Specific Conductance in the Colorado River between Glen Canyon Dam and Diamond Creek, Northern Arizona, 1988–2007

Date Series 364

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By Nicholas Voichick

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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2008

Suggested citation:
Voichick, Nicholas, 2008, Specific conductance in the Colorado River between Glen Canyon Dam and Diamond Creek, northern Arizona, 1988–2007: U.S. Geological Survey Data Series 364, 16 p.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Specific Conductance in the Colorado River between Glen Canyon Dam and Diamond Creek, Northern Arizona, 1988–2007

By Nicholas Voichick

Abstract

The construction of Glen Canyon Dam, completed in 1963, resulted in substantial physical and biological changes to downstream Colorado River environments between Lake Powell and Lake Mead—an area almost entirely within Grand Canyon National Park, Ariz. In an effort to understand these changes, data have been collected to assess the condition of a number of downstream resources. In terms of measuring water quality, the collection of specific-conductance data is a cost-effective method for estimating salinity. Data-collection activities were initially undertaken by the Bureau of Reclamation's Glen Canyon Environmental Studies (1982–96); these efforts were subsequently transferred to the U.S. Geological Survey's Grand Canyon Monitoring and Research Center (1996 to the present). This report describes the specific-conductance dataset collected for the Colorado River between Glen Canyon Dam and Diamond Creek from 1988 to 2007. Data-collection and processing methods used during the study period are described, and time-series plots of the data are presented. The report also includes plots showing the relation between specific conductance and total dissolved solids. Examples of the use of specific conductance as a natural tracer of parcels of water are presented.

Analysis of the data indicates that short-duration spikes and troughs in specific-conductance values lasting from hours to days are primarily the result of flooding in the Paria and Little Colorado Rivers, Colorado River tributaries below Glen Canyon Dam. Specific conductance also exhibits seasonal variations owing to changes in the position of density layers within the reservoir; these changes are driven by inflow hydrology, meteorological conditions, and background stratification. Longer term trends in Colorado River specific conductance are reflective of climatological conditions in the upper Colorado River Basin. For example, drought conditions generally result in an increase in specific conductance in Lake Powell. Therefore, the average annual specific conductance below Glen Canyon Dam is inversely related to the volume of water in Lake Powell.

The data used by this report are provided in downloadable spreadsheet files (http://pubs.usgs.gov/ds/364/).

Introduction

The Colorado River and its tributaries provide municipal and industrial water for more than 23 million people and irrigation water for nearly 4 million acres of land (Bureau of Reclamation, 2007). Approximately 9 million tons of salt enters the Colorado River annually, approximately 50 percent from natural sources and 50 percent from anthropogenic sources (Bureau of Reclamation, 2003). Damages resulting from these salt inputs, which primarily affect municipal, industrial, and irrigation water users, are estimated to cost $300 million annually (Bureau of Reclamation, 2003). The 1974 Colorado River Basin Salinity Control Act, which authorized the construction and operation of salinity-control units and the implementation of a basin-wide salinity-control program, has saved millions of dollars in damages; benefits are estimated to be valued at more than three times the cost of the legislation (Bureau of Reclamation, 2007). The concentration of salt in water (salinity), measured as total dissolved solids (TDS), can be estimated from specific-conductance measurements. This report includes a time series of specific-conductance data collected from several monitoring stations on the Colorado River between Glen Canyon Dam and Diamond Creek in northern Arizona (fig. 1). This data-collection effort is a cost-effective and simple method for continuously monitoring salinity in this section of the Colorado River.

The 1963 closure and operation of Glen Canyon Dam resulted in significant changes to the physical and biological environments of the Colorado River (U.S. Department of the Interior, 1995a; Topping and others, 2003; Gloss and others, 2005) between Lake Powell and Lake Mead (fig. 1). Most of this reach of the Colorado River is within the boundaries of Grand Canyon National Park, Ariz. One of the primary responsibilities of the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (GCMRC), which succeeded the Bureau of Reclamation's Glen Canyon Environmental Studies in 1996, has been to document changes in the Colorado River resulting from the operation of Glen Canyon Dam. Flow regulation by the dam, which is influenced

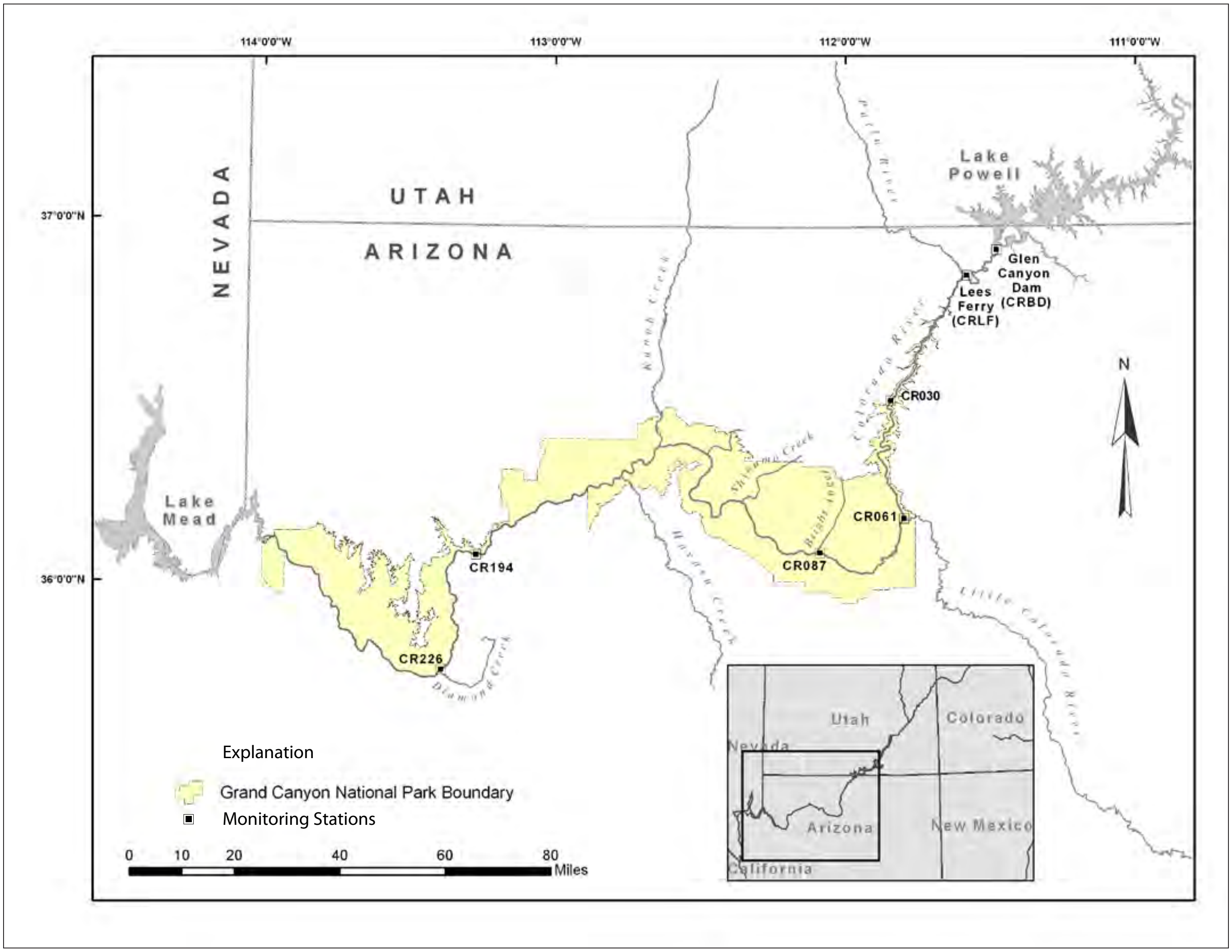

Figure 1. Map of the Colorado River between Lake Powell and Lake Mead in northern Arizona, showing the specific-conductance monitoring stations described in this report (refer to table 1 for station names).

primarily by hydropower demand, reduced annual peak flows and increased minimum flows and daily fluctuations in flows (Topping and others, 2003). As a result of dam construction and operation, sandbars and other fine-grained deposits have been eroded (Schmidt and others, 2004; Wright and others, 2005). Additionally, the design and operation of the dam have reduced the fluctuation of two water-quality parameters: temperature (Voichick and Wright, 2007) and specific conductance (fig. 2).

Purpose and Scope

This report describes the specific-conductance data collected by Glen Canyon Environmental Studies and the GCMRC at seven monitoring stations on the Colorado River between August 1988 and September 2007 (fig. 1, table 1). Locations on the Colorado River are referenced in river miles (RM) downstream from the USGS Colorado River gaging station at Lees Ferry, Ariz. The use of the river mile has a historical precedent and provides a reproducible method for describing locations along the Colorado River; Lees Ferry is the starting point, at RM 0, with mileage measured for both upstream and downstream directions (fig. 1). This report summarizes the data-collection and processing methods used and presents time-series plots of the data. The relation between specific conductance and TDS is also described. The specific-conductance data presented in this report can be used to estimate TDS, a common measure of salinity. Additionally, examples showing how specific conductance can be used to track parcels of water in the study area are presented.

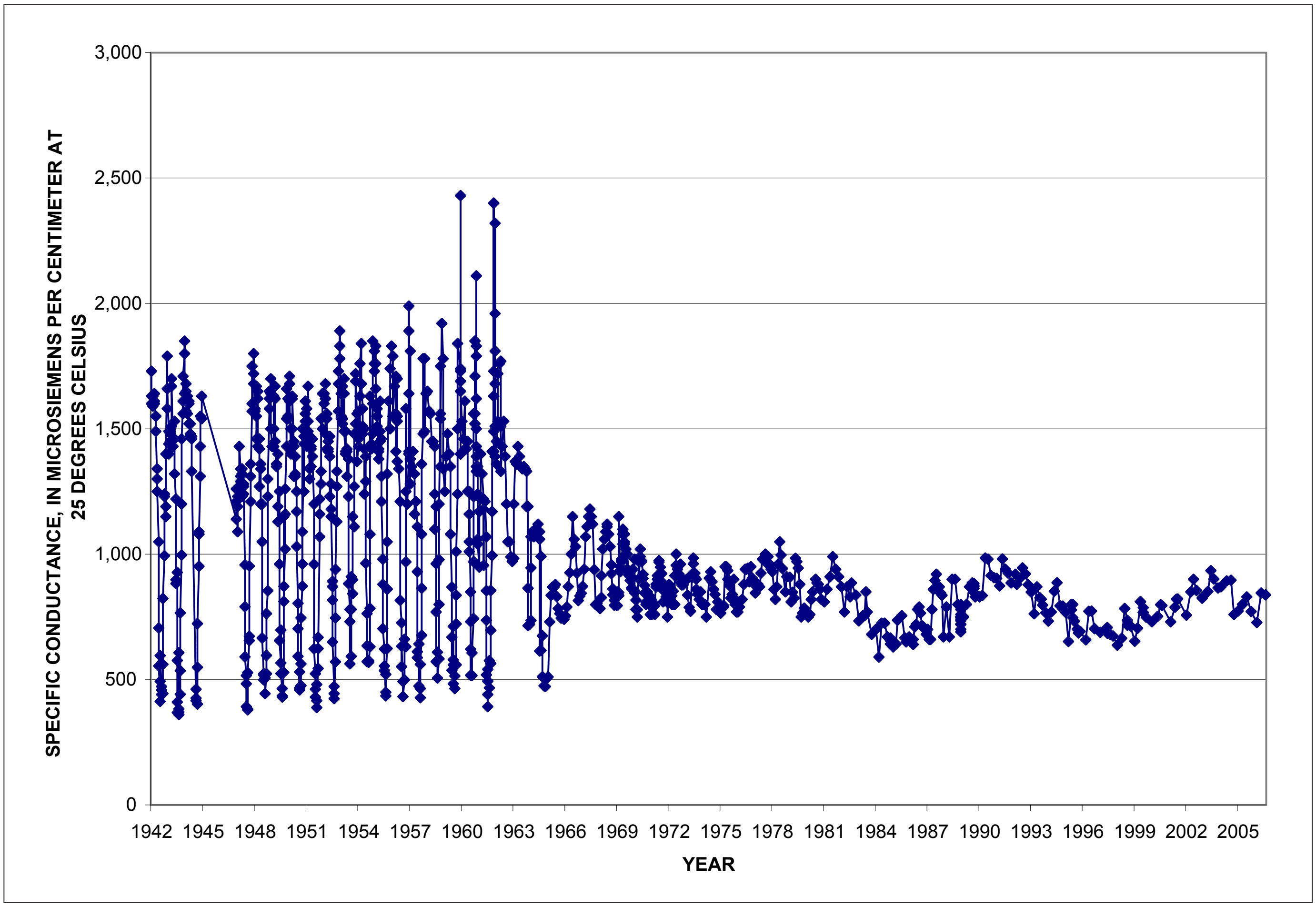

Figure 2. Graph of specific-conductance data from samples collected at the U.S. Geological Survey's Colorado River at Lees Ferry, Ariz., gaging station (station number 09380000), 1942–2006.

Methods

Instrumentation and Operation

Conductivity is a measure of an aqueous solution's ability to carry an electric current. By definition, conductivity is the reciprocal of the resistance in ohms measured between opposite faces of a centimeter cube (Hem, 1985). Specific conductance usually is defined as conductivity normalized to 25°C, expressed in microsiemens per centimeter at 25°C (µS/cm). During this study, specific conductance was measured by using multiparameter datasondes, which are capable of recording and logging several water-quality parameters simultaneously. These multiparameter datasondes were manufactured by Hydrolab and YSI Incorporated (table 1). The conductivity sensors on the instruments consist of a conductivity cell housing multiple electrodes (six on the Hydrolab instruments and four on the YSI instruments). Two electrodes on the YSI conductivity sensor are used to establish a current and two electrodes measure voltage drop, and these measurements are then converted into a conductivity value; the electrodes on the Hydrolab sensor work similarly (YSI, 2002; Hydrolab, 1995). The instruments measure water temperature at the same time they calculate a conductivity value, and these data are used to compute specific conductance. The resolution of the specific-conductance readings in this report is usually to the nearest 1 µS/cm. The accuracy of the conductivity sensors for the range of values in this report is ±15 µS/cm for the Hydrolab instruments and ±0.5 percent of the reading +1 µS/cm for the YSI 6920 instruments.

Deployment of Instruments

Five of the seven water-quality instruments were deployed in the river by being suspended from a coated steel cable attached to rocks or vegetation on the riverbank (fig. 3). At the Colorado River below Glen Canyon Dam (CRBD) monitoring station, the instrument was deployed in the river inside a perforated plastic pipe alongside a vertical cement wall on the riverbank. At the Colorado River at Lees Ferry (CRLF) monitoring station, the instrument was deployed in the river from a dock on the right side of the channel from

Table 1. Stations for monitoring specific conductance on the Colorado River, Ariz., from August 1988 to September 2007. River miles (RM) are distance upstream or downstream from Lees Ferry (RM 0); Glen Canyon Dam is 15 miles upstream from Lees Ferry and, therefore, is assigned a location of negative 15 river miles (RM -15).

Station name	Site identifier	Latitude	Longitude	Start of record	End of record	Instrument type
Colorado River below Glen Canyon Dam	CRBD	36.9361°N	111.4826°W	Aug. 10, 1988	Continuing	Hydrolab Datasonde I through June 1995 then Hydrolab Recorder through Oct. 2000, then YSI 6920 datasonde
Colorado River at Lees Ferry	CRLF	36.8653°N	111.5846°W	Dec. 16, 1991	Continuing	Hydrolab Datasonde I through June 1995 then Hydrolab Recorder through Oct. 2000, then YSI 6920
Colorado River near RM 30	CR030	36.5201°N	111.8457°W	Oct. 26, 2002	Continuing	YSI 6920 datasonde
Colorado River near RM 61	CR061	36.1964°N	111.8003°W	Oct. 28, 2002	Continuing	YSI 6920 datasonde
Colorado River near RM 87	CR087	36.1011°N	112.0863°W	Feb. 13, 2003	Continuing	YSI 6920 datasonde
Colorado River near RM 149	CR149	36.3470°N	112.6871°W	Feb. 17, 2003	Jan. 7, 2005	YSI 6920 datasonde
Colorado River near RM 226	CR226	35.7728°N	113.3665°W	Oct. 8, 2002	Continuing	YSI 6920 datasonde

1991 to 1998 and, thereafter, from a buoy in the middle of the river channel. At sites downstream from CRLF, the instruments were supported by the channel bank and placed in a vertical position when possible. All instruments were deployed in positions no less than 1 m below the water surface at any given river stage.

Cross-Section Measurements

Each water-quality instrument was deployed in flowing water that was thought to represent an entire cross section of the Colorado River at the instrument location. To test this hypothesis, cross-section measurements were taken and compared at Colorado River monitoring stations CR030, CR061, and CR226 (see table 1 for explanation of site identifiers) (Wagner and others, 2006). At each of the three monitoring stations, specific-conductance readings were taken at five locations spaced equally across the river channel in January 2005; readings were taken at two (CR030 and CR061) of the three stations in August 2007. One set of measurements was taken during each site visit, except at the CR061 monitoring station where two sets of cross-section measurements were taken during different flow conditions (approximately 280 and 480 cubic meters per second (m^3/s) flows) in August 2007. At the CR030 and CR061 monitoring stations, the readings were taken from a boat held stationary in the river channel at a position marked by a tagline strung across the river. At the CR226 monitoring station, measurements were taken from a cable car suspended over the river channel. At each of the five locations along the cross section, a weighted YSI instrument was lowered to record specific-conductance readings. At about 1-m intervals, readings were recorded from just below the water surface to the channel bottom. A separate YSI instrument was used to record readings simultaneously at the near-bank deployment site to detect any changes in specific conductance during the cross-section measurements. After the cross-section measurements were taken, both instruments were deployed at the near-bank site to check for instrument variation.

Variation in specific-conductance values within each cross section ranged from 0 to 6 µS/cm, averaging 3 µS/cm (0.4 percent of the reading). The difference in the readings between the near-bank deployments and the corresponding cross-section measurements also ranged from 0 to 6 µS/cm, averaging 2 µS/cm (0.3 percent of the reading). The results validate deploying water-quality instruments in the near-bank environment to characterize average specific conductance across the channel under a range of flow conditions (approximately 280 to 480 m^3/s) and at two different times of year, summer and winter (at the CR030 and CR061 monitoring stations).

Instrument Maintenance and Data Processing

The water-quality instruments were programmed to record data at specific time intervals, usually 15 or 20 min, which was considered an adequate amount of time to capture

Figure 3. Photograph of the east bank of the Colorado River, Ariz., looking upstream near river mile 61 (site CR061) and showing the exposed multiparameter instrument.

changes in specific conductance caused by dam operations or weather events, such as floods in upstream tributaries. The instruments at the CRBD and CRLF monitoring stations were serviced at about 1-month intervals, whereas the less accessible water-quality instruments downstream from the CRLF monitoring station were serviced at 1- to 6-month intervals. During servicing, instruments were calibrated by using a single standard (approximately 1,000 µS/cm) and then checked by collecting simultaneous readings from two or more calibrated instruments either in the Colorado River or in a circulating water bath. If the readings between instruments varied by more than the accuracy of the conductivity sensors (±15 µS/cm for the Hydrolab instruments and ±0.5 percent of the reading +1 µS/cm for the YSI 6920 instruments), the instruments were recalibrated.

Beginning in May 2005 at monitoring stations downstream from CRLF and in August 2006 at the CRBD and CRLF monitoring stations, the protocols for servicing the water-quality instruments were changed to correspond to the procedure outlined by Wagner and others (2006). During servicing, a calibrated field meter was put in place at the instrument site to collect simultaneous readings with the deployed instrument without disturbing it. The deployed instrument was then cleaned and subsequently redeployed to collect additional readings, after which a calibration check was performed. This procedure helped to distinguish between fouling of the instrument, which is determined by comparing the pre- and post-cleaning measurements, and electronic drift of the instrument, which is determined by the calibration check. The calibrated field meter collected data during the entire servicing procedure to detect any environmental change in specific conductance that may have occurred at the site during the servicing period. The field-meter readings, combined with the fouling and calibration checks of the deployed meter, helped to evaluate the specific-conductance data.

The most common incidence of instrument fouling, particularly downstream from the CRLF monitoring station, presumably occurred when sediment was deposited in the conductivity cell. This form of fouling of the conductivity sensor would occasionally correct itself when the sediment was flushed out of the conductivity cell by changes in the flow or sediment concentration of the river. More frequently, however, the sediment remained in place in the conductivity cell and its amount changed over time, causing nonlinear fouling of the conductivity sensor during the duration of the deployment. In most cases, data from instruments under these conditions were difficult to interpret and were deleted from the record.

The validity of the specific-conductance data was determined by first considering any fouling or drift detected by the fouling and calibration checks. The data also were compared with data from adjacent monitoring stations on the Colorado River and with USGS Arizona Water Science Center data from the Lees Ferry gaging station (station number 09380000), approximately 0.2 mi downstream from the CRLF monitoring station. Direct comparison of data between stations is possible because there are usually only two tributaries, the Paria River and the Little Colorado River, that substantially influence specific conductance in the Colorado River in the study area. The specific-conductance signature from the Paria River is apparent only during flood events, whereas the Little Colorado River has enough discharge and specific conductance at base flow to increase specific conductance in the Colorado River downstream from its confluence with the Colorado River. These tributary effects are described in more detail in the data summary section of this report. There are multiple monitoring stations upstream and downstream of the Paria River and the Little Colorado River (fig. 1) where specific conductance can be compared. Figure 4 compares specific-conductance data from 2005 for stations above and below the Little Colorado River. Note that the general trends in specific conductance often can be traced from the furthest upstream monitoring station (CRBD) to the furthest downstream station (CR226).

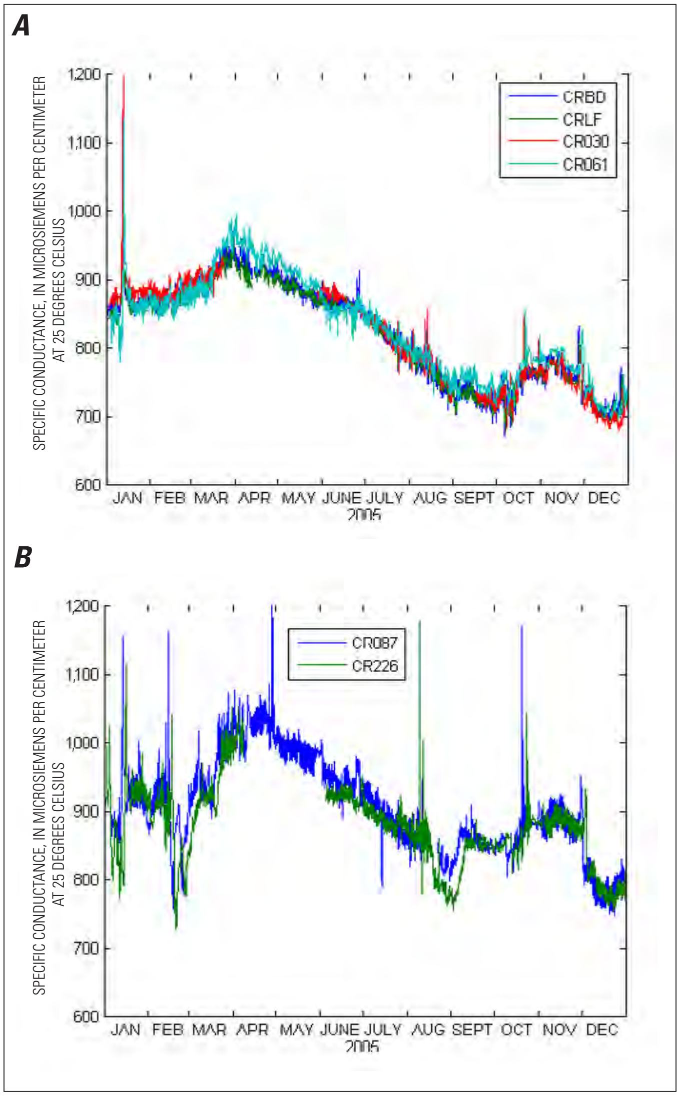

Figure 4. Comparison of 2005 specific-conductance data from monitoring stations on the Colorado River, Ariz. *A*, Upstream from the Little Colorado River. *B*, Downstream from the Little Colorado River. (Refer to table 1 for station names.)

Table 2 shows the percentage of data missing from each station during the period of record and the percentage of data to which a correction shift was applied. The missing data represent both data that were determined to be invalid with no applicable correction shift (more common) and time periods when data were not collected (less common). When it was determined that data could not be corrected with a reasonable amount of certainty, based on instrument fouling and calibration checks and comparison of data from adjacent monitoring stations, the data were deleted from the record.

When data could be corrected, one of two types of correction shifts was applied to the data: a constant shift, where all data from a time period were shifted by a constant, or a linear shift, where all data from a time period were shifted linearly with time. A constant shift was applied (1) during an entire deployment, defined as the time interval between instrument maintenance, to correct a poor calibration or (2) during only part of a deployment in the case of an event-related fouling, such as sediment suddenly collecting in the conductivity cell. A poor calibration, resulting in a constant shift (greater than the accuracy of the instrument) of all data in a single deployment, often could be determined by comparing data from previous and subsequent deployments at the same site and by noting the data correction indicated by the calibrations at the beginning and end of the deployment. An event-related fouling usually was distinguishable from a poor calibration because it generally did not affect all of the data from the deployment and often was rectified by cleaning out the conductivity cell during a fouling check. A linear data shift was applied during gradual fouling or calibration drift that was determined to be linear with time based on fouling and calibration checks and data comparisons within and among sites. Table 3 shows all of the correction shifts applied to the data presented in this report.

Wagner and others (2006) outlined criteria for making accuracy ratings of water-quality data. These recommendations were used to assign an accuracy rating to all of the specific-conductance data. Table 2 shows the percentage of data from each station assigned to the four ratings: excellent, good, fair, and poor. When the instrument-maintenance protocols outlined by Wagner and others (2006) were followed and no data correction shifts were applied, the data were given an accuracy rating of excellent. When the protocols were not followed as rigorously as outlined by Wagner and others (2006) and no data correction shifts were made, the quality of the data was downgraded to good. The specific-conductance data collected for this study generally was rated excellent or good, in part, because the data were usually comparable between two or more stations (fig. 4).

For data given a correction shift (table 3), the accuracy rating remained the same if the data correction resulted in a change of ≤3 percent of the uncorrected value. The accuracy

Table 2. Summary of specific-conductance statistics during the period of record at all Colorado River monitoring stations between Glen Canyon Dam and Diamond Creek, Ariz.

[Percentage of missing data represents the percentage of days of missing data during the period of record; refer to Wagner and others (2006) for accuracy rating information].

Station name	Site identifier	Missing data (%)	Data with correction shift applied (%)	Accuracy rating of excellent (E) (%)	Accuracy rating of good (G) (%)	Accuracy rating of fair (F) (%)	Accuracy rating of poor (P) (%)
Colorado River below Glen Canyon Dam	CRBD	10	1	9	91	0	0
Colorado River at Lees Ferry	CRLF	16	4	9	90	1	0
Colorado River near RM 30	CR030	16	6	21	79	0	0
Colorado River near RM 61	CR061	58	0	38	61	1	0
Colorado River near RM 87	CR087	7	4	30	66	1	3
Colorado River near RM 149	CR149	20	0	0	99	1	0
Colorado River near RM 226	CR226	10	13	11	81	5	3

rating was downgraded one step (for example, from good to fair) if the data correction resulted in a change of >3 percent and ≤10 percent, two steps if the data correction resulted in a change of >10 percent and ≤15 percent, and 3 steps if the data correction resulted in a change of >15 percent and ≤30 percent (Wagner, 2006). The data were not reported if the corrected value differed by >30 percent from the recorded value (Wagner, 2006).

Data Summary

Short-Duration Spikes and Troughs in Specific Conductance

Short-duration spikes and troughs in specific conductance lasting from hours to days (figs. 4 and 5) are the result of floods in tributaries of the Colorado River. Owing to differing geologic characteristics of individual tributary drainage basins, floods on tributaries may introduce water to the Colorado River that is either fresher or much more saline than the water in the Colorado River. Large parts of the drainage basins of the Paria River and Moenkopi Wash, which flows into the Little Colorado River (fig. 1), are underlain by marine siltstones and shales. Thus, the geology of these drainage basins causes floods on these tributaries to contribute highly saline water to the Colorado River, resulting in an increase in the river's specific conductance. All five of the largest spikes at site CR087 during 2005 (fig. 4*B*) coincide with floods on the Paria River and/or Moenkopi Wash. Approximately 80 percent of the spikes in specific conductance at sites CR030 and CR087 (fig. 5) coincide with floods on the Paria River (at site CR030) and floods on the Paria River and/or Moenkopi Wash (at site CR087). Because many of the smaller ungaged tributaries and washes in the study area are underlain by similar marine sedimentary rocks, the other short-duration, high-specific-conductance spikes observed at all sites in the study area are also the likely result of floods on upstream tributaries.

In contrast to the above examples, large, long-duration floods on the Little Colorado River (with minimal contribution from Moenkopi Wash) tend to bring fresher water into the Colorado River because these floods originate in the high-elevation, limestone-dominated southern part of the Little Colorado River drainage basin. Therefore, during large, long-duration Little Colorado River floods, specific conductance decreases in the Colorado River downstream from its confluence with the Little Colorado River. The decrease in specific conductance at sites CR087 and CR226 (but not at sites upstream of the confluence with the Little Colorado River) in February/March and August/September 2005 (fig. 4) coincide with large, long-duration Little Colorado River floods.

Table 3. Summary of all data-correction shifts applied to the specific-conductance data over the period of record at all Colorado River monitoring stations between Glen Canyon Dam and Diamond Creek, Ariz.

Station name	Site identifier	Start date and time of data shift	End date and time of data shift	Type of data shift	Amount of data shift (microsiemens per centimeter)	Approximate percent change of data	Accuracy rating of computed data
Colorado River below Glen Canyon Dam	CRBD	2/2/95 1600	3/10/95 0500	Constant	+15	2	Good
Colorado River at Lees Ferry	CRLF	9/9/92 900	9/30/92 1700	Constant	-40	4	Fair
Colorado River at Lees Ferry	CRLF	7/2/93 2300	8/7/93 1000	Constant	+15	2	Good
Colorado River at Lees Ferry	CRLF	12/2/93 900	1/4/94 1700	Constant	+25	4	Fair
Colorado River at Lees Ferry	CRLF	1/3/96 1730	1/31/96 900	Constant	-40	6	Fair
Colorado River at Lees Ferry	CRLF	12/21/06 1200	1/30/07 1000	Constant	+18	2.5	Excellent
Colorado River at Lees Ferry	CRLF	7/13/07 0940	8/23/07 0800	Linear	0 to +14	0 to 2	Excellent
Colorado River near RM 30	CR030	2/3/03 0000	3/3/03 1115	Linear	0 to +16	0 to 2	Good
Colorado River near RM 30	CR030	12/8/06 1200	2/24/07 1700	Linear	0 to +43	0 to 5	Good
Colorado River near RM 87	CR087	7/3/03 0000	7/23/03 0515	Linear	0 to +48	0 to 6	Fair
Colorado River near RM 87	CR087	1/20/07 0000	3/1/07 1700	Constant and Linear	+70, 0 to +142	11 to 28	Poor
Colorado River near RM 226	CR226	10/8/02 1645	11/18/02 1300	Constant	-27	3	Fair
Colorado River near RM 226	CR226	2/11/05 0000	3/21/05 1615	Linear	0 to +85	0 to 10	Fair
Colorado River near RM 226	CR226	1/25/07 0000	3/8/07 1245	Linear	0 to +171	0 to 20	Poor
Colorado River near RM 226	CR226	5/11/07 1030	9/5/07 1745	Constant	+37	5	Good

Seasonal and Long-Term Trends in Specific Conductance

The Glen Canyon Dam penstocks, the dam's primary water-release structures, are approximately halfway between the full-pool elevation of Lake Powell and the bottom of the reservoir (fig. 6). As is typical in large reservoirs, water in Lake Powell is density stratified into layers of similar temperature and salinity. The upper part of the Lake Powell hypolimnion, the dense bottom layer of the reservoir, is generally positioned at about the level of the penstocks. Because it is more saline, the hypolimnion has a higher specific conductance than the surface layer (Hueftle and Stevens, 2001; Flynn and others, 2001; Hart and Sherman, 1996). The thickness and position of the reservoir density layers change seasonally, primarily influenced by changes in inflow hydrology, meteorological conditions, and background stratification (Hueftle and Vernieu, 1998). The fall and winter inflow into Lake Powell generally moves toward the dam as a highly saline, dense underflow or interflow. Upon reaching the dam, an underflow or interflow usually rises toward the surface, resulting in an increase in specific conductance at the level of the penstocks from around January through March. From the spring through approximately the end of the year, specific conductance at the penstock level may either decrease because of the thickening of the epilimnion, the less saline surface layer of the reservoir,

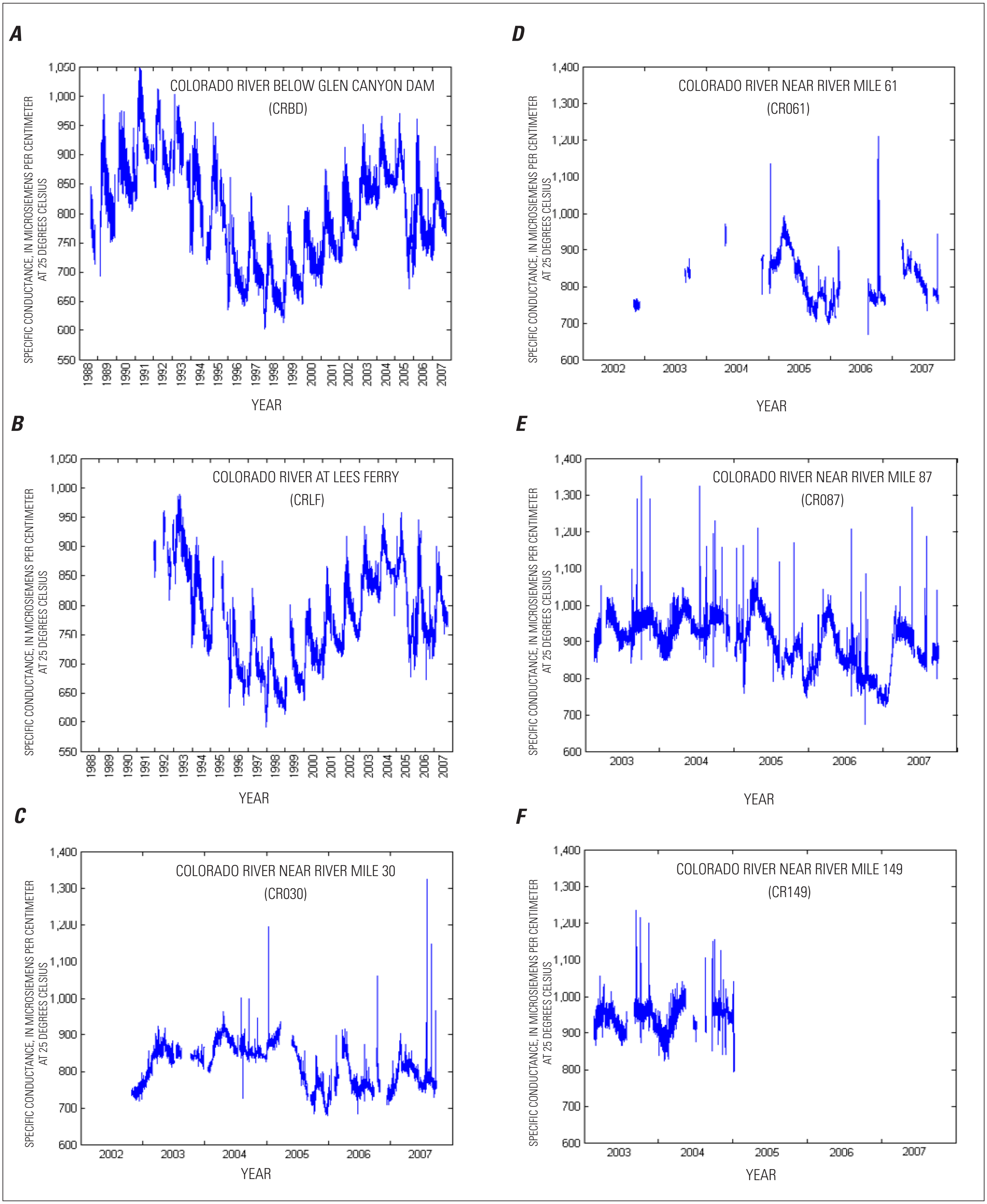

Figure 5. Time-series plots (*A* through *G*) of specific conductance at monitoring stations on the Colorado River, Ariz.
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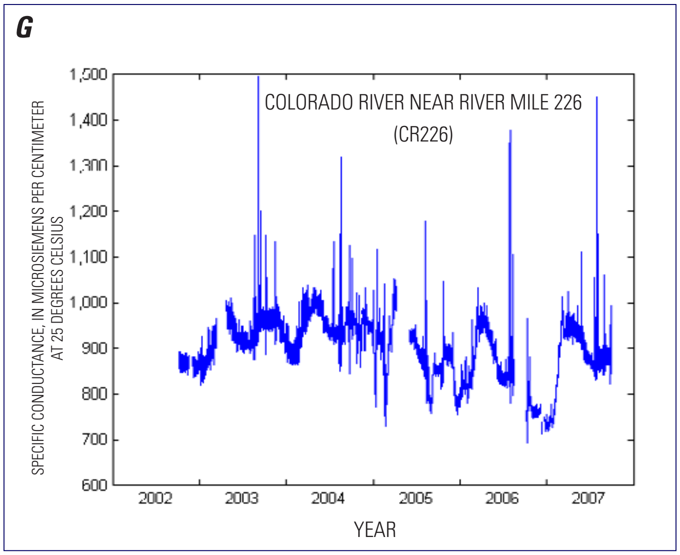

Figure 5. Time-series plots (*A* through *G*) of specific conductance at monitoring stations on the Colorado River, Ariz.—Continued

or stay relatively stable when the surface layer is far above the penstocks. Thickening of the epilimnion is caused by the addition of relatively low-density water to the reservoir during spring inflow and seasonal warming of the reservoir resulting in the lowering of the epilimnion/hypolimnion boundary (Hueftle and Vernieu, 1998).

The seasonal pattern described above—a relatively steep rise in specific conductance in Lake Powell at the penstock level early in the year, followed by a more gradual decrease in specific conductance from approximately March through the rest of the year—is visible in measurements collected at the penstock depth in the forebay of Lake Powell (fig. 7) and at the sampling sites in the Colorado River closest to Glen Canyon Dam (figs. 5*A* and 5*B*).

The longer term increase in specific conductance from 1988 to 1991, the decrease in specific conductance from 1992 to 1998, and the subsequent increase in specific conductance from 1999 to 2004 (figs. 5*A* and 5*B*) are reflective of climatological conditions in the upper Colorado River Basin (Hueftle and Stevens, 2001; Vernieu and others, 2005). Drought conditions, prevalent since 1999, generally result in an increase in specific conductance in Lake Powell (fig. 7), owing in part to the decrease in the volume of water in the reservoir (fig. 6). The average annual specific conductance below Glen Canyon Dam is, therefore, inversely related to the volume of water in Lake Powell (fig. 8).

Relation between Specific Conductance and Total Dissolved Solids

Amendments to the Federal Water Pollution Control Act included water-quality standards for TDS concentrations at various points in the Colorado River Basin (U.S. Department of the Interior, 1995b). TDS can be estimated by multiplying specific conductance by an empirical factor that is dependent on the soluble components of the water (American Public Health Association, 1992). The empirical factor can be estimated from TDS measurements (residue on evaporation, dried at 180°C) taken from samples collected at or near two of the

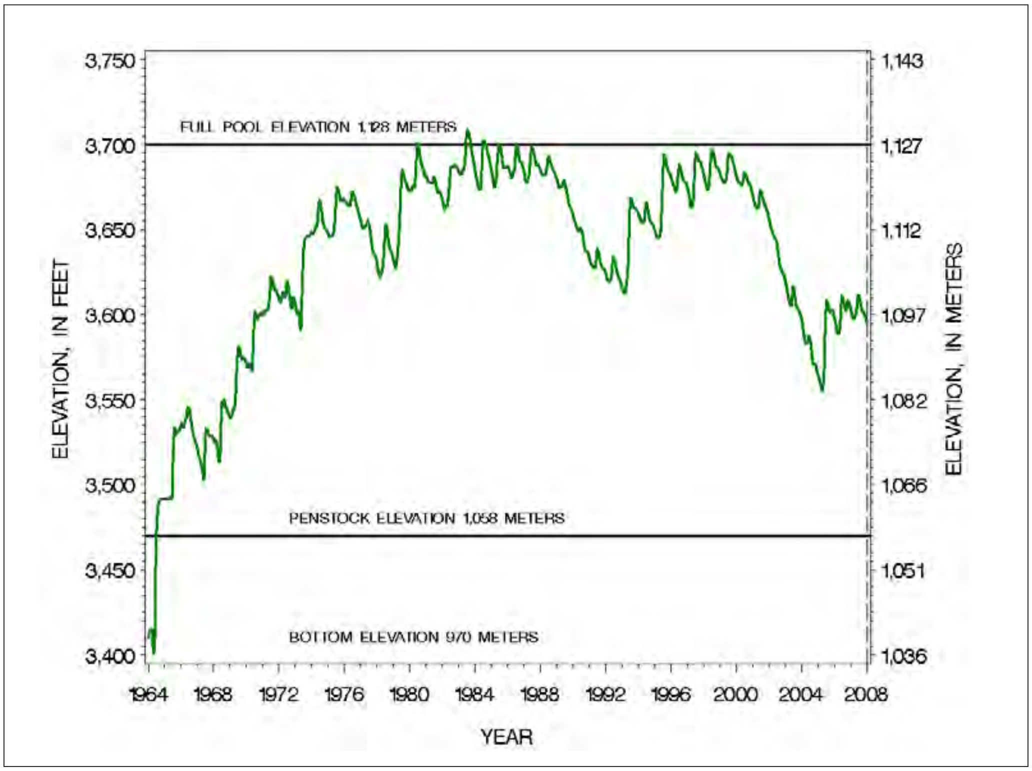

Figure 6. Graph showing the surface elevation of Lake Powell, Ariz., 1964–2007 (with full pool, penstock, and bottom elevations noted).

monitoring stations, Lees Ferry (CRLF) and above Diamond Creek (CR226), and from specific-conductance data presented in this report (fig. 9). The linear regressions were forced through the origin, yielding nearly identical slopes for the two sites, 0.653 at CRLF and 0.650 at CR226. R-squared values are not reported because they generally are not considered an appropriate statistic for evaluating regressions through the origin (Kutner and others, 2004; Eisenhauer, 2003).

Specific Conductance as a Natural Tracer

The community metabolism of a stream, which is a function of photosynthesis and respiration, is a useful index to estimate the available food resources for fish and other aquatic organisms. Stream velocity is a necessary variable for determining community metabolism (Bott, 2006). Operation of Glen Canyon Dam for daily power production typically results in large daily fluctuations in discharge (Topping and others, 2003). These fluctuations in discharge at the dam travel downstream as daily flood or discharge waves (Wiele and Smith, 1996). By conservation of mass, water travels downstream at a slower rate than do discharge waves (Lighthill and Whitman, 1955). Thus, the downstream migration of a parcel of water in the Colorado River through Grand Canyon can be complicated, with each parcel of water released from the dam being involved in multiple discharge waves before it reaches Diamond Creek. Therefore, the velocity of discharge waves can be measured by tracking downstream stage change; measuring the velocity of a parcel of water traveling downstream is more difficult.

Several approaches have been used to determine the velocity of a parcel of water in the Colorado River downstream from Glen Canyon Dam. In 1996, dye was injected into the Colorado River and tracked at several sites from Glen Canyon Dam to Diamond Creek to estimate how water velocity varies with both discharge and reach of the river (Graf, 1995; Graf, 1997). Specific conductance has been used as a natural tracer for calculating the velocity of water in the Colorado River between Glen Canyon Dam and Lees Ferry to estimate river metabolism (Marzolf and others, 1999). The dye approach is expensive and logistically intensive, and it has been used in only a few cases under a limited range of conditions. Additionally, the dye approach is also of limited appeal because it requires injecting an artificial substance into the river, which is controversial in a national park. The specific-conductance approach, in contrast, is cost effective, requires no large campaign of fieldwork, and can be applied to any number of naturally occurring cases under the full range of conditions provided by nature.

Specific conductance also can be used as a tracer below Lees Ferry. Under particular flow conditions, the Paria River and the Little Colorado River both provide pulses of higher specific conductance, which can be traced downstream. One such example occurred during a Paria River flood in January 2005, which had a peak discharge of 79 m^3/s (fig. 10*B*). Specific conductance was not measured during the peak discharge of the flood; although, measurements of 1,900 µS/cm

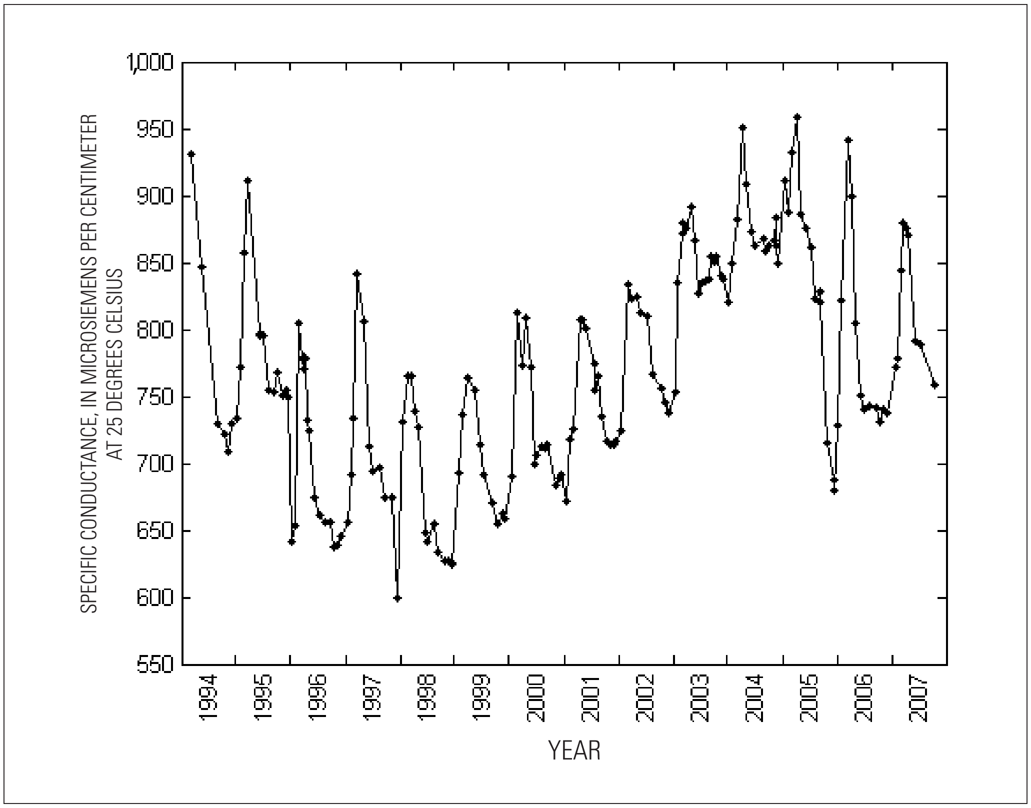

Figure 7. Time-series plot of specific conductance at the penstock depth in the forebay of Lake Powell, Ariz.

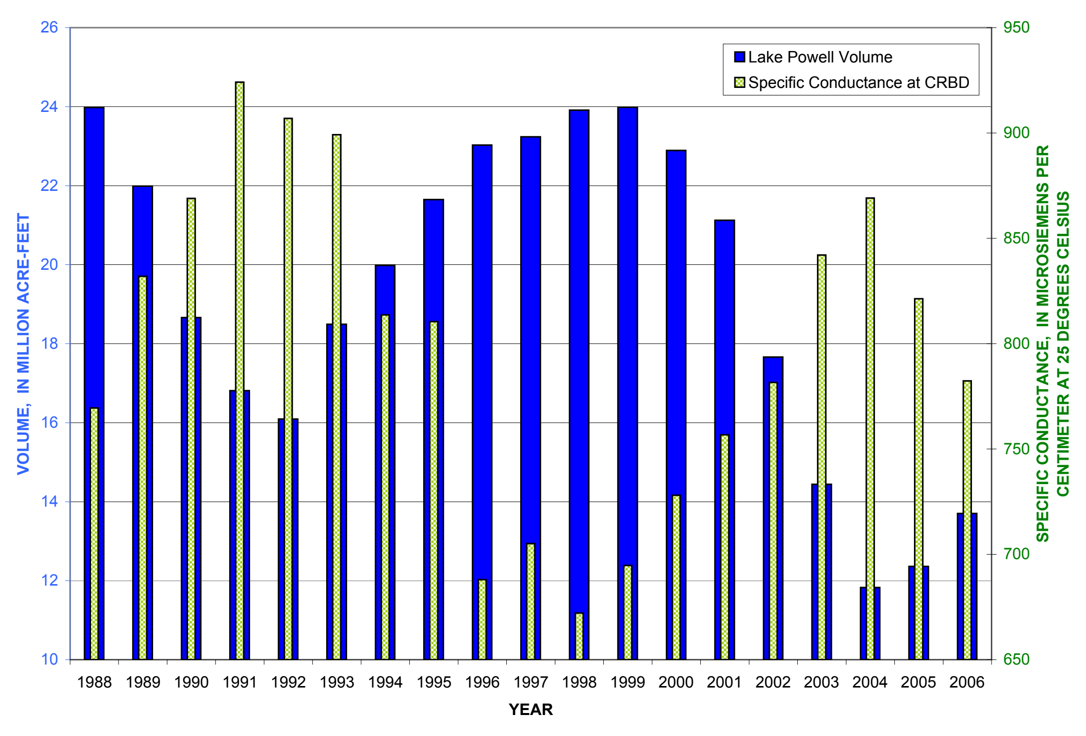

Figure 8. Bar chart showing average annual Lake Powell water volume and average annual specific conductance at Colorado River below Glen Canyon Dam (CRBD) monitoring station, Colorado River, Ariz.

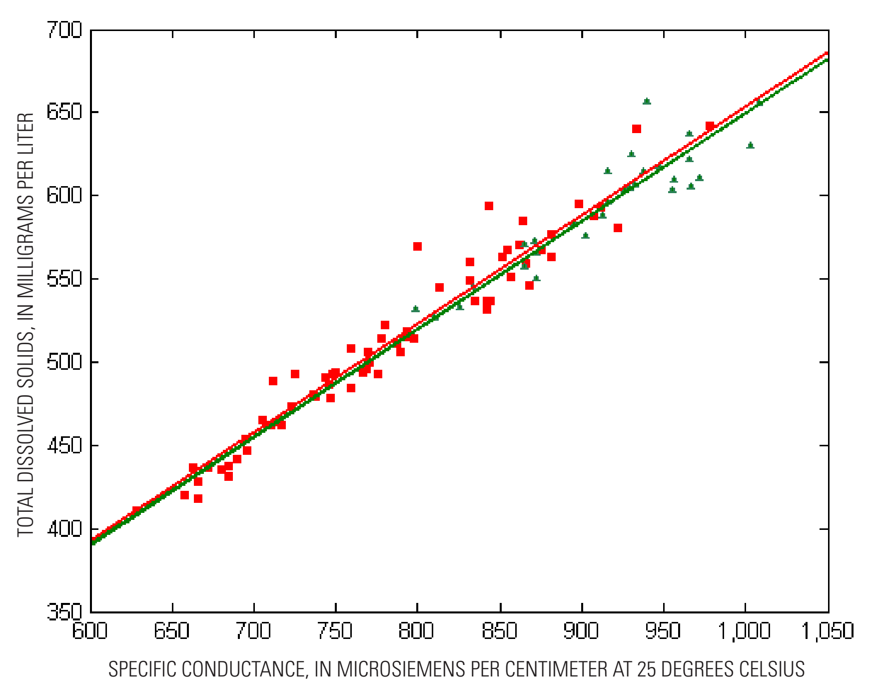

Figure 9. Graph showing relation between total dissolved solids (TDS) and specific conductance of the Colorado River at Lees Ferry, Ariz., (CRLF, station number 09380000) from 1991 to 2006 in red, and of the Colorado River above Diamond Creek, Ariz., (CR226, station number 09404200) from 2002 to 2006 in green. U.S. Geological Survey's Arizona Water Science Center, TDS data; U.S. Geological Survey's Grand Canyon Monitoring and Research Center, specific-conductance data.

were recorded at other times during the flood (U.S. Geological Survey, unpub. data, 2008). Measurements of specific conductance as high as approximately 3,000 µS/cm have been made during other Paria River floods (U.S. Geological Survey, unpub. data, 2008). During the January 2005 flood, the Paria River released a pulse of high-specific-conductance water into the Colorado River below Lees Ferry during the recession and trough of a dam-released discharge wave, when the Colorado River discharge was as low as 159 m^3/s. The specific conductance in the Colorado River at the time of this Paria River flood was 870–900 µS/cm (fig. 10*A*). This mixing of high-specific-conductance Paria River water with relatively low-specific-conductance Colorado River water resulted in a specific-conductance spike, which can be traced downstream through Grand Canyon to the CR226 monitoring station (fig. 10*A*). Because the discharge waves move downstream more quickly than the actual water (Lighthill and Whitman, 1955; Wiele and Smith, 1996; Wiele and Griffin, 1998), the specific-conductance spike, which moves with the water, occurs at different points within different discharge waves at sites downstream from the Paria River. These spikes are indicated by arrows in figures 10*B* and 10*C*.

With respect to specific conductance, the Little Colorado River typically exhibits behavior that is the opposite of that observed in the Paria River. Unlike the Paria River, Little Colorado River water, compared to Colorado River water, has a lower specific conductance during large, long-duration floods and a much higher specific conductance at base flow. In mid-June 2005, the Little Colorado River was at base flow, discharging approximately 6.2 m^3/s, and had an average specific conductance of approximately 4,500 µS/cm (U.S. Geological Survey, unpub. data, 2008). From June 13–19, 2005, the CR061 monitoring station, which is upstream from the Little Colorado River, recorded specific-conductance measurements that were fairly constant (fig. 11*A*). When the high-specific-conductance water from the Little Colorado River mixed with the low-specific-conductance water in the Colorado River, specific conductance in the Colorado River increased. Owing to the effects of dilution, peaks in specific conductance at the mouth of the Little Colorado River occur when the Colorado River discharge is at its lowest, and the specific-conductance troughs occur when Colorado River discharge is highest. As in the Paria flood example, because the discharge waves move more quickly than the water, the specific-conductance signal in the Colorado River lags behind the discharge signal downstream of the Little Colorado River. During the time period shown in figure 11, the specific-conductance peaks occur in the trough of discharge waves at the mouth of the Little Colorado River (not measured), on the rising limb of discharge waves at the CR087 monitoring station, and again near the troughs of discharge waves at the CR226 monitoring station. Thus, the discharge waves travel faster and overtake each parcel of high-specific-conductance water produced in the trough of the Colorado River discharge waves at the mouth of the Little Colorado River. As the specific-conductance spikes move downstream, their amplitudes do

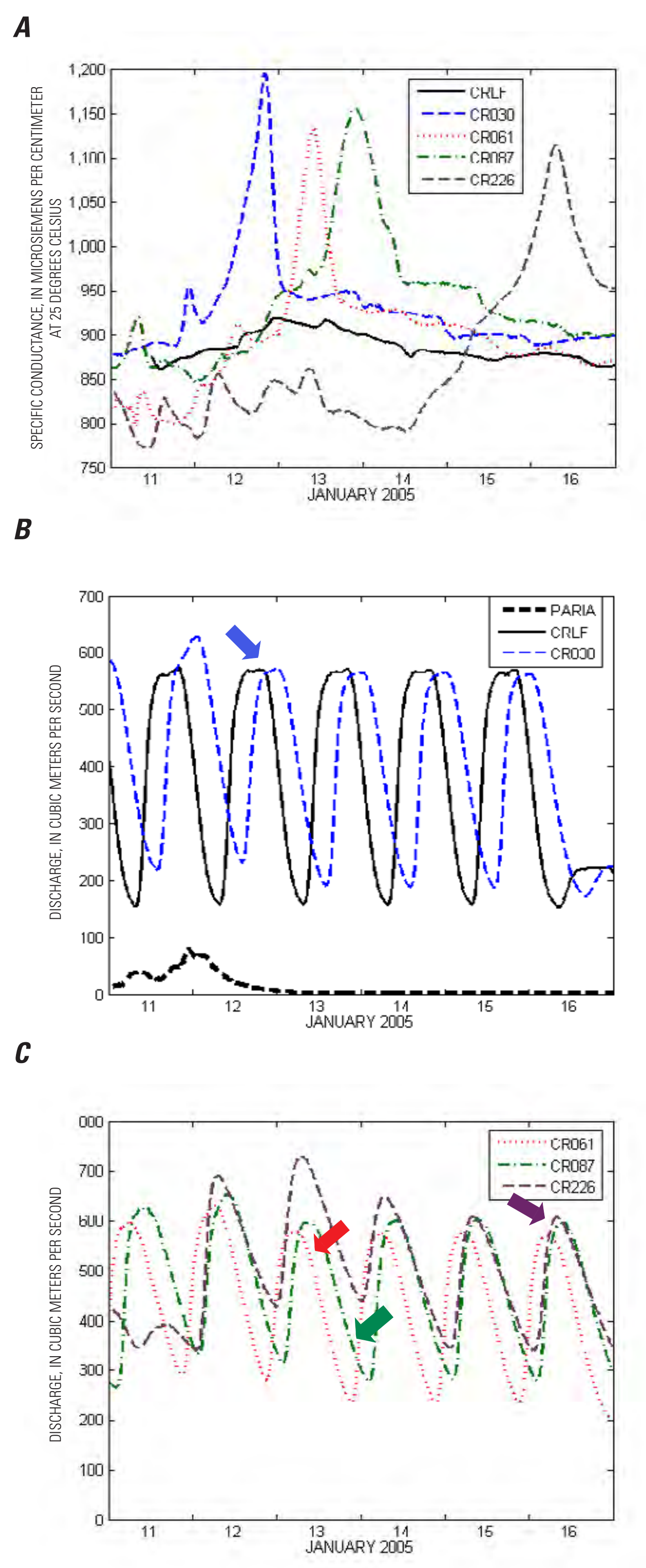

Figure 10. Graphs showing *A*, specific conductance and, *B* and *C*, discharge at five of the monitoring stations on the Colorado River (including discharge of the Paria River), Ariz., from January 11 to 16, 2005. (Refer to table 1 for station names.)

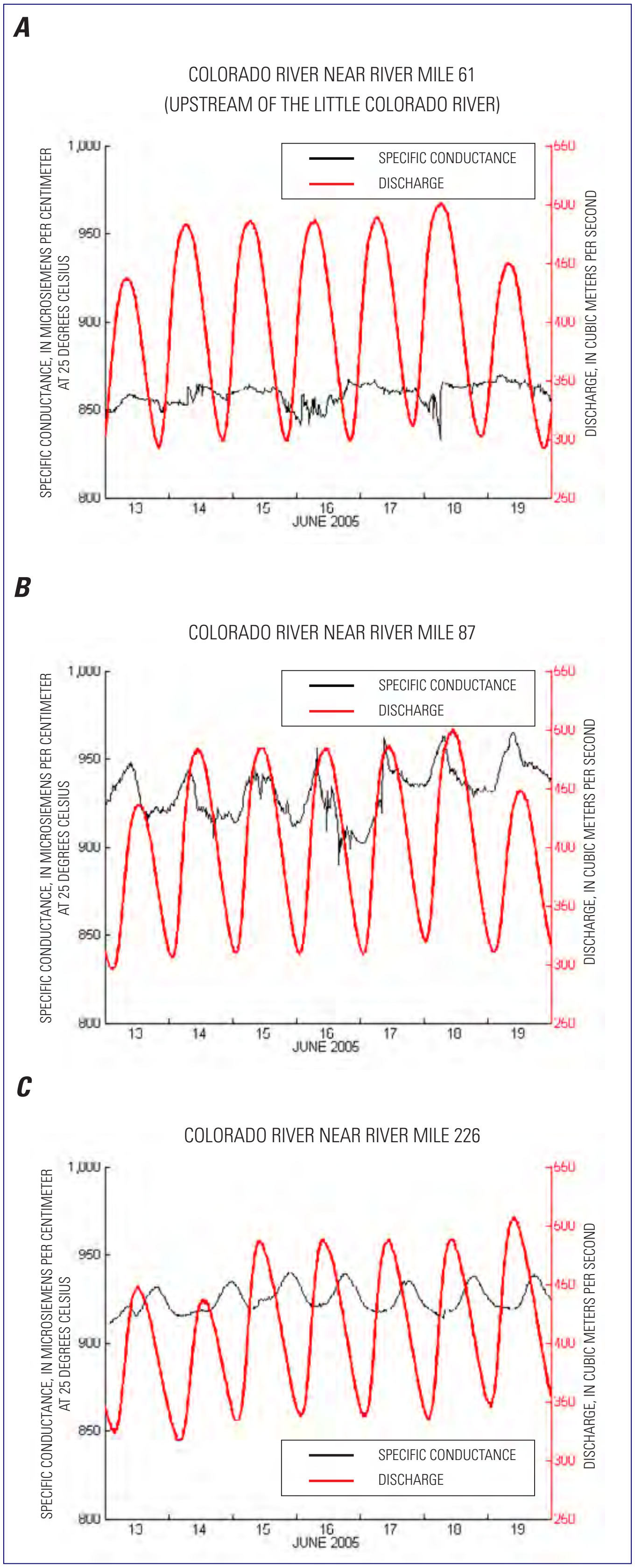

Figure 11. Graphs showing specific conductance and discharge at three of the monitoring stations on the Colorado River from June 13 to 19, 2005.

not change greatly, regardless of whether they are involved in the peak or the trough of a discharge wave. This is largely because, as a discharge wave overtakes a parcel of high-specific-conductance water, the streamwise extent of this water is shortened slightly, and, as a discharge wave outruns a parcel of high-specific-conductance water, the streamwise extent of this water is lengthened slightly. By conservation of mass (Lighthill and Whitman, 1955), this high-specific-conductance water is thus effectively “compressed” in streamwise extent under the peaks of the discharge waves and “expands” in streamwise extent under the troughs of the discharge waves (Since water is an incompressible fluid, it is not actually compressed; the streamwise distance occupied by the high-specific-conductance water is lessened.).

Data Availability

The specific-conductance records described in this report are available as downloadable spreadsheet files (http://pubs.usgs.gov/ds/364/); the data are organized by monitoring station and named by site identifier (see table 1, this report).

Acknowledgments

Many people were involved in the collection of the data presented in this report. The GCMRC’s William Vernieu and Susan Hueftle established the sites and helped maintain the instruments. William Vernieu also is responsible for creating the database. Jeanne Korn (GCMRC) and Jesse Granet (National Park Service, Glen Canyon National Recreation Area) helped maintain the instruments. Tim Andrews (GCMRC contractor), Glen Bennett (GCMRC), and Susan Hueftle were responsible for establishing real-time communication systems at four of the study sites. I would also like to extend my thanks to the technical boatmen who assisted in the data-collection efforts, in particular, Stuart Reeder, Steve Jones, Jimmy Grissom, Mark Franke, J.P. Running, Pete Weiss, and Brian Dierker. Special thanks go to the those USGS staff members who provided many kinds of invaluable assistance: Ron Griffiths, Tom Sabol, Bob Tusso, Amy Draut, Carol Fritzinger, Elizabeth Fuller, Ted Kennedy, Scott Wright, David Topping, Nancy Hornewer, Jim Parent, and many others. Thanks to William Vernieu for providing helpful editorial comments and sharing ideas for interpreting the data and David Topping for providing helpful suggestions and editorial comments.

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