and Patten, D.T., 1999, Downstream effects of Glen Canyon Dam on the Colorado River in Grand Canyon: A review, *in* Webb, R.H., Schmidt, J.C., Marzolf, G.R., and Valdez, R.A., eds., The controlled flood in Grand Canyon: Geophysical Monograph, v. 110, p. 1–21.

Wiele, S.M., Andrews, E.D., and Griffin, E.R., 1999, The effect of sand concentration on depositional rate, magnitude, and location in the Colorado River below the Little Colorado River: Geophysical Monograph, v. 110, p. 131–145.

Wiele, S.M., Graf, J.B., and Smith, J.D., 1996, Sand deposition in the Colorado River in Grand Canyon from flooding of the Little Colorado River: Water Resources Research, v. 32, no. 12, p. 3579–3596.

Wilson, R.P., 1986, Sonar patterns of Colorado riverbed, Grand Canyon: Las Vegas, Nevada, Fourth Federal Interagency Sedimentation Conference Proceedings, March 24–27, 1986, v. 2, p. 5-133 to 5-142.