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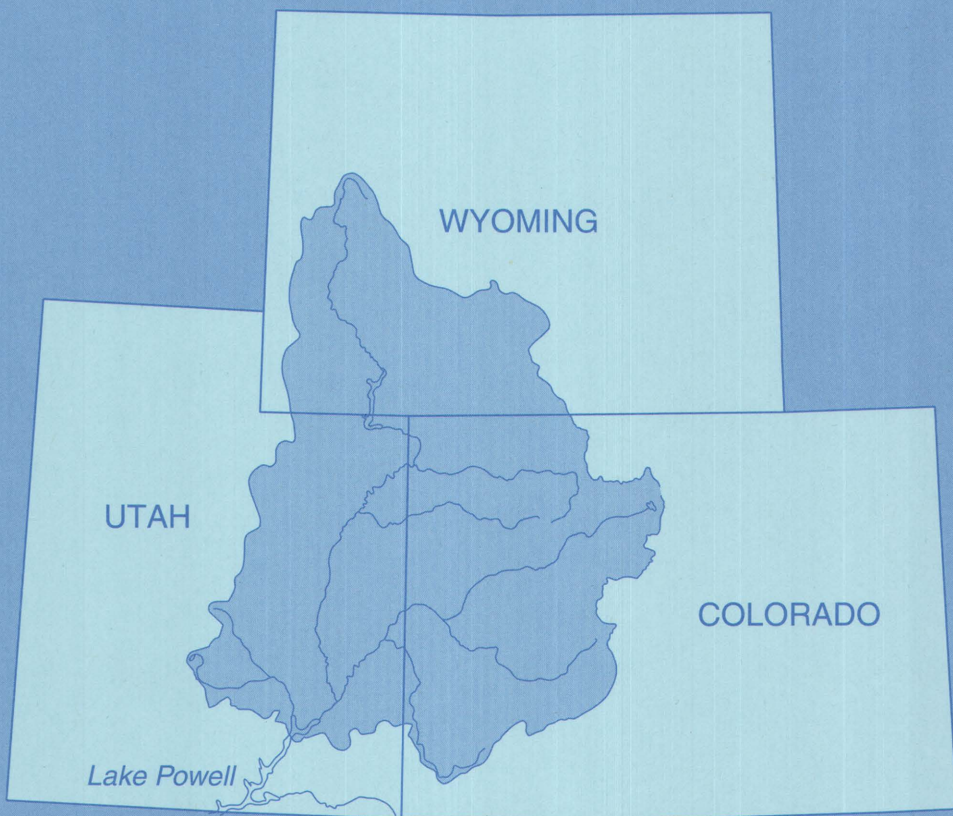
STREAMFLOW AND DISSOLVED-SOLIDS TRENDS, THROUGH 1996, IN THE COLORADO RIVER BASIN UPSTREAM FROM LAKE POWELL—COLORADO, UTAH, AND WYOMING

U.S. GEOLOGICAL SURVEY



Water-Resources Investigations Report 99–4097

Prepared in cooperation with the
BUREAU OF RECLAMATION

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By J.E. Vaill *and* David L. Butler

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Denver, Colorado
1999

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PLATE

[Plate is in pocket]

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CONVERSION FACTORS

Multiply	By	To obtain
inch	25.4	millimeter
foot (ft)	0.3048	meter
mile	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Streamflow and Dissolved Solids Trends, Through 1996, in the Colorado River Basin Upstream from Lake Powell—Colorado, Utah, and Wyoming

By J.E. Vaill *and* David L. Butler

Abstract

Annual and monthly concentrations and loads of dissolved solids were estimated for 60 streamflow-gaging stations in the Colorado River Basin upstream from Lake Powell. Trends in streamflow, dissolved-solids concentrations, and dissolved-solids loads were identified. Nonparametric trend-analysis techniques were used to determine step trends resulting from human activities and long-term monotonic trends.

A primary factor affecting streamflow has been the construction of large reservoirs. The focus of the trend analysis was on the period of record since the last major reservoir interventions in the basin in the early 1960's. Significant annual trends were identified at 31 of the 41 sites that had a sufficient period of record, and significant monthly trends were identified at 56 sites.

Generally, significant downward trends in annual dissolved-solids concentrations and loads were determined in the Colorado River Basin upstream from Lake Powell. Downward trends were determined in the Colorado River Basin upstream from the Green River. There were downward trends upstream and downstream from salinity control projects near Grand Junction, Colorado. In general, trends in the Green River Basin were downward except in the Yampa River Basin. The Yampa River Basin had significant upward trends in annual dissolved-solids concentrations and loads.

INTRODUCTION

The Colorado River and its tributaries compose one of the primary sources of water in the arid American West. The Colorado River provides 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 water uses, dissolved solids have increased in the Colorado River. The term "dissolved solids" refers to the sum of the individual dissolved constituents in water. Dissolved-solids concentration is the quantity of dissolved solids in a unit volume of water. Dissolved-solids load is the product of dissolved-solids concentration and streamflow and represents the quantity of dissolved material transported downstream. Dissolved solids can have adverse effects on crops and on municipal and industrial users, primarily in downstream parts of the basin. [The terms "salinity" and "dissolved solids" are considered synonymous and often are used interchangeably.]

The seven States (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) that encompass the Colorado River Basin adopted dissolved-solids criteria for the Lower Colorado River (below Lees Ferry, Arizona) in response to the Federal Water Pollution Control Act of 1972 (Public Law 92–500). Under Public Law 92–500, the Bureau of Reclamation (BOR) assumed the role of the lead agency responsible for planning and implementing a program to maintain dissolved-solids concentrations at or below existing levels to allow water development by States in the basin upstream from Lake Powell. Another important issue concerning dissolved solids in the Colorado River involved relations between the United States and Mexico. To decrease dissolved solids in the Colorado River Basin and to satisfy treaty obligations with Mexico, the U.S. Congress passed the Colorado River Basin Salinity Control Act of 1974 (Public Law 93–320). The act authorized construction of 4 salinity control projects and the development of plans for 12 other projects in the Colorado River Basin by the U.S. Department of the Interior (DOI). The BOR was named the lead agency for coordinating these salinity control projects. Public Law 93–320 also directed the Secretary of the Interior to cooperate with the Secretary of Agriculture in implementation of on-farm improvements as part of salinity control. A 1984 amendment (Public Law 98–569) to the Salinity Control Act provided a separate authority for implementing salinity control projects in the Colorado River Basin by the U.S. Department of Agriculture (USDA) and established cost effectiveness as the decision-making criterion for implementing new projects.

During a review of the Salinity Control Program in 1993, the DOI expressed concern that the effects of the salinity control projects had not been adequately determined or documented. To address concerns raised by the DOI, the BOR submitted a study plan to determine the effectiveness of the salinity control projects on reducing dissolved solids in the Colorado River. Beginning in 1994, as part of several cooperative agreements with the BOR, the U.S. Geological Survey (USGS) has completed studies to provide information that will help in evaluating and planning for salinity control needs. Butler (1996) reported a downward trend in dissolved solids in the Colorado River upstream and downstream from a salinity control project in the Grand Valley. Bauch and Spahr (1998) reported either no trend or a downward trend in dissolved solids at numerous sites in the Colorado River Basin upstream from Cameo, Colo., and in the Gunnison River Basin. It was not determined if the downward trends reported by Butler (1996) and Bauch and Spahr (1998) were occurring basinwide, nor was it determined if trends were related to changes in streamflow. The USGS began an evaluation in 1997, under a cooperative agreement with the BOR, of the trends in historical streamflow and dissolved-solids data for selected sites in the Colorado River Basin upstream from Lake Powell at Hite, Utah (pl. 1).

Purpose and Scope

This report presents results of trend analysis of monthly and annual streamflow and dissolved-solids concentrations and loads at selected streamflow-gaging stations in the Colorado River Basin upstream from Lake Powell at Hite, Utah. The general objective is to determine if there are basinwide trends in salinity. Included in the general objective is an update of the trend analyses for selected stations done by Liebermann and others (1989) using the additional period of record 1984–96. For sites that had major intervention (reservoirs and transbasin diversions), trend results for the post-intervention periods from this study were compared to results of the pre-intervention periods reported by Liebermann and others (1989). However, this report does not attempt to identify specific cause and effect relations.

The specific objectives are:

1. Compute monthly and annual mean streamflow for selected stations in the Colorado River Basin upstream from Lake Powell at Hite, Utah.
2. Compute monthly and annual dissolved-solids concentrations and loads for the selected stations.
3. Determine trends in monthly and annual streamflow and dissolved-solids concentrations and loads for the selected stations.
4. Determine changes in streamflow and dissolved-solids concentrations and loads related to major interventions such as reservoir construction, transbasin diversions, and salinity control projects.

Previous Investigations

Numerous studies concerning dissolved-solids concentrations and water quality in the Colorado River Basin have been done since the 1960's in response to international agreements, national legislation, and increasing demands for water development. The reports mentioned in this section are provided to give the reader an idea of the broad range in topics of previous reports. The report by Liebermann and others (1989) contains a more extensive list of reports. Ground-water investigations include those of Price and Arnow (1974), Warner and others (1985), and Freethey and Cordy (1991). The BOR has published biennial progress reports since 1963 documenting salinity, water use, and salinity control measures (U.S. Department of the Interior, 1985).

Beginning in 1985, the BOR and USDA jointly published an annual evaluation of salinity control programs (U.S. Department of the Interior, 1985). Prior to 1985, their reports were published separately. The U.S. Environmental Protection Agency (1971) also has studied water quality in the Colorado River Basin. Analyses of trends in dissolved solids in the basin were done by Kircher and others (1984), Moody and Mueller (1984), Liebermann and others (1989), Butler (1996, 1998), and Bauch and Spahr (1998).

DESCRIPTION OF STUDY AREA

The Colorado River Basin upstream from Lake Powell at Hite, Utah, encompasses about 72,340 mi^2 in the States of Colorado, Utah, and Wyoming (pl. 1) and includes the Green River Basin. About 3,960 mi^2 is in the Great Divide Basin of Wyoming and does not contribute to the streamflow of the Colorado River. Originally, the stream reach known as the Colorado River only extended upstream to the mouth of the Green River in Utah. Upstream from that confluence, it was known as the Grand River. In 1921, a joint resolution of Congress changed the name of the Grand River to the Colorado River (Follansbee, 1929).The Colorado River originates at the Continental Divide in the Rocky Mountains of Colorado and flows generally south and west through Utah into Arizona where it flows west and then south, forming part of the Arizona-Nevada State boundary and the entire Arizona-California State boundary. The Colorado River continues its flow into Mexico, where its natural outlet is the Gulf of California.

The study area was divided into two major regions to be consistent with the format used by Liebermann and others (1989): the region drained by the Colorado River and its tributaries upstream from the confluence with the Green River (called the Grand Region) and the region drained by the Green River and its tributaries plus the drainage to the Colorado River from the Green River confluence downstream to Lake Powell at Hite, Utah (called the Green Region). Most of the streamflow in the Colorado River in the Grand Region originates on the western slope of the Rocky Mountains in Colorado. Drainage areas in Utah contribute only a minor portion to the total streamflow from this region. Major tributaries of the region include the Eagle, Gunnison, and Dolores Rivers. Most of the flow in the Green Region originates in the Rocky Mountains of Colorado and Wyoming. Major tributaries to the Green River are the Big Sandy River, the Blacks Fork and Henrys Fork, the Yampa, Duchesne, White, Price, and San Rafael Rivers.

Physiography and Climate

Parts of the Colorado River Basin near the Continental Divide contain a series of mountain ranges and intermontane basins with elevations ranging from 5,000 ft to more than 14,000 ft above sea level. Parts of the Green River Basin in Utah and Wyoming contain isolated mountain ranges and semiarid intermontane basins with elevations ranging from 5,000 ft to 12,000 ft. The middle and lower parts of the basins are composed of plateaus, ranging in elevation from 3,100 ft to 11,000 ft, that are semiarid and deeply incised by numerous canyons.

Climate in the Colorado and Green River Basins is diverse because of physiographic features, prevailing wind patterns, and wide ranges in elevation and latitude. The northern and high-elevation parts of the basins are characterized by long, cold winters and short, warm summers. Plateaus and high, intermontane basins may have cold winters and hot summers. The southern parts of the two basins generally have mild winters and very hot summers. Mountainous areas generally receive most of their precipitation as snow, whereas the lower areas have dry winters and receive most of their precipitation from summer thunderstorms. Although the mountainous headwater areas of the basin receive a large quantity of snow, most of the basin consists of semiarid or arid plains that do not contribute substantially to streamflow. Almost 85 percent of the streamflow originates in 15 percent of the area (Stockton and Jacoby, 1976). Annual runoff from the Colorado and Green River Basins varies from 0.5 inch throughout much of the downstream drainage area to more than 20 inches in the high mountains (Liebermann and others, 1989).

Geology

The geology of the study area is diverse and characterized predominantly by igneous and metamorphic rocks in the high mountains and sedimentary rocks elsewhere. Structural features, including anticlines, domes, and faults, expose large sequences of strata. Several geologic units are major natural contributors of dissolved solids to streams. The most important formation regarding salinity sources is the Upper Cretaceous Mancos Shale and equivalent formations such as the Tropic Shale that contain gypsum, calcite, dolomite, and sodium-rich clay. The Mancos Shale is most widely exposed in the lower Gunnison and Uncompahgre River Basins, the Colorado River Basin downstream from Grand Junction, and the Yampa, Price, and San Rafael River Basins. Other major natural salt sources include the Paradox Member of the Hermosa Formation near the Colorado-Utah border, several coal-bearing formations in the upper basins, the Green River Formation near the Colorado-Utah-Wyoming border, and the Uinta Formation near the Utah-Wyoming border. These formations contain halite, nahcolite, dolomite, calcite, and gypsum. A more detailed description of the geology and mineral characteristics of various formations is contained in Liebermann and others (1989).

Human Activities Potentially Affecting Dissolved Solids

Much of the Colorado and Green River Basins are composed of sparsely populated rural areas, and most of the population is concentrated in or near towns and cities. Agriculture is one of the primary industries and sources of income in the basin. Irrigated agriculture was reported to be a major source of dissolved solids to the Colorado River (Iorns and others, 1965). Salinity control measures were initiated in the 1970's to decrease dissolved-solids loading from some irrigated areas. Mining brought the first non-native settlers to the region and is still the major industry in some areas. Oil and gas have been produced in the basins since the early 1900's. Mining and energy resource development can contribute dissolved solids to water by mineral dissolution from exposed unweathered soils or from surface runoff from spoil piles. Abandoned oil and gas wells can serve as conduits for deep, saline ground water to enter stream systems.

Several metropolitan areas outside the Colorado and Green River Basins are dependent on water diversions from the headwaters of the basins. Also, major reservoir construction for water storage and flood control has affected streamflow. As the population in the Western United States continues to increase, the demand for water, energy, and food produced in the basin also increases.

Irrigation

Most of the water used in the Colorado and Green River Basins is for irrigated agriculture. The practice of irrigation began with the first settlements and increased substantially after the passage of the Reclamation Act in 1902 (Follansbee, 1929). Most of the irrigated lands are in river valleys or on plateaus and are supplied by an extensive system of canals and ditches.

Irrigated agriculture is one of the largest sources of dissolved solids in the Colorado and Green River Basins (U.S. Department of the Interior, 1997). Irrigation return flows generally have a higher dissolved-solids concentration than the applied water because of the loading effect of salt dissolution in the soil and subsurface materials and the concentrating effect of evapotranspiration. Many low-elevation areas in the basins have low natural runoff and thus do not contribute significant dissolved-solids loading. The increase in dissolved-solids loading due to irrigation can only be estimated because collection of streamflow and water-quality records did not begin until well after irrigation started.

Salinity Control Program

Title II of the Colorado River Basin Salinity Control Act of 1974 (Public Law 93–320) authorized several BOR salinity control projects within the study area. Subsequent amendments (Public Laws 96–375 and 98–569) to the act have authorized additional BOR and USDA salinity control projects. Salinity control projects in the Colorado River Basin upstream from the confluence with the Green River are the Grand Valley, Lower Gunnison, and Paradox Units. The Grand Valley Unit is a combined effort of the BOR and USDA to reduce salinity added to the Colorado River as a result of conveyance system seepage and irrigation practices. The BOR has lined numerous canals and laterals within the project to decrease the salinity contribution from this area. Salinity contributions from the Lower Gunnison Unit are primarily from irrigation return flow passing through highly saline soils and the Mancos Shale (U.S. Department of the Interior, 1997). The BOR has installed an expansion of the existing culinary water system using small-diameter pipe to eliminate winter livestock watering from the unlined canal and lateral system. The USDA has initiated improved irrigation methods (such as irrigation-water control structures and irrigation systems) within the area. The Paradox Valley Unit is located in southwestern Colorado along the Dolores River, a tributary to the Colorado River. Salinity contributions from this area are related to the collapsed salt dome that forms Paradox Valley. Ground water in the valley comes in contact with the surface of the salt dome where it becomes nearly saturated with sodium chloride (U.S. Department of the Interior, 1997). The saline ground water then surfaces in the Dolores River. An ongoing effort by the BOR has been to drill a series of brine interception wells along one side of the river in the valley and dispose of the brine by deep-well injection. The Meeker Dome Unit is located on the White River (a tributary to the Green River) in northwestern Colorado. Salinity increases from this area to the river were due to discharge of highly saline water from several abandoned oil and gas exploratory wells (Bureau of Reclamation, 1985). The BOR effort consisted of plugging eight wells in the area that were identified as contributors of salinity to the White River.

Salinity control efforts in the Big Sandy River Unit, on the Big Sandy River west of Eden, Wyo. (pl. 1), was a combined effort of the BOR and USDA to reduce salinity through on-farm irrigation practices and a limited amount of selective lining of canals and laterals. The Uinta Basin Salinity Control Unit is located in northwestern Utah in the Duchesne and Uinta River drainages that contribute to the Green River. The increase in salinity from this area is due to the dissolution of salts in the soils and subsurface materials from application of irrigation water (U.S. Department of the Interior, 1997). Salinity control efforts in this project consisted of lining of selected canals and laterals by the BOR and introduction of more efficient irrigation practices by the USDA.

Transbasin Diversions and Reservoirs

Large volumes of water are exported from the Colorado and Green River Basins to other basins. Transbasin exports may increase the downstream concentration of dissolved solids. Exports are primarily from the headwater regions where dissolved-solids concentrations are low. The removal of this low-salinity water leaves less water for dilution downstream.

The major effect of reservoirs on streamflow is to decrease the seasonal variability in streamflow by decreasing the peak flows occurring during the snowmelt seasons in spring and early summer and by increasing the low-flow discharges during late summer, autumn, and winter. The major effect of reservoirs on dissolved solids is associated with evaporation. Evaporation from a reservoir removes water but leaves the dissolved solids behind; this increases the concentration of dissolved solids in the reservoir and ultimately in the water released.

METHODS OF DATA ANALYSIS

The sole source of the data used in this report was the U.S. Geological Survey data base. All daily values of streamflow, specific conductance, and water-quality analyses were retrieved from these data sources.

Selection of Streamflow-Gaging Stations

Initially, site selection was based on the streamflow-gaging stations in the Colorado and Green River Basins analyzed for the period of record through 1983 by Liebermann and others (1989). Of the 59 stations upstream from Lake Powell at Hite, Utah, that were analyzed for trends in Liebermann and others (1989), 28 stations had sufficient dissolved-solids data collected after 1983 to conduct further trend analysis. Retrievals from the U.S. Geological Survey water-quality data base were used to identify additional gaging stations that had (through 1996) sufficient data to do trend analysis. The data retrievals identified 32 additional gaging stations not included in Liebermann and others (1989) with sufficient data for trend analysis; those 32 stations are included in this report. The 60 stations are listed in table 1 and shown on plate 1.

Table 1. List of streamflow-gaging stations used in trend analysis

[Period of water-quality record is complete water years (October 1 through September 30) used in this report, but actual record length may be different; --, not applicable]

Site number (plate 1)	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Period of water-quality record
		GRAND REGION		
		Upper Colorado Subregion		
1	09013000	Alva B. Adams Tunnel at East Portal near Estes Park, Colo.*	--	1976–96
2	09034500	Colorado River at Hot Sulphur Springs, Colo.*	825	1947–94
3	09041090	Muddy Creek above Antelope Creek near Kremmling, Colo.	145	1991–96
4	09041500	Muddy Creek at Kremmling, Colo.	290	1985–95
5	09058000	Colorado River near Kremmling, Colo.	2,382	1982–96
6	09060550	Rock Creek at Crater, Colo.	72.6	1985–96
7	09060770	Rock Creek at McCoy, Colo.	198	1985–93
8	09067000	Beaver Creek at Avon, Colo.	14.8	1975–87
9	09069000	Eagle River at Gypsum, Colo.*	944	1947–96
10	09071750	Colorado River above Glenwood Springs, Colo.*	4,566	1950–96
11	09095500	Colorado River near Cameo, Colo.*	8,050	1934–96
12	09105000	Plateau Creek near Cameo, Colo.*	592	1969–79, 1991–96
		Gunnison Subregion		
13	09147500	Uncompahgre River at Colona, Colo.	448	1988–96
14	09149500	Uncompahgre River at Delta, Colo.*	1,115	1959–80, 1991–96
15	09152500	Gunnison River near Grand Junction, Colo.*	7,928	1934–96
		Lower Colorado Subregion		
16	09163500	Colorado River near Colorado-Utah State Line, Colo.*	17,843	1966–96
17	09169500	Dolores River at Bedrock, Colo.	2,024	1988–96
18	09171100	Dolores River near Bedrock, Colo.	2,145	1988–96
19	09179200	Salt Creek near Gateway, Colo.	31.2	1980–85
20	09180000	Dolores River near Cisco, Utah*	4,580	1952–95
21	09180500	Colorado River near Cisco, Utah*	24,100	1950–96
		GREEN REGION		
		Upper Green Subregion		
22	09209400	Green River near La Barge, Wyo.*	3,910	1964–94
23	09211200	Green River below Fontenelle Reservoir, Wyo.*	4,280	1968–96
24	09215550	Big Sandy River below Farson, Wyo.	1,097	1982–96
25	09216050	Big Sandy River at Gasson Bridge, near Eden, Wyo.*	1,720	1975–96
26	09217000	Green River near Green River, Wyo.*	14,000	1952–96
27	09224700	Blacks Fork near Little America, Wyo.*	3,100	1965–96
28	09234500	Green River near Greendale, Utah*	19,350	1941–96
29	09237500	Yampa River below Stagecoach Reservoir, Colo.	278	1985–92
30	09242500	Elk River near Milner, Colo.	415	1991–96

Table 1. List of streamflow-gaging stations used in trend analysis—Continued

[Period of water-quality record is complete water years (October 1 through September 30) used in this report, but actual record length may be different; --, not applicable]

Site number (plate 1)	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Period of water-quality record
31	09243700	Middle Creek near Oak Creek, Colo.	23.5	1976–88
32	09243900	Foidel Creek at mouth, near Oak Creek, Colo.	17.5	1976–88
33	09249750	Williams Fork at mouth, near Hamilton, Colo.	419	1986–92
34	09251000	Yampa River near Maybell, Colo.*	3,410	1951–96
35	09253000	Little Snake River near Slater, Colo.	285	1978–86
36	09256000	Savery Creek near Savery, Wyo.	330	1986–91
37	09261000	Green River near Jensen, Utah*	29,660	1962–92
38	09302000	Duchesne River near Randlett, Utah*	4,247	1941–96
		White Subregion		
39	09303000	North Fork White River at Buford, Colo.	259	1982–92, 1995–96
40	09304000	South Fork White River near Buford, Colo.	177	1986–92, 1995–96
41	09304200	White River above Coal Creek, near Meeker, Colo.	648	1979–84, 1987–92, 1995–96
42	09304800	White River below Meeker, Colo.*	1,024	1974–83, 1987–96
43	09306007	Piceance Creek below Rio Blanco, Colo.	177	1975–96
44	09306022	Stewart Gulch above West Fork near Rio Blanco, Colo.	44.0	1975–85
45	09306058	Willow Creek near Rio Blanco, Colo.	48.4	1975–85
46	09306061	Piceance Creek above Hunter Creek, near Rio Blanco, Colo.	309	1975–87
47	09306200	Piceance Creek below Ryan Gulch, near Rio Blanco, Colo.*	506	1971–96
48	09306222	Piceance Creek at White River, Colo.*	652	1971–87, 1990–96
49	09306242	Corral Gulch near Rangely, Colo.	31.6	1975–96
50	09306255	Yellow Creek near White River, Colo.*	262	1974–82, 1989–96
51	09306290	White River below Boise Creek near Rangely, Colo.	2,530	1983–96
52	09306500	White River near Watson, Utah*	4,020	1951–96
		Lower Green and Main Stem Subregions		
53	09307200	Pariette Draw near Ouray, Utah	153	1976–84
54	09307300	Pariette Draw at mouth, near Ouray, Utah	298	1976–84
55	09310700	Mud Creek below Winter Quarters Canyon at Scofield, Utah	29.1	1979–84
56	09314500	Price River at Woodside, Utah*	1,540	1949–88
57	09315000	Green River at Green River, Utah*	44,850	1929–96
58	09328500	San Rafael River near Green River, Utah*	1,628	1947–96
59	09330410	Bull Creek near Hanksville, Utah	7.53	1984–90
60	09331950	Christiansen Wash near Emery, Utah	13.6	1979–84

*Data from site were analyzed by Liebermann and others (1989).

Estimation of Dissolved-Solids Concentrations and Loads

Annual and monthly dissolved-solids concentrations and loads were computed using a program called SLOAD (Salt LOAD) developed by Liebermann and others (1987). Daily streamflow, daily specific conductance, and periodic dissolved-solids data are used to estimate loads. Regression equations are computed using a 3-year moving average that relates dissolved-solids load to streamflow and dissolved-solids load to streamflow and specific conductance. The equations are then used to compute daily loads from daily streamflow and, if available, daily specific conductance. Daily loads are summed to obtain monthly and annual dissolved-solids loads. The SLOAD program also computes the monthly and annual streamflow. The flow-weighted monthly and annual dissolved-solids concentrations are then computed from the streamflow and load data for each month and each water year (October to September).

Monotonic 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 streamflow and dissolved-solids data. A monotonic trend means that the water-quality variable of interest has changed over time, but the monotonic trend test will not specify if the change occurred continuously, linearly, or in abrupt or discrete steps (Hirsch and others, 1991). In this report, monotonic trend analysis is referred to as trend analysis in the discussion for each site.

Monotonic trends were examined on annual and monthly streamflow, dissolved-solids concentrations, and dissolved-solids loads using a computerized procedure called EStimate TREND (ESTREND) (Schertz and others, 1991). A nonparametric test called the seasonal Kendall test is used in ESTREND for monotonic trend analysis. The seasonal Kendall test accounts for seasonality by comparing only water-quality data collected during the same seasonal period 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 seasonal period (Hirsch and others, 1982). The null hypothesis for the test is that there is no trend. Compared to parametric tests, nonparametric procedures have 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).

Dissolved-solids and major-ion concentrations commonly are highly correlated with streamflow. In the Colorado and Green River Basins, increasing streamflow generally 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 variability of concentrations and loads caused by streamflow might overwhelm any human-induced changes; therefore, removal of the variance due to streamflow is desirable. For example, if all other dissolved-solids inputs are constant, an upward trend in streamflow could cause a downward trend in dissolved-solids concentration and an upward trend in dissolved-solids load. After flow adjustment, trends in dissolved-solids concentration and load might not be significant because the effect of streamflow was removed. It is possible that an upward trend in dissolved-solids concentration before flow adjustment could become downward after flow adjustment. This would occur if the input of dissolved solids actually decreased during a period of decreasing streamflow. If the streamflow-induced variability in salinity is decreased, then the chance of detecting a trend that resulted from some influence other than streamflow is enhanced. Usually, monotonic trend tests on flow-adjusted water-quality data are not done for 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. Second, 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, 1989; Schertz and others, 1991). Third, the flow-adjusted concentrations are then tested for trends with the seasonal Kendall test. Multiple regression of the logarithm of concentration to the logarithm of streamflow and the square of the logarithm of streamflow was used for flow adjustment of dissolved-solids concentrations (monthly and annual). A linear regression was used for flow adjustment of annual and monthly loads. Flow-adjusted concentrations should not be confused with flow-weighted concentrations. An annual flow-weighted concentration is determined by dividing the total annual load by total annual flow (plus a conversion factor). Therefore, the concentration is "weighted" by flow and can be defined as the concentration resulting from the filling of an empty reservoir with a year's streamflow.

The seasonal Kendall test was applied to the monthly and annual time series of streamflow, dissolved-solids concentration, dissolved-solids loads, and flow-adjusted concentrations and loads. A minimum of 10 years of record was needed for annual trend tests and a minimum of 5 years for monthly tests is recommended by Schertz and others (1991) for running ESTREND. 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, 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. The percent rate of change is extracted from the slope of the residuals trend and is then 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; in other words, the probability increases that there is in fact a trend in the data. Trends were deemed significant if the p value was 0.05 or less. When comparing trend results between annual and monthly data, it should be noted that the p value is affected by sample size. For a given magnitude 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 for annual data than for monthly data.

The trend slopes derived by ESTREND represent a median rate of change of streamflow, concentration, or load and are measures of monotonic trends during the selected time period. A positive slope indicates and upward trend and a negative slope indicates a downward trend. The slope is an approximation of the variation over the entire period, and it may mask short-term variations. Monotonic trend slopes are not specific about when changes occurred; however, more specific information can be obtained by other methods. 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 it may be highly nonlinear. The curve-smoothing technique was used in conjunction with monotonic trend results to determine in what part of the record a trend had occurred in selected cases.

Step Trend Analysis

Step trend tests are used instead of monotonic tests if a known event or change occurred at a specific time in a watershed and 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. 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. Step trend tests were done using procedures in SAS (SAS Institute, Inc., 1982).

Liebermann and others (1989) performed step trend analyses using unadjusted streamflow and dissolved-solids data. Step trend analyses, at the same sites, in this report were also performed using unadjusted data in order to be comparable with results from Liebermann and others (1989). Results of step trend analysis related to reservoirs may not be very conclusive. Changes in streamflow and salinity may have occurred over a period of time rather than at a specific time. Also, multiple interventions that may have occurred are hard to distinguish due to the concurrent time periods of the interventions.

CHARACTERISTICS AND TRENDS OF STREAMFLOW AND DISSOLVED SOLIDS

This section contains a summary and analysis of the historical streamflow and water-quality data at the 60 selected stations. The analysis contains determination of annual and monthly means of streamflow, dissolved-solids concentrations, dissolved-solids loads, and results of trend analyses. Trends in annual data are not reported for a site if the period of record is less than 10 years. Trends in monthly data are reported for all sites. The period of record ranged from 5 to 68 years at the 60 stations and includes data through 1996. Statistics and trends were computed for the period of record unless there was a major intervention such as reservoir construction or a large transbasin diversion that may have affected streamflow. For sites with major interventions, statistics and trends were computed for pre- and post-intervention periods.

Grand Region

Streamflow and water-quality data from 21 sites were analyzed for the Grand Region (pl. 1 and table 1). Long-term mean annual streamflow, flow-weighted dissolved-solids concentrations, and dissolved-solids loads were computed for each site (table 2). Results of trend analysis at the sites are reported in table 3 and results of step trend analysis at selected sites are reported in table 4. To be consistent with the format of Liebermann and others (1989) and for discussion purposes, the Grand Region was subdivided into the Upper Colorado subregion, the Gunnison subregion, and the Lower Cond Region.

Upper Colorado Subregion

The Upper Colorado Subregion includes the main-stem Colorado River from its headwaters to the confluence with the Gunnison River. Numerous diversions and reservoirs affect the streamflow in this subregion. Although small diversions began about 1900, major diversions within the subregion did not being until 1950 (Alva B. Adams Tunnel).

Streamflow and water-quality data from 12 sites were used in the trend analyses for the Upper Colorado Subregion. Two sites within the subregion did not have a sufficient period of record (at least 10 years) for annual analysis (table 3).

Alva B. Adams Tunnel at East Portal near Estes Park, Colorado (Site 1)

The gaging station at this site monitors water exported from Grand Lake. Samples collected at this site represent the water quality in the headwaters of the Colorado River. Trend analysis of mean annual streamflow and dissolved-solids concentrations and loads did not indicate any significant trends in the annual data (table 3).

Trend analysis of monthly streamflow, dissolved-solids concentrations, and loads determined a significant ($p < 0.05$) upward trend only for dissolved-solids concentrations. Trend analysis of the flow-adjusted monthly dissolved-solids concentrations and load data indicated significant upward trends (table 3).

Table 2. Mean annual streamflow, flow-weighted dissolved-solids concentrations, and dissolved-solids loads, Grand Region

[Period of record in complete water years (October 1 through September 30); mg/L, milligrams per liter]

Site (plate 1 and table 1)	Period of record	Streamflow		Dissolved solids	
		(acre-feet)	(cubic feet per second)	Flow-weighted concentration (mg/L)	Load (tons)
1	1976-96	231,700	320	28.9	9,100
2	1947-94	192,400	266	70.5	18,500
3	1991-96	42,800	59.0	139	8,100
4	1985-95	58,300	80.5	345	27,400
5	1982-96	821,400	1,130	126	141,000
6	1985-96	22,400	31.0	58.5	1,800
7	1985-93	44,500	61.4	155	9,400
8	1975-87	9,900	13.7	79.9	1,100
9	1947-96	417,800	577	282	160,000
10	1950-96	1,579,000	2,180	263	564,000
11	1934-49	2,986,000	4,120	377	1,530,000
11	1950-96	2,763,000	3,810	389	1,460,000
12	1969-79	124,300	172	325	55,000
12	1991-96	163,900	226	248	55,300
13	1988-96	166,300	230	317	71,800
14	1959-80	200,000	276	1,260	342,000
14	1991-96	234,700	324	917	293,000
15	1934-65	1,692,000	2,330	620	1,430,000
15	1966-96	1,876,000	2,590	497	1,270,000
16	1966-96	4,689,000	6,470	515	3,280,000
17	1988-96	187,000	258	263	67,000
18	1988-96	189,000	261	689	177,000
19	1980-85	1,190	1.6	8,740	14,000
20	1952-83	581,500	803	584	462,000
20	1984-95	705,500	974	466	447,000
21	1950-65	4,595,000	6,340	615	3,840,000
21	1966-96	5,143,000	7,100	522	3,650,000

Colorado River at Hot Sulphur Springs, Colorado (Site 2)

The trends in mean annual streamflow and flow-adjusted annual dissolved-solids concentrations and loads for the period of record 1947–94 at this site were not statistically significant (table 3). Liebermann and others (1989) reported a significant upward trend only for mean annual dissolved-solids concentrations for the period 1947–83. Bauch and Spahr (1998) reported a downward trend in flow-adjusted annual dissolved-solids loads for the period 1986–93 but not for 1970–93.

Trend analysis of the monthly data for 1947–94 indicated a significant downward trend in streamflow. A significant upward trend in dissolved-solids concentrations and a significant downward trend in dissolved-solids load were determined (table 3). After flow adjustment of the data, the trends were not statistically significant. Bauch and Spahr (1998) reported a downward trend in flow-adjusted monthly dissolved-solids loads for the period 1970–93.

Table 3. Results of monotonic trend analysis for selected time periods at sites in the Grand Region

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; percent is the slope expressed as the percent change per year; A, annual time series; M, monthly time series; p value, attained significance level; --, not applicable; <, less than]

Site number (plate 1, table 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
1	A/76-96	no	-1.8	-0.55	0.381	0.06	0.21	0.251	-59.0	-0.65	0.291
	A/76-96	yes	--	--	--	.07	.23	.264	12.4	.14	.450
	M/76-96	no	-2.2	-.70	.134	.12	.40	<.001	-3.2	-.43	.408
	M/76-96	yes	--	--	--	.11	.39	<.001	2.1	.28	<.001
2	A/47-94	no	-1.8	-.69	.090	.24	.31	.045	-110	-.60	.104
	A/47-94	yes	--	--	--	.06	.07	.230	9.5	.05	.461
	M/47-94	no	-.35	-.14	<.001	.08	.09	.003	-2.1	-.14	.001
	M/47-94	yes	--	--	--	.03	.04	.173	.12	.01	.636
3	M/90-96	no	.90	1.50	.001	-2.52	-.96	.473	17.3	2.85	.002
	M/90-96	yes	--	--	--	.39	.15	.666	7.2	1.18	.013
4	A/85-95	no	-7.50	-9.32	.062	3.13	.87	.533	-2,055	-7.52	.013
	A/85-95	yes	--	--	--	-4.19	-1.17	.119	-364	-1.33	.276
	M/85-95	no	-1.78	-2.38	<.001	7.71	1.21	.026	-94.6	-4.15	<.001
	M/85-95	yes	--	--	--	-11.78	-1.85	<.001	-44.0	-1.93	<.001
5	A/82-96	no	-17.2	-1.52	.553	.76	.57	.767	-2,205	-1.56	.488
	A/82-96	yes	--	--	--	-.36	-.27	.322	-172	-.12	.692
	M/82-96	no	-13.6	-1.24	.001	.49	.34	.219	-170	-1.44	<.001
	M/82-96	yes	--	--	--	-.03	-.02	.786	-9.76	-.08	.520
6	A/85-96	no	-.53	-1.70	.837	-1.12	-1.89	.047	-91.9	-5.15	.115
	A/85-96	yes	--	--	--	-1.45	-2.45	.011	-45.0	-2.52	.002
	M/85-96	no	-.57	-1.85	<.001	-.51	-.63	<.001	-4.67	-3.14	<.001
	M/85-96	yes	--	--	--	-1.37	-1.67	<.001	-2.69	-1.81	<.001
7	M/85-93	no	-2.76	-4.89	<.001	4.69	2.25	<.001	-43.3	-6.24	<.001
	M/85-93	yes	--	--	--	-3.91	-1.87	.002	-19.0	-2.74	<.001
8	A/75-87	no	.38	2.78	.246	.96	1.16	.502	37.7	3.50	.127
	A/75-87	yes	--	--	--	1.71	2.06	.127	14.6	1.36	.127
	M/75-87	no	.23	1.67	<.001	.36	.26	.360	3.17	3.53	<.001
	M/75-87	yes	--	--	--	2.92	2.11	<.001	2.14	2.39	<.001

Table 3. Results of monotonic trend analysis for selected time periods at sites in the Grand Region—Continued

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; percent is the slope expressed as the percent change per year; A, annual time series; M, monthly time series; p value, attained significance level; --, not applicable; <, less than]

Site number (plate 1, table 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
9	A/47-96	no	-0.33	-0.06	0.828	-1.23	-0.42	0.048	-734	-0.46	0.004
	A/47-96	yes	--	--	--	-1.30	-.44	<.001	-676	-.42	<.001
	M/47-96	no	-.17	-.03	.340	-2.26	-.47	<.001	-55.2	-.42	<.001
	M/47-96	yes	--	--	--	-2.37	-.49	<.001	-53.7	-.41	<.001
10	A/50-96	no	1.76	.08	.826	-.66	-.24	.354	-906	-.16	.255
	A/50-96	yes	--	--	--	-.64	-.23	<.001	-1,268	-.22	<.001
	M/50-96	no	3.74	.18	<.001	-1.18	-.35	<.001	-31.3	-.07	.064
	M/50-96	yes	--	--	--	-.80	-.23	<.001	-70.6	-.15	<.001
11	A/50-96	no	1.76	.08	.826	-.66	-.24	.354	-906	-.16	.255
	A/50-96	yes	--	--	--	-.64	-.23	<.001	-1,268	-.22	<.001
	M/50-96	no	8.08	.22	<.001	-1.96	-.36	<.001	-7.87	-.01	.842
	M/50-96	yes	--	--	--	-.84	-.15	<.001	-129	-.11	<.001
12	A/69-79	no	-8.95	-5.21	.213	5.66	1.62	.640	-2,208	-4.02	.161
	A/69-79	yes	--	--	--	-3.19	-.92	.350	-523	-.95	.350
	M/69-79	no	-6.84	-4.20	<.001	2.15	.51	.121	-230	-5.03	<.001
	M/69-79	yes	--	--	--	-4.27	-1.02	<.001	-118	-2.58	<.001
	M/91-96	no	11.5	5.87	<.001	-7.80	-2.15	.357	329	7.14	<.001
	M/91-96	yes	--	--	--	8.87	2.45	<.001	186	4.03	<.001
13	M/88-96	no	6.32	2.76	.001	-18.1	-4.58	<.001	31.8	.53	.833
	M/88-96	yes	--	--	--	-12.6	-3.20	<.001	-113	-1.89	<.001
14	A/59-80	no	1.65	.60	.612	-19.6	-1.53	<.001	-3,773	-1.10	.042
	A/59-80	yes	--	--	--	-18.8	-1.47	<.001	-4,728	-1.38	<.001
	M/59-80	no	1.05	.38	.063	-15.9	-1.09	<.001	-210	-.74	<.001
	M/59-80	yes	--	--	--	-17.0	-1.17	<.001	-289	-1.02	<.001
	M/91-96	no	14.2	4.38	.020	-36.7	-3.60	<.001	343	1.41	.116
	M/91-96	yes	--	--	--	-15.2	-1.50	<.001	-238	-.98	<.001
15	A/66-96	no	27.7	1.07	.163	-9.49	-1.70	.010	-6,037	-.48	.341
	A/66-96	yes	--	--	--	-5.02	-.90	<.001	-11,030	-.87	<.001
	M/66-96	no	14.3	.57	.005	-9.32	-1.43	<.001	-566	-.54	<.001
	M/66-96	yes	--	--	--	-5.42	-.83	<.001	-763	-.72	<.001

Table 3. Results of monotonic trend analysis for selected time periods at sites in the Grand Region—Continued

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; percent is the slope expressed as the percent change per year; A, annual time series; M, monthly time series; p value, attained significance level; --, not applicable; <, less than]

Site number (plate 1, table 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
16	A/66-96	no	39.6	0.61	0.395	-7.50	-1.31	0.038	-18,560	-0.56	0.083
	A/66-96	yes	--	--	--	-4.44	-.78	<.001	-24,530	-.74	<.001
	M/66-96	no	20.1	.32	.031	-7.20	-1.05	<.001	-1,509	-.55	<.001
	M/66-96	yes	--	--	--	-5.62	-.82	<.001	-2,081	-.76	<.001
17	M/88-96	no	-2.24	-.98	.120	-11.84	-2.73	<.001	-92.3	-1.77	.022
	M/88-96	yes	--	--	--	-15.12	-3.48	<.001	-137	-2.63	<.001
18	M/88-96	no	-2.14	-.92	.170	10.89	.55	.599	-109	-.74	.567
	M/88-96	yes	--	--	--	-45.38	-2.29	.152	-194	-1.31	.176
19	M/80-85	no	.03	5.60	.026	-2,935	-8.25	<.001	20.0	2.03	.377
	M/80-85	yes	--	--	--	-1,408	-3.96	.004	6.22	.63	.912
20	A/52-83	no	13.9	1.73	.236	-5.82	-.74	.466	4,987	1.08	.008
	A/52-83	yes	--	--	--	4.58	.58	.002	2,763	.60	.002
	M/52-83	no	1.69	.22	.006	-.91	-.05	.819	327	.86	<.001
	M/52-83	yes	--	--	--	12.44	.76	<.001	251	.66	<.001
	A/84-95	no	-81.4	-8.36	.373	-10.58	-1.89	.837	-42,220	-9.45	.047
	A/84-95	yes	--	--	--	-26.52	-4.73	.005	-22,470	-5.03	<.001
	M/84-95	no	-19.1	-2.21	<.001	-15.80	-1.58	.041	-2,835	-7.62	<.001
	M/84-95	yes	--	--	--	-52.69	-5.28	<.001	-2,344	-6.30	<.001
21	A/50-65	no	-52.9	-.83	.685	2.79	.41	.893	-8,260	-.22	.753
	A/50-65	yes	--	--	--	-1.08	-.16	.589	-8,358	-.22	.059
	M/50-65	no	1.82	.03	.866	-5.39	-.56	.073	-893	-.28	.217
	M/50-65	yes	--	--	--	-1.71	-.18	.275	-447	-.14	.258
	A/66-96	no	39.6	.56	.415	-5.97	-1.03	.072	-14,590	-.40	.292
	A/66-96	yes	--	--	--	-4.15	-.72	<.001	-24,440	-.67	<.001
	M/66-96	no	17.3	.26	.052	-6.83	-.97	<.001	-1,411	-.46	<.001
	M/66-96	yes	--	--	--	-4.96	-.70	<.001	-1,789	-.59	<.001

Table 4. Step trend tests on annual streamflow and dissolved-solids data for stations affected by major interventions in the Grand Region

[Period in water years (October 1 through September 30); Pre, pre-intervention period; post, post-intervention period; mg/L, milligrams per liter; T, attained significance level based on t-tests; W, attained significance level based on Wilcoxon rank-sum test; Significance levels attained: HS, highly significant, significance level (p value) less than or equal to 0.01; S, significant, p value is greater than 0.01 and less than or equal to 0.05; MS, marginally significant, p value is greater than 0.05 and less than or equal to 0.10; NS, not significant, p value is greater than 0.10]

Site (table 1, plate 1)	Intervention	Period (water years)		Mean annual streamflow (cubic feet per second)				Mean annual dissolved-solids concentration (mg/L)				Mean annual dissolved-solids load (tons)			
		Pre	Post	Pre	Post	T	W	Pre	Post	T	W	Pre	Post	T	W
10	Adams Tunnel	1941–49	1950-96	2,520	2,180	NS	MS	233	276	S	HS	576,000	564,000	NS	NS
11	Adams Tunnel	1934-49	1950-96	4,120	3,810	NS	NS	386	411	NS	NS	1,530,000	1,461,000	NS	MS
12	Break in record	1969-79	1991-96	172	226	NS	NS	348	280	MS	MS	55,000	55,300	NS	NS
14	Break in record	1959-80	1991-96	276	324	MS	NS	1,280	938	HS	HS	342,000	293,000	S	S
15	Blue Mesa Reservoir	1934-65	1966-96	2,340	2,590	NS	NS	685	559	HS	HS	1,426,000	1,268,000	S	S
20	McPhee Reservoir	1941-83	1984-95	858	974	NS	NS	741	560	NS	NS	464,000	447,000	NS	NS
21	Blue Mesa Reservoir	1950-65	1966-96	6,340	7,100	NS	NS	677	577	MS	MS	3,843,000	3,648,000	NS	NS

Muddy Creek Basin (Sites 3 and 4)

Two sites, Muddy Creek above Antelope Creek near Kremmling (site 3) and Muddy Creek near Kremmling (site 4), are located on this tributary to the Colorado River. Analysis of the annual data at site 3 was omitted due to the short period of record (less than 10 years) (table 3).

At site 3, trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads indicated significant upward trends in streamflow and dissolved-solids loads. No trend was determined for dissolved-solids concentrations. The trend in flow-adjusted monthly dissolved-solids loads was significantly upward.

Site 4, located downstream from site 3, had a statistically significant downward trend in the mean annual dissolved-solids loads (table 3) but no trends in dissolved-solids concentrations or streamflow. Flow adjustment of the mean annual dissolved-solids concentrations and loads did not indicate any statistically significant trends.

Trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads determined statistically significant trends in all three parameters. The trend for streamflow was downward, the trend for dissolved-solids concentrations was upward, and the trend for dissolved-solids loads was downward (table 3). The trend in flow-adjusted monthly dissolved-solids concentrations and loads was a statistically significant downward trend. The difference in trend slope between sites 3 and 4 in the flow-adjusted data may be due to a longer period of record at site 4.

Colorado River near Kremmling, Colorado (Site 5)

The trend in mean annual streamflow was not significant, nor were trends in annual dissolved-solids concentrations and loads, even after flow adjustment (table 3). Trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads indicated large, significant downward trends in streamflow and dissolved-solids loads. However, no trend was determined in the dissolved-solids concentrations (table 3). The trends in the flow-adjusted monthly dissolved-solids concentrations and loads were not statistically significant.

Rock Creek Basin (Sites 6 and 7)

Rock Creek near Crater (site 6) is located in the upper part of the basin and has a longer period of record than the lower site, Rock Creek at McCoy (site 7). Trend analysis of the mean annual streamflow, dissolved-solids concentrations, and loads at site 6 determined a significant downward trend in dissolved-solids concentrations only (table 3). However, the trends for both mean annual flow-adjusted dissolved-solids concentrations and loads were significantly downward, with larger decreases in loads. Bauch and Spahr (1998) reported a downward trend in flow-adjusted annual dissolved-solids loads for the period 1986–93.

Trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads determined significant downward trends in all three parameters (table 3). The trend in flow-adjusted monthly dissolved-solids concentrations and loads was significantly downward.

At site 7, trend analysis of the annual data was not determined due to the short period of record (less than 10 years). The trend in monthly streamflow and dissolved-solids loads was significantly downward, but the trend in dissolved-solids concentrations was significantly upward (table 3). The trends of the flow-adjusted dissolved-solids concentrations and loads were both significantly downward (table 3).

Eagle River Basin (Sites 8 and 9)

Beaver Creek at Avon (site 8) is a tributary to the Eagle River and is located in the middle part of the basin. The trend of the mean annual streamflow, dissolved-solids concentrations, and loads was not statistically significant (table 3). Trend analysis of the flow-adjusted mean annual dissolved-solids concentrations and loads did not detect a significant trend (table 3).

Trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads determined significant upward trends in streamflow and dissolved-solids loads (table 3). The trend for monthly dissolved-solids concentrations was not significant. The trends in the flow-adjusted monthly dissolved-solids concentrations and loads were significantly upward (table 3).

Eagle River at Gypsum (site 9) is located near the mouth of the Eagle River and should indicate the combined effects of any changes in the basin. Mean annual streamflow has not changed significantly;

however, significant downward trends were determined for mean annual dissolved-solids concentrations and loads (table 3). The trends in the flow-adjusted dissolved-solids concentrations and loads were also statistically significant and downward. These trends in the annual data are consistent with the trends for the shorter time period reported by Liebermann and others (1989). Bauch and Spahr (1998) reported downward trends in flow-adjusted annual dissolved-solids loads for the periods 1970–93 and 1986–93.

The trend in monthly streamflow was not statistically significant. Analysis of the monthly dissolved-solids concentrations and loads indicated significant downward trends (table 3). The trends in the flow-adjusted monthly dissolved-solids concentrations and loads were significantly downward.

Colorado River above Glenwood Springs, Colorado (Site 10)

Trend analysis for the period of record (1950–96) indicated no statistically significant trends in annual streamflow, dissolved-solids concentrations, or loads. However, trends for the flow-adjusted dissolved-solids concentrations and loads were significantly downward (table 3). Bauch and Spahr reported a downward trend in flow-adjusted annual dissolved-solids loads for the period 1986–93 but not for 1970–93.

Trend analysis of the monthly streamflow, dissolved-solids concentrations and loads indicated a significant upward trend in streamflow and a significant downward trend in concentrations (table 3). The slope of the trend in monthly dissolved-solids load was downward but was not statistically significant. The trends for monthly dissolved-solids concentrations and loads were significantly downward after the data were flow adjusted.

The largest source of dissolved-solids load at this site is contributed by very saline, thermal springs between the towns of Dotsero and Glenwood Springs. Changes in discharge from the thermal springs could affect dissolved-solids loads but have no significant effect on streamflow.

Step trend analysis at site 10 was done between the period prior to exports by the Adams Tunnel (1941–49) and the period after exports began (1950–96). A marginally significant ($0.05<p<0.10$) difference in annual streamflow was determined between the two periods (table 4). Annual dissolved-solids concentrations were significantly higher in 1950–96 compared to 1941–49. No significant difference was determined in annual dissolved-solids load between the two periods. These results are similar to those reported by Liebermann and others (1989).

Colorado River near Cameo, Colorado (Site 11)

The period of record was divided into a pre-intervention period (1934–49) and a post-intervention period (1950–96) based on the Adams Tunnel exports. Annual trend analysis for 1950–96 determined significant downward trends in flow-adjusted dissolved-solids concentrations and loads but no related trend in streamflow (table 3). Bauch and Spahr (1998) reported a downward trend in flow-adjusted dissolved-solids loads for the period 1986–93 but not for 1970–93.

Trend analysis of monthly streamflow for the period 1950–96 determined a significant upward trend. A statistically significant downward trend was determined for flow-adjusted monthly dissolved-solids loads. Liebermann and others (1989) did not report any significant annual trends for the shorter period of record 1950–83 but did report that monthly trends generally indicated increased streamflow and decreased dissolved-solids concentrations. Bauch and Spahr (1998) reported a downward trend in flow-adjusted dissolved-solids loads for the period 1970–93 and Butler (1996) reported significant downward trends in dissolved-solids concentrations and loads at this site.

Step trend analysis at site 11 of the pre-intervention period (1934–49) and the post-intervention period (1950–96) detected no statistically significant differences in mean annual streamflow and dissolved-solids concentration and only a marginally significant difference in mean annual dissolved-solids load between the two periods (table 4). These results differ slightly from those of Liebermann and others (1989) where a marginally significant decrease in mean annual streamflow was reported.

Plateau Creek near Cameo, Colorado (Site 12)

Streamflow at this site drains a high plateau area along the southern banks of the Colorado River and is less saline than nearby tributaries along the northern side of the river (Liebermann and others, 1989).

Liebermann and others (1989) did not report any statistically significant annual trends for the period 1969–79. Annual data for the period 1991–96 were not analyzed in this report due to the short period of record.

Trends of the monthly streamflow for the periods 1969–79 and 1991–96 indicated significant trends for both periods of record. A significant downward trend in monthly streamflow was determined for the period 1969–79, and a significant upward trend was noted for the period 1991–96. No significant trends were determined for dissolved-solids concentrations for the two periods. A significant downward trend was determined for flow-adjusted monthly dissolved-solids concentrations and loads for the period 1969–79. The trends for flow-adjusted monthly dissolved-solids concentrations and loads for the period 1991–96 were significantly upward. Although streamflow was higher in 1991–96 than in 1969–79, dissolved-solids loads were nearly equal for the two periods (table 4).

Gunnison Subregion

The Gunnison River is the largest tributary to the Colorado River in Colorado and originates in high mountainous terrain. Irrigation is widespread in the basin, and most of the irrigated acreage is in the lower basin downstream from Blue Mesa Reservoir. Blue Mesa Reservoir began regulation and storage in 1965. Considerable areas in the Uncompahgre River and lower Gunnison River Basins are underlain by the Mancos Shale, which is a natural contributor of dissolved solids. Irrigation return flows contain larger dissolved-solids loads than in the source water before diversion. This makes the Gunnison Subregion the largest agricultural source of dissolved solids in the Colorado River Basin upstream from Lees Ferry, Ariz. (not shown on plate 1) (U.S. Department of the Interior, 1985).

Gunnison River Basin (Sites 13–15)

Streamflow and water-quality data from three sites were analyzed for trends in the Gunnison Subregion (pl. 1 and table 1). Streamflow at Uncompahgre River at Colona (site 13) is affected by regulation from Ridgway Reservoir (regulation began in 1986) and at Uncompahgre River at Delta (site 14) by imports from the Gunnison River and evapotranspiration from irrigated croplands.These two sites were not used in the analysis of annual trends. Site 13 did not have a sufficient period of record for analysis and site 14 did not have 10 additional years of record beyond the period analyzed by Liebermann and others (1989).

Trend analysis of the monthly streamflow at site 13 indicated a significant upward trend in streamflow and s significant downward trend in dissolved-solids concentrations (table 3). A statistically significant downward trend was determined in flow-adjusted monthly dissolved-solids concentrations and loads.

Trend analysis at site 14 did not determine any trend in annual streamflow for the period 1959–80. Significant downward trends were determined for unadjusted and flow-adjusted dissolved-solids concentrations and loads for the same period. Trend analysis of the monthly streamflow at site 14 did not detect a trend for the period 1959–80; however, a significant upward trend was determined for 1991–96. Significant downward trends were detected for monthly dissolved-solids concentrations and loads for 1959–80 and for monthly dissolved-solids concentrations for 1991–96. The flow-adjusted monthly dissolved-solids concentrations and loads had significant downward trends for both periods.

Trend analysis of the annual streamflow at Gunnison River near Grand Junction (site 15) for the post-intervention period (1966–96) did not indicate any significant trend. Significant downward trends were determined for the flow-adjusted annual dissolved-solids concentrations and loads (table 3). The trends determined in this study are consistent with the findings of Liebermann and others (1989) and Butler (1996). Bauch and Spahr (1998) reported a downward trend in flow-adjusted dissolved-solids loads for the period 1970–93.

Trend analysis of the monthly streamflow at site 15 determined a significant upward trend (table 3). A significant downward trend in monthly dissolved-solids concentrations and loads was determined. The flow-adjusted monthly dissolved-solids concentrations and loads had significant downward trends.

Step trend tests for Uncompahgre River at Delta (site 14) indicate a significant difference in dissolved-solids load and a highly significant difference in dissolved-solids concentration for 1959–80 compared to 1991–96 (table 4). Step trend tests for Gunnison River near Grand Junction (site 15) indicate highly significant differences in mean annual dissolved-solids concentrations and loads between the periods 1934–

65, prior to regulation by Blue Mesa Reservoir, and 1966–96 (table 4), but there was not a significant change in streamflow. Liebermann and others (1989) reported no significant difference in annual streamflow or dissolved-solids concentrations and only a marginally significant difference in dissolved-solids loads at site 15.

Site 13 is located upstream and sites 14 and 15 are downstream from salinity control efforts in the lower Gunnison River Basin that began in 1988. Salinity control efforts have included on-farm ditch lining, changing winter livestock-watering sources and delivery systems, and irrigation techniques.

Although there are limited water-quality data for the subregion available from USGS data bases for use in this report, previous investigations have used data collected and stored in separate data bases by other agencies. Bauch and Spahr (1998) utilized water-quality data collected by the Colorado Department of Public Health and Environment (CDPHE) in an analysis of trends in mean annual dissolved-solids concentrations and loads at sites located upstream from those reported in Butler (1996). The analysis utilized data from the U.S. Environmental Protection Agency STOrage and RETrieval system (STORET). Bauch and Spahr (1998) reported significant downward trends in monthly flow-adjusted dissolved-solids loads for the Taylor and East Rivers (pl. 1), two major tributaries that join near Almont, Colo., to form the Gunnison River. No significant trends were reported in the flow-adjusted annual dissolved-solids loads for either site. However, a highly significant ($p < 0.01$) downward trend in flow-adjusted monthly dissolved-solids loads was reported for the Taylor River at Almont for the period 1970–92. A significant downward trend was reported for the East River at the confluence with the Taylor River for the period 1970–91. It is uncertain to what degree the salinity-control projects in the lower Gunnison River Basin have contributed to the downward trends at site 15 considering that there also are downward trends upstream from the salinity-control project at site 13 and in the upper Gunnison River Basin as reported by Butler (1996) and by Bauch and Spahr (1998).

Lower Colorado Subregion

The Lower Colorado Subregion includes the drainage areas of the Dolores River and its tributaries and the Colorado River between Grand Junction, Colo., and the confluence with the Green River. Streamflow and water-quality data for six sites were analyzed for this subregion (pl. 1 and table 1).

Colorado River near Colorado-Utah State Line, Colorado (Site 16)

The streamflow and water quality at site 16 includes the cumulative effects of transbasin exports, irrigation return flow, and reservoir regulation. The post-intervention period after 1965 has a decreased snowmelt-runoff peak and increased base flows during the fall and winter months. Trend analysis did not determine a trend in annual streamflow for the period 1966–96. A significant downward trend was determined in the annual dissolved-solids concentrations but not in dissolved-solids loads. Trends in flow-adjusted annual dissolved-solids concentrations and loads were significantly downward for the period (table 3). Liebermann and others (1989) reported a marginally significant decrease in the annual dissolved-solids concentrations and a highly significant decrease in the flow-adjusted annual dissolved-solids concentrations for 1966–83.

Trend analysis of the monthly data indicated a significant upward trend in streamflow. Significant downward trends were determined in the dissolved-solids concentrations and loads. The flow-adjusted monthly dissolved-solids concentrations and loads had significant downward trends.

Significant decreases for the period 1966–96 are also indicated in plots of mean annual flow-adjusted dissolved-solids concentrations and loads and LOWESS smooth curves (figs. 1 and 2). Dissolved-solids concentrations and loads decreased before construction of salinity control projects in the Grand Valley Unit in 1980. During construction of Stage One of the Grand Valley Unit in 1980–83 (U.S. Department of the Interior, 1997), dissolved-solids concentrations and loads remained fairly constant. Construction of Stage Two of the Grand Valley Unit began in 1986 and much of that work was completed by 1996 (U.S. Department of the Interior, 1997). Dissolved-solids concentrations and loads began to decrease again about 1986, and the downward trends have continued through 1996. Salinity control projects in the Grand Valley Unit may have contributed to the decrease in dissolved-solids concentrations and loads since about 1980, but that does not explain decreases before 1980 (Butler, 1996).

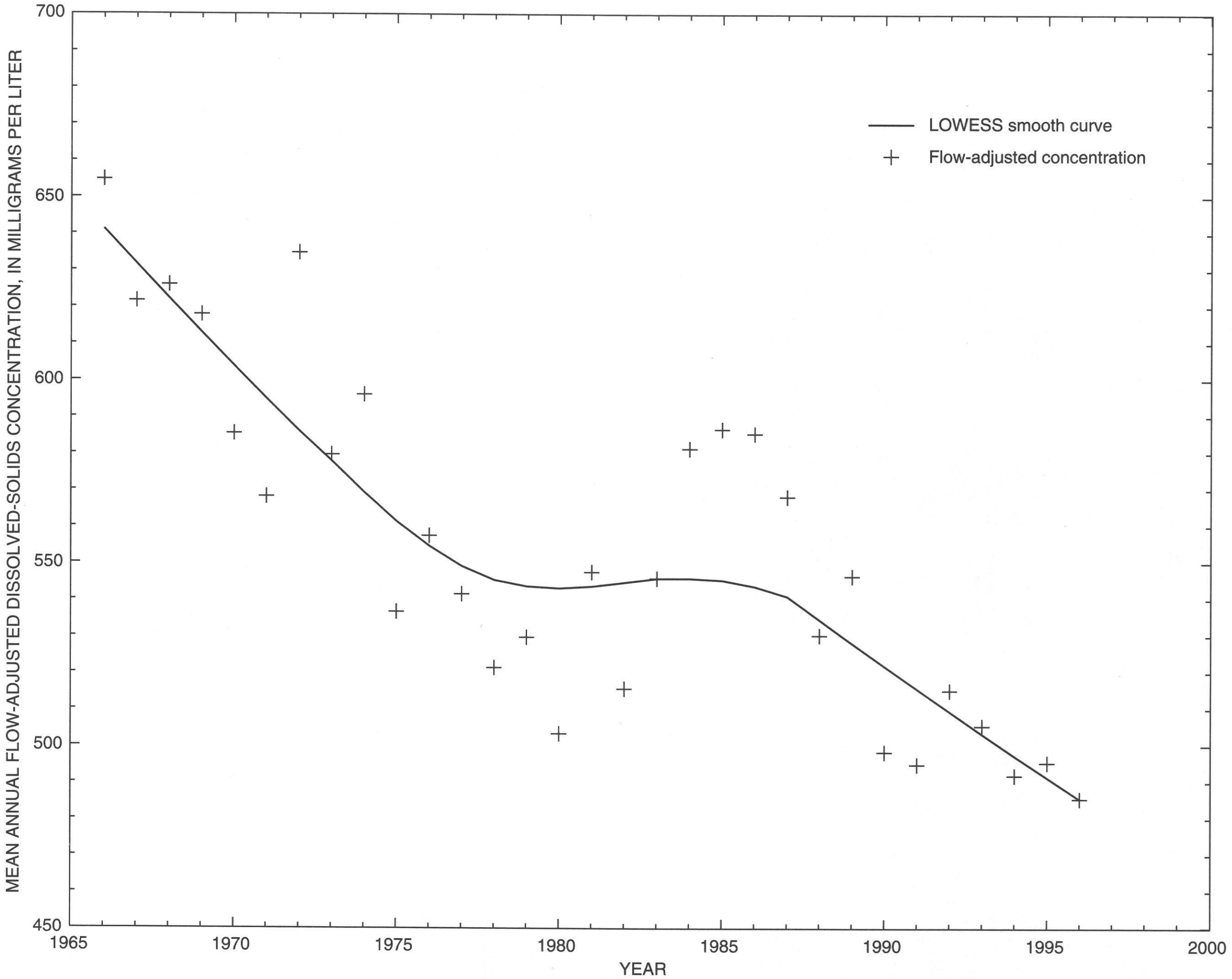

Figure 1. Mean annual flow-adjusted dissolved-solids concentrations and LOWESS smooth curve, station 09163500, Colorado River near Colorado-Utah State Line, Colorado (site 16), water years 1966–96.

Upper Dolores River Basin (Sites 17–19)

Streamflow and water-quality data for three sites in the upper Dolores River Basin were analyzed. The period of record analyzed for the main-stem Dolores River is after completion of McPhee Reservoir in 1984. Dolores River at Bedrock (site 17) is located upstream from the site of salinity control efforts in the Paradox Valley Unit and did not have the required 10 years of record for analysis of the annual record. Trend analysis of the monthly streamflow did not indicate any significant trends (table 3). Significant downward trends were determined for the unadjusted and flow-adjusted monthly dissolved-solids concentrations and loads.

Dolores River near Bedrock (site 18) is located downstream from the Paradox Valley Unit. The period of record at this site was not sufficient for analysis of the annual trends. Trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads did not determine any significant trends; however, the trend slope was negative for all three parameters.

Salt Creek near Gateway (site 19) is a tributary to the Dolores River that drains the Sinbad Valley anticline, which contains highly saline ground water. Salt Creek is a minor tributary but a concentrated source of salt loading to the Dolores River (Liebermann and others, 1989). The period of record at this site was not long enough for analysis of the annual data. Trend analysis of monthly streamflow indicated a statistically significant upward trend (table 3). Trend analysis

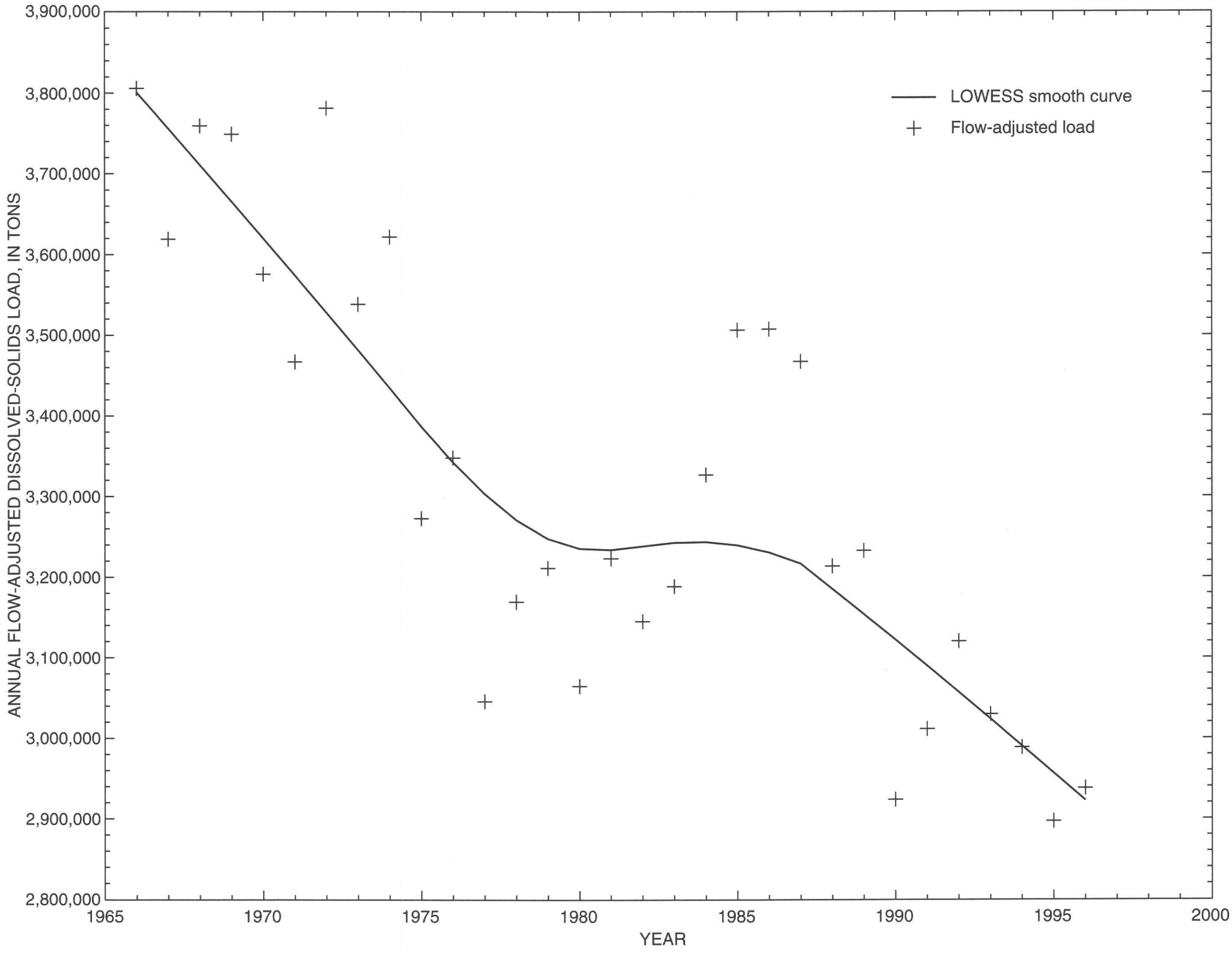

Figure 2. Annual flow-adjusted dissolved-solids load and LOWESS smooth curve, station 09163500, Colorado River near Colorado-Utah State Line, Colorado (site 16), water years 1966–96.

of the monthly dissolved-solids concentrations determined a significant downward trend. Trends for monthly dissolved-solids loads were not statistically significant. A downward trend was determined for the flow-adjusted monthly dissolved-solids concentrations. No trend was determined for flow-adjusted monthly dissolved-solids loads.

Dolores River near Cisco, Utah (Site 20)

This site is located near the confluence of the Dolores and Colorado Rivers. About one-half of the dissolved solids contributed annually by the Dolores River may be attributed to dissolution from salt domes, primarily where the Dolores River crosses the Paradox Valley (U.S Department of the Interior, 1997). Liebermann and others (1989) reported a significant increase in the annual dissolved-solids loads and in the flow-adjusted dissolved-solids concentrations for the period of record prior to regulation by McPhee Reservoir (1984). Trend analysis of the annual streamflow for the period of record since the intervention of McPhee Reservoir (1984–95) did not indicate any significant trends (table 3). However, significant downward trends were determined for the flow-adjusted annual dissolved-solids concentrations and loads for 1984–95. Perhaps the salinity control project in the Paradox Valley and possibly reservoir regulation have affected dissolved-solids loads since 1984.

Trend analysis of the monthly streamflow, dissolved-solids concentrations and loads indicated significant downward trends for all parameters. Trend analysis of the flow-adjusted monthly dissolved-solids concentrations and loads also indicated significant downward trends.

Step trend analysis of the annual streamflow, dissolved-solids concentrations, and loads for the pre-intervention period (1952–83) and post-intervention period (1984–95) did not indicate any statistically significant differences between periods (table 4). This may be because values used in the step trend tests were not flow adjusted.

Colorado River near Cisco, Utah (Site 21)

Site 21 is the farthest downstream site in the Grand Region. Streamflow at this site includes the cumulative effects of streamflow depletion (such as transbasin diversions, agricultural uses, and municipal uses) and effects from reservoirs. Annual trends were analyzed for the post-intervention period of 1966–96. No statistically significant trends were determined in annual streamflow, dissolved-solids concentrations, or loads (table 3). The flow-adjusted annual dissolved-solids concentrations and loads had significant downward trends. Liebermann and others (1989) reported only a marginally significant decrease in the flow-adjusted annual dissolved-solids concentration for the period 1966–83.

Trend analysis of the monthly streamflow indicated a significant upward trend (table 3). The flow-adjusted annual dissolved-solids concentrations and loads both had statistically significant downward trends.

Step trend analysis of annual streamflow and dissolved-solids loads for the periods of record based on the intervention of Blue Mesa Reservoir did not indicate any significant differences between periods (table 4). Only a marginally significant difference in annual dissolved-solids concentrations was indicated between the two periods. This is similar to the findings reported by Liebermann and others (1989) for the period of record 1966–83.

General Trends in the Grand Region

Trends were determined for the period of record for all sites except for sites 12, 14, 20, and 21. A break in the period of record occurred at sites 12 and 14. The trend summaries discussed in this section were based on trends for the longer and earlier period for sites 12 and 14. The post-intervention period related to reservoir construction was used for sites 20 and 21.

No significant trends in annual streamflow were determined for 15 of the 21 sites in the Grand Region. The other six sites did not have a sufficient period of record to do annual trend tests. Downward trends in the flow-adjusted annual dissolved-solids concentrations and loads were determined at 9 of the 15 sites; no upward trends were determined. There were significant trends in monthly streamflow at 15 of the 21 sites (7 downward, 8 upward) (table 3). Six sites had no trend in monthly streamflow. There were significant trends in flow-adjusted monthly dissolved-solids concentrations for 17 sites (15 downward, 2 upward) and significant trends in flow-adjusted monthly dissolved-solids loads for 17 sites (14 downward, 3 upward). Four sites had no trend in the flow-adjusted monthly dissolved-solids concentration or load.

Six sites were selected on the Colorado and Gunnison Rivers in the Grand Region based on length of record and site location to provide a basinwide comparison of possible trends in streamflow, flow-adjusted annual dissolved-solids concentrations, or loads. The period 1966–96, after construction of Blue Mesa Reservoir, was selected for comparison to determine if any trends detected were representative of the same time period. Trend results for streamflow, flow-adjusted annual dissolved-solids concentrations, and loads for the selected sites are listed in table 5. No significant trends in streamflow were determined at the six sites. Comparison of trends in flow-adjusted dissolved-solids data allows examination of changes in salinity independent of flow. Comparison of trends in flow-adjusted dissolved-solids concentrations and loads for the concurrent period of record (1966–96) at the six sites indicate large-scale significant downward trends occur basinwide. The magnitude of the downward trends increase substantially between site 2 and site 21 as shown by the increase in magnitude of the slope and percent values in table 5.

Downward trends in dissolved-solids concentrations and loads also were determined in the Eagle River Basin, a major tributary to the Colorado River. Butler (1996) also reported significant downward trends in dissolved-solids concentrations and loads at sites 11, 15, and 16 in the vicinity of the Grand Valley near Grand Junction.

Table 5. Summary of annual trends for 1966–96 at selected sites in the Grand Region

[Period of record in complete water years (October 1 through September 30); site 2 period of record is 1966–94; percent is the slope expressed as percent change per year; mg/L, milligrams per liter; p, significance level; <, less than]

Site number (plate 1)	Streamflow (cubic feet per second)			Flow-adjusted dissolved-solids concentration (mg/L)			Flow-adjusted dissolved-solids load (tons)		
	Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
2	-0.79	-0.33	0.694	-0.24	-0.30	0.034	-50	-0.29	0.045
10	1.82	0.08	0.892	-0.46	-0.17	0.053	-1,098	-0.20	0.041
11	9.49	0.24	0.634	-1.4	-0.33	0.007	-4,664	-0.32	0.007
15	27.7	1.07	0.163	-5.0	-0.90	<0.001	-11,030	-0.87	<0.001
16	39.6	0.61	0.395	-4.4	-0.78	<0.001	-24,530	-0.74	<0.001
21	39.6	0.56	0.415	-4.2	-0.72	<0.001	-24,440	-0.67	<0.001

Step trend analysis for sites 10 and 11 (table 1, pl. 1), related to the intervention of the Alva B. Adams Tunnel, indicated a significant difference in mean annual dissolved-solids concentrations at site 10 between the periods 1941–49 and 1950–1996 (table 4) but no significant difference at site 11. These results are comparable to those reported by Liebermann and others (1989). Although the significance level varies between the studies, the direction of slopes (downward) of the trends are the same.

LOWESS smooth curves for flow-adjusted dissolved-solids concentrations and loads were compared at four sites in the Grand Region for the period 1966–96 (figs. 3 and 4). Significant decreases were indicated at all four sites prior to salinity control efforts in the region, which indicates there are natural or human-induced effects in the upper part of the region that may be related to the trends. Abrupt decreases in concentration and load occurred during the period 1986–88 at Colorado River near Colorado-Utah State Line (site 16) and Colorado River near Cisco (site 21). Salinity control efforts began in the Lower Gunnison and Grand Valley Units in the 1980's, indicating that salinity control might also have an effect on trends. Downward trends in flow-adjusted dissolved-solids concentrations and loads at site 16 also were reported by Butler (1996).

Comparison of trends determined for the longer period of record in this study to those reported by Liebermann and others (1989) indicates generally similar downward trends in annual dissolved-solids concentrations and loads in the region. At Eagle River at Gypsum (site 9), the trend in annual dissolved-solids concentrations and loads was downward for both studies. Liebermann and others (1989) did not determine any trends in the annual data for Colorado River near Cameo (site 11). Significant downward trends in annual dissolved-solids concentrations and loads were determined with the additional period of record in this study. There were no significant trends in the annual data reported by Liebermann and others (1989) for Colorado River near Cisco (site 21). This study did not detect trends in the unadjusted annual data for site 21; however, significant downward trends were determined for flow-adjusted dissolved-solids concentrations and loads at site 21 for 1966–96.

Green Region

Streamflow and water-quality data for 39 sites were evaluated in the Green Region (pl. 1 and table 1). Long-term mean annual runoff, streamflow, and flow-weighted dissolved concentrations and loads were computed for each site (table 6). Results of trend analysis at the sites are reported in table 7, and results of step trend analysis at selected sites are reported in table 8. For discussion purposes the Green Region was subdivided into: the Upper Green Subregion, the Middle Green Subregion, the White Subregion, and the Lower Green and Main Stem Subregions.

Upper Green Subregion

The Upper Green Subregion includes all of the drainage area upstream from the USGS streamflow-gaging station on the Green River near Greendale, Utah, exclusive of the Great Divide Basin. Major

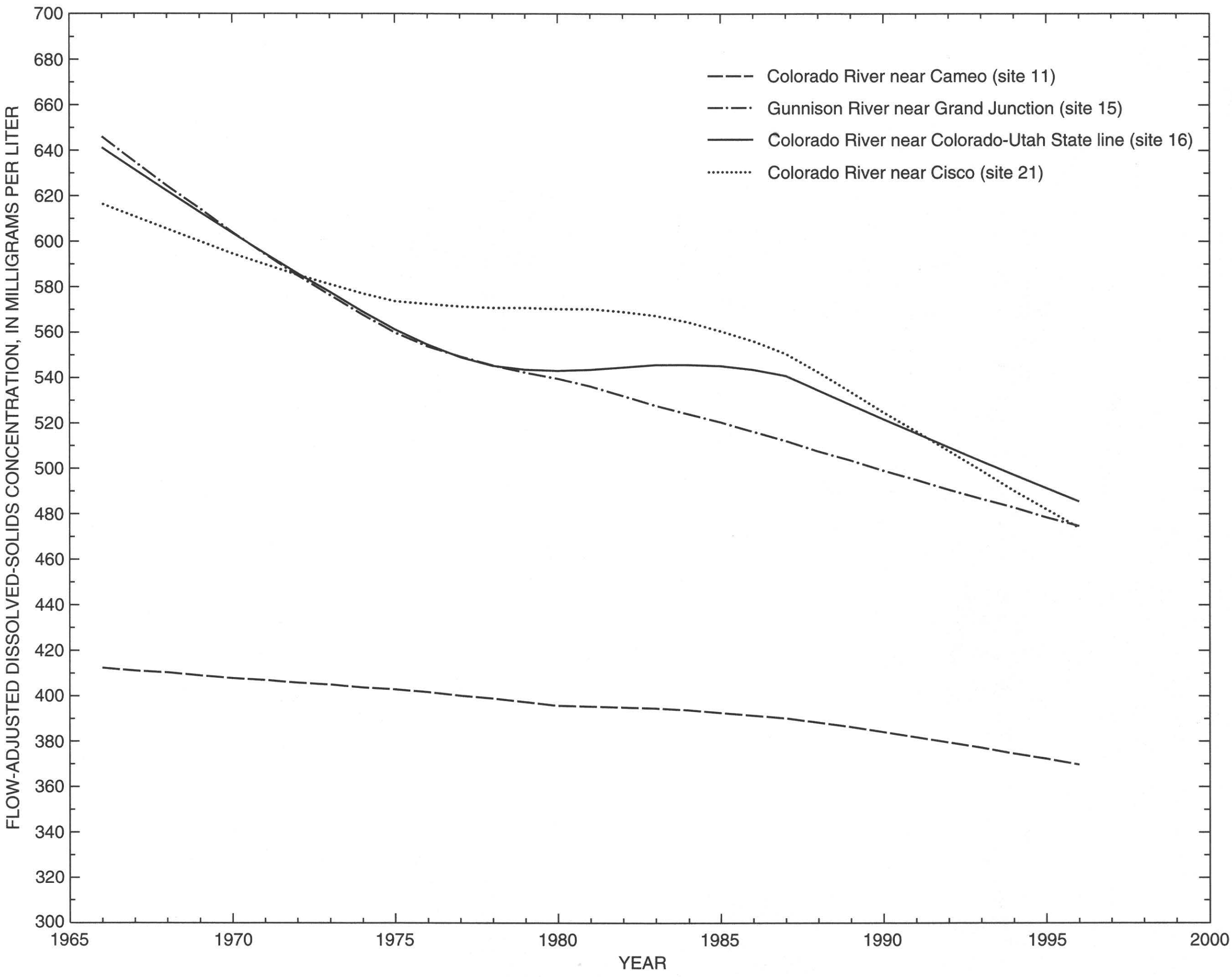

Figure 3. LOWESS curves for flow-adjusted concentrations at four sites in the Grand Region.

drainages in the subregion include the Big Sandy River and the Blacks Fork. Streamflow and water-quality data for seven sites were analyzed for trends in this subregion (pl. 1 and table 1).

Green River Headwaters (Sites 22 and 23)

Green River near La Barge, Wyo. (site 22), was the most upstream site analyzed in the Upper Green Subregion. Annual trend analysis did not indicate any statistically significant trends in streamflow or dissolved-solids loads (table 7). There was a significant upward trend in the annual dissolved-solids concentrations.

Trend analysis of the monthly streamflow and dissolved-solids loads indicated significant downward trends, but a significant upward trend in monthly dissolved-solids concentrations was detected (table 7). The trend in the flow-adjusted monthly dissolved-solids concentration was significantly upward. The slope of the trend in the flow-adjusted dissolved-solids loads was upward but was not statistically significant. Liebermann and others (1989) did not detect any significant trends.

Site 23 is located on the Green River downstream from Fontenelle Reservoir, between the towns of La Barge and Fontenelle, Wyo. Fontenelle Reservoir was built to provide storage for irrigation purposes beginning in 1964. The reservoir has inun-

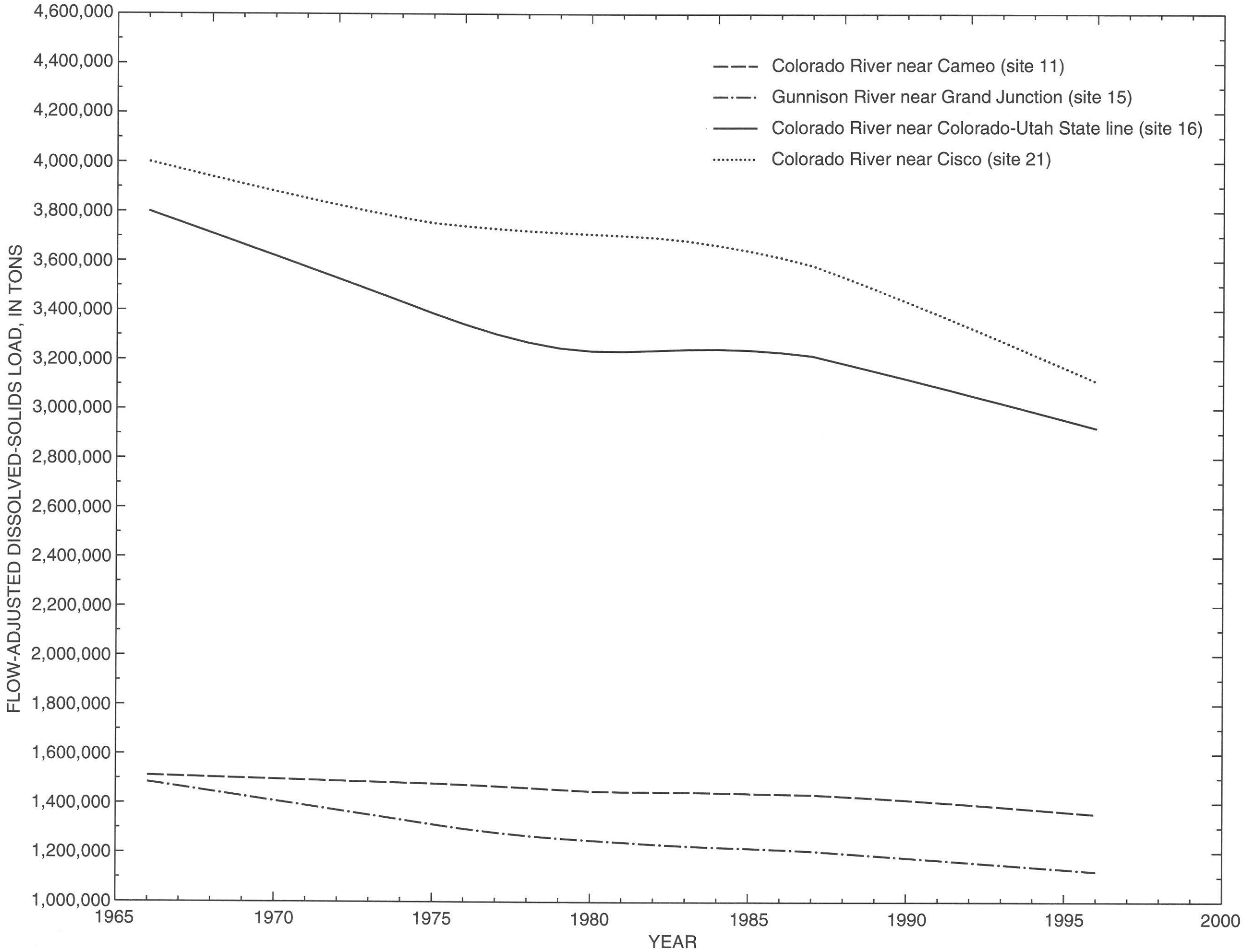

Figure 4. LOWESS curves for flow-adjusted loads at four sites in the Grand Region.

dated outcrops of the Laney Member and the Wilkins Peak Member of the Green River Formation (Liebermann and others, 1989). Annual trend analysis of streamflow did not indicate any significant trend (table 7). A significant downward trend was determined for the unadjusted and flow-adjusted annual dissolved-solids concentrations. No trends were determined for dissolved-solids loads.

Trend analysis of the monthly streamflow did not indicate any statistically significant trends; however, there were significant downward trends in the flow-adjusted monthly dissolved-solids concentrations and loads (table 7). No statistically significant trends were reported by Liebermann and others (1989).

Big Sandy River Basin (Sites 24 and 25)

Annual trend analysis of the data for Big Sandy River below Farson, Wyo. (site 24), determined significant downward trends in the flow-adjusted dissolved-solids concentrations and loads (table 7). Trend analysis of the monthly streamflow determined a significant downward trend. Significant downward trends were also determined for the flow-adjusted monthly dissolved-solids concentrations and loads.

Trend analysis of the annual data for Big Sandy River at Gasson Bridge, near Eden, Wyo. (site 25), indicated significant downward trends in the flow-adjusted dissolved-solids concentrations and loads. No trends were detected in the annual streamflow (table 7). Trend analysis of monthly streamflow indicated a significant downward trend. Significant downward trends were also detected for the unadjusted and flow-adjusted monthly dissolved-solids concentrations and loads.

Salinity control efforts in the Big Sandy River Basin began in 1988 (the Big Sandy River Unit) (U.S. Department of the Interior, 1997). Plots of mean annual flow-adjusted dissolved-solids concentrations and loads and LOWESS smooth curves indicate significant decreases for the period 1975–96 (figs. 5 and 6). Salinity control may have contributed to the decrease in salinity since 1988 but does not explain earlier downward trends.

Table 6. Mean annual streamflow, flow-weighted dissolved-solids concentrations, and dissolved-solids loads, Green Region

[Period of record in water years (October 1 through September 30); mg/L, milligrams per liter]

Site number (plate 1 and table 1)	Period of record	Streamflow		Dissolved solids	
		Volume (acre-feet)	Discharge (cubic feet per second)	Flow-weighted concentration (mg/L)	Load (tons)
22	1964–94	1,177,000	1,620	185	295,600
23	1968–96	1,184,000	1,630	222	356,700
24	1982–96	31,300	43.1	942	40,100
25	1975–96	52,200	72.1	2,030	144,200
26	1952–63	1,125,000	1,550	293	448,400
	1964–96	1,247,000	1,720	308	522,100
27	1965–96	240,900	331	572	187,300
28	1941–62	1,621,000	2,240	365	805,000
	1965–96	1,542,000	2,130	475	996,700
29	1985–92	56,900	78.5	269	20,900
30	1991–96	343,900	475	50.4	23,600
31	1976–88	3,400	4.7	313	1,450
32	1976–88	2,500	3.4	1,110	3,710
33	1986–92	128,800	178	241	42,200
34	1950–96	1,102,000	1,520	170	254,000
35	1978–86	216,300	299	50.8	14,900
36	1986–91	64,700	89.3	166	14,600
37	1962–92	3,127,000	4,320	344	1,463,000
38	1941–72	436,400	602	655	388,000
38	1973–96	360,000	497	577	282,000
39	1982–92, 1995–96	251,700	347	157	53,500
40	1986–92, 1995–96	173,100	239	139	32,800
41	1979–84, 1988–92, 1995–96	406,500	561	178	98,200
42	1974–83, 1987–96	447,600	618	294	178,700
	1974–83	443,800	613	296	178,400
	1987–96	458,500	633	293	182,600
43	1975–96	14,400	19.8	645	12,600
44	1975–85	1,680	2.3	899	2,050
45	1975–85	2,300	3.2	838	2,620
46	1975–87	23,800	32.8	735	23,800

Table 6. Mean annual streamflow, flow-weighted dissolved-solids concentrations, and dissolved-solids loads, Green Region—Continued

Site number (plate 1 and table 1)	Period of record	Streamflow		Dissolved solids	
		Volume (acre-feet)	Discharge (cubic feet per second)	Flow-weighted concentration (mg/L)	Load (tons)
47	1971–96	24,700	34.0	884	29,600
48	1971–87, 1990–96	29,000	40.0	1,100	43,500
	1971–87	32,600	45.1	1,080	47,800
	1990–96	20,200	27.9	1,210	33,200
49	1975–96	1,530	2.1	929	1,930
50	1974–82, 1989–96	1,770	2.4	2,280	5,460
	1974–82	1,400	1.9	2,140	4,070
	1989–96	2,180	3.0	2,380	7,020
51	1983–96	573,600	792	387	301,800
52	1951–96	509,300	703	428	296,200
	1969–81	477,700	659	387	251,400
	1982–96	583,800	806	415	329,300
53	1976–84	20,100	27.7	1,980	54,100
54	1976–84	16,600	22.8	2,060	46,400
55	1979–84	13,200	18.2	239	4,290
56	1949–88	95,600	132	1,840	238,900
57	1929–62	4,072,000	5,620	429	2,377,000
	1965–96	4,211,000	5,810	451	2,583,000
58	1947–65	94,800	131	1,550	200,100
	1966–96	83,900	116	1,460	167,000
59	1984–90	1,180	1.6	227	363
60	1979–84	2,880	4.0	1,480	5,800

Green River near Green River, Wyoming (Site 26)

The seasonal pattern of streamflow at site 26 has been altered by regulation of streamflow by Fontenelle Dam and Reservoir, which are located about 50 miles upstream. No statistically significant trends were detected in annual streamflow for the post-intervention period of record 1964–96. Trend analysis indicated significant downward trends for the flow-adjusted annual dissolved-solids concentrations and loads (table 7).

Trend analysis of the monthly data indicated no statistically significant trends in streamflow. Significant downward trends were determined in the unadjusted and flow-adjusted dissolved-solids concentrations and loads.

Step trend analysis related to the intervention of Fontenelle Reservoir indicated no significant differences in annual streamflow or dissolved-solids loads (table 8). The mean annual dissolved-solids concentration was significantly higher in the post-intervention period (1964–96) than in the pre-intervention period (1941–63). Liebermann and others (1989) reported significantly higher post-intervention (1964–83) dissolved-solids loads.

Blacks Fork near Little America, Wyoming (Site 27)

Trend analysis of the annual data for site 17 did not determine any trends in streamflow or dissolved-solids concentrations. A downward trend was determined in the annual dissolved-solids loads (table 7). Liebermann and others (1989) reported a significant

Table 7. Results of monotonic trend analysis for selected time periods at sites in the Green Region

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; A, annual time series; M, monthly time series; percent is the slope expressed as percent change per year; p value, attained significance level; --, not applicable]

Site number (plate 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
22	A/64-94	no	-19.8	-1.22	0.103	0.89	0.47	0.027	-2,253	-0.76	0.153
	A/64-94	yes	--	--	--	.30	.16	.163	647	.22	.135
	M/64-94	no	-4.58	-.29	.001	.51	.23	<.001	-62.7	-.26	.004
	M/64-94	yes	--	--	--	.25	.11	.035	12.0	.05	.268
23	A/68-96	no	-13.74	-.84	.339	-.52	-.23	.223	-4,171	-1.17	.149
	A/68-96	yes	--	--	--	-.77	-.34	.011	-736	-.21	.196
	M/68-96	no	-5.21	-.33	.129	-.72	-.30	<.001	-171	-.59	.001
	M/68-96	yes	--	--	--	-1.01	-.42	<.001	-90.9	-.31	<.001
24	A/82-96	no	-2.72	-6.31	.198	9.57	.85	.767	-2,313	-5.78	.138
	A/82-96	yes	--	--	--	-20.42	-1.81	.002	-970	-2.42	.038
	M/82-96	no	-1.09	-2.70	<.001	-6.60	-.46	.304	-148	-4.45	<.001
	M/82-96	yes	--	--	--	-28.18	-1.97	<.001	-104	-3.12	<.001
25	A/75-96	no	-.86	-1.19	.430	-15.27	-.69	.612	-2,499	-1.73	.032
	A/75-96	yes	--	--	--	-23.85	-1.08	<.001	-2,191	-1.52	<.001
	M/75-96	no	-.42	-.61	.010	-15.57	-.61	<.001	-184	-1.54	<.001
	M/75-96	yes	--	--	--	-31.07	-1.22	<.001	-166	-1.39	<.001
26	A/52-63	no	-64.3	-4.14	.150	2.73	.91	.631	-15,610	-3.48	.087
	A/52-63	yes	--	--	--	-1.17	-.39	.150	-3,056	-.68	.150
	M/52-63	no	-21.1	-1.37	.002	-.95	-.24	.259	-718	-1.92	<.001
	M/52-63	yes	--	--	--	-4.47	-1.13	<.001	-394	-1.05	<.001
	A/64-96	no	-18.37	-1.07	.159	-.38	-.12	.698	-6039	-1.16	.027
	A/64-96	yes	--	--	--	-1.75	-.54	.001	-2635	-.50	.003
	M/64-96	no	-3.27	-.20	.253	-2.11	-.54	<.001	-295	-.68	<.001
	M/64-96	yes	--	--	--	-2.57	-.66	<.001	-211	-.48	<.001
27	A/65-96	no	-.86	-1.19	.430	6.82	1.03	.054	-2,499	-1.73	.032
	A/65-96	yes	--	--	--	1.57	.24	.224	-2,191	-1.52	<.001
	M/65-96	no	-1.39	-.45	.001	2.34	.24	.179	-110	-.73	<.001
	M/65-96	yes	--	--	--	-2.91	-.30	<.001	-28.1	-.19	.072
28	A/41-62	no	-32.1	-1.43	.128	.82	.22	.176	-10,387	-1.29	.128
	A/41-62	yes	--	--	--	-.24	-.06	.259	-469	-.06	.367
	M/41-62	no	-4.25	-.19	.157	.34	.08	.301	-157	-.23	.159
	M/41-62	yes	--	--	--	-.08	-.02	.58	-48.5	-.07	.082
	A/65-96	no	-18.2	-.85	.200	-1.88	-.39	.002	-11,661	-1.17	.050
	A/65-96	yes	--	--	--	-1.81	-.38	.005	-5,219	-.52	<.001

Table 7. Results of monotonic trend analysis for selected time periods at sites in the Green Region—Continued

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; A, annual time series; M, monthly time series; percent is the slope expressed as percent change per year; p value, attained significance level; --, not applicable]

Site number (plate 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
28	M/65-96	no	-22.0	-1.05	<.001	-2.03	-.42	<.001	-1,154	-1.40	<.001
	M/65-96	yes	--	--	--	-2.22	-.46	<.001	-341	-.41	<.001
29	M/85-93	no	-7.25	-9.25	<.001	5.39	1.94	<.001	-129	-7.42	.001
	M/85-93	yes	--	--	--	3.30	1.19	<.001	21.5	1.24	<.001
30	M/90-96	no	14.0	2.87	<.001	3.02	4.45	<.001	113	5.71	<.001
	M/90-96	yes	--	--	--	4.45	6.56	<.001	62.7	3.18	<.001
31	A/76-88	no	.30	6.42	.300	12.6	3.74	.127	104	7.16	.044
	A/76-88	yes	--	--	--	17.4	5.16	.003	49.5	3.42	.009
	M/76-88	no	.10	2.46	<.001	10.8	2.80	<.001	4.47	4.13	.001
	M/76-88	yes	--	--	--	12.0	3.11	<.001	2.67	2.47	<.001
32	A/76-88	no	.43	12.85	.017	91.4	9.08	<.001	566	15.25	.003
	A/76-88	yes	--	--	--	66.6	6.62	.009	129	3.48	.127
	M/76-88	no	.13	3.91	<.001	115	10.52	<.001	22.2	7.17	<.001
	M/76-88	yes	--	--	--	89.1	8.12	<.001	20.6	6.64	<.001
33	M/86-92	no	-8.88	-5.01	<.001	-3.43	-.99	.034	-302	-8.59	<.001
	M/86-92	yes	--	--	--	-15.4	-4.47	<.001	-175	-4.99	<.001
34	A/51-96	no	6.69	.44	.353	1.09	.64	<.001	2,738	1.08	.015
	A/51-96	yes	--	--	--	1.05	.61	<.001	1,447	.57	.002
	M/51-96	no	1.60	.11	.002	1.65	.59	<.001	74.6	.36	<.001
	M/51-96	yes	--	--	--	1.68	.60	<.001	60.2	.29	<.001
35	M/78-86	no	3.57	1.20	<.001	-.31	-.35	.470	28.3	2.27	<.001
	M/78-86	yes	--	--	--	1.43	1.61	<.001	14.9	1.20	<.001
36	M/86-91	no	-7.56	-7.47	<.001	-5.22	-2.52	<.001	-159	-11.62	<.001
	M/86-91	yes	--	--	--	-10.7	-5.14	<.001	-59.5	-4.35	<.001
37	A/62-92	no	-37.4	-.87	.324	1.44	.41	.144	-3,145	-.21	.708
	A/62-92	yes	--	--	--	1.44	.41	.144	4,944	.34	.118
	M/62-92	no	-13.2	-.31	.119	.67	.16	.018	-387	-.33	.174
	M/62-92	yes	--	--	--	.37	.09	.287	107	.09	.493
38	A/41-72	no	-7.19	-1.19	.168	4.25	.60	.072	-2,688	-.69	.236
	A/41-72	yes	--	--	--	.70	.10	.615	229	.06	.758
	M/41-72	no	-3.89	-.68	<.001	6.69	.67	<.001	-147	-.46	.010
	M/41-72	yes	--	--	--	1.80	.18	.001	-42.7	-.13	.108

Table 7. Results of monotonic trend analysis for selected time periods at sites in the Green Region—Continued

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; A, annual time series; M, monthly time series; percent is the slope expressed as percent change per year; p value, attained significance level; --, not applicable]

Site number (plate 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
38	A/73-96	no	-12.5	-2.52	.189	5.91	.79	.747	-8,689	-3.08	.056
	A/73-96	yes	--	--	--	-9.36	-1.25	.005	-4,684	-1.66	.006
	M/73-96	no	-6.86	-1.51	<.001	.84	.09	.780	-606	-2.62	<.001
	M/73-96	yes	--	--	--	-13.1	-1.37	<.001	-415	-1.79	<.001
39	A/82-92	no	-29.0	-8.36	.005	3.96	2.43	.043	-2,922	-5.40	.003
	A/82-92	yes	--	--	--	-.12	-.07	.876	-264	-.49	.213
	M/82-92	no	-11.5	-3.33	<.001	2.04	1.08	<.001	-162	-3.59	<.001
	M/82-92	yes	--	--	--	-1.44	-.76	<.001	-59.7	-1.32	<.001
40	M/86-92	no	-14.3	-5.77	<.001	1.40	.88	<.001	-183	-6.35	<.001
	M/86-92	yes	--	--	--	-1.84	-1.16	<.001	-46.9	-1.63	<.001
41	M/78-84	no	23.6	3.68	<.001	-1.34	.66	.335	396	4.61	<.001
	M/78-84	yes	--	--	--	3.56	1.75	<.001	172	2.00	<.001
	M/87-92	no	-28.8	-6.79	<.001	.01	.00	1.00	-520	-7.42	<.001
	M/87-92	yes	--	--	--	-5.38	-2.37	<.001	-238	-3.39	<.001
42	M/74-83	no	2.39	.39	.361	-7.80	-2.19	<.001	-118	-.80	.022
	M/74-83	yes	--	--	--	-4.70	-1.32	<.001	-202	-1.37	<.001
	M/87-96	no	-4.02	-.67	.519	-3.63	-1.02	.002	-234	-1.56	.014
	M/87-96	yes	--	--	--	-3.86	-1.08	<.001	-202	-1.35	<.001
43	A/75-96	no	.12	.61	.597	5.27	.77	.139	174	1.43	.342
	A/75-96	yes	--	--	--	6.16	.91	.005	49.5	.41	.091
	M/75-96	no	.07	.42	.216	5.69	.79	<.001	7.93	.84	.006
	M/75-96	yes	--	--	--	5.33	.74	<.001	3.33	.35	<.001
44	A/75-85	no	.17	7.21	.213	-3.02	-.33	.035	146	7.12	.213
	A/75-85	yes	--	--	--	-.84	-.09	.640	-1.52	-.07	.436
	M/75-85	no	.09	3.90	.001	-3.60	-.40	<.001	6.00	3.64	.004
	M/75-85	yes	--	--	--	-1.87	-.21	<.001	-.37	-.23	.001
45	A/74-85	no	.43	14.60	.011	-8.64	-1.01	.001	335	13.76	.016
	A/74-85	yes	--	--	--	-1.61	-.19	.086	-4.03	-.17	.451
	M/74-85	no	.29	10.0	<.001	-8.22	-.96	<.001	18.3	9.15	<.001
	M/74-85	yes	--	--	--	-4.09	-.48	<.001	-.80	-.40	<.001
46	A/75-87	no	3.53	11.43	.009	-9.10	-1.15	.155	2,787	12.44	.004
	A/75-87	yes	--	--	--	5.28	.67	.381	106	.47	.511
	M/74-87	no	1.92	6.97	<.001	-3.78	-.45	.007	139	7.50	<.001
	M/74-87	yes	--	--	--	6.18	.74	<.001	30.0	1.62	<.001

Table 7. Results of monotonic trend analysis for selected time periods at sites in the Green Region—Continued

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; A, annual time series; M, monthly time series; percent is the slope expressed as percent change per year; p value, attained significance level; --, not applicable]

Site number (plate 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
47	A/71-96	no	.27	.81	.402	-3.30	-.35	.217	143	.48	.659
	A/71-96	yes	--	--	--	-2.72	-.29	.186	-45.4	-.15	.508
	M/71-96	no	.10	.31	.178	-3.20	-.31	.001	5.29	.23	.334
	M/71-96	yes	--	--	--	-1.18	-.12	.039	-2.14	-.09	.218
48	A/71-88	no	3.55	7.89	.003	-45.4	-3.64	.001	2,999	6.28	.015
	A/71-88	yes	--	--	--	-8.00	-.64	.232	-128	-.27	.592
	M/71-88	no	2.17	5.16	<.001	-46.8	-3.17	<.001	142	3.63	<.001
	M/71-88	yes	--	--	--	-9.58	-.65	<.001	2.26	.06	.783
48	M/90-96	no	2.44	8.96	.001	-91.7	-5.73	<.001	162	5.85	.008
	M/90-96	yes	--	--	--	-35.5	-2.22	<.001	-33.4	-1.21	.020
49	A/75-96	no	.00	-.13	.833	8.55	.92	.091	-5.71	-.31	.874
	A/75-96	yes	--	--	--	6.04	.65	.113	3.60	.19	.597
	M/74-96	no	-.01	-.88	.008	8.97	.92	<.001	-.79	-.60	.085
	M/74-96	yes	--	--	--	8.75	.90	<.001	.03	.02	.804
50	M/74-82	no	-.02	-.94	.734	-19.4	-.79	.042	-4.73	-1.48	.259
	M/74-82	yes	--	--	--	-40.1	-1.64	<.001	-6.06	-1.90	.004
	M/88-96	no	-.31	-9.94	<.001	-14.9	-.62	.019	-71.0	-11.7	<.001
	M/88-96	yes	--	--	--	-42.8	-1.76	<.001	-17.2	-2.83	<.001
51	A/83-96	no	-45.7	-5.77	.063	-2.93	-.74	.443	-20,067	-6.65	.009
	A/83-96	yes	--	--	--	-5.63	-1.43	.016	-4,321	-1.43	.016
	M/83-96	no	-22.8	-2.97	<.001	-3.34	-.74	<.001	-1,157	-4.69	<.001
	M/83-96	yes	--	--	--	-10.7	-2.37	<.001	-674	-2.73	<.001
52	A/69-81	no	-5.50	-.83	.360	-1.08	-.28	.855	-4,453	-1.77	.200
	A/69-81	yes	--	--	--	-2.40	-.61	.360	-1,783	-.71	.502
	M/69-81	no	-7.51	-1.14	<.001	-1.36	-.30	.351	-394	-1.88	<.001
	M/69-81	yes	--	--	--	-4.78	-1.04	<.001	-252	-1.2	<.001
	A/82-96	no	-41.5	-5.15	.060	-.52	-.12	-.843	-13,663	-4.15	.029
	A/82-96	yes	--	--	--	-3.72	-.89	.553	-4,356	-1.32	.322
	M/82-96	no	-20.7	-2.57	<.001	-3.20	-.69	.011	-1,015	-3.70	<.001
	M/82-96	yes	--	--	--	-6.78	-1.46	<.001	-399	-1.45	<.001
	A/51-96	no	2.50	.36	.384	-1.74	-.40	.015	-724	-.24	.426
	A/51-96	yes	--	--	--	-1.94	-.45	.003	-1,173	-.39	.009
	M/51-96	no	1.27	.18	.001	-2.66	-.53	<.001	-56.8	-.23	<.001
	M/51-96	yes	--	--	--	-2.48	-.50	<.001	-86.4	-.35	<.001

Table 7. Results of monotonic trend analysis for selected time periods at sites in the Green Region—Continued

[Period of water-quality data analyzed is complete water years (October 1 through September 30) for annual time series. The period of record for the monthly time series may vary if data from a partial water year was used; A, annual time series; M, monthly time series; percent is the slope expressed as percent change per year; p value, attained significance level; --, not applicable]

Site number (plate 1)	Period of water-quality data analyzed (time series)	Data flow adjusted	Streamflow (cubic feet per second)			Dissolved-solids concentrations (milligrams per liter)			Dissolved-solids loads (tons)		
			Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
53	M/76-84	no	1.30	4.70	.001	-93.2	-4.07	<.001	80.2	1.78	.044
	M/76-84	yes	--	--	--	-42.9	-1.88	<.001	-94.9	-2.11	<.001
54	M/76-84	no	1.53	6.69	<.001	-87.9	-3.71	<.001	115	2.98	.017
	M/76-84	yes	--	--	--	-47.7	-2.01	<.001	-79.9	-2.07	<.001
55	M/78-84	no	1.49	8.22	<.001	-.42	-.14	.568	42.4	11.86	<.001
	M/78-84	yes	--	--	--	8.44	2.79	<.001	15.9	4.45	<.001
56	A/49-88	no	1.68	1.27	.087	-38.0	-1.65	.001	198	.08	.807
	A/49-88	yes	--	--	--	-17.9	-.78	<.001	-1,987	-.83	.002
	M/49-88	no	1.02	.85	<.001	-44.4	-1.53	<.001	22.5	.11	.422
	M/49-88	yes	--	--	--	-29.4	-1.01	<.001	-107	-.54	<.001
57	A/29-62	no	2.37	.04	.953	-.31	-.08	.767	-1,654	-.07	.882
	A/29-62	yes	--	--	--	-.53	-.12	.553	-4,562	-.19	.234
	M/29-62	no	7.27	.13	.196	.41	.07	.342	532	.27	.058
	M/29-62	yes	--	--	--	.99	.17	.043	371	.19	.001
	A/65-96	no	-55.5	-.95	.116	-1.95	-.43	.058	-37,458	-1.45	.016
	A/65-96	yes	--	--	--	-2.55	-.56	<.001	-15,500	-.60	.001
	M/65-96	no	-46.4	-.81	<.001	-.258	-.48	<.001	-2,848	-1.34	<.001
	M/65-96	yes	--	--	--	-3.78	-.71	<.001	-1,870	-.88	<.001
58	A/47-65	no	-.96	-.74	.726	1.03	.05	1.000	-2,642	-1.31	.294
	A/47-65	yes	--	--	--	-12.9	-.69	.142	-2,200	-1.10	.042
	M/47-65	no	-1.05	-.96	.024	-1.74	-.06	.816	-259	-1.59	.001
	M/47-65	yes	--	--	--	-24.0	-.88	<.001	-215	-1.32	<.001
58	A/66-96	no	-.90	-.78	.475	-17.6	-.91	.292	-2,497	-1.49	.077
	A/66-96	yes	--	--	--	-21.9	-1.13	<.001	-2,439	-1.46	.001
	M/66-96	no	-.35	-.34	.058	-23.1	-.97	<.001	-165	-1.25	<.001
	M/66-96	yes	--	--	--	-28.7	-1.20	<.001	-151	-1.14	<.001
59	M/83-91	no	-.13	-7.74	<.001	-.78	-.26	.752	-3.33	-11.2	<.001
	M/83-91	yes	--	--	--	-8.43	-2.85	<.001	-1.20	-4.02	<.001
60	M/78-84	no	.50	12.7	<.001	-177	-7.92	.015	64.8	13.4	<.001
	M/78-84	yes	--	--	--	-92.8	4.15	<.001	27.5	5.70	<.001

Table 8. Step trend tests on annual streamflow and dissolved-solids data for stations affected by major interventions in the Green Region

[Periods in water years (October 1 through September 30); Pre, pre-intervention period; post, post-intervention period; mg/L, milligrams per liter; T, attained significance level based on *t*-tests; W, attained significance level based on Wilcoxon rank-sum test; Attained significance levels: HS, highly significant, significance level (p value) less than or equal to 0.01; S, significant, p value is greater than 0.01 and less than or equal to 0.05; MS, marginally significant, p value is greater than 0.05 and less than or equal to 0.10; NS, not significant, p value is greater than 0.10]

Site number (table 1, plate 1)	Intervention	Period		Mean annual streamflow (cubic feet per second)				Mean annual dissolved-solids concentration (mg/L)				Annual dissolved-solids load (tons)			
		Pre	Post	Pre	Post	T	W	Pre	Post	T	W	Pre	Post	T	W
26	Fontenelle Reservoir	1941–63	1964–96	1,740	1,720	NS	NS	291	322	S	S	486,000	522,000	NS	NS
28	Flaming Gorge Reservoir	1941–62	1965–96	2,240	2,130	NS	NS	371	478	HS	HS	805,000	997,000	S	S
38	Strawberry Reservoir expansion	1941–72	1973–96	602	497	NS	MS	712	746	NS	NS	388,000	282,000	HS	HS
41	Break in record	1979–84	1987–96	572	494	NS	NS	170	196	S	S	92,100	93,500	NS	NS
42	Meeker Dome salinity control	1974–81	1983–96	589	637	NS	NS	313	299	NS	NS	174,000	182,000	NS	NS
48	Break in record	1971–87	1990–96	45.1	25.7	NS	MS	1,250	1,340	NS	NS	47,800	30,700	MS	S
50	Break in record	1974–82	1989–96	1.9	2.9	HS	S	2,200	2,260	NS	NS	4,070	6,610	HS	HS
52	Meeker Dome salinity control	1969–81	1982–96	659	806	NS	NS	393	418	NS	MS	251,000	329,000	S	NS
57	Flaming Gorge Reservoir	1929–62	1965–96	5,620	5,810	NS	NS	439	458	NS	MS	2,377,000	2,580,000	NS	NS
58	Joes Valley Reservoir	1935–65	1966–96	135	116	NS	MS	1,774	1,937	NS	NS	207,400	167,000	MS	S

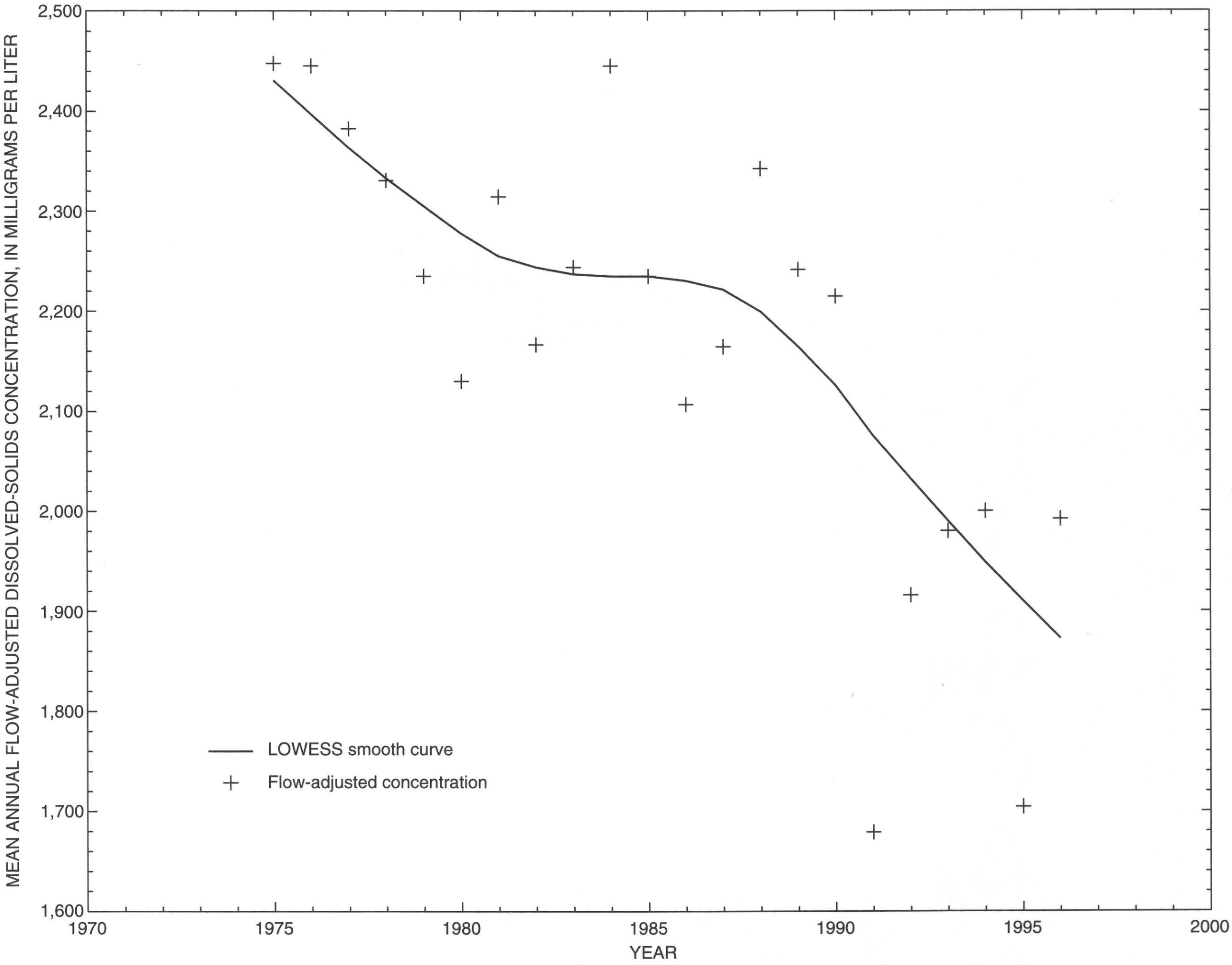

Figure 5. Mean annual flow-adjusted dissolved-solids concentrations and LOWESS smooth curve, station 09216050, Big Sandy River at Gasson Bridge, near Eden, Wyoming (site 25), water years 1975–96.

increase in flow-adjusted annual concentration at this site. The only trend in the flow-adjusted data was downward for dissolved-solids loads.

Trend analysis of the monthly data indicated a significant downward trend in streamflow. No trend was determined in dissolved-solids concentrations; however, a significant downward trend was determined in dissolved-solids loads. A downward trend was determined in the flow-adjusted dissolved-solids concentrations. No tend was determined in flow-adjusted loads.

Green River near Greendale, Utah (Site 28)

Site 28 is located about 0.5 mile downstream from Flaming Gorge Reservoir. Streamflow of the river has been completely controlled since the reservoir began filling in 1962. Dissolved-solids concentrations are remarkably constant throughout the year since the reservoir was constructed (Liebermann and others, 1989). Trend analysis of the period 1965–96, since Flaming Gorge, determined significant downward trends in the annual dissolved-solids concentrations and loads and in the flow-adjusted dissolved-solids concentrations and loads (table 7).

Trend analysis of the monthly data indicated significant downward trends in streamflow, dissolved-solids concentrations, and loads. The trends in dissolved-solids concentrations and loads also were significantly downward after the data were flow adjusted.

Step trend tests related to the intervention of Flaming Gorge Reservoir were evaluated at this site.

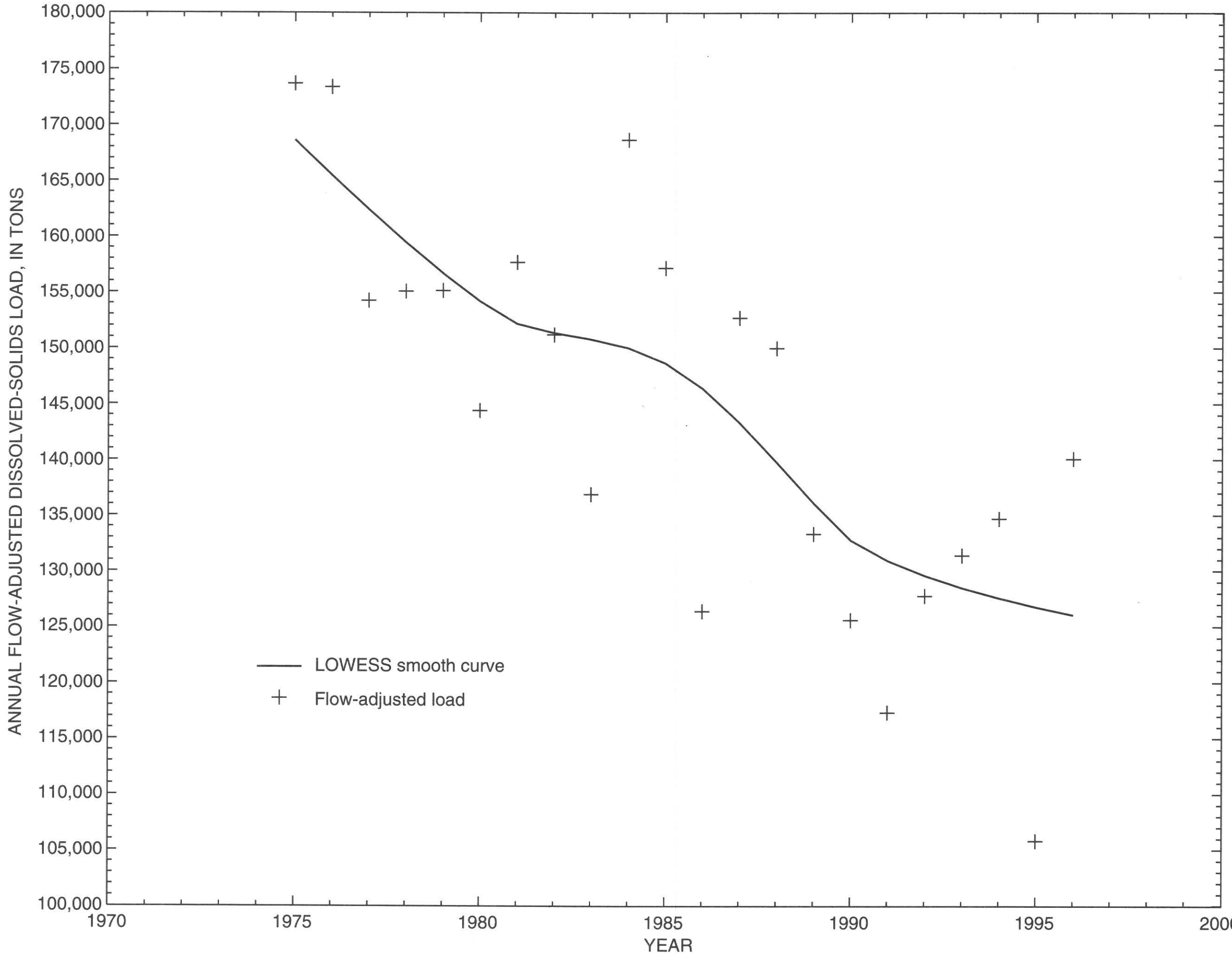

Figure 6. Annual flow-adjusted dissolved-solids load and LOWESS smooth curve, station 09216050, Big Sandy River at Gasson Bridge, near Eden, Wyoming (site 25), water years 1975–96.

The mean annual dissolved-solids concentrations and loads for the post-intervention period were significantly higher than in the pre-intervention period (table 8). This is consistent with the findings reported by Liebermann and others (1989), who attributed the increases to several possible factors, including higher streamflow in the post-intervention period and dissolution of salts in the reservoir bank material from 1963 to 1972.

Middle Green Subregion

The Middle Green Subregion includes the Yampa River Basin and tributaries and all of the tributaries to the Green River downstream from Greendale, Utah, to the confluence with the White River. The only transbasin export from the Green River Basin in Wyoming is from the Little Snake River Basin. Numerous reservoirs in Utah regulate and divert water for irrigation purposes. Streamflow and water-quality data from 10 sites in the subregion were analyzed for annual and monthly trends (pl. 1 and table 1).

Yampa River Headwaters (Sites 29–32)

Yampa River below Stagecoach Reservoir (site 29) is the most upstream site in the subregion analyzed for trends. The site is about 0.3 mile downstream from Stagecoach Reservoir and should reflect the quantity and quality of flow in the headwaters of the Yampa River. The period of record was not long enough to analyze for trends in the annual data. Trend analysis of the monthly streamflow determined a significant downward trend (table 7). A significant upward trend was determined for monthly dissolved-solids concentrations and a significant downward trend was determined for monthly loads. After the data were flow adjusted, the trends for dissolved-solids concentrations and loads were upward.

The Elk River is a major tributary that drains from the north and enters the Yampa River downstream from Steamboat Springs. Elk River near Milner, Colo. (site 30) is located near the confluence. Middle Creek near Oak Creek (site 31) and Foidel Creek at mouth, near Oak Creek (site 32) represent smaller tributaries that drain from the south and enter the Yampa River downstream from site 30.

At site 30, the period of record is not long enough for analysis of trends in the annual data. Trend analysis of the monthly streamflow indicated a significant upward trend (table 7). Trend analysis of the monthly dissolved-solids concentrations and loads determined significant upward trends. Upward trends in monthly dissolved-solids concentrations and loads were determined after the data were flow adjusted.

Trend analysis at site 31 indicated significant upward trends in the annual dissolved-solids load (table 7). The trend in the flow-adjusted annual dissolved-solids concentration and load was upward. Trend analysis of the monthly streamflow, dissolved-solids concentrations, and loads indicated significant upward trends. The trends were upward in the flow-adjusted dissolved-solids concentrations and loads.

Trend analysis at site 32 indicated significant upward trends in annual streamflow, dissolved-solids concentrations, and loads (table 7). The trend in the flow-adjusted annual dissolved-solids concentrations was upward. No trend was determined for the flow-adjusted annual dissolved-solids loads. Significant upward trends were detected for monthly streamflow and unadjusted and flow-adjusted dissolved-solids concentrations and loads.

In general, significant upward trends in flow-adjusted monthly dissolved-solids concentrations and loads were detected throughout the headwaters of the Yampa River. Trends in streamflow varied among the sites analyzed.

Williams Fork at mouth, near Hamilton, Colorado (Site 33)

The Williams Fork is a major tributary that drains from the south and enters the Yampa River near the middle of the basin. Site 33 is located near the mouth of the Williams Fork. The period of record at this site was not long enough for analysis of annual trends. Trend analysis of the monthly data determined significant downward trends in streamflow and the unadjusted and flow-adjusted dissolved-solids concentrations and loads (table 7). This contrasts with the upward trends detected in the headwaters at sites 29–32.

Yampa River near Maybell, Colorado (Site 34)

The streamflow and water quality at site 34 represents about two-thirds of the Yampa River watershed. No statistically significant trends were determined in annual streamflow (table 7). Trend analysis indicated significant upward trends in the unadjusted and flow-adjusted annual dissolved-solids concentrations and loads. These results are consistent with the trends reported by Liebermann and others (1989) for the period 1951–83. Trend analysis of the monthly data determined significant upward trends in streamflow, dissolved-solids concentrations, and loads.

The major land-use change in the basin upstream from this site has been the expansion of coal-resource development since the early 1960's. Liebermann and others (1989) cited several references that might indicate the upward trends in dissolved-solids concentrations and loads could be attributed to spoil piles and the associated runoff.

Little Snake River Basin (Sites 35 and 36)

Little Snake River near Slater (site 35) is located on the main stem in the headwaters of the basin. The period of concurrent streamflow and water-quality record was not long enough to evaluate trends in the annual data. Trend analysis of the monthly data determined significant upward trends in streamflow, dissolved-solids concentrations, and loads (table 7). The trends in flow-adjusted dissolved-solids concentrations and loads were upward.

Savery Creek is a tributary to the Little Snake River in the upper part of the basin. Savery Creek near Savery, Wyo. (site 36), is located near the mouth. A sufficient period of record was not available for analysis of trends in the annual data. Trend analysis of the monthly data determined significant downward trends in streamflow, unadjusted and flow-adjusted dissolved-solids concentrations, and loads (table 7). These results contrast with the findings at site 35.

Green River near Jensen, Utah (Site 37)

Streamflow at this site is a combination of water released from Flaming Gorge Reservoir and the inflow from the Yampa River. The Yampa River dilutes the dissolved-solids concentrations of the Green River by about 150 mg/L (Liebermann and others, 1989). The period of record (1962–93) for dissolved solids coincides with the period following completion of Flaming Gorge Reservoir. The only significant trend detected for this site was upward for the unadjusted monthly dissolved-solids concentration (table 7). Liebermann and others (1989) did not detect any trends for the period 1962–83.

Duchesne River near Randlett, Utah (Site 38)

Streamflow at site 38 near the mouth of the Duchesne River is greatly depleted by transbasin exports and by irrigation usage. Strawberry Reservoir is located on the upper Strawberry River, a major tributary of the Duchesne River. The capacity of Strawberry Reservoir was nearly quadrupled in 1972 by construction of a new dam. A considerable part of the base flow in the Duchesne River is from irrigation return flows that contribute most of the dissolved salts delivered to the Green River from the Duchesne River Basin (Liebermann and others, 1989). Salinity control efforts in the Uinta Basin Project began about 1987 and have included selective lining of canals and laterals by the BOR and improved irrigation delivery systems and practices by the USDA.

Annual trend analysis for the period 1941–72, prior to expansion of Strawberry Reservoir, did not determine any significant trends in streamflow, dissolved-solids concentrations, or loads (table 7). Significant downward trends were determined in the monthly streamflow and dissolved-solids loads, but a significant upward trend was detected for monthly dissolved-solids concentrations. After the data were flow adjusted, the trend in monthly dissolved-solids concentrations was upward, but there was no trend in dissolved-solids loads.

Annual trend analysis for the period 1973–96, after expansion of Strawberry Reservoir, determined significant downward trends in the flow-adjusted dissolved-solids concentrations and loads but no trend in streamflow. Trend analysis of the monthly streamflow determined significant downward trends for the period 1973–96. Significant downward trends were also detected for flow-adjusted monthly dissolved-solids concentrations and loads.

Annual step trend analyses were evaluated in relation to expansion of Strawberry Reservoir. Differences in mean annual streamflow, dissolved-solids concentrations, and loads were compared for the periods 1941–72 and 1973–96 associated with reservoir expansion. A highly significant difference was determined for dissolved-solids load but only a marginally significant difference in streamflow (table 8). There was no significant difference between periods in dissolved-solids concentration. Liebermann and others (1989) did not report significant annual step trends due to the expansion of Strawberry Reservoir and did not report any significant annual trends for the period 1957–83.

Salinity control efforts in the Duchesne River Basin began in 1987 in the Uinta Basin Project (U.S. Department of the Interior, 1997). The LOWESS smooth curves indicate large decreases in dissolved-solids concentrations and loads after the early 1970's, as shown in figures 7 and 8. The LOWESS smooth curves indicate that the trends for 1973–96 occurred throughout the entire period, which included reservoir expansion and salinity control projects.

White Subregion

The White Subregion includes the entire White River Basin. Dissolved-solids data on tributary drainages was limited primarily to the Piceance Creek Basin. No transbasin exports occur from the subregion, and no large reservoirs exist. Streamflow and water-quality data for 14 sites were analyzed for trends in this subregion (pl. 1 and table 1).

White River Headwaters (Sites 39 and 40)

Two sites located in the headwaters of the White River (North Fork White River at Buford, site 39, and South Fork White River near Buford, site 40) represent the initial quantity and quality of streamflow in the White River. Trend analysis at site 39 determined a significant downward trend in annual streamflow, an upward trend in dissolved-solids concentrations, and a downward trend in dissolved-solids loads (table 7). The trends were not significant when the dissolved-solids data were flow adjusted for variations in stream-

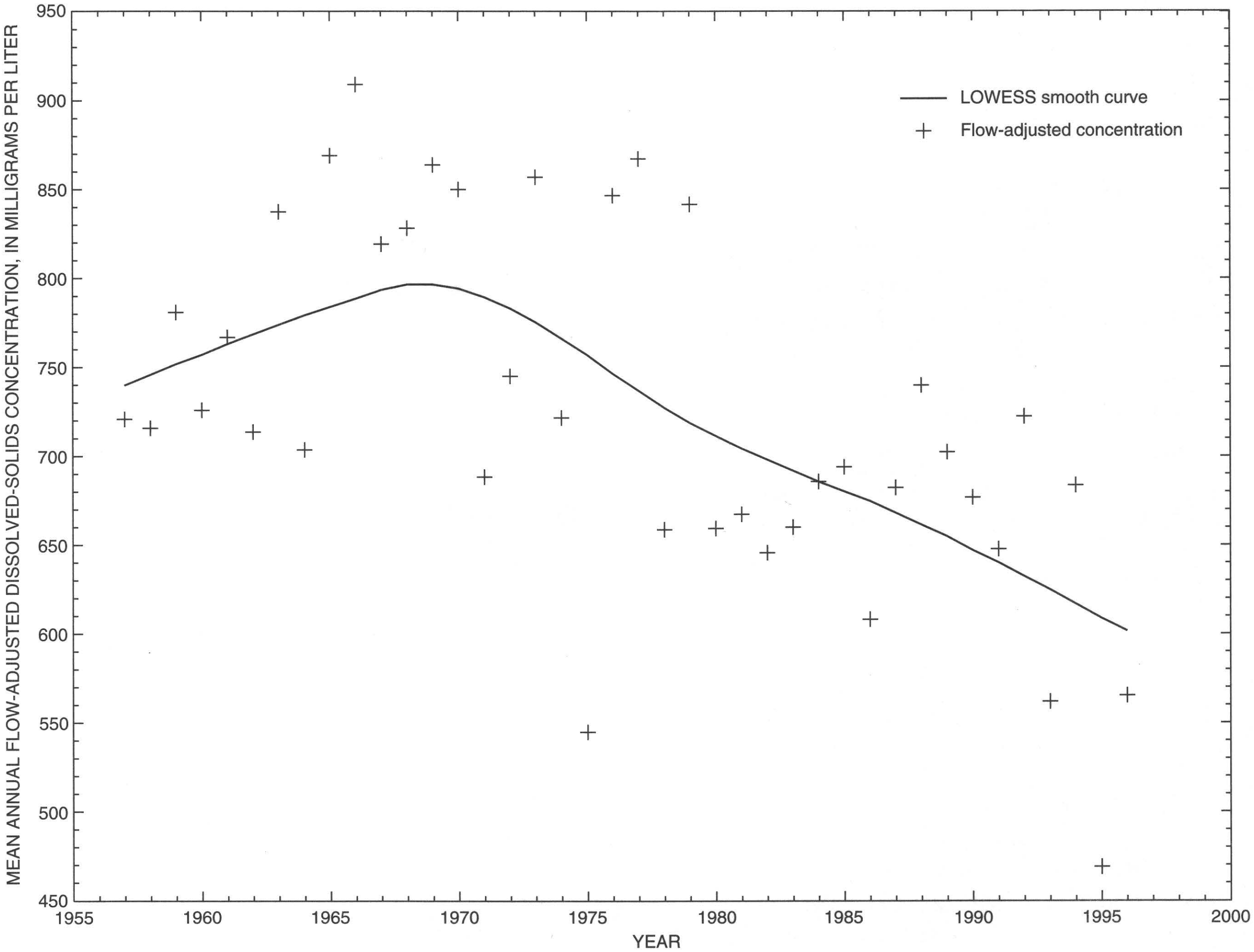

Figure 7. Annual flow-adjusted dissolved-solids concentration and LOWESS smooth curve, station 09302000, Duchesne River at Randlett, Utah, site 38, water years 1957–96.

flow. Trend analysis of the monthly data determined a significant downward trend in streamflow, an upward trend in dissolved-solids concentrations, and a downward trend in dissolved-solids loads (table 7). The trends in flow-adjusted dissolved-solids concentrations and loads were downward.

The period of record at site 40 was too short for analysis of annual data. Trend analysis of the monthly data determined a significant downward trend in streamflow, an upward trend in dissolved-solids concentrations, and a downward trend in dissolved-solids loads (table 7). After the data were flow adjusted, the trends were downward for dissolved-solids concentrations and loads. These results are similar to site 39.

White River above Coal Creek, near Meeker, Colorado (Site 41)

Annual data were not analyzed for trends due to the short periods of record. Trend analysis of the monthly data for the period 1978–84 detected significant upward trends in streamflow, flow-adjusted dissolved-solids concentrations, and unadjusted dissolved-solids loads (table 7). Trends determined for the period 1987–92 were significant downward trends in streamflow, flow-adjusted dissolved-solids concentrations, and unadjusted and flow-adjusted dissolved-solids loads (table 7). The reason for the change in trend slope between the periods is not readily apparent. The site is located upstream from the Meeker Dome Unit and should not reflect salinity control efforts during the early 1980's. Step trend

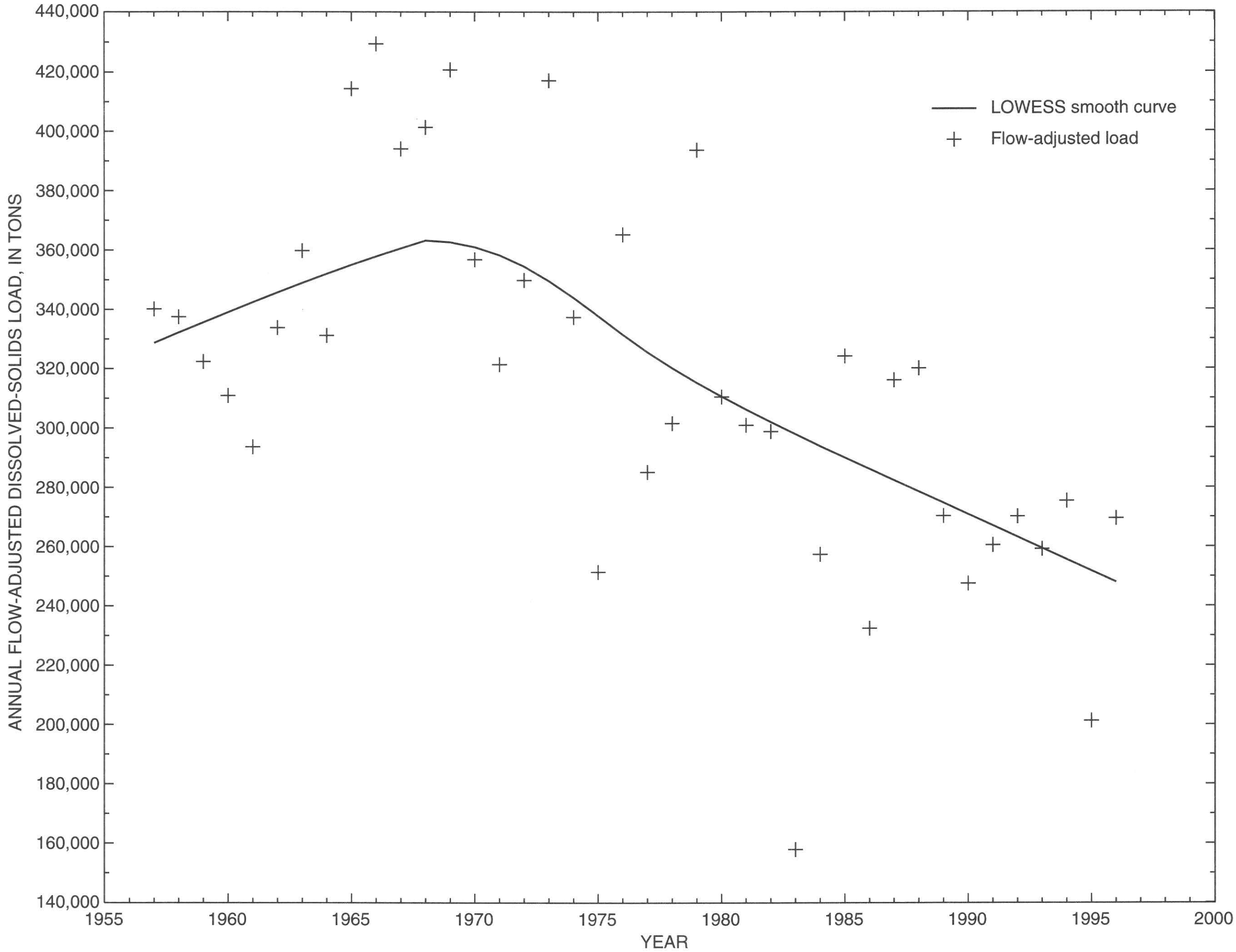

Figure 8. Annual flow-adjusted dissolved-solids concentration and LOWESS smooth curve, station 09302000, Duchesne River at Randlett, Utah, site 38, water years 1957–96.

analysis between the two periods of record indicated a significant difference in mean annual dissolved-solids concentrations (table 8).

White River below Meeker, Colorado (Site 42)

Site 42 is located on the main-stem White River downstream from the Meeker Dome Unit. Liebermann and others (1989) reported a significant downward trend in the annual flow-adjusted dissolved-solids concentrations for the period 1974–83. Butler (1996) analyzed water-quality data for 1973–92 and reported significant downward trends in the chloride and sodium concentrations that were related to well plugging for the Meeker Dome Unit in 1980–81. The additional period of record of dissolved-solids data, 1987–96, was not long enough for trend analysis of the annual data. Significant downward trends for 1987–96 were determined in monthly unadjusted and flow-adjusted dissolved-solids concentrations and loads, but no trends were determined in monthly streamflow. The Meeker Dome Unit could have affected trends in the 1974–83 period but would not be expected to affect trends in the 1987–96 period. The continued downward trends for 1987–96 suggest there maybe other causes for the continued downward trend.

Step trend analysis of mean annual streamflow, dissolved-solids concentrations, and loads for the periods 1974–81 and 1983–96 related to salinity control efforts at the Meeker Dome Unit did not indicate any significant differences (table 8). Step trend analysis does not account for flow-adjusted values and may not reflect trends determined by monotonic trend analysis. Also, the decrease in annual dissolved-solids load of about 19,000 tons attributed to the Meeker

Dome Unit (Bureau of Reclamation, 1985) is only about 11 percent of the annual load in the White River at site 42.

Piceance Creek Basin (Sites 43–48)

Six sites are located within the Piceance Creek Basin. Results of trend analysis of the annual data varied among the sites. Upward trends were only determined in annual streamflow at three sites (sites 45, 46, and 48). Site 43, Piceance Creek below Rio Blanco, was the only site where a significant trend was determined in flow-adjusted annual dissolved-solids concentration; the trend was upward (table 7). Several sites had significant trends in the unadjusted data that are related to streamflow.

Trend analysis of the monthly streamflow determined a consistent significant upward trend at four (sites 44–46, and 48) of the six sites (table 7). Significant trends in flow-adjusted monthly dissolved-solids concentrations were reported for all six sites. The trend was downward at site 43 and upward at sites 44–48 (table 7). Except for site 47, the trend in monthly dissolved-solids loads was significantly upward at sites 44–48. Trends in the flow-adjusted monthly dissolved-solids loads were significant at five sites (43–46, 48) (table 7). Trends in monthly loads were not in the same direction among sites, which may be due to local land use, irrigation practices, or analysis of different periods of record.

Step trend analysis at site 48, Piceance Creek at White River, related to a break in record, determined a marginally significant difference in annual streamflow and dissolved-solids load between 1971–87 and 1990–96 (table 8). The difference may be due to changes in climate or irrigation practices within the basin.

Middle White River Tributaries (Sites 49 and 50)

Corral Gulch near Rangely (site 49) and Yellow Creek near White River (site 50) are tributaries of the White River that drain from the south and discharge into the White River in the middle part of the basin. There were no significant annual trends determined for site 49. Trend analysis determined a significant downward trend in monthly streamflow and an upward trend in unadjusted and flow-adjusted dissolved-solids concentrations. No trends were found for unadjusted or flow-adjusted dissolved-solids loads.

At site 50, two periods of record are available for analysis (1974–82 and 1988–96). Neither period is long enough for analysis of the annual trends. No trends were determined in monthly streamflow for the period 1974–82. Trend analysis of monthly flow-adjusted dissolved-solids concentrations and loads determined significant downward trends (table 7). Trend analysis for the period 1988–96 detected significant downward trends in monthly streamflow, unadjusted and flow-adjusted dissolved-solids concentrations, and loads (table 7).

Step trend tests for the break in record at site 50 determined a significant difference in mean annual streamflow and mean annual dissolved-solids load (table 8). There was no difference in the mean annual dissolved-solids concentration between the two periods.

White River below Boise Creek, near Rangely, Colorado (Site 51)

Annual trend analysis determined significant downward trends in flow-adjusted dissolved-solids concentrations and in unadjusted and flow-adjusted dissolved-solids loads (table 7). No significant trend was determined in the mean annual streamflow. Significant downward trends were determined in the monthly streamflow, dissolved-solids concentrations, and loads (table 7).

White River near Watson, Utah (Site 52)

Site 52 is located about 8 miles downstream from the Colorado-Utah State line and represents the flow from the entire White River Basin. The period of record analyzed at this site was 1951–96. An abandoned exploratory oil well called the Meeker Well that leaked saline ground water into the White River was plugged by the BOR in 1968 using funds provided by the Federal Water Pollution Control Administration to reduce salt loading. The period of record after the Meeker Well plugging (1969–96) was separated into a pre-intervention period (1969–81) and a post-intervention period (1982–96) based on the Meeker Dome Unit salinity control efforts in 1981. Annual trend analyses were performed for the period 1951–96 because there were no interventions in streamflow. No trend was determined in annual streamflow. A downward trend was determined for annual dissolved-solids concentrations but not for loads. After the data were flow adjusted, the trend was downward for dissolved-solids concentrations and loads (table 7).

Trend analysis of the monthly data for the period 1951–96 determined a significant upward trend in streamflow. The trends in the monthly, unadjusted, and flow-adjusted dissolved-solids concentrations and loads were downward.

Step trend analysis based on the Meeker Dome Unit intervention determined a significant difference in annual dissolved-solids load between the two periods, 1969–81 and 1982–96 (table 8). Step trend analysis does not account for effects of variation in streamflow on dissolved-solids concentrations and loads. Liebermann and others (1989) reported a significant difference in dissolved-solids concentration between the periods 1951–68 and 1969–83 based on the initial plugging of the Meeker Well in 1968.

Plots of the LOWESS smooth curves for annual flow-adjusted dissolved-solids concentrations and loads (figs. 9 and 10) for 1951–96 indicate a downward trend prior to plugging of the Meeker Well. The plots do not indicate any abrupt decreases related to the plugging of the well. The downward trends continue until the mid-1970's when a slight increase in dissolved-solids concentrations and loads occurs. No noticeable changes occur after completion of the Meeker Dome Unit well plugging in 1981.

Lower Green and Main Stem Subregions

These subregions include the drainages of the Price and San Rafael Rivers and all other tributaries to the Green River from the confluence with the White River to the Colorado River, and tributaries to the main-stem Colorado River from the confluence of the Green River to Lake Powell at Hite, Utah. Mancos Shale deposits underlie much of the irrigated agricultural areas in this subregion. There are numerous small transbasin exports in the upper part of these two subregions.

Pariette Draw Basin (Sites 53 and 54)

Pariette Draw is a small tributary to the Green River that enters downstream from the confluence of the White River. Pariette Draw near Ouray, Utah (site 53), is located about mid-basin, and Pariette Draw at mouth, near Ouray, Utah (site 54), is located near the mouth of the basin. No annual trend analyses were determined at either site due to the short periods of record. At site 53, trend analysis determined a significant upward trend in monthly streamflow and dissolved-solids concentrations (table 7). A significant downward trend in dissolved-solids loads was determined. Trends in flow-adjusted monthly dissolved-solids concentrations and loads were downward (table 7).

At site 54, a significant upward trend in monthly streamflow and dissolved-solids concentrations was determined (table 7). A significant downward trend in dissolved-solids loads was determined. Trends in flow-adjusted monthly dissolved-solids concentrations and loads were downward (table 7).

Price River Basin (Sites 55 and 56)

Mud Creek below Winter Quarters Canyon at Scofield, Utah (site 55), is located on a tributary to the Price River near the headwaters. The period of record at this site was not long enough for trend analysis of the annual data. Trend analysis determined significant upward trends in the monthly streamflow, the flow-adjusted monthly dissolved-solids concentrations, and unadjusted and flow-adjusted dissolved-solids loads (table 7).

Price River at Woodside, Utah (site 56), is located near the mouth of the river. Streamflow at this site is greatly affected by storage, diversions for public supply and agriculture, and irrigation return flows (Liebermann and others, 1989). Trend analysis indicated significant downward trends in the unadjusted and flow-adjusted annual dissolved-solids concentrations, and in the flow-adjusted annual dissolved-solids loads (table 7).

Trend analysis determined a significant upward trend in monthly streamflow and significant downward trends in unadjusted and flow-adjusted monthly dissolved-solids concentrations and flow-adjusted dissolved-solids loads (table 7). Liebermann and others (1989) only reported significant decreases in the annual dissolved-solids concentrations and the flow-adjusted annual dissolved-solids concentrations.

Green River at Green River, Utah (Site 57)

The Green River at Green River, Utah, is the farthest downstream site on the Green River. The San Rafael River is the only major tributary of the Green River downstream from this site. Streamflow at this

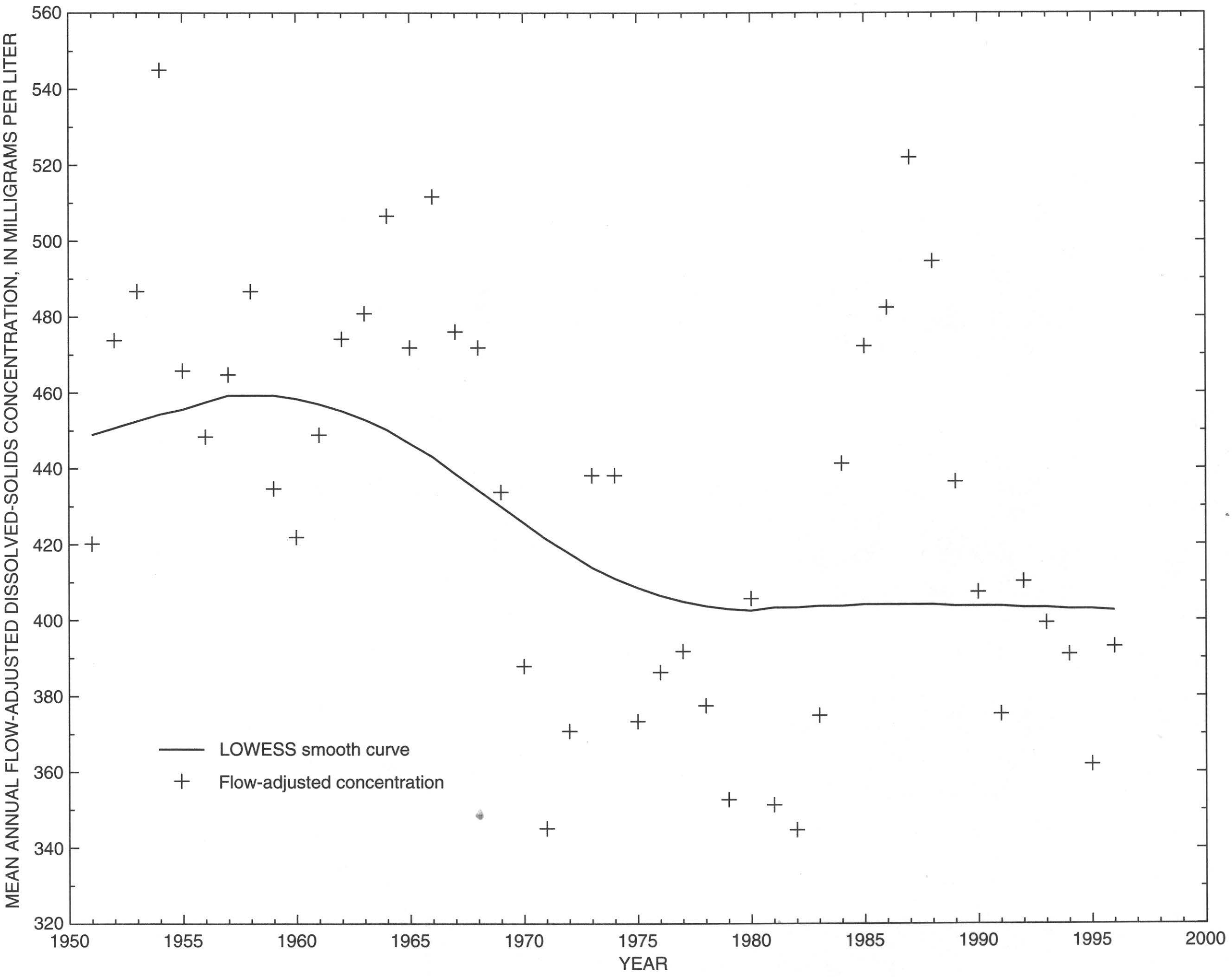

Figure 9. Annual flow-adjusted dissolved-solids concentration and LOWESS smooth curve, station 09306500, White River near Watson, Utah, site 52, water years 1951–96.

site should be representative of the cumulative hydrology of almost the entire Green Region (Liebermann and others, 1989). Annual trend analysis of the period of record after the intervention of Flaming Gorge Reservoir (1965–96) did not detect a trend in streamflow. Significant downward trends were determined in the flow-adjusted annual dissolved-solids concentrations and unadjusted and flow-adjusted annual dissolved-solids loads (table 7).

Trend analysis determined significant downward trends in the monthly streamflow and the flow-adjusted monthly dissolved-solids concentrations and loads (table 7). Liebermann and others (1989) did not detect any statistically significant annual trends for 1965–83.

Step trend analysis for the pre-intervention period (1929–62) and the post-intervention period (1965–96) of Flaming Gorge Reservoir determined only a marginally significant difference in the mean annual dissolved-solids concentrations (table 8). Liebermann and others (1989) reported significant differences in annual dissolved-solids concentrations and loads (1965–83).

San Rafael River near Green River, Utah (Site 58)

Site 58 is located about 20 miles upstream from the confluence with the Green River. Since the filling of Joes Valley Reservoir in 1965–66, streamflow has not greatly changed other than the snowmelt-runoff peak occurring later in the season (Liebermann and others, 1989). For 1966–96, since reservoir construction, trend analysis of the annual data did not detect a

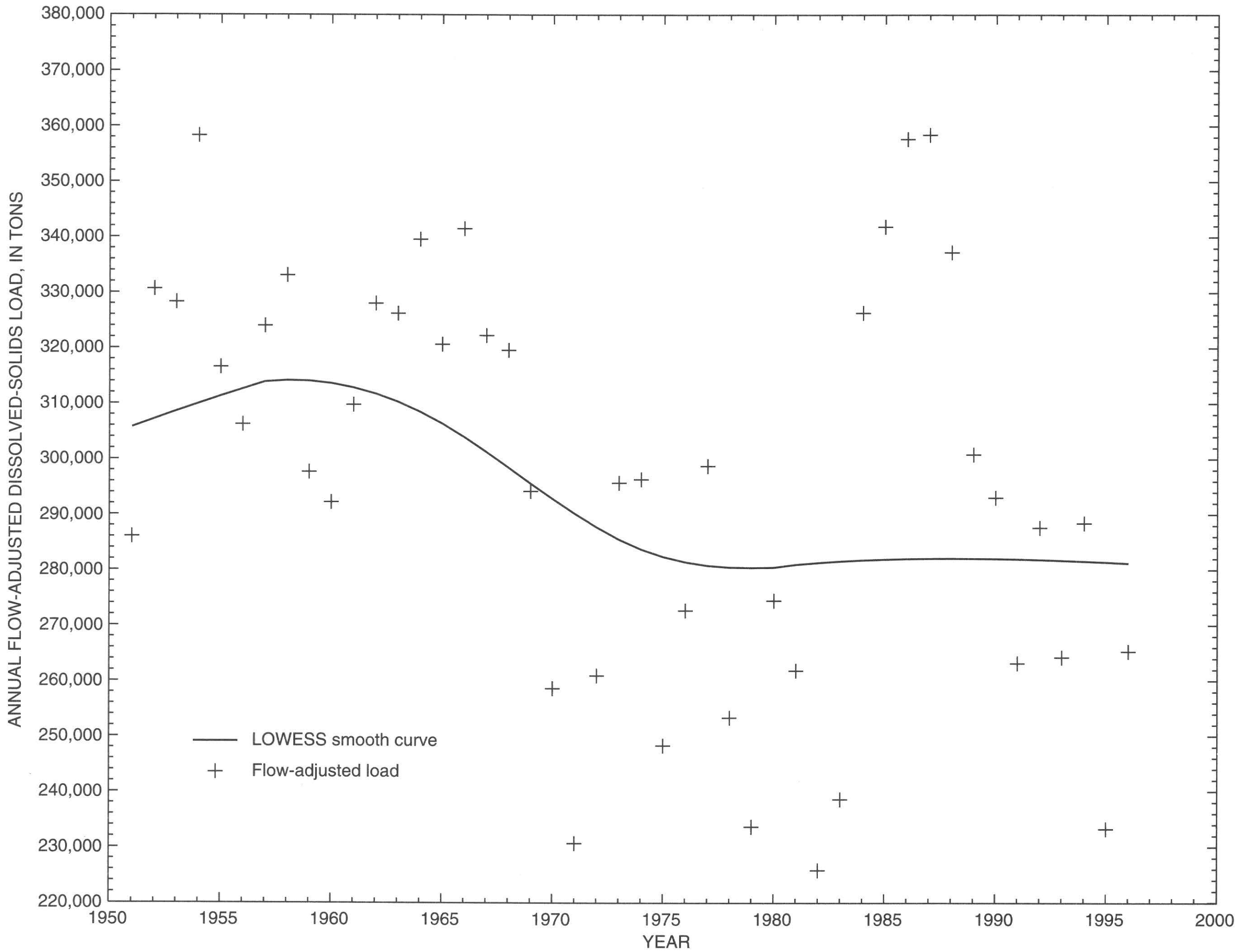

Figure 10. Annual flow-adjusted dissolved-solids load and LOWESS smooth curve, station 09306500, White River near Watson, Utah, site 52, water years 1951–96.

trend in streamflow. Significant downward trends were determined in the flow-adjusted dissolved-solids concentrations and loads (table 7).

The trend in monthly streamflow was not statistically significant. Trend analysis determined a significant downward trend in the unadjusted and flow-adjusted monthly dissolved-solids concentrations and loads (table 7).

Step trend analysis determined a marginally significant difference in mean annual streamflow for the pre- and post-intervention periods of Joes Valley Reservoir (1935–65 and 1966–96). A significant difference was determined in mean annual dissolved-solids loads from 1935–65 to 1966–96 (table 8). No statistically significant annual step trends or annual monotonic trends were determined by Liebermann and others (1989).

Main-Stem Colorado River Tributaries (Sites 59 and 60)

Bull Creek near Hanksville, Utah (site 59), and Christiansen Wash near Emery, Utah (site 60), are tributaries to the Dirty Devil River, which is a tributary to the Colorado River. Since the construction of Glen Canyon Dam and the filling of Lake Powell, the Dirty Devil River flows into the lake at the most upstream end of the lake near the Colorado River. The period of record was not sufficient at either site for analysis of trends in the annual data. Trend analysis at site 59 determined significant downward trends in the monthly streamflow dissolved-solids loads. Trends in the flow-adjusted monthly dissolved-solids concentrations and loads were downward (table 7).

Trend analysis at site 60 determined significant upward trends in the monthly streamflow and the unadjusted and flow-adjusted monthly dissolved-solids load. Significant downward trends in unadjusted and flow-adjusted monthly dissolved-solids concentrations were determined (table 7).

General Trends in the Green Region

For sites with more than one period, the later period of record was used in summarizing trends in the Green Region except at site 48, where the earlier period was used, and at site 52, where the entire period of record was used. Trends in annual streamflow were determined at 5 of the 25 sites that had sufficient data for annual analysis in the Green Region (1 downward, 4 upward) (table 7). Trends in flow-adjusted annual dissolved-solids concentrations were determined at 15 sites (11 downward, 4 upward). Trends in flow-adjusted annual dissolved-solids loads were determined at 13 sites (11 downward, 2 upward).

Trend analysis of the monthly streamflow for the 39 sites in the region determined downward trends at 17 sites and upward trends at 15 sites (table 7). Trend analysis of flow-adjusted monthly dissolved-solids concentrations determined downward trends at 27 sites and upward trends at 11 sites. Trend analysis of the flow-adjusted monthly dissolved-solids load determined downward trends at 23 sites and upward trends at 10 sites.

Comparison of trend results in streamflow, flow-adjusted annual dissolved-solids concentrations, and loads at five sites on the main stem and on major tributaries to the Green River for approximately concurrent periods of record (mid-1960's to 1993–96) indicated generally significant downward trends in flow-adjusted dissolved-solids concentrations and loads basinwide. The downward trends in streamflow were not statistically significant (table 9). Trends in flow-adjusted dissolved-solids concentrations and loads were compared to obtain a clearer idea of changes in salinity independent of streamflow. Trends in flow-adjusted dissolved-solids concentrations and loads on the main stem of the Green River appear to correlate to trends on the major tributaries and related activities within the basins. Small but not significant trends in flow-adjusted annual dissolved-solids concentrations and loads were determined in the upper part of the basin (site 22, table 9). Trends at site 26, Green River near Green River, Wyo., are significant and opposite (downward) of those at site 22 (table 9). The significant downward trends at site 26 reflect the effect of the Big Sandy River and the large decreases in dissolved-solids load determined in that basin, which might be related to the salinity control project (the Big Sandy Unit). A pattern of the downward trends in dissolved-solids concentrations and loads increasing in slope continues progressively downstream, as noted at site 28. The Yampa River flows into the Green River between sites 28 and 37 and has a diluting effect on dissolved-solids concentrations. Because of the significant upward trends in dissolved-solids concentrations and loads in the Yampa River Basin (site 34, table 7), the slope of the trends in the Green River reverses, but the trends are not statistically significant, as recorded at site 37, Green River near Jensen, Utah (table 9). Three major tributaries enter the Green River between sites 37 and 57. The Duchesne River had downward trends in annual dissolved-solids concentrations and loads. The White River had small upward trends in annual dissolved-solids concentrations and loads that

Table 9. Summary of annual trends at selected sites in the Green Region

[Water year, October 1 through September 30; percent is the slope expressed as percent change per year; mg/L, milligrams per liter; p, significance level; <, less than]

Site number	Period, water years	Streamflow (cubic feet per second)			Flow-adjusted concentration (mg/L)			Flow-adjusted load (tons)		
		Slope	Percent	p value	Slope	Percent	p value	Slope	Percent	p value
22	1964-94	-19.8	-1.22	0.103	0.30	0.16	0.163	647	0.22	0.135
26	1964-96	-18.4	-1.07	.159	-1.75	-.54	.001	-2,635	-.50	.003
28	1965-96	-18.2	-0.85	.200	-1.81	-.38	.005	-5,219	-.52	<.001
37	1962-93	-37.4	-.87	.324	1.44	.41	.144	4,944	.34	.118
57	1965-96	-55.5	-.95	.116	-2.55	-.56	<.001	-15,500	-.60	.001

were not significant; monthly flow-adjusted dissolved-solids concentrations and loads had significant downward trends. The Price River had highly significant downward trends in annual and monthly dissolved-solids concentrations and loads. At the most downstream site on the Green River (Green River at Green River, Utah, site 57) significant downward trends in the flow-adjusted dissolved-solids concentrations and loads were determined (table 9).

Liebermann and others (1989) did not report significant trends at numerous sites in the Green Region. The additional period of record analyzed in this study may be the cause of trends being determined at sites that had been previously reported as having no trend. Comparison of trend results at sites reported by Liebermann and others (1989) to the results of this study indicates generally similar trends in the Green Region. Liebermann and others (1989) reported step trend results of significant differences in annual dissolved-solids concentrations and loads at site 28. Significant differences in annual dissolved-solids concentrations and loads were also determined in this study. At site 56, significant downward trends in flow-adjusted annual dissolved-solids concentration were reported by Liebermann and others (1989) and in this study.

SUMMARY

Annual and monthly concentrations and loads of dissolved solids were estimated for 60 streamflow-gaging stations in the Colorado River Basin upstream from Lake Powell at Hite, Utah. The basin was divided into two major regions, the Grand Region and the Green Region. A nonparametric test was used to determine monotonic trends in streamflow, dissolved-solids concentrations, and dissolved-solids loads that may be related to human activities. Parametric and nonparametric tests were used in the step trend analysis to determine any differences at sites where a known intervention had occurred.

Significant trends in annual streamflow were not determined at any site in the Grand Region; however, monthly trends in streamflow were determined at 15 of the 21 sites. Downward trends in flow-adjusted annual dissolved-solids concentrations and loads were determined at 9 of 15 sites in the Grand Region. Downward trends in flow-adjusted monthly dissolved-solids concentrations were determined at 15 sites, and downward trends in flow-adjusted monthly dissolved-solids loads were determined at 14 sites.

Upstream from salinity control projects in the Grand Region, long-term annual trends were determined at selected sites on the main-stem Colorado River and major tributaries. These downward trends indicate that there are natural or human-induced effects on salinity loading sources in the upper part of the region. Abrupt downward trends in dissolved-solids concentrations and loads at sites located downstream from salinity control projects on the Colorado River (Grand Valley and Lower Gunnison Units) indicate that the projects may have affected salinity trends in the Colorado River upstream from the Green River.

Significant trends in annual streamflow were determined at 5 of 25 sites with sufficient data in the Green Region. Monthly trends in streamflow were determined at 32 of 39 sites. Trends in flow-adjusted annual dissolved-solids concentrations were determined at 15 of 25 sites (11 downward trends) and at 38 of 39 sites from the monthly data (27 downward trends). Trends in flow-adjusted annual dissolved-solids loads were determined at 13 of 25 sites (11 downward trends) and at 33 of 39 sites from the monthly data (23 downward trends).

Comparison of trend results in flow-adjusted dissolved-solids concentrations and loads in the Green Region indicate significant downward trends region-wide except in the Yampa River Basin, where trends were mostly upward and are opposite of the trends in other tributary basins in the Green Region. Small upward trends that were not statistically significant were determined in the upper part of the region. Trend analysis indicated a reversal in the trend slope direction that became downward and statistically significant at sites progressively downstream on the Green River. Major tributaries affect trends in the Green River. The Big Sandy, Duchesne, and Price Rivers has significant downward trends in dissolved-solids concentrations and loads. Part of the downward trends in the Big Sandy and Duchesne Rivers might be the result of salinity control projects in the drainage basins.

The periods of record for 17 sites were each divided into pre- and post-intervention time periods to evaluate step trends associated with specific interventions upstream. The time periods varied depending on when the intervention occurred. The interventions included the last major reservoir constructed above the site, salinity control projects, and breaks in streamflow or water-quality records. The post-reservoir (Blue Mesa Reservoir) period for the Gunnison River near Grand Junction (site 15) had significantly lower dissolved-solids concentrations and loads than the post-reservoir period; however, for Colorado River at Cisco, Utah (site 21), concentrations and loads for the pre- and post-reservoir periods were not significantly different. On the Green River, the post-reservoir period had higher dissolved-solids concentrations and loads than the pre-reservoir period at the site near Greendale, Utah, downstream from Flaming Gorge Reservoir.

Factors that can affect trends can be related to climatic changes, transbasin exports, changes in land and water use, salinity control efforts, or reservoir development. This report does not attempt to delineate what specific factors are causing the trends. Further analysis of the factors that can affect salinity trends would be useful to relate specific factors to salinity trends in specific basins or at specific sites.

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