Trend Analysis of Selected Water-Quality Data Associated With Salinity-Control Projects in the Grand Valley, in the Lower Gunnison River Basin, and at Meeker Dome, Western Colorado

by David L. Butler

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
acre	4,4047	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
ton	0.9072	metric ton
ton per day (ton/d)	0.9072	metric ton per day
ton per year (ton/yr)	0.9072	metric ton per year

The following term and abbreviation also is used in this report:

milligram per liter per year [(mg/L)/yr]

Trend Analysis of Selected Water-Quality Data Associated With Salinity-Control Projects in the Grand Valley, in the Lower Gunnison River Basin, and at Meeker Dome, Western Colorado

By David L. Butler

Abstract

To decrease salt loading to the Colorado River from irrigated agriculture, salinity-control projects have been under construction since 1979 by the Bureau of Reclamation and the U.S. Department of Agriculture in the Grand Valley and since 1988 in the lower Gunnison River Basin of western Colorado. In 1980, a salinity-control project was initiated at Meeker Dome, which involved plugging three abandoned oil wells that were discharging saline water to the White River. Trend analysis was used to determine if the salinity-control projects had affected salinity in the Colorado and White Rivers.

The mean annual dissolved-solids load in the Colorado River near the Colorado-Utah State line for water years 1970–93 was about 3.32 million tons. About 46 percent of that load was from the Colorado River upstream from the Grand Valley and about 38 percent was from the Gunnison River. About 16 percent of the dissolved-solids load in the Colorado River near the State line was discharged from the Grand Valley, and most of the Grand Valley dissolved-solids load was from irrigation-induced sources.

Monotonic trend analysis of dissolved-solids and major-ion data for the Colorado and Gunnison Rivers was used for determining if salinity-control projects had affected salinity (dissolved solids) in the Colorado River. Data collected in water years 1970–93 at gaging stations on the Colorado River—one near Cameo and the other near the Colorado-Utah State line, and at the station on the Gunnison River near Grand Junction—were analyzed for trends. A computerized procedure developed by the U.S. Geological Survey that uses the nonparametric seasonal Kendall test with adjustment for streamflow was used for trend analysis of periodic and monthly data, and linear regression was used for trend analysis of annual data. Three time periods were tested, including periods that were concurrent with work on salinity-control projects. Many of the trends in unadjusted concentration and load data were not statistically significant. There were downward trends in flow-adjusted dissolved-solids and major-ion concentrations and in monthly dissolved-solids loads for all three stations in the 1970's, prior to the salinity-control projects. The two stations on the Colorado River also had significant downward trends in flow-adjusted concentrations and loads for water years 1986–93. The cumulative effects of salinity-control projects in the Grand Valley and in the lower Gunnison River Basin on salinity in the Colorado River would have become more substantial after the mid-1980's. Part of the decrease in dissolved solids in the Colorado River near the State line probably was related to salinity-control projects; however, there apparently are other factors that are affecting dissolved solids in the upper Colorado River in addition to salinity-control projects.

A significant decrease in chloride and sodium concentrations in the White River downstream from Meeker Dome indicated that the well plugging in 1981 was successful in stopping much of the discharge of saline water from the wells. Chloride and sodium concentrations have not changed in the White River at Meeker or downstream from Meeker during water years 1982–95, indicating that the well plugging has remained intact.

INTRODUCTION

The Colorado River is used for municipal and industrial water for more than 18 million people in seven Western States and provides irrigation water for about 1.7 million acres of land (U.S. Department of the Interior, 1993). Because of these uses of water, dissolved solids, or salinity, has increased in the Colorado River. The terms "salinity" and "dissolved-solids concentration" often are considered synonymous, and in other reports on the Colorado River Basin, the term "dissolved solids" often is referred to as salinity. Dissolved solids can have adverse effects on crops and on municipal and industrial users, especially in the lower part of the basin. In response to the Federal Water Pollution Control Act of 1972 (Public Law 92–500), the seven States in the Colorado River Basin adopted numeric dissolved-solids criteria for the lower Colorado River. The States suggested that the Bureau of Reclamation (BOR) plan and implement a program to maintain dissolved-solids concentrations at or below existing levels to allow upper basin States to develop their water. Also, dissolved solids in the Colorado River were a factor in relations between the United States and Mexico. To meet treaty obligations with Mexico and to decrease salinity effects in the Colorado River Basin, the U.S. Congress passed the Colorado River Basin Salinity Control Act (Public Law 93–320) in 1974. The act authorized construction of 4 salinity-control projects and the planning of 12 other projects in the Colorado River Basin by the U.S. Department of the Interior (DOI). One of the authorized construction projects was the Grand Valley Unit, which concerned irrigation in the Grand Valley in western Colorado (fig. 1). The Lower Gunnison Basin Unit, which concerned irrigation in the Uncompahgre Project and other areas in the lower Gunnison River Basin (fig. 1), and the Meeker Dome Unit, which concerned dissolved-solids discharge into the White River (fig. 2) from abandoned oil wells, were authorized for planning under the Salinity Control Act of 1974.

The Salinity Control Act of 1974 directed the Secretary of the Interior to cooperate with the Secretary of Agriculture in implementing on-farm improvements as part of salinity control. In 1984, an amendment (Public Law 98–569) to the Salinity Control Act was signed that provided a separate authority for implementation of salinity-control projects in the Colorado River Basin by the U.S. Department of Agriculture (USDA). The USDA has done salinity-control work in the Grand Valley and Lower Gunnison Basin Units. Therefore, the salinity programs in these two areas have consisted of two parts: (1) The BOR has directed improvement of the water-distribution systems; and (2) the USDA has been responsible for the on-farm improvements.

In a review of the Salinity Control Program in 1993, the DOI was concerned that the effects of the salinity-control projects on dissolved solids in the Colorado River Basin had not been adequately determined or documented. To address concerns raised by the DOI, the BOR submitted a study plan to determine effects of the salinity-control projects in the Grand Valley and in the lower Gunnison River Basin on dissolved solids in the Colorado River.

Work on the Meeker Dome Unit was completed in 1981, and initial analyses of the effects of the project (CH2M Hill, 1982; Bureau of Reclamation, 1985b) indicated that the project had decreased dissolved-solids loading to the White River. The salinity-control work at Meeker Dome needed to be evaluated to verify the initial conclusions and to determine if salinity control had remained effective since 1984.

In 1994, the BOR requested the U.S. Geological Survey (USGS) to examine trends in dissolved-solids data for the Colorado and Gunnison Rivers to address concerns raised by the DOI. The BOR also requested the USGS to examine chloride and sodium data for the White River to verify the effectiveness of the salinity-control project at Meeker Dome.

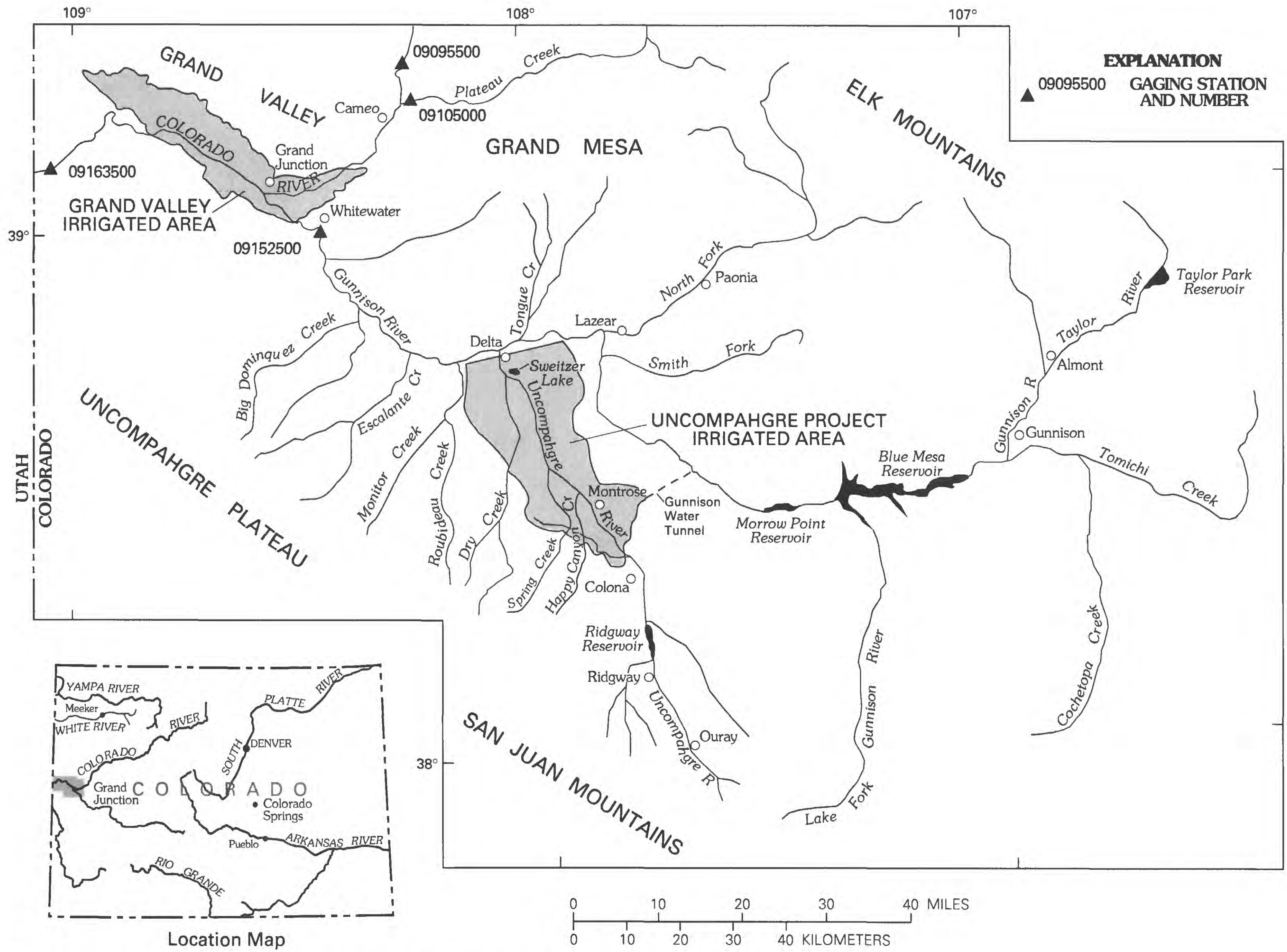

Figure 1. Location of the Grand Valley, the Gunnison River Basin, and selected gaging stations.

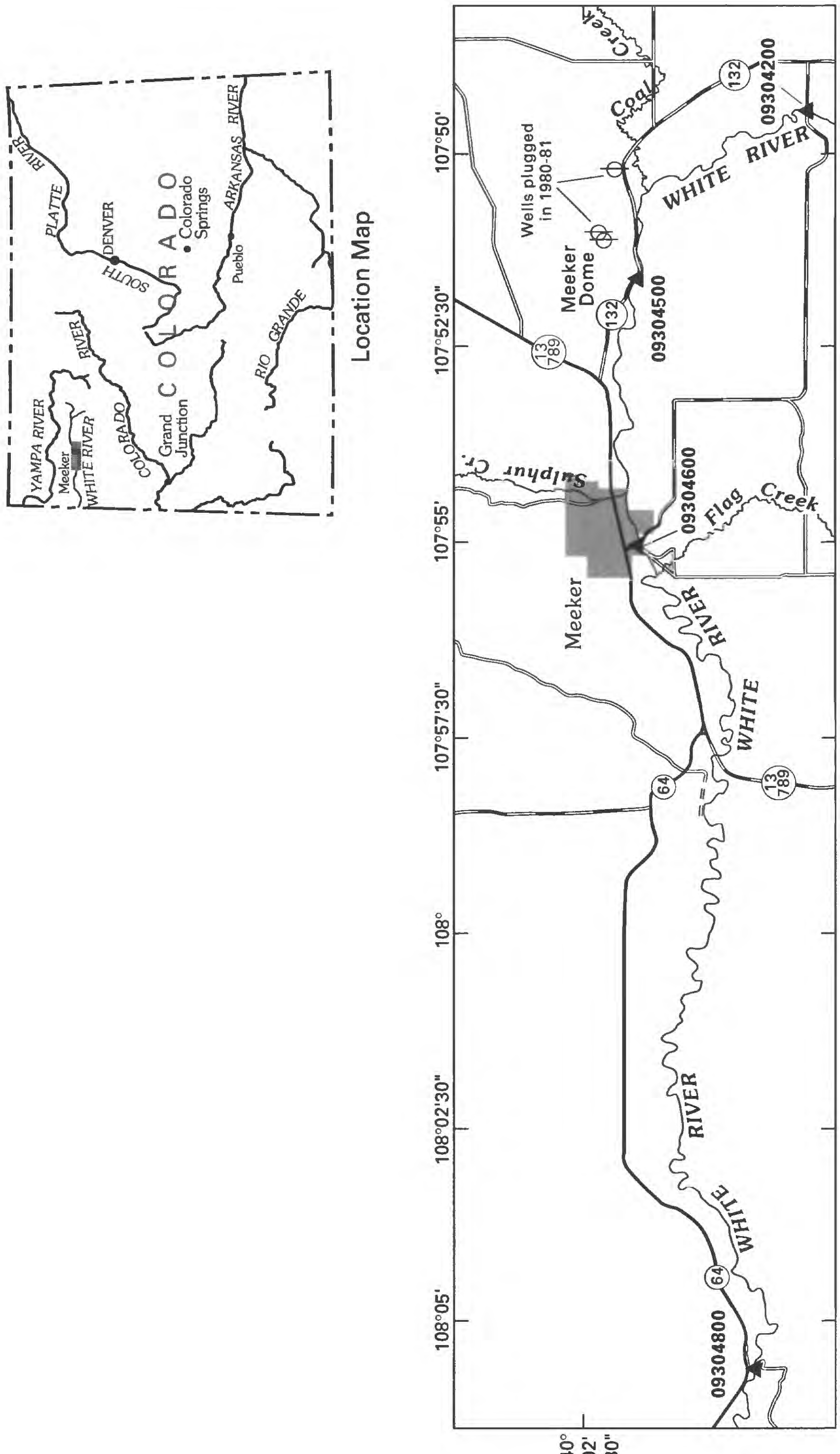

Figure 2. Location of the White River Basin and selected gaging stations in the vicinity of Meeker Dome.

Purpose and Scope

This report presents trend results for several water-quality variables for the Colorado, Gunnison, and White Rivers and relates these trends to salinity-control projects in the Grand Valley, in lower Gunnison River Basin, and at Meeker Dome in the White River Basin. The specific objectives are to:

1. Estimate dissolved-solids loads for inflow and outflow stations for the Grand Valley Unit, which includes the outflow site for the Lower Gunnison Basin Unit.
2. Determine trends in dissolved-solids concentrations and loads and selected major-ion concentrations for inflow and outflow stations for the Grand Valley Unit.
3. Determine if significant water-quality trends in the Colorado River are related to salinity-control projects.
4. Determine trends in chloride and sodium concentrations in the White River upstream and downstream from Meeker Dome.
5. Verify that the Meeker Dome Unit salinity-control project has remained effective since 1984.

Monthly and annual dissolved-solids loads were computed for water years 1970–93 for the four USGS gaging stations shown in figure 1. The annual dissolved-solids load from the Grand Valley area also was computed. In the remainder of the report, data analysis is presented by water year unless otherwise noted. Dissolved-solids loads at stations 09095500, 09105000, and 09152500 are the inflow loads into the Grand Valley Unit, and the dissolved-solids load at station 09163500 is the outflow load from the Grand Valley Unit. The station on the Gunnison River (09152500) also represents outflow from the Gunnison River Basin and is downstream from the Lower Gunnison Basin Unit. Monotonic trend analyses were done on periodic dissolved-solids, calcium, magnesium, sodium, and sulfate concentrations and on monthly, annual, and seasonal dissolved-solids loads for the two stations on the Colorado River (stations 09095500 and 09163500) and the station on the Gunnison River (station 09152500) (fig. 1). Trend analysis was done for three time periods: 1970–93, 1980–93, and 1986–93. The trend results were used with a graphical technique to determine if the trends in concentrations or loads could be related to the salinity-control projects.

Chloride and sodium data collected at three USGS gaging stations on the White River (fig. 2) from 1973 to early 1995 were analyzed to verify the effectiveness of the salinity-control project at Meeker Dome. Chloride and sodium concentrations were examined for the White River because those constituents were most affected by the salinity-control work at Meeker Dome.

DESCRIPTION OF SALINITY-CONTROL PROJECTS

Grand Valley Unit

The Grand Valley Unit is the irrigated area in the Grand Valley shown in figure 1. There are about 70,000 acres of irrigated land in the Grand Valley that contributed an estimated 580,000 tons/yr of salt to the Colorado River through deep percolation of water from canals, laterals, and on-farm irrigation (Bureau of Reclamation, 1983, 1985a). The salt load from the Grand Valley was about 7 percent of the salt load in the Colorado River at Imperial Dam, near Yuma, Arizona (U.S. Department of the Interior, 1993). In the Grand Valley, the salinity-control program consisted of two parts. In the first part, the BOR lined canals and placed laterals in pipes to decrease leakage from the water-distribution system. In the second part, the National Resources Conservation Service (formerly the Soil Conservation Service) initiated the USDA on-farm improvements, which involved upgrading farm irrigation systems and improving irrigation management. The USDA on-farm improvements included activities such as replacing ditches with underground pipelines or lining the ditches with concrete, land leveling, and installation of more efficient irrigation systems such as drip irrigation or surge irrigation systems.

The BOR salinity-control program has been done in stages. Stage I involved lining 7 mi of canal and placing 34 mi of laterals in underground pipe during 1980–82 in the west end of the Grand Valley. Post construction monitoring indicated that Stage I had decreased annual dissolved-solids loading to the Colorado River by 19,900 tons (Bureau of Reclamation, 1985a, 1986). Construction on

Stage II, which began in 1986, involved lining about 40 mi of canals and replacing about 320 mi of laterals with underground pipeline. When Stage II is completed, the estimated decrease in salt load to the Colorado River would be 151,000 tons/yr (Bureau of Reclamation, 1985a, 1986). By early 1994, about two-thirds of Stage II was completed.

The USDA on-farm salinity-control program was started in 1979 in the Grand Valley and has continued through 1994. Once completed, the estimated decrease in dissolved-solids loading attributed to the on-farm improvements would be 132,000 tons/yr for the Grand Valley Unit (Hedlund, 1994). Approximately 50 percent of the USDA salinity program in the Grand Valley was completed by early 1994 (Emory Johnson, Natural Resources Conservation Service, oral commun., 1994).

Lower Gunnison Basin Unit

The Lower Gunnison Basin Unit consists of the Gunnsion River Basin downstream from Blue Mesa Reservoir, including the North Fork Basin (fig. 1). The primary irrigation project in this area is the Uncompahgre Project (fig. 1), which supplies water for irrigation of about 86,000 acres. The BOR salinity program in the Lower Gunnison Basin Unit was focused only on the Uncompahgre Project. The BOR (1982, 1984) estimated that about 360,000 tons/yr of salt came from irrigation-induced sources in the Uncompahgre Project. The estimated annual dissolved-solids loading from the entire Lower Gunnison Basin Unit was about 640,000 tons (Bureau of Reclamation, 1984). The BOR's Winter Water Replacement Program was designed to replace the practice of using winter flows in canals and laterals for livestock watering by expanding the existing rural domestic water systems in the Uncompahgre Project (Bureau of Reclamation, 1987). The replacement program was estimated to decrease the annual dissolved-solids loading from this area by 74,000 tons. Construction of the Winter Water Replacement Program began in 1990 and, by late 1994, was about 95 percent completed (D.W. Crabtree, Bureau of Reclamation, oral commun., 1994).

Another salinity-control feature planned for the Lower Gunnison Basin Unit is the East Side Lateral Program, which is planned to replace about 188 mi of laterals and 7 mi of small canals on the east side of the Uncompahgre Project with underground pipeline (Bureau of Reclamation, 1994). That program would decrease dissolved-solids loading from the Uncompahgre Project by about 64,000 tons/yr. The East Side Lateral Program was scheduled to begin in 1995, but presently (1995) has been deferred (U.S. Department of the Interior, 1995).

The total irrigated area in the Lower Gunnison Basin Unit that was studied by the USDA for their salinity-control work is 171,000 acres, which includes the Uncompahgre Project. Once completed, the USDA on-farm improvements were estimated to decrease dissolved-solids loading from the Lower Gunnison Basin Unit by about 166,000 tons/yr (Hedlund, 1994). The USDA on-farm improvements were initiated in 1988 in the Lower Gunnison Basin Unit.

Meeker Dome Unit

Meeker Dome is a local uplift located east of Meeker in the White River Basin (fig. 2). The White River is a tributary of the Green River, which is tributary to the Colorado River. The Meeker Dome Unit was a BOR project that consisted of plugging three abandoned oil wells drilled in Meeker Dome. The wells provided conduits for the vertical movement of saline, deep ground water into shallow aquifers, which then discharged into the White River (CH2M Hill, 1979, 1982). The purpose of the well plugging was to decrease discharge of the saline ground water into the White River. One well was plugged in December 1980; the other two wells were plugged by June 1981. A post-project study by CH2M Hill (1982) reported significant decreases in chloride loading with measurable decreases in dissolved-solids loading from Meeker Dome. Also, seeps and springs dried up, and water levels in observation wells decreased after the wells were plugged. Detailed monitoring activities ended in 1984 and, in a concluding study, the BOR (1985b) estimated that about 19,000 tons/yr of salt was removed from the White River by the Meeker Dome Unit well plugging. The saline ground water had high chloride and sodium concentrations; the BOR (1985b) reported marked decreases in concentrations of those constituents in the river after the well plugging.

DISSOLVED-SOLIDS LOADS IN THE COLORADO AND GUNNISON RIVERS

Monthly and annual dissolved-solids loads were computed for the four gaging stations in the Grand Valley area (fig. 1) for water years 1970–93. Loads were computed for two stations (09095500 and 09163500) on the Colorado River, one station (09152500) on the Gunnison River, and one station (09105000) on Plateau Creek (fig. 1). Stream discharge in the Gunnison River has been highly regulated since 1965 after completion of the Aspinall Unit (Blue Mesa and Morrow Point Reservoirs in fig. 1), and most of the major water-storage projects in the Colorado River Basin upstream from Cameo were completed prior to 1965 (Liebermann and others, 1988). Major changes in the flow regime of a river can cause trends in water-quality concentrations that might not be related to other anthropogenic effects, such as salinity-control projects. To avoid the possible effects of water-storage projects, the trend analysis of salinity data was limited to periods after 1965. The first water year after 1965 that had concurrent data for all dissolved-solids and major-ion constituents that were used in the trend analysis was 1970; therefore, dissolved-solids loads were computed for water years 1970–93.

The monthly and annual dissolved-solids loads were computed for use in trend analysis. Also, the dissolved-solids loads for the four gaging stations were used to estimate the dissolved-solids load from the Grand Valley. Trend tests also were done on the annual Grand Valley dissolved-solids load.

Method of Computation

A computer program called SLOAD (Liebermann and others, 1987) was used to estimate dissolved-solids loads. The program uses the daily stream-discharge record and periodic water-quality samples to estimate loads. If available, the program can incorporate daily specific conductance into the load determinations, which often improves the estimate of dissolved-solids load. The program is written in Statistical Analysis System (SAS) language (SAS Institute, 1982).

Regression relations are computed by SLOAD using periodic, instantaneous data that relate dissolved-solids loads as a function of stream discharge or of stream discharge and specific conductance. Equations are of the form:

$$\ln(dsload) = a + b[\ln(Q)] \qquad (1)$$

where

- ln = natural logarithm;
- dsload = dissolved-solids load, in tons;
- a and b = regression coefficients; and
- Q = stream discharge, in cubic feet per second;

or

$$\ln(dsload) = c + d[\ln(Q)] + e[\ln(SC)] \qquad (2)$$

where

- c, d, and e = regression coefficients; and
- SC = specific conductance, in microsiemens per centimeter at 25 degrees Celsius.

Liebermann and others (1987) used a logarithmic transformation of the data to approximate normal distributions. SLOAD computes 3-year moving regressions for each regression relation. The 3-year moving regression method does not remove existing time trends (Kircher and others, 1984; Liebermann and others, 1987). Once regression coefficients are computed, the program computes daily dissolved-solids loads from equation 1 using daily mean stream discharge. If daily mean specific conductance also is available, then equation 2 is used. An assumption for use of this method of computing daily loads is that the regression coefficients derived from periodic, instantaneous data are applicable to the daily mean values (Liebermann and others, 1987). The daily loads are summed by month to compute monthly loads, which then are summed to compute annual loads (either by water year or calendar year).

The SLOAD program was used to compute dissolved-solids loads for stations 09095500, 09152500, and 09163500. For station 09105000, Plateau Creek near Cameo (fig. 1), there were only sufficient data to use SLOAD for 1970–79. For 1980–93, monthly loads for Plateau Creek were estimated from regression relations with the monthly load at station 09095500.

Annual Dissolved-Solids Loads

The annual dissolved-solids loads for water years 1970–93 for the four gaging stations in the Grand Valley area are listed in table 1. Also included in table 1 are the mean, standard deviation, and 95-percent confidence interval of the mean for the annual loads. If the population is normally distributed, the true population mean will be within the 95-percent confidence interval on average 95 percent of the time (Helsel and Hirsch, 1992).

Based on the mean annual loads for 1970–93 in table 1, about 46 percent of the dissolved-solids load of about 3.32 million tons in the Colorado River near the State line (station 09163500) was in the Colorado River upstream from the Grand Valley (stations 09095500 plus 09105000), 38 percent came from the Gunnison River (station 09152500), and 16 percent was from the Grand Valley. Considerable variation in annual loads between years is evident for each station. Some of the variability is related to streamflow, because years with the largest dissolved-

Table 1. Annual dissolved-solids loads for four gaging stations in the Grand Valley area and the annual Grand Valley dissolved-solids load, water years 1970–93

[Annual loads in tons; upper and lower 95-percent confidence intervals (95% CI) are the upper and lower 95% CI of the mean]

Water year	Station 09095500	Station 09105000	Station 09152500	Station 09163500	Grand Valley dissolved-solids load
1970	1,587,000	68,100	1,579,000	3,772,000	538,000
1971	1,616,000	65,100	1,391,000	3,635,000	563,000
1972	1,454,000	53,100	1,052,000	3,473,000	914,000
1973	1,518,000	71,600	1,323,000	3,711,000	798,000
1974	1,473,000	54,800	1,435,000	3,536,000	573,000
1975	1,529,000	58,300	1,330,000	3,284,000	367,000
1976	1,404,000	46,700	1,294,000	3,010,000	265,000
1977	1,183,000	22,800	955,000	2,343,000	182,000
1978	1,364,000	48,000	1,026,000	2,964,000	526,000
1979	1,509,000	79,200	1,446,000	3,450,000	416,000
1980	1,523,000	60,500	1,225,000	3,195,000	387,000
1981	1,157,000	44,700	877,000	2,729,000	650,000
1982	1,279,000	49,700	1,225,000	3,103,000	549,000
1983	1,779,000	68,900	1,558,000	4,014,000	608,000
1984	2,053,000	81,800	1,758,000	4,577,000	684,000
1985	2,014,000	81,700	1,489,000	4,258,000	673,000
1986	2,004,000	79,100	1,464,000	4,204,000	657,000
1987	1,534,000	59,900	1,534,000	3,594,000	466,000
1988	1,352,000	52,900	1,043,000	2,918,000	470,000
1989	1,232,000	48,100	880,000	2,768,000	608,000
1990	1,101,000	42,300	857,000	2,317,000	317,000
1991	1,218,000	47,400	1,064,000	2,718,000	389,000
1992	1,185,000	46,000	1,160,000	2,780,000	389,000
1993	1,501,000	60,000	1,402,000	3,407,000	444,000
Annual mean	1,482,000	57,900	1,265,000	3,323,000	518,000
Standard deviation	268,000	14,500	252,000	592,000	169,000
Upper 95% CI	1,589,000	63,700	1,366,000	3,560,000	586,000
Lower 95% CI	1,375,000	52,100	1,164,000	3,086,000	450,000

solids loads generally occurred in years of largest annual mean stream discharge (fig. 3). However, not all differences in dissolved-solids loads are directly dependent on streamflow. The loads do not increase or decrease in a 1:1 linear relation with changes in stream discharge. For example, compare the annual loads and annual mean stream discharge for station 09163500 for 1981 and 1984 (table 1 and fig. 3). In 1984, the stream discharge was about 3.5 times greater than in 1981, but the dissolved-solids load was about 1.7 times greater than in 1981. High-flow years on the upper Colorado River are characterized by larger than average snowpack and spring runoff, which have low dissolved-solids concentrations. Consequently, the increase in dissolved-solids load will not be proportional to the increase in stream discharge for high-flow years.

Some of the variability in annual dissolved-solids loads (table 1) probably is related to errors associated with the computational method. The regression coefficients used in equations 1 and 2 were derived from relations of instantaneous loads to instantaneous stream discharge and specific conductance. It is assumed these relations also represent mean daily loads. Outliers can have undue influence on regression relations. The SLOAD program has an input-checking routine to flag dissolved-solids, specific-conductance, and stream-discharge data for outliers. Highly suspect data were deleted prior to computation of regression coefficients.

Because specific conductance has a high correlation to dissolved-solids concentration in most natural water, the standard error of estimate using equation 2 usually would be less than the standard error of estimate associated with equation 1, which is based only on streamflow. The standard error of estimate associated with each regression relation for each station can be expressed as a percentage for regressions done with logarithm data. For station 09095500, the standard errors of estimate for the 3-year moving regressions generally were between 4 and 10 percent, with errors for equation 2 slightly less than for equation 1. For station 09152500, the standard errors of estimate for regressions based on equation 1 were much higher (17–30 percent) than the errors for the regressions based on equation 2, which were between about 3 and 7 percent. For station 09163500, the standard errors of estimate ranged from 3 to 9 percent for regressions based on equation 2 compared to errors of 11 to 22 percent for regressions based on equation 1. Because the completeness of the daily specific-conductance record varied from year to year for each station, the number of days in which the dissolved-solids load was calculated using equation 2 also varied among stations and years. There might be less uncertainty in annual dissolved-solids loads for years with more complete daily specific-conductance records than in annual loads for years with less complete specific-conductance records.

The annual Grand Valley dissolved-solids load also is included in table 1, and that load is the difference between the annual dissolved-solids load at station 09163500 and the annual loads for the other three stations. The BOR (1983) reported the annual mean Grand Valley dissolved-solids load (called the Grand Valley salt pickup in that report) as 580,000 tons for 1952–80, compared to 518,000 tons for 1970–93 as listed in table 1. According to the BOR (1986), at least 95 percent of the dissolved-solids load was from shallow ground-water sources in the Grand Valley, and a large percentage of the ground water was recharged by irrigation. The annual Grand Valley dissolved-solids load ranged from 182,000 to 914,000 tons (table 1). It seems unlikely that the dissolved-solids loads from the Grand Valley would vary by such a large amount from year to year because the irrigated acreage and amount of water diverted for irrigation did not change substantially on a year-to-year basis. There has been some decrease in irrigated acreage in the Grand Valley from the development of agricultural land for commercial and residential purposes.

The magnitude of the Grand Valley dissolved-solids load is affected by errors in the dissolved-solids-load calculations for the four gaging stations. These errors probably vary from year to year, depending on errors associated with the water-quality, streamflow, and daily specific-conductance data and on errors in the regression equations. There also are year-to-year variations in precipitation runoff, cropping patterns, irrigation practices, and land use that could cause relatively small changes in the dissolved-solids load from irrigated areas in the Grand Valley. Another factor that could have an effect on the dissolved-solids load to the Colorado River was the salinity-control projects.

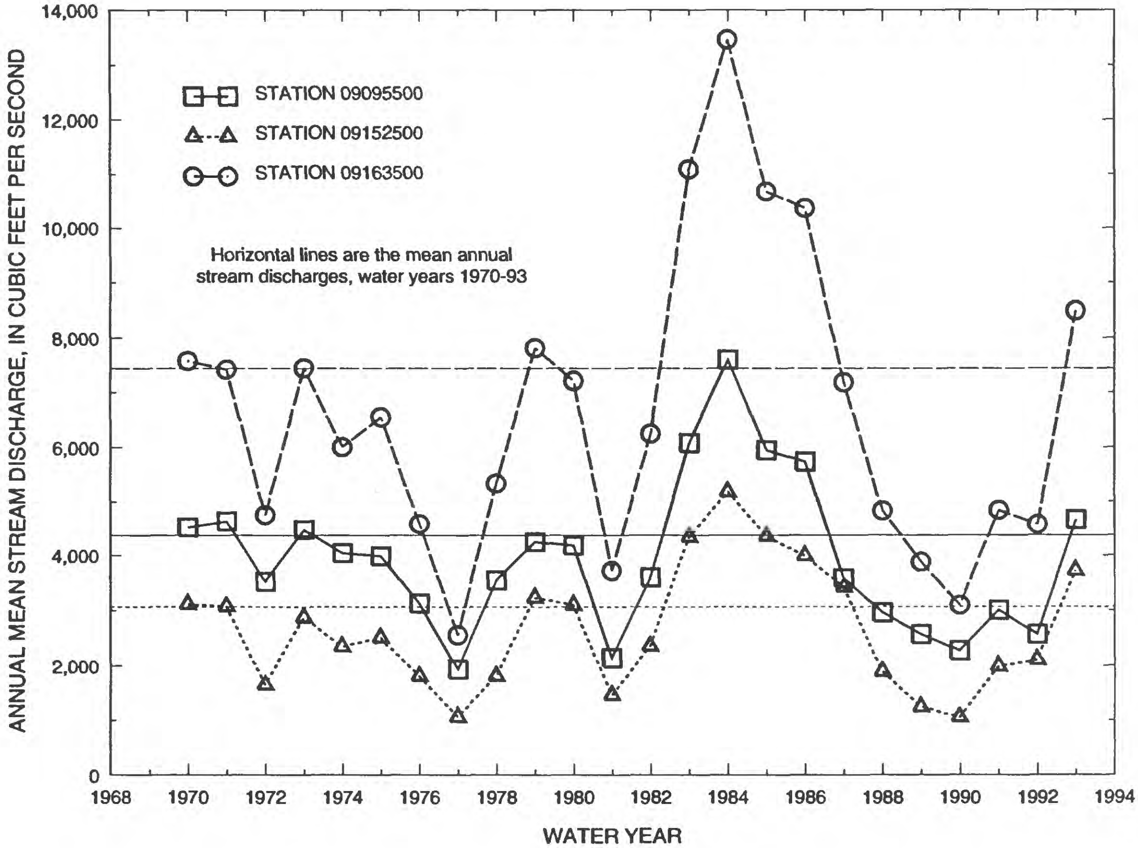

Figure 3. Annual mean stream discharge for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93.

METHODS OF TREND ANALYSIS

Trend analysis can be used to determine if stream-water quality has changed over time. Two general types of trend tests, monotonic and step-trend tests, were used to examine dissolved-solids and major constituent data associated with the salinity-control projects. A monotonic trend means that the water-quality variable of interest has changed over time. A monotonic trend test will not specify if the change occurred continuously, linearly, or in abrupt or discrete steps (Hirsch and others, 1991). Step-trend tests are used instead of monotonic tests where a known event or change occurred at a specific time in a watershed that could have significantly altered constituent concentrations or loads. In such cases, the data can be divided into "before" and "after" periods relative to the known event. An example of such a known event is the well plugging for the Meeker Dome Unit. Another case for use of step-trend tests is when the water-quality record is broken by a relatively long time gap. Conversely, step-trend tests would not be used if water-quality changes were incremental over a rather long time period. For a long-term effect, such as the salinity-control projects in the Grand Valley and lower Gunnison River Basin, monotonic trend tests are more appropriate for trend analysis.

Monotonic Trend Analysis Using the Seasonal Kendall Test

Monotonic trends on periodic concentration data and monthly dissolved-solids loads were examined using a computerized procedure developed by the USGS called EStimate TREND (ESTREND) (Schertz and others, 1991). The program is designed to investigate trends in water-quality data that often have non-normal distributions, seasonality, outliers, missing data, or have censored data (values reported as less than). The program is written in FORTRAN language for the USGS Prime minicomputer system (Schertz and others, 1991).

A nonparametric test called the seasonal Kendall test is used in ESTREND. The null hypothesis for the test is that there is no trend. Nonparametric methods often are used for trend tests on water-quality data because the data often do not meet assumptions required for parametric methods. To appropriately use parametric methods for multiple station tests with several variables, every data set for every station would need to be tested for violation of the assumptions of the test. Compared to parametric tests, nonparametric procedures had small disadvantages where the data were normally distributed, but can have major advantages where data distributions depart from normality (Hirsch and others, 1991). Further discussion about parametric and nonparametric statistical methods are in Iman and Conover (1983), Hirsch and others (1991), and Helsel and Hirsch (1992).

Differences in water-quality data between seasons of the year can be a source of variability that can prevent or complicate trend detection (Schertz and others, 1991; Helsel and Hirsch, 1992). Dissolved-solids and major-ion data for the Colorado, Gunnison, and White Rivers indicate distinct seasonal variations, primarily because of dilution by snowmelt runoff during May and June. Often, most of the seasonal variation in water quality is related to seasonal variation in streamflow; however, seasonality often remains after the effect of streamflow has been removed (Helsel and Hirsch, 1992). In the study area, there could be seasonal effects on dissolved-solids and major-ion concentrations and loads that could be related to agricultural return flows that would not necessarily be related to streamflow.

The seasonal Kendall test accounts for seasonality by only comparing water-quality data collected during the same season of each year. For example, for data collected monthly, only data collected in January of each year are compared; only data collected in February are compared, and so on. The seasonal Kendall test statistic for the overall monotonic trend is the sum of all Mann-Kendall test statistics for each season (Hirsch and others, 1982). In ESTREND, one value of the constituent being tested is used for each season for each year. For seasons with more than one value, the most central observation with respect to time for that season is used (Schertz and others, 1991).

Users of ESTREND can define the number of seasons per year and the length of each season. If the data frequency is uniform, the number of seasons can be equal to the sampling frequency. For monthly data, such as monthly dissolved-solids loads, the number of seasons is 12. Where sampling frequency has changed, the number of seasons per year is based on the years of least frequent sampling. The goal is to provide uniform coverage of the entire period being tested without biasing the results toward years of denser data collection and yet define the seasons so that there will be data in most seasons in most of the years. The seasonal definitions should reflect the actual seasonal cycles in streamflow or water quality in the watershed being studied. Although there are general guidelines for selecting seasonal definitions, some element of subjectivity can enter into the selection.

Dissolved-solids and major-ion concentrations often are highly correlated with streamflow. In the Upper Colorado River Basin, increasing streamflow often causes decreasing concentrations because of dilution, especially during snowmelt runoff. Because streamflow is used to compute dissolved-solids loads, dissolved-solids loads also will be correlated with streamflow. The purpose of the monotonic trend tests on salinity data collected at the gaging stations on the Colorado and Gunnison Rivers is to determine if the salinity-control projects have affected salinity in the Colorado River. The variability of concentrations and loads caused by streamflow might overwhelm any human-induced changes; therefore, removal of the variance due to streamflow is desirable. If the streamflow-induced variability in salinity data is decreased, then the chance of detecting a trend that resulted from some effect other than streamflow is enhanced. Generally, monotonic trends on flow-adjusted water-quality data should not be done during a period when major changes to the stream-discharge regime occurred, such as reservoir construction or major changes in water diversions or water use.

The procedure in ESTREND to decrease streamflow-related variability in the data set is done in three steps. First, a relation is determined for concentration (or load) to streamflow through a linear-regression fit or a nonlinear smoothing method. Then the residuals (the observed value minus the predicted value from the regression) are computed for every data pair. The residuals are referred to as the flow-adjusted concentrations (Liebermann and others, 1988; Schertz and others, 1991). The flow-adjusted concentrations then are tested for trends with the seasonal Kendall test. There are 12 possible regression models available for flow adjustment in ESTREND. Models 1 through 11 are functions that have various linear, logarithmic, hyperbolic, or inverse forms. Model 12 is a multiple regression of the logarithm of concentration to the logarithm of streamflow and the square of the logarithm of streamflow. The regression model for a particular variable was selected after review of regression statistics, such as the coefficient of determination and predicted error sum of squares (PRESS statistic) and review of plots of regression residuals. For dissolved-solids and major-ion concentrations, model 12 was used for flow adjustment. Hyperbolic functions were used for flow adjustment of monthly loads.

The output from ESTREND lists summary statistics, regression statistics for the various regression flow-adjustment models, and the results of the monotonic tests for the original data (not flow adjusted) and the flow-adjusted data (Schertz and others, 1991). The trend slope is reported in original units per year and is computed by the method in Sen (1968). The trend slope equals the median slope of all pairwise comparisons (the difference between two observed values divided by the number of years between observations). The trend slopes also are reported as a percentage of the mean value (the slope divided by the mean times 100). For logarithm-transformed data (model 12), the slope in original units is computed from the expression (e^b minus 1) times the mean concentration, where b is the seasonal Kendall slope in natural logarithm (base e) units. The corresponding percent change for logarithm units is computed from the expression (e^b minus 1) times 100. The trend slopes for flow-adjusted data also are reported in original units by ESTREND. The percent rate of change is extracted from the slope of the residuals trend and then is used to estimate the slope in original units from the median concentration of the original data.

Along with computing the trend slopes and percent rate of change, ESTREND also computes the p value for each test (on the original data and the flow-adjusted data). The p value is the attained significance level of the test. The p value is a measure of the evidence to accept or reject the null hypothesis (Helsel and Hirsch, 1992). As the p value gets smaller, the probability of rejecting the null hypothesis (no trend) increases, or in other words, the probability increases that there is in fact a trend in the data.

The trend slopes derived by ESTREND represent a median rate of change of concentration or load and are measures of monotonic trends during the selected time period. The slope is an approximation of the time variation for the entire period, and it might mask short-term changes in the data. Monotonic trend slopes are not specific about when changes occurred; however, more specific information was needed for this study because the objective was to relate salinity-control projects to salinity trends, if any were present. To aid in interpretation of the monotonic trend results, graphical examination of the data also was done using a smoothing technique called LOWESS, or LOcally WEighted Scatterplot Smoothing (Cleveland, 1979). The LOWESS technique fits a smooth curve to a data set by use of weighting functions with weighted least squares. The LOWESS smooth is robust, which means that the effect of outliers is minimized, and might be highly nonlinear. The curve-smoothing technique was used with the ESTREND results to determine in what part of the record a trend had occurred in instances where a significant monotonic trend was reported.

Monotonic Trend Analysis Using Linear Regression

Linear-regression analysis for trends is a parametric method that involves a regression of the variable of interest to time. Parametric methods are more powerful than nonparametric methods for trend analysis if the residuals are normally distributed (Hirsch and others, 1991). Also, parametric methods might be more effective for data sets that have small departures from normality and for small sample sizes. Trends in annual and seasonal dissolved-solids loads were analyzed using the linear-regression method. Data sets consisting of annual or seasonal loads have only one value per year and have much smaller sample sizes than data sets derived from periodic data, and the potential seasonality problem associated with periodic data is removed for data sets consisting of annual values.

The simple linear regression of annual (or seasonal) dissolved-solids loads to time is of the form:

$$L = a + bT \qquad (3)$$

where

L = annual or seasonal dissolved-solids load, in tons;

a and b = regression coefficients; and

T = time (year or water year in the case of annual data).

The null hypothesis is that there is no trend, or the value of coefficient b equals zero. If there is a significant trend, the value of b is the magnitude of the trend. Use of equation 3 does not adjust the annual or seasonal loads for the effects of streamflow. To remove the variation in annual or seasonal loads caused by streamflow, the same flow-adjustment method that was used for the seasonal Kendall test also was used for the regression method. Flow-adjusted linear regression was done in a two-step method. First, the loads were regressed against streamflow using hyperbolic functions, which had the highest coefficients of determination when compared to other flow-adjustment models. Residuals from the flow-adjustment models were tested for normality and constant variance to verify that assumptions for using the parametric method were not violated. Second, the residuals from the flow-adjustment models, or the flow-adjusted loads, were regressed against time using equation 3. The null hypothesis is that there is no trend in the flow-adjusted loads or that the value of coefficient b in equation 3 is not significantly different from zero. Regression trend tests were done using procedures in SAS (SAS Institute, 1982).

Step-Trend Analysis

Step-trend analysis can be used to determine if there is a difference in population means or medians between two or more sets of data. Parametric or nonparametric methods can be used. The parametric test for step trends is the two-sample t-test (Iman and Conover, 1983). When using the t-test, it is assumed that the data sets are normally distributed about their mean values. The t-test determines if there is a significant difference between the means of two data sets. Parametric tests have diminished power to detect true differences in mean values when applied to data that are not normally distributed. A commonly used nonparametric test for step trends is the Wilcoxon rank-sum test. That test is computed using a two-sample t-test applied to the ranks of the data instead of using the original data. The Wilcoxon rank-sum test has no assumptions concerning data distributions. The rank-sum test is used to test for the difference in medians between two data sets.

The step-trend tests were done using procedures in SAS (SAS Institute, 1982). For tests involving comparisons among three or more data sets, multiple t-tests were used on the original data (parametric method) and on the ranks of the data (nonparametric method). Repeated t-tests were done because they are more applicable to unequal sample sizes than are other tests, such as the Duncan multiple range test (SAS Institute, 1982).

TREND ANALYSIS FOR THE COLORADO AND GUNNISON RIVERS

Monotonic trends in dissolved-solids and major-ion data at three sites were investigated to examine possible effects on salinity in the Colorado River from salinity-control projects in the Grand Valley (the Grand Valley Unit) and in the lower Gunnison River Basin (the Lower Gunnison Basin Unit). Gaging station 09163500 (fig. 1) on the Colorado River near the Colorado-Utah State line is the outflow site and is downstream from the Grand Valley and the Gunnison River. It was not sufficient to evaluate trends only at station 09163500 because trends at that station might have been induced by salinity trends in the Colorado River upstream from the Grand Valley or by trends in the Gunnison River. Based on data in table 1, about 83 percent of the annual mean dissolved-solids load at station 09163500 for water years 1970–93 was accounted for at inflow gaging stations 09095500 Colorado River near Cameo and 09152500 Gunnison River near Grand Junction (fig. 1). Therefore, stations 09095500 and 09152500 were included in the trend analysis. Plateau Creek (station 09105000) accounted for only about 2 percent of the annual mean dissolved-solids load at station 09163500 during 1970–93 (table 1). Trends in Plateau Creek were unlikely to have an effect on trends in the Colorado River; therefore, trend analysis was not done for station 09105000.

The period of record for the trend analysis was water years 1970–93 (October 1969–September 1993). Most major water-storage projects in the Colorado River Basin upstream from the Grand Valley were completed by 1965. Reservoir construction during a time period being analyzed for water-quality trends would complicate the flow-adjustment trend analysis or render it unfeasible. Although there are dissolved-solids data for 1966–93, the trend tests were done on data from water years 1970–93 so as to have concurrent records with periodic major-ion data for the three stations. Two shorter periods also were examined for trends. Water years 1980–93 were tested because that period was when all of the salinity-control work was done in the Grand Valley and lower Gunnison River Basin (through September 1993). Water years 1986–93 also were tested for trends because Stage II salinity work began in the Grand Valley in 1986 and involved more extensive salinity-control work than Stage I, and salinity-control work began in the Lower Gunnison Basin Unit in 1988. The greatest effect of the salinity-control projects on dissolved solids in the Colorado River should have occurred after 1986.

Several variables that represent various measures of salinity were tested for trends. The seasonal Kendall test and the ESTREND program were used for trend analysis on periodic dissolved-solids, calcium, magnesium, sodium, and sulfate concentrations and on monthly dissolved-solids loads. Linear-regression analysis was used for the trend analysis of annual and seasonal dissolved-solids loads and of the annual Grand Valley dissolved-solids load. The trend results on unadjusted data and flow-adjusted data for water years 1970–93 were compared to LOWESS smooth curves for the same period. If statistically significant trends of decreasing concentrations or loads were reported, then the LOWESS smooth curves might aid in delineation of when the trends had occurred, either before or after initiation of the salinity-control projects. The trend results for 1980–93 and 1986–93 were compared to the results for 1970–93 and to the LOWESS curves in attempts to identify trends in concentrations or loads that could be related to the salinity-control work. All trend results are presented, and then the relation of the trend results to salinity-control projects are discussed at the end of this section of the report.

Trend results are listed in tables that include the trend-slope magnitude, trend slope as a percent rate of change, the p value of the test, and the significance level of the slope. Hypothesis testing by statistical methods requires the selection of an alpha level, which also is referred to as the significance level of the test, for making the decision to reject or not to reject the null hypothesis of no trend. The alpha level is the probability of incorrectly rejecting the null hypothesis when, in fact, the null hypothesis is true. The alpha level also is called the type I error (Helsel and Hirsch, 1992). In terms of trend analysis, the alpha level is the probability of reporting a trend when, in fact, there is not a trend. Thus, the alpha level is the risk level that an investigator is willing to accept for making a type I error. For example, an alpha level of 0.05 (5 percent) implies that in 95 percent of the cases, the test will correctly indicate no trend when there actually is no trend. Selection of a very small alpha level would minimize a type I error; however, that selection increases the chance of committing a type II error, which is failing to reject the null hypothesis when, in fact, it is false (or reporting no trend when there actually might be a trend).

An alpha level commonly used in hypothesis testing is 0.05. The null hypothesis then is evaluated by comparing the p value from the statistical test of the data to 0.05. When the p value is less than 0.05, the null hypothesis is rejected; if the p value is greater than 0.05, then the null hypothesis is not rejected. As described in many statistical texts, such as Helsel and Hirsch (1992), not rejecting the null hypothesis is not the same as saying the hypothesis is actually proven. All that can be said is that, based on the data available, the null hypothesis cannot be rejected. Instead of selecting only one alpha level for describing the significance of the trends, a range of alpha levels was used for comparison to the p values by using a scheme similar to one used by Liebermann and others (1988). The monotonic trend results were considered highly significant (HS) if the p value was less than or equal to 0.01; significant (S) if the p value exceeded 0.01 and was less than or equal to 0.05; marginally significant (MS) if the p value exceeded 0.05 and was less than or equal to 0.10; and the trend was not significant (NS) if the p value exceeded 0.10.

Trends in Dissolved-Solids Concentrations

Periodic dissolved-solids concentrations represent discrete water samples collected at varying frequencies at gaging stations 09095500, 09152500, and 09163500 during water years 1970–93. Monotonic trend results for periodic dissolved-solids concentrations and for flow-adjusted concentrations for the three stations for 1970–93, 1980–93, and 1986–93 are summarized in table 2. Most trends in unadjusted dissolved-solids concentrations were not significant (table 2). The trend results indicate increasing dissolved-solids concentrations for 1980–93 and 1986–93 at all three stations, although only the trend for 1980–93 for station 09095500 and the trend for 1986–93 for station 09152500 were significant. Increasing concentrations probably reflect the effect of streamflow during 1980–93, when above-average flows occurred during 1983–86 and below-average flows occurred during 1988–92 (fig. 3). Low dissolved-solids concentrations occurred during the high-flow period, and higher concentrations generally occurred during the low-flow period, which caused an upward trend in concentration. Also, there might have been carryover or persistence of lower dissolved-solids concentrations into 1987 caused by discharge of dilute water stored from the high runoff years in reservoirs and in shallow aquifers.

In contrast to unadjusted concentrations for water years 1970–93, the flow-adjusted concentrations for 1970–93 were decreasing and had highly significant trends for the three stations (table 2). The LOWESS smooth curves for the flow-adjusted dissolved-solids concentrations for 1970–93 are shown in figure 4. The flow-adjusted concentrations are residuals from log-log regressions of concentration to streamflow. All regression relations used for flow adjustment were significant and had p values less than 0.001. The LOWESS smooth curve for 1970–93 seems to indicate that all of the decrease in flow-adjusted dissolved-solids concentrations at station 09152500 in 1970–93 had occurred before about 1981 (fig. 4). Salinity-control projects did not start in the Gunnison River Basin until 1988. The smooth curves in figure 4 for stations 09095500 and 09163500 indicate that there were decreasing flow-adjusted dissolved-solids concentrations in the Colorado River during the 1970's.

Flow-adjusted dissolved-solids concentrations did not have significant trends (alpha 0.05) for water years 1980–93 (table 2). The LOWESS smooth curves for the flow-adjusted concentration data for 1980–93 are shown in figure 5. The large variations in streamflow during 1980–93 (fig. 3) might have affected the flow adjustment of data for this period. The flow-adjustment regressions tended to underpredict (positive residuals) the dissolved-solids concentrations during 1983–86, and perhaps the flow adjustment was overcompensating for high streamflow during the mid-1980's. The LOWESS plots in figure 5 also indicate generally decreasing trends in flow-adjusted concentrations after about 1986, especially for stations 09095500 and 09163500. The trend results (table 2) for 1986–93 indicated highly significant trends of decreasing flow-adjusted concentrations for these two stations. If significant trends had occurred only at station 09163500, those trends could be evidence that the salinity-control projects were causing a decrease in dissolved-solids concentrations during 1986–93. However, there were similar trends (table 2)

Table 2. Monotonic trends in periodic dissolved-solids concentrations for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93

[Periods are in water years; slopes are in milligrams per liter per year; percent is the slope expressed as percent change per year; p value is the significance level of the test; SL, significance levels, which are: HS is highly significant, p is less than or equal to 0.01; S is significant, p is greater than 0.01 and less than or equal to 0.05; MS is marginally significant, p is greater than 0.05 and less than or equal to 0.10; and NS is not significant, p is greater than 0.10; <, less than]

Station	Period	Unadjusted concentration				Flow-adjusted concentration			
		Slope	Percent	p value	SL	Slope	Percent	p value	SL
09095500	1970–93	0.50	0.10	0.669	NS	–2.23	–0.44	0.001	HS
	1980–93	6.88	1.42	.014	S	–3.20	–.66	.051	MS
	1986–93	3.60	.71	.539	NS	–14.3	–2.82	<.001	HS
09152500	1970–93	–6.35	–.96	.055	MS	–4.86	–.73	<.001	HS
	1980–93	6.86	1.14	.385	NS	.53	.09	.804	NS
	1986–93	42.6	6.69	.045	S	–4.67	–.73	.274	NS
09163500	1970–93	–2.50	–.36	.300	NS	–3.37	–.48	.002	HS
	1980–93	5.90	.89	.149	NS	–1.14	–.17	.479	NS
	1986–93	7.22	1.04	.524	NS	–12.5	–1.80	<.001	HS

of decreasing dissolved-solids concentrations at upstream station 09095500 on the Colorado River. Climatic-induced changes in dissolved solids during the period of the salinity-control projects could mask or overwhelm the human-induced changes.

Trends in Dissolved-Solids Loads

Trends also were examined by using ESTREND on monthly dissolved-solids loads for the three gaging stations on the Colorado and Gunnison Rivers in the Grand Valley area. Monthly loads were computed by the method described in the "Dissolved-Solids Loads in the Colorado and Gunnison Rivers" section of this report. Using monthly dissolved-solids-load data has an advantage when compared to periodic data because the loads represent a uniform time series, and selection of seasons is not a concern. However, the monthly loads also are computed numbers, and various errors are associated with the computations as described previously in this report.

Trend analysis also was done on annual dissolved-solids loads using linear-regression analysis instead of the seasonal Kendall test in ESTREND. Seasonality is not a concern for annual data as it is for periodic or monthly data. Normality tests indicated that the annual loads approximated normal distributions, and the data sets were not severely skewed. Therefore, the parametric method was used for the trend tests on annual loads.

In addition to trend tests on monthly and annual dissolved-solids loads, loads for certain parts of the year, or seasonal loads, were tested for monotonic trends. Two seasonal periods were tested: August through October, which is the late irrigation season in the Grand and Uncompahgre Valleys, and November through February, which is a low-flow period of the year. If the salinity-control projects have decreased discharge of subsurface irrigation drainage, then a trend in dissolved-solids loads during November through February might be detectable. One other time series of loads was tested for trends—the annual Grand Valley dissolved-solids load (table 1).

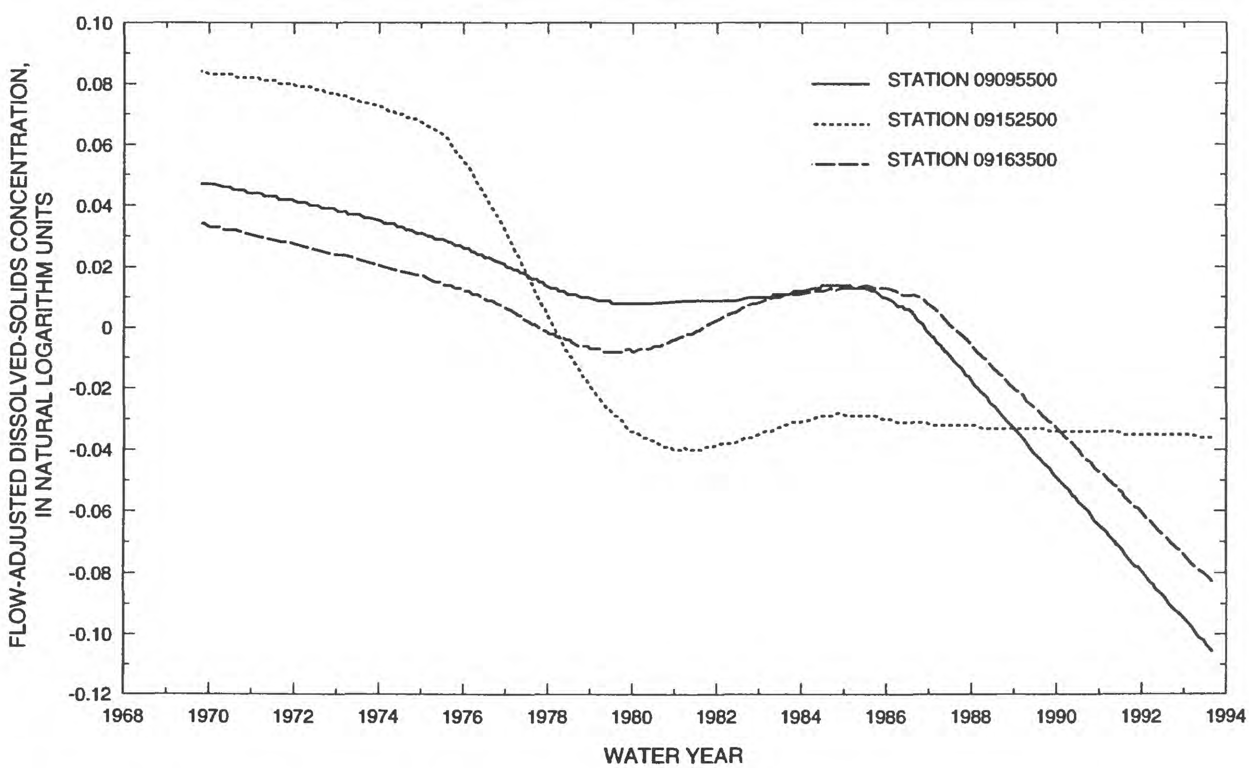

Figure 4. LOWESS smooth curves of flow-adjusted dissolved-solids concentrations for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93.

The Grand Valley dissolved-solids load is a salinity-related variable that would be most affected by salinity-control projects in the Grand Valley. The seasonal loads and the Grand Valley dissolved-solids load were tested for trends using the linear-regression method.

Monthly Dissolved-Solids Loads

All trends in unadjusted dissolved-solids loads and flow-adjusted loads for the three time periods tested for stations 09095500 (Colorado River near Cameo; inflow station) and 09163500 (Colorado River near the State line; outflow station) were highly significant and indicated decreasing loads with time (table 3). For station 09152500 (Gunnison River near Grand Junction; inflow station), the trends were highly significant and loads were decreasing for water years 1970–93, but the trends were not significant or were marginally significant for the two shorter periods. The LOWESS curves (fig. 6) indicate that some of the downward trends in flow-adjusted loads for 1970–93 at all three stations occurred in the 1970's before implementation of salinity-control projects in western Colorado. In addition, the LOWESS curves in figures 6 and 7 also seem to indicate decreasing flow-adjusted monthly loads for stations 09095500 and 09163500 after 1986. The trend results (table 3) are consistent with the graphical information in figures 6 and 7 because the trends for both stations for 1980–93 and 1986–93 were highly significant with decreasing flow-adjusted monthly dissolved-solids loads. By contrast, flow-adjusted monthly loads for 1980–93 and 1986–93 for station 09152500 on the Gunnison River were increasing slightly, but the trend slopes were statistically not significant (table 3).

The highly variable streamflow during water years 1980–93 might have masked some of the trends in monthly dissolved-solids loads, as was suspected with periodic dissolved-solids concentrations for the same period. Information in table 3 and figure 7 indicates highly significant, downward trends in flow-adjusted monthly loads after 1985 or 1986 for stations 09095500 and 09163500, which is the same result as for the flow-adjusted concentrations (fig. 6; table 2) for the two stations for 1986–93.

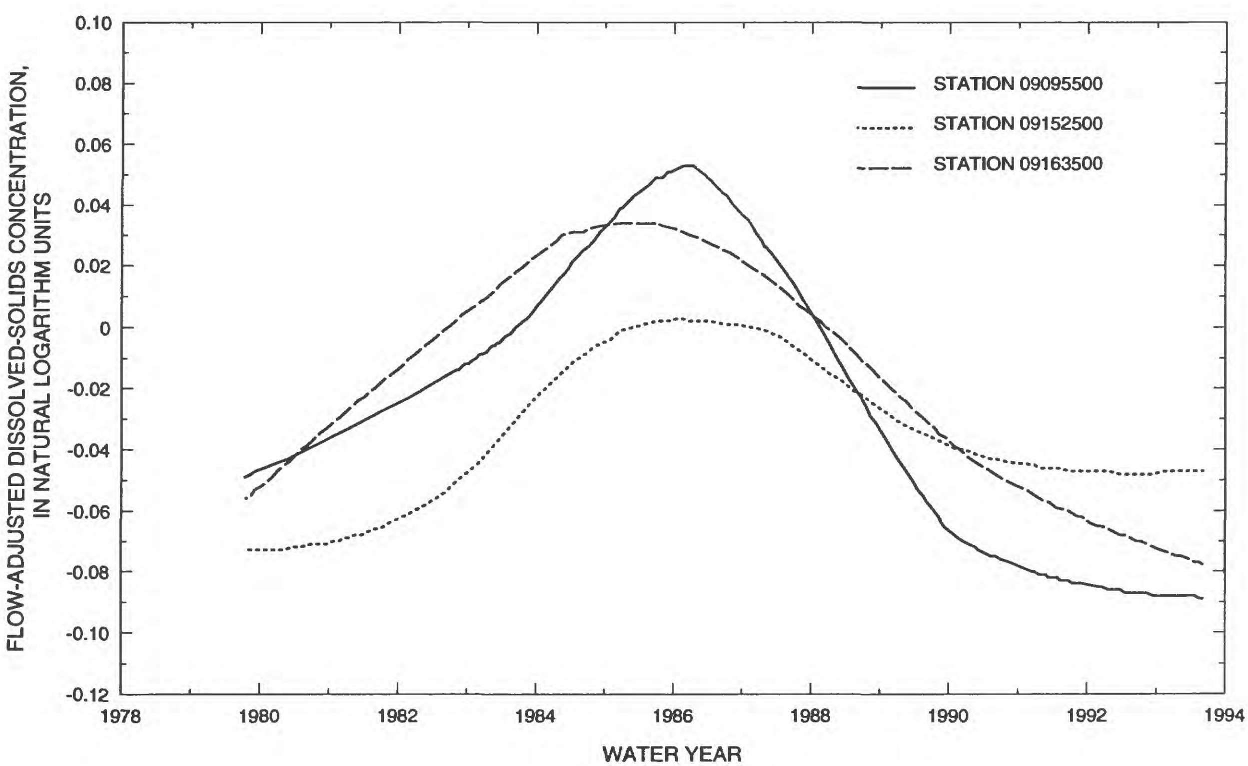

Figure 5. LOWESS smooth curves of flow-adjusted dissolved-solids concentrations for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1980–93.

Table 3. Monotonic trends in monthly dissolved-solids loads for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93

[Periods are in water years; slopes are in tons per month per year; percent is the slope expressed as percent change per year; p value is the significance level of the test; SL, significance levels, which are: HS is highly significant, p is less than or equal to 0.01; S is significant, p is greater than 0.01 and less than or equal to 0.05; MS is marginally significant, p is greater than 0.05 and less than or equal to 0.10; and NS is not significant, p is greater than 0.10; <, less than]

Station	Period	Unadjusted monthly load				Flow-adjusted monthly load			
		Slope	Percent	p value	SL	Slope	Percent	p value	SL
09095500	1970–93	–686	–0.56	<0.001	HS	–333	–0.27	<0.001	HS
	1980–93	–1,280	–1.03	<.001	HS	–687	–.55	.001	HS
	1986–93	–5,440	–4.69	<.001	HS	–3,840	–3.31	<.001	HS
09152500	1970–93	–660	–.63	.002	HS	–451	–.43	<.001	HS
	1980–93	–866	–.83	.074	MS	317	.30	.201	NS
	1986–93	–2,210	–2.26	.125	NS	332	.34	.592	NS
09163500	1970–93	–2,180	–.80	<.001	HS	–1,680	–.61	<.001	HS
	1980–93	–2,930	–1.06	.001	HS	–1,080	–.39	.009	HS
	1986–93	–12,100	–4.72	<.001	HS	–4,480	-1.74	<.001	HS

Annual Dissolved-Solids Loads

None of the trends in the unadjusted annual dissolved-solids loads were significant (table 4). The flow-adjusted annual loads for the Gunnison River at station 09152500 and for the Colorado River at station 09163500 had significant or highly significant downward trends for water years 1970–93. The LOWESS smooth curve in figure 8 indicates that the flow-adjusted annual loads decreased at station 09163500 during the 1970's and again after 1986. The trend slope of –62,300 tons/yr for 1986–93 for station 09163500 was highly significant (table 4). The flow-adjusted annual loads for 1986–93 at station 09095500 also were decreasing, and the trend was highly significant. The LOWESS smooth curve for station 09152500 (fig. 8) indicates that most of the trend in flow-adjusted annual loads for 1970–93 in the Gunnison River occurred before 1980. The trends in flow-adjusted annual loads for 1980–93 and 1986–93 (table 4) for station 09152500 were not significant.

There were fewer significant trends in annual dissolved-solids loads than in monthly dissolved-solids loads. One problem with using annual data is that the sample sizes are decreased compared to data sets composed of monthly data. The p value for hypothesis testing is affected by sample size. For a given magnitude (trend magnitude for trend tests) and variance, p values tend to increase as the sample size decreases (Helsel and Hirsch, 1992); therefore, it becomes more difficult to reject the null hypothesis (of no trend) as sample size becomes smaller. Although the trend tests on the flow-adjusted annual loads for water years 1986–93 are based on only eight values, the magnitude of the slopes for the two Colorado River stations (09095500 and 09163500 in table 4) were sufficiently large to have highly significant p values.

Seasonal Dissolved-Solids Loads

Seasonal dissolved-solids loads represent the total load for selected periods, or seasons, within a year. Seasonal loads were computed by summing the monthly loads of the individual months in a season and then were treated as annual values for performing trend tests using linear-regression analysis. The trend results would reflect only the trend slopes and p values for loads for a particular season and would be independent from the remainder of the year. Flow-adjusted trends were determined by using the average daily streamflows for each seasonal period of each year in the flow-adjustment models. Trends were analyzed for two seasonal periods; August through October (late irrigation-season effects) and November through February (low-flow effects).

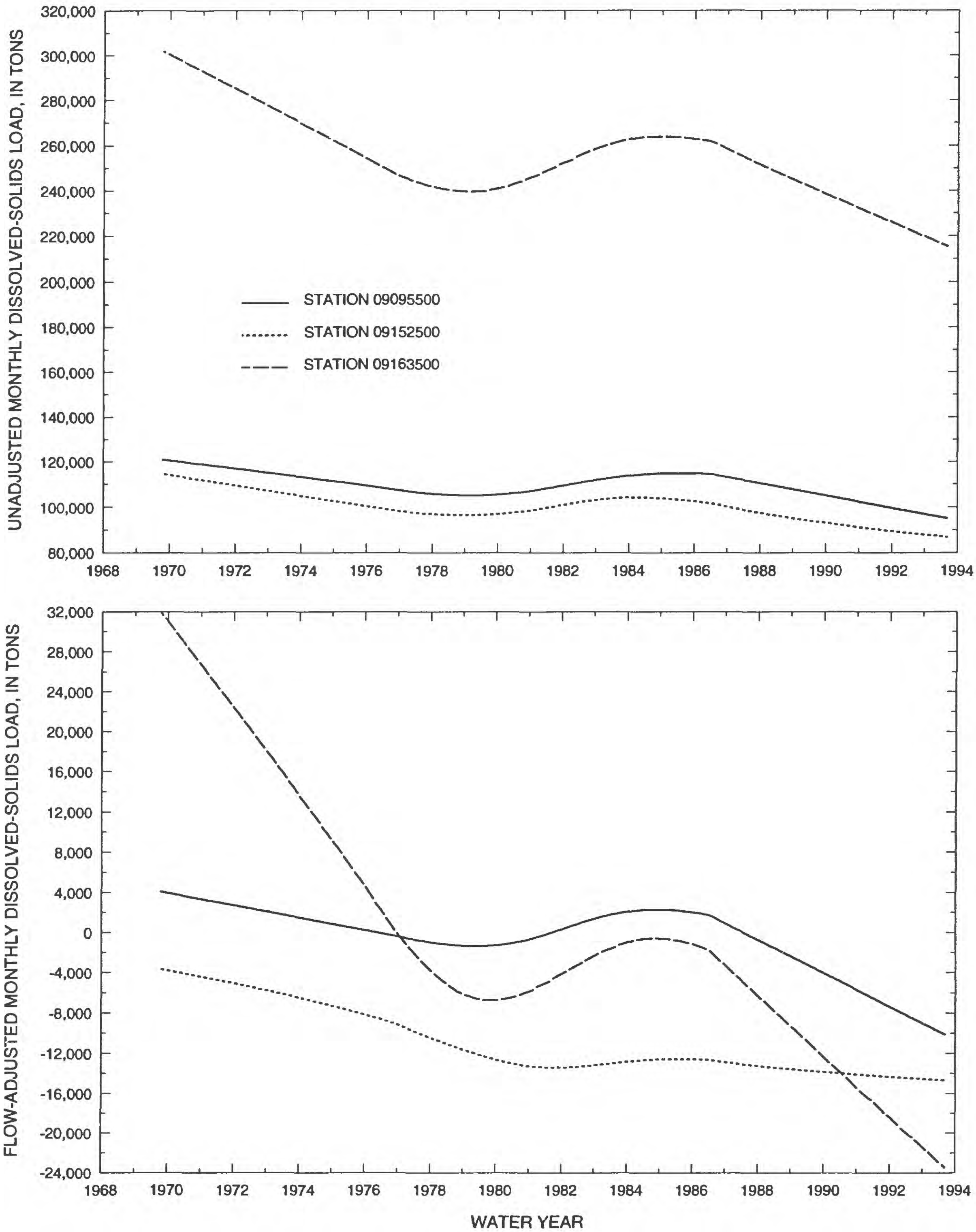

Figure 6. LOWESS smooth curves of unadjusted monthly dissolved-solids loads and flow-adjusted monthly dissolved-solids loads for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93.

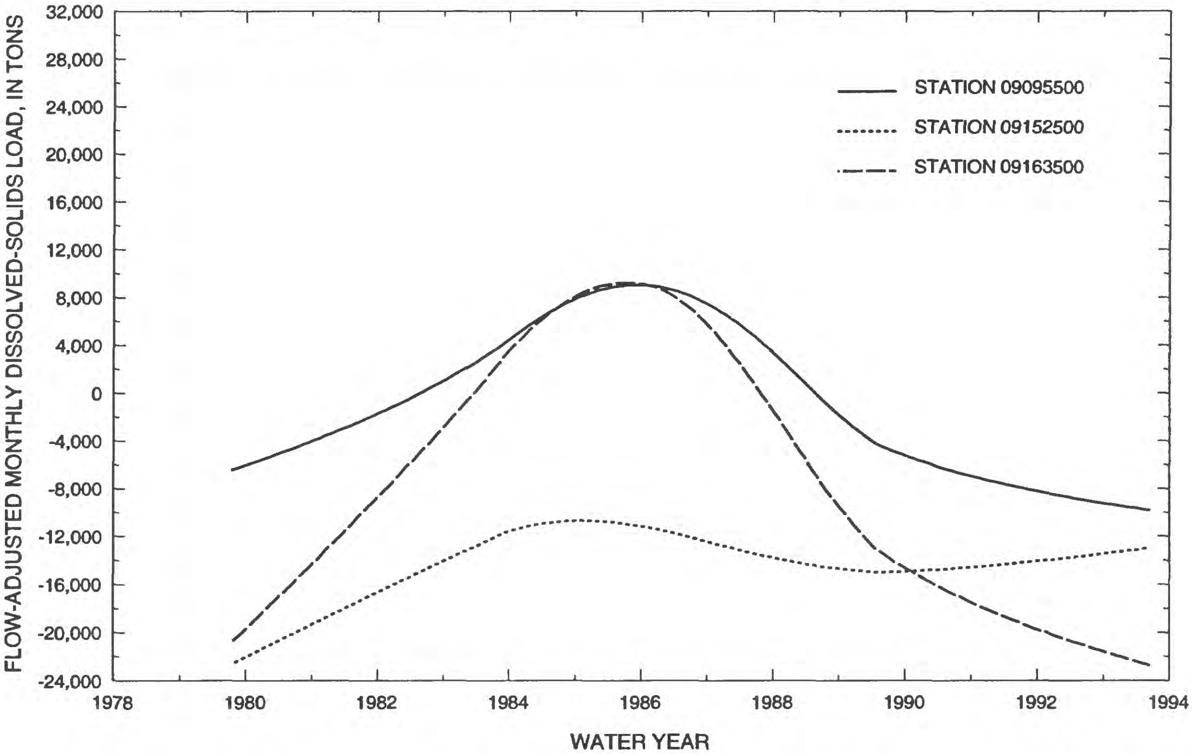

Figure 7. LOWESS smooth curves of flow-adjusted monthly dissolved-solids loads at stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1980–93.

Trend results on the seasonal loads for August through October and November through February were variable (table 5). None of the trends in unadjusted seasonal loads for August through October were significant (alpha 0.05). Trends in flow-adjusted loads for August through October were highly significant (decreasing loads with time) for station 09095500 for water years 1986–93 and for station 09152500 for 1970–93 (table 5). Although the flow-adjusted loads for August through October for the three test periods indicated decreasing loads with time for station 09163500, the p values of the trends were not significant.

Trends in unadjusted dissolved-solids loads for November through February (table 5) were variable, and the most notable result is the highly significant downward trend in loads at station 09095500 for water years 1986–93. The trend in flow-adjusted load also was highly significant and downward for 1986–93 for station 09095500. The salinity-control projects in the Grand Valley primarily are designed to decrease the quantity of subsurface irrigation drainage, which is the mechanism of transport of irrigation-induced salinity to the Colorado River (Bureau of Reclamation, 1986). During the low-flow period of the year, a decrease in irrigation-drainage load from the Grand Valley might cause a trend in dissolved-solids loads at station 09163500 during November through February. Although the trend for the November through February loads was downward for 1986–93 at station 09163500, the trend was statistically not significant (table 5). As discussed with annual loads, the small sample size (eight values) for the seasonal data for 1986–93 make it more difficult to reject the null hypothesis of no trend.

Grand Valley Dissolved-Solids Load

The Grand Valley dissolved-solids load is the annual dissolved-solids load to the Colorado River from the Grand Valley (fig. 1), and at least 95 percent of that load was irrigation induced (Bureau of Reclamation, 1986). The trends in annual Grand Valley dissolved-solids load (table 1) were downward for water years 1970–93, 1980–93, and 1986–93 (table 6). Only the trend for 1980–93 had a significant p value (0.05 or less). The large variability of the Grand Valley dissolved-solids load (table 1) and small sample size made it more difficult to detect statistically significant trends.

The annual Grand Valley dissolved-solids load should be a sensitive variable for determining the effects of the salinity-control projects on dissolved-solids load from irrigated areas. However, the Grand Valley dissolved-solids load is not directly measured; it is a residual term calculated from a mass balance of dissolved-solids loads in the Colorado and Gunnison Rivers. The range and variability of annual Grand Valley dissolved-solids load (table 1) seem unrealistic because the irrigated acreage and amount of water applied each year in the Grand Valley do not have large year-to-year changes. Therefore, the variation in the Grand Valley dissolved-solids load does not seem related to actual physical changes in the Grand Valley. The annual Grand Valley dissolved-solids load was a function of the magnitude and errors associated with the annual loads in the rivers, especially of loads at station 09163500. For example, a 3-percent error in the annual load for water year 1988 at station 09163500 would change the computed Grand Valley dissolved-solids load for 1988 by about 88,000 tons, or about a 19-percent change. There is a significant correlation coefficient of 0.61 between the annual Grand Valley dissolved-solids load and the annual dissolved-solids load at station 09163500. That correlation implies that the magnitude of the Grand Valley dissolved-solids load is dependent on the magnitude of the annual load at station 09163500. If the errors associated with determining the Grand Valley dissolved-solids load are randomly distributed through a relatively long time period, then the mean value might be a reasonably realistic approximation of the annual dissolved-solids load over the time period. Because of the large year-to-year variability, the annual Grand Valley dissolved-solids load might be less suitable than other variables for use in trend tests that have the purpose of showing effects of the salinity-control project in the Grand Valley.

Trends in Selected Major-Ion Concentrations

Dissolved solids, or salinity, is a measure of the dissolved inorganic constituents in water. In the Colorado and Gunnison Rivers in the study area, nearly all the dissolved solids consist of calcium, magnesium, sodium, sulfate, chloride, and bicarbonate ions, with

Table 4. Monotonic trends in annual dissolved-solids loads for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93

[Periods are in water years; slopes are in tons per year; percent is the slope expressed as percent change per year; p value is the significance level of the test; SL, significance levels, which are: HS is highly significant, p is less than or equal to 0.01; S is significant, p is greater than 0.01 and less than or equal to 0.05; MS is marginally significant, p is greater than 0.05 and less than or equal to 0.10; and NS is not significant, p is greater than 0.10; <, less than]

Station	Period	Unadjusted annual load				Flow-adjusted annual load			
		Slope	Percent	p value	SL	Slope	Percent	p value	SL
09095500	1970–93	–5,020	–0.34	0.537	NS	–1,350	–0.09	0.605	NS
	1980–93	–26,000	–1.74	.265	NS	–2,960	–.20	.689	NS
	1986–93	–69,000	–4.96	.130	NS	–41,000	–2.95	<.001	HS
09152500	1970–93	–6,650	–.53	.383	NS	–6,350	–.50	.027	S
	1980–93	–14,500	–1.16	.469	NS	2,220	.18	.676	NS
	1986–93	–27,000	–2.29	.548	NS	–8,620	–.73	.413	NS
09163500	1970–93	–17,400	–.52	.331	NS	–16,100	–.49	.004	HS
	1980–93	–56,500	–1.52	.237	NS	–7,770	–.23	.497	NS
	1986–93	–127,000	–4.13	.191	NS	–62,300	–2.02	.003	HS

minor amounts of potassium, silica, fluoride, carbonate, and nitrate. For most natural waters, alkalinity is a measure of dissolved carbon dioxide in water and, in the study area, almost all the alkalinity in the Colorado and Gunnison Rivers is from bicarbonate ions. A statistical summary of major-ion and alkalinity concentrations for samples collected during water years 1970–93 at the three gaging stations for the Grand Valley Unit is in table 7. A large proportion of the gain in dissolved solids in the Colorado River from irrigation in the Grand Valley is from calcium, magnesium, sodium, and sulfate. That conclusion was determined using approximate mass-balance calculations on major-ion loads for the three gaging stations and using chemical data for irrigation-drainage samples from the Grand Valley and Uncompahgre Project (Butler and others, 1994). The mean chloride concentration for station 09163500 (table 7) can be derived directly from chloride loads for stations 09095500 and 09152500 and inclusion of some consumptive water loss in the Grand Valley. The differences in mean alkalinity concentrations among the three stations are small (table 7). Alkalinity concentrations probably are controlled by chemical equilibria of carbonate minerals. Therefore, monotonic trend tests using the seasonal Kendall test were done on calcium, magnesium, sodium, and sulfate concentrations because these major ions would most be affected by irrigation practices and potentially by salinity-control projects. Trend tests were done for three time periods: 1970–93, 1980–93, and 1986–93.

Only 5 of 36 trend tests on unadjusted major-ion concentrations were significant or highly significant (table 8). The only highly significant trends in major-ion concentrations were for magnesium concentrations at station 09095500 for water years 1986–93 and for sodium concentrations at station 09152500 for 1970–93. The trends in major-ion concentrations for 1986–93 were either zero or increasing, except for the magnesium concentrations for station 09095500, which seems to be anomalous. The upward trends for concentrations during 1986–93 were not unexpected because the beginning of the period generally had low concentrations at the end of the high-flow years, which then were followed by several dry years when concentrations of major ions were expected to increase.

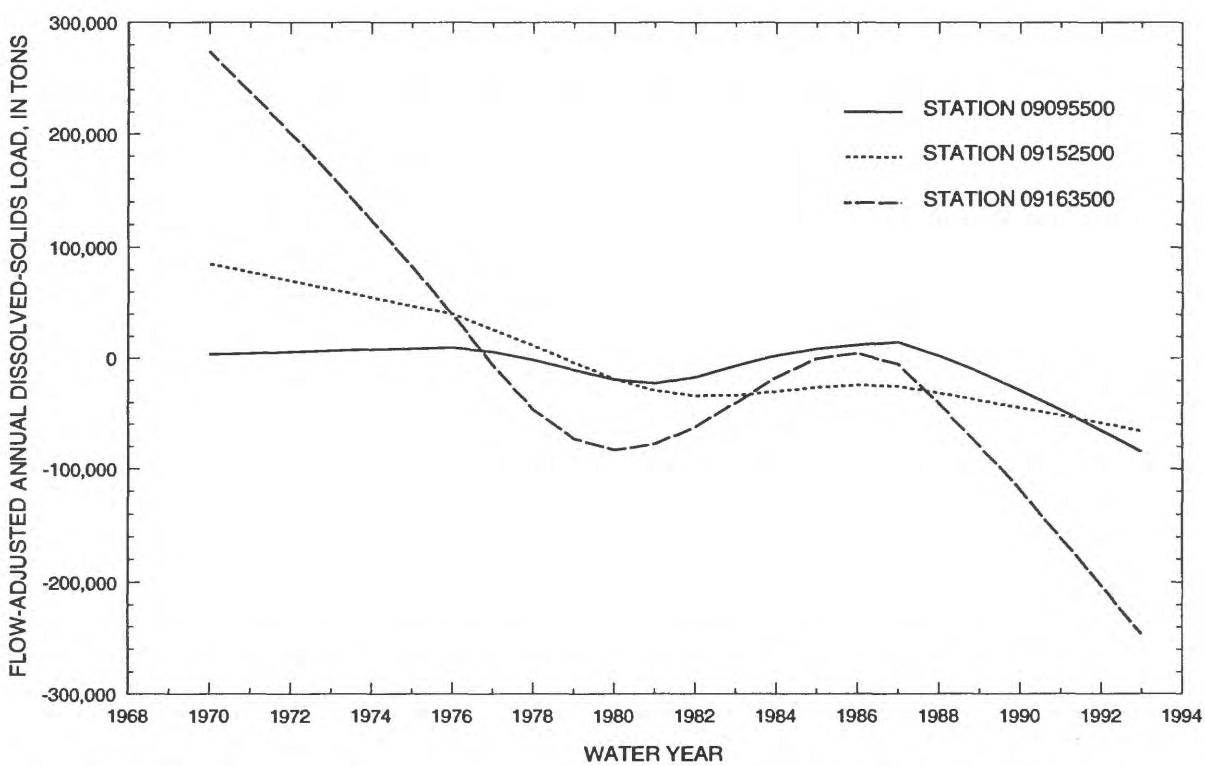

Figure 8. LOWESS smooth curves of flow-adjusted annual dissolved-solids loads for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and station 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93.

Table 5. Monotonic trends in seasonal dissolved-solids loads (August through October and November through February) for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93

[Trend tests done on the sum of the monthly dissolved-solids loads in each seasonal period; periods are in water years; slopes are in tons per season per year; percent is the slope expressed as percent change per year; p value is the significance level of the test; SL, significance levels, which are defined as: HS is highly significant, p is less than or equal to 0.01; S is significant, p is greater than 0.01 and less than or equal to 0.05; MS is marginally significant, p is greater than 0.05 and less than or equal to 0.10; and NS is not significant, p is greater than 0.10; <, less than]

Station	Period	Unadjusted seasonal load				Flow-adjusted seasonal load			
		Slope	Percent	p value	SL	Slope	Percent	p value	SL
				August through October					
09095500	1970–93	–1,260	–0.37	0.471	NS	–657	–0.19	0.252	NS
	1980–93	–5,530	–1.61	.280	NS	–524	–.15	.767	NS
	1986–93	–17,900	–5.61	.061	MS	–8,560	–2.68	.005	HS
09152500	1970–93	–1,240	–.38	.527	NS	–2,160	–.67	.010	HS
	1980–93	–187	–.06	.966	NS	2,100	.65	.090	MS
	1986–93	–9,590	–3.03	.356	NS	–1,450	–.46	.544	NS
09163500	1970–93	1,230	.16	.778	NS	-749	–.10	.584	NS
	1980–93	–17,500	–2.14	.097	MS	–4,310	–.53	.239	NS
	1986–93	–44,900	–5.93	.053	MS	–13,900	–1.83	.128	NS
				November through February					
09095500	1970–93	–1,590	–.41	.284	NS	231	.06	.652	NS
	1980–93	–4,030	–1.05	.335	NS	187	.06	.879	NS
	1986–93	–24,100	–6.31	.006	HS	–6,550	–1.72	<.001	HS
09152500	1970–93	–3,780	–1.07	.022	S	–1,100	–.31	.202	NS
	1980–93	–5,210	–1.53	.179	NS	1,530	.45	.880	NS
	1986–93	–16,200	–4.97	.103	NS	–388	–.12	.221	NS
09163500	1970–93	–9,660	–1.02	.011	S	–4,460	–.47	.027	S
	1980–93	–10,200	–1.12	.259	NS	5,160	.57	.214	NS
	1986–93	–56,200	–6.23	.010	S	–13,200	–1.47	.112	NS

Table 6. Monotonic trends in the annual Grand Valley dissolved-solids load, water years 1970–93

[Periods are in water years; slopes are in tons per year; percent is the slope expressed as percent change per year; p value is the significance level of the trend test; SL, significance levels, which are: HS is highly significant, p is less than or equal to 0.01; S is significant, p is greater than 0.01 and less than or equal to 0.05; MS is marginally significant, p is greater than 0.05 and less than or equal to 0.10; and NS is not significant, p is greater than 0.10]

Period	Slope	Percent	p value	SL
1970–93	–6,730	–1.27	0.168	NS
1980–93	–17,000	–3.22	.031	S
1986–93	–28,700	–6.14	.104	NS

Table 7. Statistical summary of selected major-ion concentrations for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93

[Concentrations in milligrams per liter; range is minimum and maximum concentrations]

Station	Constituent	Number of samples	Mean	Standard deviation	Median	Range
09095500	Calcium	254	62.6	15.3	68	29–100
	Magnesium	254	15.5	4.3	17	6.4–25
	Sodium	253	95.2	43.2	104	14–200
	Sulfate	255	124	44.8	136	32–220
	Chloride	255	124	60.6	134	11–270
	Alkalinity	255	130	22.9	137	69–180
09152500	Calcium	204	100	44.8	91.5	30–240
	Magnesium	204	34.2	14.4	32	7.8–68
	Sodium	204	60.9	28.6	57	12–130
	Sulfate	204	361	189	330	62–930
	Chloride	204	9.8	5.6	8.4	2.3–58
	Alkalinity	204	138	33.3	137.5	17–221
09163500	Calcium	210	93.4	32.7	88.5	37–200
	Magnesium	210	31.0	11.6	31	9.6–73
	Sodium	210	90.6	36.6	93	18–190
	Sulfate	209	296	132	270	67–670
	Chloride	210	80.0	35.7	82	11–170
	Alkalinity	210	144	26.6	150	82–220

Tests on individual ions generally had similar trend test results as the unadjusted dissolved-solids concentrations (table 2) for the same stations and periods, except for station 09152500 on the Gunnison River for water years 1986–93. There were upward trends in the four major-ion concentrations for station 09152500 for 1986–93 (table 8). Although the magnitude of the slopes might seem large [such as 25.1 (mg/L)/yr for sulfate], the p values were not significant or were marginally significant. The cumulative effect of the upward trends for individual ions manifests itself in a significant upward trend slope of 42.6 (mg/L)/yr (table 2) in dissolved-solids concentrations for 1986–93 for the Gunnison River.

When flow adjusted (from log-log regressions), many major-ion concentrations had significant or highly significant downward trends for certain time periods. All flow-adjusted major-ion trends were either significant or highly significant for water years 1970–93 for all three stations (table 8). By contrast, many of the trend slopes for 1980–93 were not significant. Flow-adjusted sodium concentrations had significant downward trends at both Colorado River stations, and flow-adjusted magnesium concentrations had a highly significant downward trend at station 09095500 in 1980–93. As with dissolved solids, there were differences in the trend results among time periods.

Table 8. Monotonic trends in periodic calcium, magnesium, sodium, and sulfate concentrations for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93

[Periods are in water years; slopes are in milligrams per liter per year; percent is the slope expressed as percent change per year; p value is the significance level of the test; SL, significance levels, which are: HS is highly significant, p is less than or equal to 0.01; S is significant, p is greater than 0.01 and less than or equal to 0.05; MS is marginally significant, p is greater than 0.05 and less than or equal to 0.10; and NS is not significant, p is greater than 0.10; <, less than]

Station	Period	Unadjusted concentration				Flow-adjusted concentration			
		Slope	Percent	p value	SL	Slope	Percent	p value	SL
				Calcium					
09095500	1970–93	0.00	0.00	0.508	NS	–0.24	–0.38	<0.001	HS
	1980–93	.48	.79	.053	MS	–.21	–.35	.257	NS
	1986–93	.00	.00	.918	NS	–1.31	–2.10	.002	HS
09152500	1970–93	–.47	–.47	.233	NS	–.47	–.47	.014	S
	1980–93	1.17	1.27	.294	NS	.47	.52	.197	NS
	1986–93	4.73	4.81	.098	MS	–.59	–.60	.466	NS
09163500	1970–93	.00	.00	.503	NS	–.37	–.39	.018	S
	1980–93	.83	.92	.077	MS	.10	.11	.860	NS
	1986–93	.00	.00	.378	NS	–1.30	–1.39	.056	MS
				Magnesium					
09095500	1970–93	.00	.00	.963	NS	–.06	–.41	.005	HS
	1980–93	.00	.00	.894	NS	–.19	–1.27	.008	HS
	1986–93	–.40	–2.57	.001	HS	–.86	–5.58	<.001	HS
09152500	1970–93	–.31	–.92	.038	S	–.30	–.87	<.001	HS
	1980–93	.29	.95	.382	NS	–.03	–.08	.843	NS
	1986–93	1.36	4.21	.127	NS	–.40	–1.24	.145	NS
09163500	1970–93	–.17	–.56	.056	MS	–.27	–.88	<.001	HS
	1980–93	.18	.63	.387	NS	–.16	–.56	.111	NS
	1986–93	.00	.00	.915	NS	–.90	–2.96	<.001	HS
				Sodium					
09095500	1970–93	.00	.00	.388	NS	–.51	–.54	<.001	HS
	1980–93	1.51	1.69	.022	S	–1.29	–1.44	<.001	HS
	1986–93	.71	.75	.465	NS	–3.96	–4.18	<.001	HS
09152500	1970–93	–.86	–1.42	.008	HS	–.77	–1.27	<.001	HS
	1980–93	.45	.86	.618	NS	–.26	–.51	.197	NS
	1986–93	3.03	5.56	.127	NS	–.69	–1.27	.068	MS
09163500	1970–93	–.25	–.28	.322	NS	–.54	–.60	<.001	HS
	1980–93	.62	.72	.309	NS	–.60	–.69	.023	S
	1986–93	.00	.00	.746	NS	–2.52	–2.80	<.001	HS

Table 8. Monotonic trends in periodic calcium, magnesium, sodium, and sulfate concentrations for gaging stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93--Continued

Station	Period	Unadjusted concentration				Flow-adjusted concentration			
		Slope	Percent	p value	SL	Slope	Percent	p value	SL
				Sulfate					
09095500	1970–93	0.00	0.00	0.963	NS	–0.46	–0.37	0.020	S
	1980–93	1.15	.97	.023	S	–.55	–.46	.147	NS
	1986–93	.00	.00	.875	NS	–3.96	–3.21	<.001	HS
09152500	1970–93	–4.02	–1.12	.055	MS	–3.19	–.89	<.001	HS
	1980–93	3.25	1.03	.500	NS	–.25	–.08	.921	NS
	1986–93	25.1	7.41	.067	MS	–3.17	–.94	.395	NS
09163500	1970–93	–1.33	–.45	.165	NS	–1.96	–.66	<.001	HS
	1980–93	4.10	1.47	.110	NS	–.70	–.25	.448	NS
	1986–93	5.93	2.02	.594	NS	–5.90	–2.01	.009	HS

The LOWESS smooth curves for flow-adjusted major-ion concentrations based on water years 1970–93 data are shown in figures 9 and 10. The LOWESS smooth curves show downward trends in all four major-ion concentrations at the Colorado River stations after about 1985 or 1986, which is substantiated by the trend results for 1986–93 (table 8). Except for calcium concentrations at station 09163500, the flow-adjusted trends in all four major-ion concentrations for stations 09095500 and 09163500 for 1986–93 are highly significant, and all trend slopes indicate decreasing major-ion concentrations with time (table 8). The smooth curves indicate that much of the decrease in flow-adjusted major-ion concentrations during 1970–93 in the Gunnison River (station 09152500 in figs. 9 and 10) occurred during about 1974–81. The trends in flow-adjusted major-ion concentrations for station 09152500 for 1980–93 and for 1986–93 were not significant or were marginally significant (table 8). Reasons for the downward trends in major-ion concentrations in the Gunnison River during 1974–81 are not known, but might be related to the streamflow regulation by Blue Mesa Reservoir. The LOWESS smooth curves for the Colorado River stations do not mimic this apparent trend for the Gunnison River (figs. 9 and 10).

Many of the flow-adjusted trend results for periodic calcium, magnesium, sodium, and sulfate concentrations were similar to the flow-adjusted trends in the dissolved-solids concentrations for water years 1970–93, 1980–93, and 1986–93 for all three gaging stations. The largest trend slopes for the Colorado River stations (09095500 and 09163500) were for 1986–93 (table 8), which was during construction of major parts of the salinity-control project in the Grand Valley and start-up of salinity-control work in the Lower Gunnison Basin Unit. In terms of the slope expressed as a percent rate of change, calcium concentrations changed less in 1986–93 than did the other three major-ion concentrations tested. The trend slopes (flow-adjusted data) for the two Colorado River stations were almost always in agreement in terms of the direction of the trend (upward or downward) and in significance level. As with dissolved-solids trends, the similarity of the trend results for the major ions for both Colorado River stations complicates the issue of how much of the observed trend at station 09163500 at the State line was related to salinity-control projects and how much was caused by climatic or other factors. That issue is discussed in more detail in the following section.

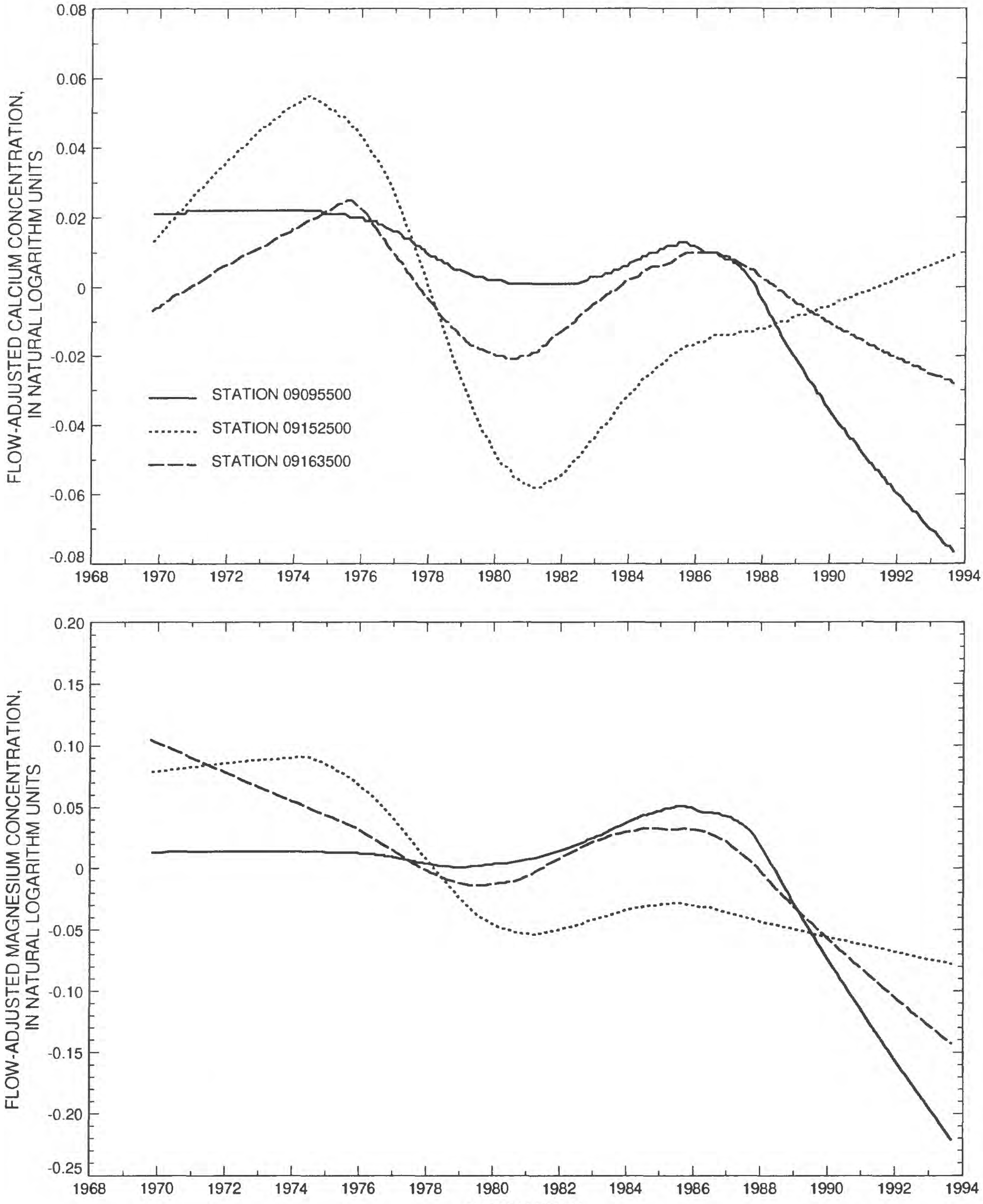

Figure 9. LOWESS smooth curves of periodic flow-adjusted calcium and magnesium concentrations for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93.

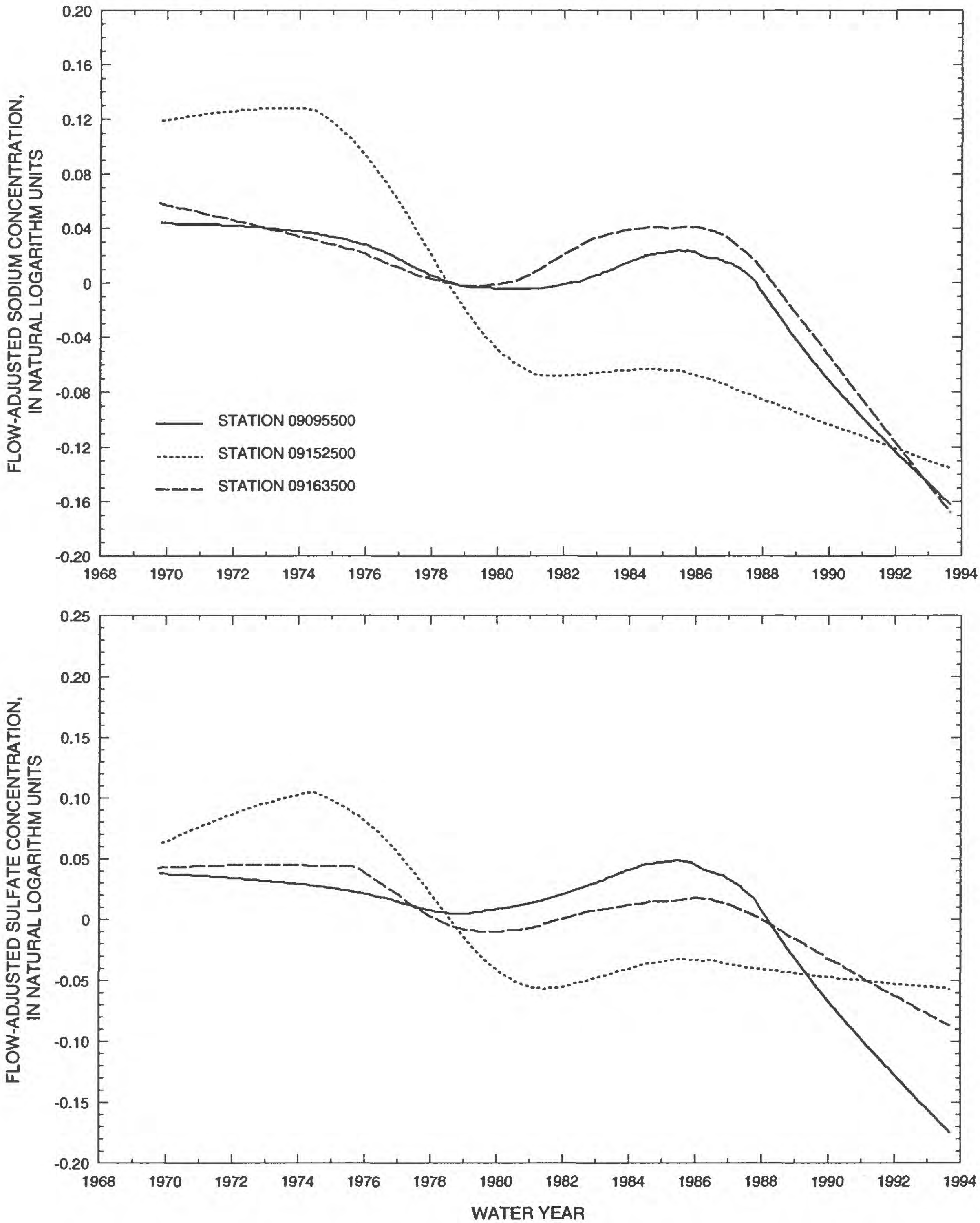

Figure 10. LOWESS smooth curves of periodic flow-adjusted sodium and sulfate concentrations for stations 09095500 Colorado River near Cameo, 09152500 Gunnison River near Grand Junction, and 09163500 Colorado River near the Colorado-Utah State line, water years 1970–93.

Relation of Trend Results for the Colorado and Gunnison Rivers to the Salinity-Control Projects

The purpose of the trend analyses for the Colorado and Gunnison Rivers was to determine if the salinity-control projects (Grand Valley Unit and Lower Gunnison Basin Unit) have decreased dissolved solids in the Colorado River. Station 09163500 on the Colorado River near the State line is downstream from both salinity-control projects, and decreases in dissolved-solids loads from irrigated areas could affect the dissolved solids at station 09163500. Trends of decreasing dissolved-solids concentrations or loads at station 09163500 could indicate that the salinity-control projects have removed some dissolved-solids loading to the Colorado River. Trends for station 09163500 need to be compared to trends at stations 09095500 (Colorado River near Cameo) and 09152500 (Gunnison River near Grand Junction) before conclusions regarding effects of salinity control can be stated with confidence. Station 09095500 is upstream from the Grand Valley, and station 09152500 is the outflow site for the Gunnison River Basin and is downstream from the Lower Gunnison Basin Unit. Trends at the inflow stations 09095500 and 09152500 potentially could be the primary cause of trends at station 09163500. Downward dissolved-solids trends at station 09095500 could not be caused by salinity-control projects in the Grand Valley or in the lower Gunnison River Basin. Trends at station 09152500 could be related to salinity-control work in the Lower Gunnison Basin Unit or to other factors affecting dissolved solids in the Gunnison River. Because the salinity-control project did not start until 1988 in the Lower Gunnison Basin Unit, there was less likelihood that significant trends at station 09152500 would be related to salinity-control projects.

A consideration in relating salinity trends in the Colorado River to salinity-control projects concerns the quantity of dissolved solids removed by the salinity-control projects. Have the salinity-control projects removed a sufficient quantity of dissolved-solids load to cause detectable trends in concentrations or loads in the Colorado River? The quantity of dissolved solids that should have been removed by BOR and USDA salinity-control projects in the Grand Valley and Lower Gunnison Basin Units by 1993 was estimated. Various reports (Bureau of Reclamation, 1986, 1987; Hedlund, 1994; U.S. Department of the Interior, 1994, 1995) were used to estimate the quantity of dissolved solids removed through water year 1993. Perhaps as much as 190,000 to 210,000 tons/yr of dissolved solids was removed by the salinity-control projects by 1993. About 75 percent of the estimated decrease in dissolved-solids load would have resulted from salinity-control projects in the Grand Valley Unit. The annual mean dissolved-solids load at station 09163500 for 1970–80 (table 1) was about 3.31 million tons; theoretically, the salinity-control projects would have caused about a 6-percent decrease in pre-project annual dissolved-solids loads in the Colorado River by 1993. However, the dissolved-solids load removed by 1993 was cumulative because the salinity-control work began in the Grand Valley Unit in 1979 and in the Lower Gunnison Basin Unit in 1988. Decreases in dissolved solids by 1993 have been incrementally added since 1979, and the year-to-year salinity decreases probably were variable, as more salinity-control work was done in some years than in other years. Because nearly all of the dissolved-solids loading from irrigation sources is from ground-water discharge, there might be some lag time between construction of a particular salinity-control feature and its effect on dissolved-solids loading to the Colorado River. There is the question whether incremental decreases in dissolved-solids loading from irrigated areas caused by the salinity-control projects over a 14-year period would produce detectable trends in dissolved-solids and major-ion concentrations or loads that are distinguishable from natural variability, climate-induced changes, or human-induced changes in the Upper Colorado River Basin. Some of the decreases in dissolved solids in the Colorado River caused by salinity-control projects could partly be offset by increases in dissolved solids from natural causes or by increasing development and water use in the Upper Colorado River Basin.

Trend tests indicated highly significant downward trends for the flow-adjusted dissolved-solids (table 2), magnesium, sodium, and sulfate concentrations (table 8) and for monthly and annual dissolved-solids loads (tables 3 and 4) at station 09163500 during water years 1986–93. If only the trends for station 09163500 on the Colorado River near the State line for 1986–93 were considered, a relation between the salinity-control projects and trends of decreasing dissolved-solids concentrations and loads and decreasing major-ion concentrations at station 09163500 could be inferred. The cumulative decreases in dissolved-solids loading to the Colorado River resulting from the salinity-control projects would have become more substantial after the mid-1980's. The LOWESS smooth curves for the flow-adjusted periodic concentration (figs. 9 and 10) and monthly load data (fig. 6) for 1970–93 and 1980–93 for station 09163500 indicated the beginning of downward trends after about 1985 or 1986, which is consistent with the trend test results. The LOWESS smooth curves for 1970–93 also indicated decreasing concentrations and loads in at least part of the pre-1980 record at station 09163500. The trend results and the LOWESS smooth curves indicated fairly definitive, downward trends in dissolved-solids and major-ion data at station 09163500 during 1986–93.

However, a relation between the salinity-control projects and trends at station 09163500 is not straightforward because of the trend results for station 09095500, the inflow site on the Colorado River that is upstream from the salinity-control projects. Significance levels and direction of change (downward) in the trend slopes for station 09095500 generally were the same as for station 09163500 for water years 1986–93 for many of the same variables, and LOWESS curves for the two stations show similar trends. For station 09095500 for 1986–93, all trends were highly significant and indicated decreasing flow-adjusted constituent concentrations and dissolved-solids loads. Although none of the flow-adjusted trends in salinity variables at station 09152500 on the Gunnison River were statistically significant (alpha 0.05) for 1986–93, all of the trend slopes were downward for flow-adjusted data, except for monthly dissolved-solids loads. Trends at station 09152500 could have cumulative effects with trends in the Colorado River at station 09095500 that could induce significant trends at station 09163500. The downward trends at station 09163500 during 1986–93 could have been related to other factors that affected dissolved solids in the Colorado River upstream from Cameo and in the Gunnison River Basin that were not related to the salinity-control projects.

In attempting to directly relate the trend results to salinity-control projects, it might seem logical to compare the magnitude of the trend slopes among the three stations to determine if upstream changes in concentrations and loads could cause the trends at the State line station on the Colorado River. If upstream changes were not sufficient to cause all of the downward trend at the State line station, then it could be inferred that the salinity-control projects were causing some of the decrease in dissolved solids in the Colorado River. However, the trend slopes computed for the nonparametric seasonal Kendall test are estimates of the overall monotonic rate of change for the period. The slopes are medians of all possible pairwise comparisons, and such values are not that informative for making direct comparisons between stations, which is especially true for the slope estimators for log-transformed data that were done for the trend tests on periodic data. Therefore, comparison of trend slopes among stations for variables that were determined by the nonparametric method, which includes dissolved-solids and major-ion concentrations and monthly dissolved-solids loads, was not done.

If trend slopes can be compared among the three stations for the trend tests that were done using parametric methods, such comparisons could indicate if the trends at station 09163500 on the Colorado River were related to salinity-control projects or if the trends were solely the result of trends at the inflow stations. The trend slopes for the annual and seasonal dissolved-solids loads were determined by linear regression, which is a parametric method. Trend slopes determined by linear regression represent a linear rate of change, and comparison of slopes among stations is more justified than it is for nonparametric trend slopes. However, many of the trends in the annual and seasonal loads (after flow adjustment) were not statistically significant (tables 4 and 5). The only annual or seasonal load that had significant trends at both Colorado River stations for the same time period were the trends for flow-adjusted annual dissolved-solids loads for water years 1986–93. Both stations on the Colorado River have highly significant downward trends in flow-adjusted annual loads for 1986–93. The trend slope in annual loads for the station near the State line (09163500) is 21,300 tons greater than the trend slope for the station near Cameo (09095500) (table 4). That annual rate of decrease represents a total decrease in dissolved-solids load of about 170,000 tons over the 8-year period. The 170,000-ton decrease in load at station 09163500 would be caused by decreases in dissolved-solids loads from the Grand Valley and from the Gunnison River. Compared to the projected decreases in dissolved-solids loads through 1993 for the salinity-control projects in the Grand Valley and Lower Gunnison Basin Units, the decrease in annual dissolved-solids load at station 09163500 seems plausible. If the trend slope (not significant) for the Gunnison River (station 09152500) also is subtracted from the slope for station 09163500, the net decrease in annual dissolved-solids load at station 091635000 is about 12,700 tons, or about 102,000 tons for 1986–93. The 102,000 tons represents only the decrease in dissolved-solids load from the Grand Valley in 1986–93. That load decrease also seems plausible when compared to the projected decreases in dissolved-solids load for the Grand Valley Unit. Neither of the previously stated decreases in annual dissolved-solids loads at station 09163500 for 1986–93 should be interpreted as direct measures of salinity decreases in the Colorado River that are attributable to the salinity-control projects. However, after accounting for the trend in annual loads in the Colorado River upstream from the Grand Valley (station 09095500), there seems to be evidence that decreases in the annual dissolved-solids loads in the Colorado River downstream from the Grand Valley (station 09163500) during 1986–93 were, in part, caused by salinity-control projects.

TREND ANALYSIS FOR THE WHITE RIVER

Preliminary analysis of data for water years 1978–84 indicated that plugging of the three wells on Meeker Dome in 1980–81 had caused a decrease in dissolved solids in the White River (CH2M Hill, 1982; Bureau of Reclamation, 1985b). The saline ground water that was discharging from the wells had high chloride and sodium concentrations, and there were marked decreases in concentrations of those ions. Trend tests on chloride and sodium data collected at three gaging stations on the White River in the Meeker Dome area were used to statistically verify the initial conclusions about the effects of the well plugging in 1980–81 and to verify that the well plugging has remained effective since 1984. Data collected at three gaging stations were tested: station 09304200 White River above Coal Creek; station 09304600 White River at Meeker; and station 09304800 White River below Meeker (fig. 2). Station 09304200 is upstream from Meeker Dome and is a background site relative to the project. Station 09304600 is downstream from Meeker Dome, and all effects on water quality from ground-water discharge from Meeker Dome were assumed to be between stations 09304200 and 09304600. Station 09304800 was the outflow site for the Meeker Dome Unit study, and dissolved-solids and major-ion concentrations were affected by natural and agricultural inflows between Meeker and this station. The period examined for trend tests was 1973–92.

Sampling frequency has varied during the period of study, as is apparent in the chloride and sodium data collected at stations 09304200 and 09304800 (figs. 11 and 12). There was a period of intensive sampling from July 1978 through September 1984 at stations 09304200 and 09304600 and from July 1978 through September 1983 at station 09304800, when samples were collected approximately weekly by the USGS for studies of the Meeker Dome Unit. Sampling was done on a quarterly basis in water years 1988–92 at stations 09304200 and 09304800. No chloride and sodium data were collected at station 09304600 after 1984 until water year 1995. Three sets of concurrent samples were collected in water year 1995 during November to early March at the three stations to confirm that chloride and sodium concentrations had not changed since 1992. Three sets of samples also were collected at station 09304500, White River near Meeker (adjacent to Meeker Dome, fig. 2), concurrently with sampling at the other three stations in water year 1995 for comparative purposes with samples collected at station 09304600.

A review of figure 11 indicates that chloride and sodium concentrations have not changed at the background station 09304200, except for an anomalous fluctuation in water year 1982. By contrast, review of figure 12 indicates a large change in chloride and sodium at station 09304800 after completion of well plugging in 1981. Step-trend tests were done to statistically verify those observations for stations 09304200 and 09304800, and trend tests also were done for station 09304600. Step-trend tests were done by dividing the chloride and sodium data into four periods during 1973–92. Data collected before July 1981 were in the pre-project period (PRE); data collected from July 1981 through March 1982 were in the transition period (TRANS); data collected from April 1982 through December 1984 were in the first post-project period (POST1); and data collected from May 1987 through September 1992 were in the second post-project period (POST2). The TRANS period was when existing saline ground water that had flowed through the wells prior to the well plugging was draining from the aquifer at Meeker Dome (Bureau of Reclamation, 1985b). Only stations 09304200 and 09304800 had data for the POST2 period. There virtually were no chloride and sodium data collected between the POST1 and POST2 periods.

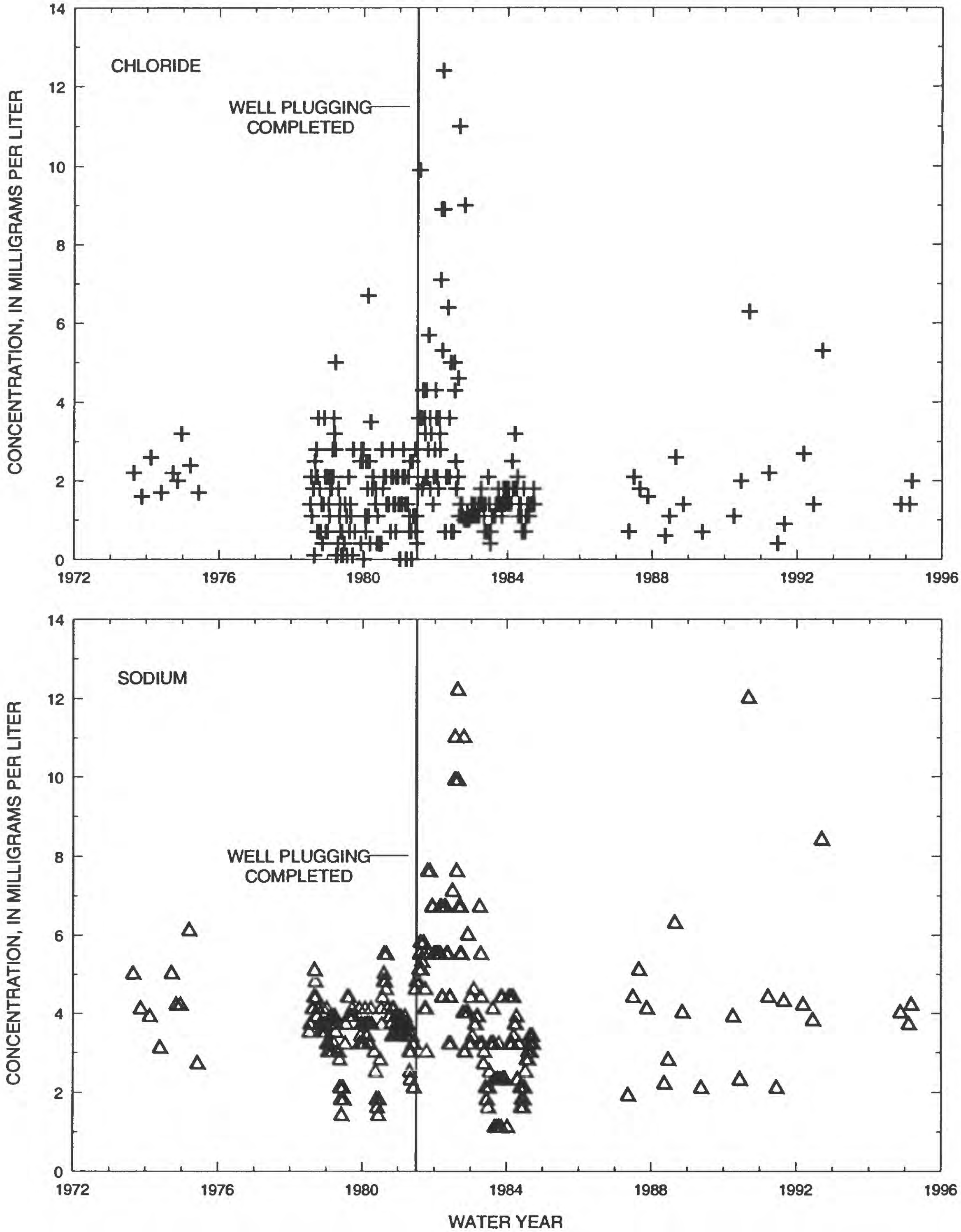

Figure 11. Periodic chloride and sodium concentrations for station 09304200 White River above Coal Creek, water years 1973–95.

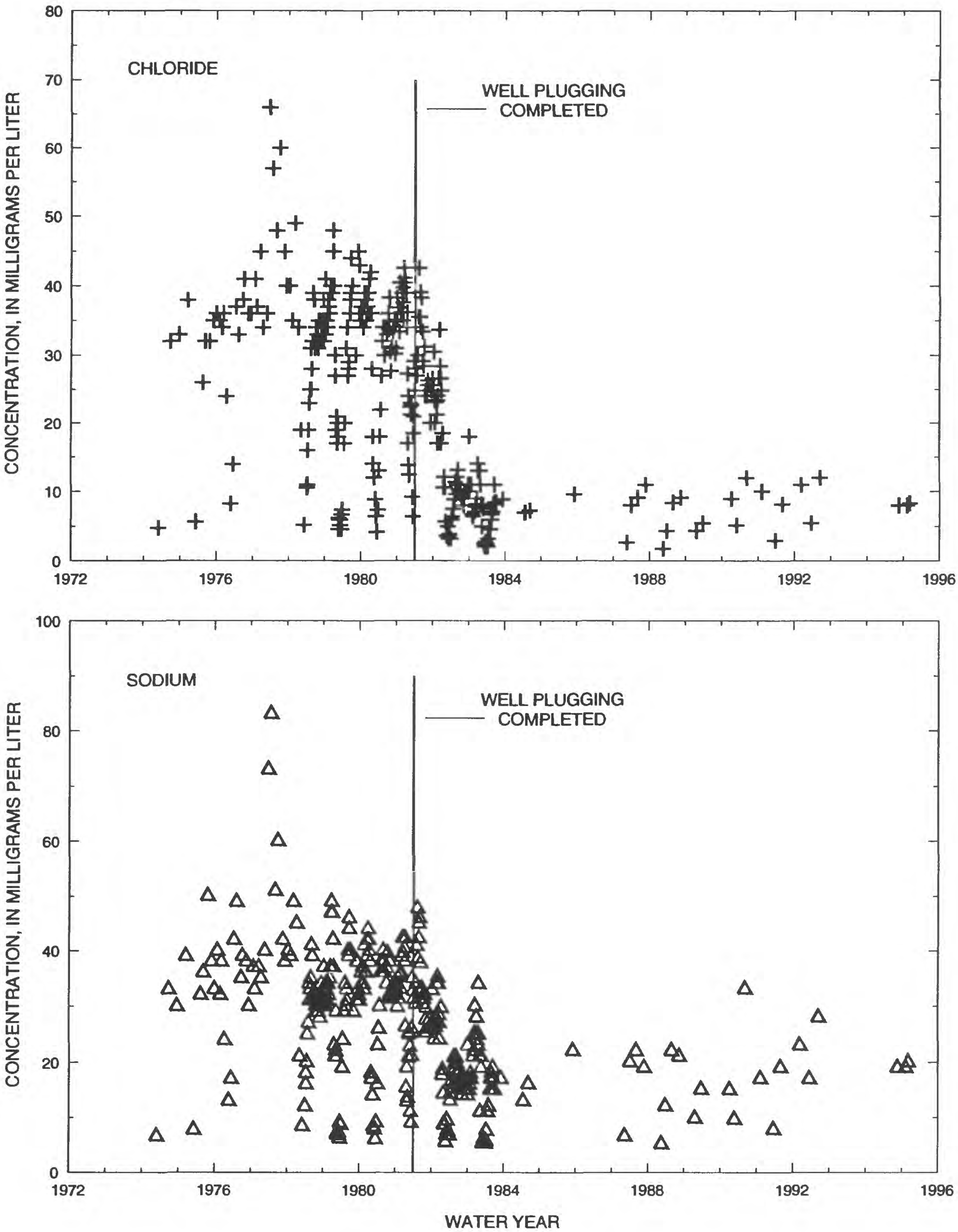

Figure 12. Periodic chloride and sodium concentrations for station 09304800 White River below Meeker, water years 1974–95.

The step-trend results of multiple t-tests on chloride and sodium concentrations and on ranks of the data (Wilcoxon rank-sum test) among the various periods for each station are summarized in table 9. The t-tests on concentrations (the T-group results in table 9) test for differences in means between data sets; t-tests on the ranks (the W-group results) test for differences in medians between data sets. An alpha level of 0.01 was selected as the significance level for the t-tests. At the background station 09304200, chloride and sodium have not changed, except for the anomalous fluctuations after completion of well plugging in 1981, and the TRANS period had significantly higher concentrations than the other three periods. The cause of the higher concentrations during the TRANS period at station 09304200 is unclear, but the BOR (1985b) reported that there might have been a short-term change in the ground-water flow system after the well plugging that caused discharge of some saline water into the White River near station 09304200. At stations 09304600 and 09304800, mean chloride and sodium concentrations were almost equal for the PRE and TRANS periods, and those periods had significantly greater concentrations than the post-project periods (table 9). All step-trend results were the same among stations and time periods when using the parametric or nonparametric method. Based on step-trend tests, significant decreases in chloride and sodium concentrations occurred in the White River after completion of the well plugging at Meeker Dome in 1981.

Mean chloride and sodium concentrations at station 09304800 for the POST1 and POST2 periods were not statistically different (table 9). Also, the chloride and sodium concentrations in the three sets of samples collected in water year 1995 at station 09304800 (fig. 12) were similar to concentrations in the POST2 period, and the 1995 data collected at station 09304600 were similar to the concentrations from the POST1 period for that station. The chloride and sodium data for the POST1 and POST2 periods and the new data collected in 1995 indicate that the well plugging at Meeker Dome has remained intact because there is no indication that chloride and sodium concentrations have increased in the White River since April 1982.

The chloride and sodium data collected in water year 1995 at the four gaging stations on the White River (fig. 2) were used to calculate dissolved-solids, chloride, and sodium loads for comparison of loading along the White River. The gain in dissolved solids between stations 09304200 and 09304600 primarily would be from ground-water discharge from Meeker Dome (natural discharge plus perhaps some small leakage in the wells) and from Coal Creek. The dissolved-solids loading into the White River between stations 09304200 and 09304600 accounted for about 24 percent of the dissolved-solids load, for about 75 percent of the chloride load, and for about 38 percent of the sodium load at station 09304800 for the three sets of samples. The chloride loading indicates that some ground water continues to discharge from the Meeker Dome area into the White River.

The step-trend results were based on chloride and sodium concentrations, and t-tests were not done on flow-adjusted concentrations. As in other drainage basins in the Upper Colorado River Basin, stream discharge was above normal in water years 1983 and 1984 in the White River Basin. The instantaneous stream discharges measured when chloride and sodium samples were collected indicated that the samples from the POST1 and POST2 periods generally were collected at higher stream discharges than the samples collected during the PRE period. However, the chloride and sodium data for stations 09304600 and 09304800 indicate that ion concentrations were much lower in the POST1 and POST2 periods compared to the PRE period for samples collected at approximately the same stream discharge. To more rigorously confirm that observation, ESTREND was used to determine flow-adjusted trends for chloride and sodium data during the intensive data-collection period (July 1978–September 1984). The well plugging would have had no measurable effect on streamflow in the White River; therefore, the flow-adjustment procedure was used to remove the variance in concentrations caused by changes in streamflow. The mean chloride and sodium concentrations of samples for each month were used for the monotonic trend tests because of the weekly sampling frequency. The flow-adjusted chloride and sodium trends for stations 09304600 and 09304800 are highly significant (p value less than 0.01) and indicated decreasing concentrations (table 10). LOWESS smooth curves were examined for flow-adjusted chloride and sodium concentrations, and the curves (not shown) indicated that flow-adjusted concentrations for stations 09304600 and 09304800 decreased after 1982. Therefore, the trend tests on flow-adjusted concentrations also confirm that significant decreases in chloride and sodium concentrations occurred in the White River downstream from Meeker Dome after completion of well plugging in 1981.

Table 9. Step-trend results on chloride and sodium concentrations for gaging stations 09304200 White River above Coal Creek, 09304600 White River at Meeker, and 09304800 White River below Meeker, water years 1973–92

[Mean is the mean constituent concentration in milligrams per liter; N, number of samples; periods are: PRE, prior to July 1981; TRANS, July 1981–March 1982; POST1, April 1982–December 1984; POST2, May 1987–September 1992; T-group, constituent means for periods with the same letter for the same station are not statistically different at the 0.01 significance level based on t-tests; W-group, periods with the same letter for the same station are not statistically different at the 0.01 significance level based on the Wilcoxon rank-sum test]

Station	Chloride					Sodium				
	Mean	N	Period	T-group	W-group	Mean	N	Period	T-group	W-group
09304200	4.0	34	TRANS	A	A	5.4	34	TRANS	A	A
09304200	1.9	18	POST2	B	B	4.4	18	POST2	B	B
09304200	1.7	120	POST1	B	B	3.8	116	POST1	B	B
09304200	1.6	141	PRE	B	B	3.6	141	PRE	B	B
09304600	31.5	135	PRE	A	A	26.5	135	PRE	A	A
09304600	29.8	32	TRANS	A	A	25.6	32	TRANS	A	A
09304600	7.7	120	POST1	B	B	11.5	120	POST1	B	B
09304800	30.4	195	PRE	A	A	31.6	38	TRANS	A	A
09304800	27.5	38	TRANS	A	A	31.2	194	PRE	A	A
09304800	8.3	79	POST1	B	B	17.0	19	POST2	B	B
09304800	7.4	19	POST2	B	B	16.1	79	POST1	B	B

Table 10. Monotonic trends in flow-adjusted mean monthly chloride and sodium concentrations for gaging stations 09304200 White River above Coal Creek, 09304600 White River at Meeker, and 09304800 White River below Meeker, July 1978–September 1984

[Period in month and year; slopes are in milligrams per liter per year; percent is the slope expressed as percent rate of change per year; p value is the significance level of the test; <, less than]

Station	Period	Chloride			Sodium		
		Slope	Percent	p value	Slope	Percent	p value
09304200	7/78–9/84	0.10	5.15	0.094	0.03	0.85	0.722
09304600	7/78–9/84	–4.73	–21.5	<.001	–2.43	–11.8	<.001
09304800	[1]7/78–9/83	–5.10	–21.9	<.001	–2.90	–11.0	<.001

[1]Data collected only through September 1983.

SUMMARY

Salinity, or the dissolved-solids concentration, can have adverse effects on crops and on municipal and industrial users in the Colorado River Basin. The Colorado River Basin Salinity Control Act was passed in 1974 and authorized construction and planning of salinity-control projects to maintain salinity at or below existing levels in the Colorado River. This report presents the trends in salinity data and relates the trend results to three salinity-control projects in western Colorado. Two of the salinity projects were in the Grand Valley and in the lower Gunnison River Basin, and their purpose was to decrease dissolved-solids loading to the Colorado River from irrigation-induced sources. The salinity-control projects began in 1979 in the Grand Valley and in 1988 in the lower Gunnison River Basin. The third project concerned dissolved-solids loading to the White River from three abandoned oil wells on Meeker Dome, near the town of Meeker. The wells were plugged by June 1981 by the Bureau of Reclamation.

Monthly and annual dissolved-solids loads were estimated for water years 1970–93 for four gaging stations that represent the major inflow and outflow of surface water in the Grand Valley. The load data were used to estimate annual dissolved-solids load from the Grand Valley and also were used in trend analysis. For water years 1970–93, the mean annual dissolved-solids (salinity) load in the Colorado River near the Colorado-Utah State line was about 3.32 million tons, and about 16 percent of that load was from the Grand Valley.

To determine if the salinity-control projects in the Grand Valley and the lower Gunnison River Basin have affected salinity in the Colorado River, monotonic trend analysis was done using periodic dissolved-solids and selected major-ion concentrations and monthly, annual, and seasonal dissolved-solids loads for three gaging stations. The stations were 09095500 Colorado River near Cameo, which is upstream from the Grand Valley; station 09152500 Gunnison River near Grand Junction, which is the outflow site for the Gunnison River; and station 09163500 Colorado River near the Colorado-Utah State line, which is downstream from the Gunnison River and the Grand Valley. Trend analysis also was done on the annual dissolved-solids load from the Grand Valley. The period selected for trend analysis was water years 1970–93 and two periods within those years, 1980–93 and 1986–93. The salinity-control projects would not have begun to affect dissolved solids in the Colorado River until 1980, and most of the reductions in dissolved solids probably occurred after 1985. Monotonic trends for dissolved-solids and major-ion concentrations and monthly dissolved-solids loads were examined using a computerized procedure developed by the U.S. Geological Survey called ESTREND. The program ESTREND uses the nonparametric seasonal Kendall test and determines the magnitude of the trend slope and the associated significance level of the test. Trends in annual and seasonal dissolved-solids loads at the three gaging stations and the annual Grand Valley dissolved-solids load were analyzed using linear regression, which is a parametric method. Because streamflow can affect trend tests, the original concentration and load data and the flow-adjusted data were analyzed for trends. A graphical technique that involved use of a data-smoothing procedure called LOWESS was used to aid in interpretation of the trend results.

Except for monthly dissolved-solids loads, many trends for the three time periods in dissolved-solids, calcium, magnesium, sodium, and sulfate concentrations and annual and seasonal dissolved-solids loads that were not adjusted for streamflow were not significant (significance level greater than 0.10) or were marginally significant (significance level between 0.05 and 0.10). After flow adjustment, many trend tests on dissolved-solids and the four major-ion concentrations and on the monthly loads were significant (significance level between 0.01 and 0.05) or were highly significant (significance level less than or equal to 0.01). Most of the trend tests on flow-adjusted annual and seasonal loads and on the annual Grand Valley dissolved-solids load were not significant. Flow-adjusted monthly dissolved-solids loads and many of the flow-adjusted concentrations had significant or highly significant downward trends during water years 1970–93 for all three stations. The LOWESS smoothing indicated downward trends in the pre-1980 period at all three stations and downward trends after 1985 or 1986 at the two Colorado River stations. Many trend tests for water years 1980–93 on flow-adjusted data were not significant. The flow-adjustment method might not have completely adjusted for the highly variable streamflows during 1980–93. Many of the flow-adjusted trends for water years 1980–93 and 1986–93 for the Gunnison River (at station 09152500) were not significant.

There were statistically significant downward trends during water years 1986–93 in the Colorado River near the State line (station 09163500) for flow-adjusted dissolved-solids, magnesium, sodium, and sulfate concentrations and flow-adjusted monthly and annual dissolved-solids loads. The cumulative effects of salinity-control projects in the Grand Valley and the lower Gunnison River Basin on dissolved solids in the Colorado River would have become more pronounced after the mid-1980's. The decreasing constituent concentrations and dissolved-solids loads at station 09163500 for 1986–93 also were reported for the Colorado River near Cameo (station 09095500), which is upstream from the salinity-control projects. Some of the decreases in dissolved solids at station 09163500 may have resulted from decreases in dissolved solids in the Colorado River at station 09095500. Apparently, there are natural or man-induced effects in the Upper Colorado River Basin that may be related to the trends of decreasing salinity in the Colorado River near Cameo. Comparison of trend slopes for annual dissolved-solids loads indicated that some of the decrease in dissolved-solids loads in the Colorado River near the State line since 1986 probably were related to salinity-control projects in the Grand Valley and in the lower Gunnison River Basin.

Step-trend tests on chloride and sodium data collected at three gaging stations on the White River in the vicinity of Meeker Dome were used to verify that plugging of three wells on Meeker Dome in 1980–81 was effective in decreasing the discharge of saline ground water from the leaking wells and to verify that the well plugging had remained intact through early 1995. Multiple t-tests were done on concentrations and on ranks of the concentrations to compare chloride and sodium data collected before and after the well plugging. Also, flow-adjusted chloride and sodium concentrations were tested using ESTREND. Chloride and sodium concentrations have remained relatively unchanged from water years 1973 to 1995 in the White River above Coal Creek, which is upstream from Meeker Dome. At two stations downstream from Meeker Dome, White River at Meeker and White River below Meeker, chloride and sodium concentrations had highly significant (significance level less than 0.01) decreases after the well plugging was completed. Chloride and sodium concentrations have not changed significantly since April 1982 in the White River downstream from Meeker Dome, indicating that the well plugging has remained intact.

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