USGS
science for a changing world

Prepared in cooperation with the Bureau of Reclamation

Effects of the Paradox Valley Unit on Dissolved Solids, Sodium, and Chloride in the Dolores River near Bedrock, Colorado, Water Years 1988–98

INTRODUCTION

Discharge of saline ground water (brine) to the Dolores River, as it crosses the Paradox Valley (fig. 1), increases the dissolved-solids load of this river, a tributary of the Colorado River, by an estimated 205,000 tons per year (Bureau of Reclamation, 1997). Increases in concentrations of dissolved sodium and chloride account for most of the increase in salinity. The brine, which is more saline than seawater, has a dissolved-solids concentration of about 250,000 milligrams per liter (mg/L) (Bureau of Reclamation, 1997). The Colorado River Basin Salinity Control Act of 1974 (Public Law 93–320; amended in 1984 as Public Law 98–569) authorized construction of the Paradox Valley Unit by the Bureau of Reclamation as one of the projects implemented to control salinity in the Colorado River Basin.

During 1999, a study was conducted by the U.S. Geological Survey (USGS) in cooperation with the Bureau of Reclamation to evaluate the effect of the Paradox Valley Unit on dissolved solids, sodium, and chloride in the Dolores River downstream from the Paradox Valley Unit. This report describes this evaluation and presents the results from this study. Daily mean flow and daily mean specific conductance, measured at gages upstream and downstream from the Paradox Valley Unit, and results from monthly water-quality samples are used to estimate changes in the dissolved-solids load and concentrations of sodium and chloride in the river as it crosses the valley and to correlate these changes with withdrawals of brine by the Paradox Valley Unit. The time period for this evaluation was restricted to October 1987–September 1998 (water years 1988–98) because regular collection of water-quality samples from the Dolores River in the valley began in 1987. (A water year [WY] begins on October 1 of one year and ends on September 30 of the following year.)

As configured in 1998, the Paradox Valley Unit consists of 12 shallow (less than 80 feet deep) production wells, a pipeline connecting the wells to a treatment facility, and a deep injection well (fig. 2). The well field is located along the Dolores River and is designed to intercept brine before it flows to the river. The brine is mixed with freshwater and treated before it is injected into rocks of Precambrian and Paleozoic age, primarily the Leadville

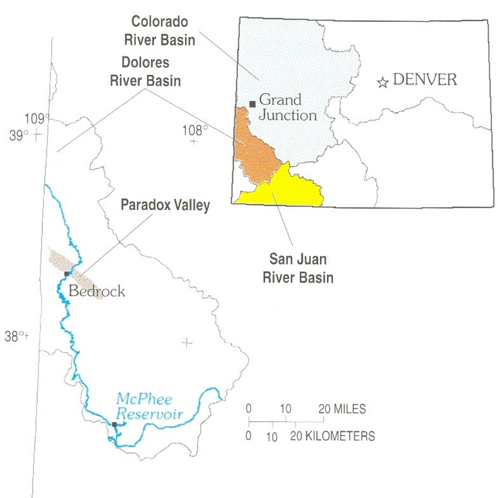

Figure 1. Location of the study area.

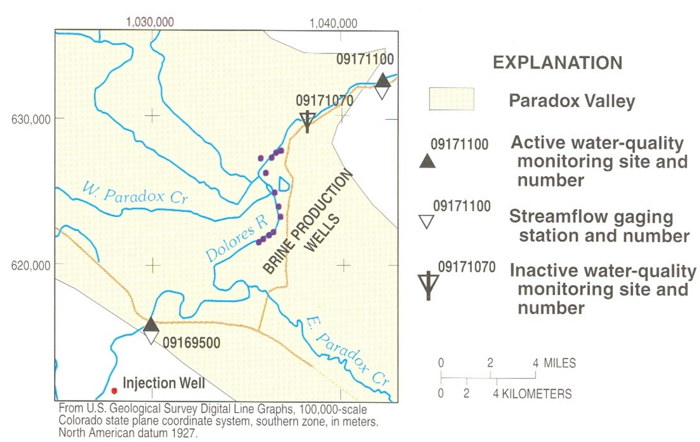

Figure 2. Locations of the U.S. Geological Survey gaging stations and Paradox Valley Unit production wells and injection well.

Limestone of Mississippian age. The injection zone is at depths of 14,068 to 15,857 feet below land surface. Test operation of the Paradox Valley Unit began in 1980, and production operation began in 1996. Total withdrawals of brine were about 104 million cubic feet (ft^3) during January 1980 through September 1987, minimal during October 1988 through September 1993, and about 41.4 million ft^3 during October 1993 through September 1998 (Andrew Nicholas, Bureau of Reclamation, 1999, written commun.).

GEOHYDROLOGIC SETTING

Paradox Valley, in southwestern Colorado (fig. 1), is a collapsed diapiric salt anticline, trending northwest-southeast. The Paradox Valley is about 24 miles long and 3 to 5 miles wide. The Dolores River crosses the valley about midway across the long axis of the valley, entering and leaving through deep and narrow canyons that were eroded several hundred feet through the sandstone and shale that form the valley walls. Unconsolidated alluvium overlies the salt- and gypsum-bearing rocks along the flood plain of the Dolores River and, locally, the valley floor. Maximum reported thickness of the alluvium is 129 feet. The alluvium is a source of ground water for irrigation wells in the western end of the valley.

STREAMFLOW AND SELECTED WATER-QUALITY CHARACTERISTICS

Streamflow and specific conductance of the Dolores River are measured continuously by the USGS at two streamflow-gaging stations in the Paradox Valley. One gaging station, the Dolores River at Bedrock (station 09169500), is upstream and the other, the Dolores River near Bedrock (station 09171100) is downstream from the well field (fig. 2). Daily mean flow and specific conductance values were retrieved from the National Water Information System (NWIS) data base of the USGS. Before December 14, 1987, the downstream water-quality monitor was located at the Dolores River below West Paradox Creek (station 09171070), which was about 2.5 miles upstream from the current downstream monitor, station 09171100 (fig. 2). Since WY 1988, water-quality samples have been collected, approximately monthly, at stations 09169500 and 09171100 to determine concentrations of dissolved solids and selected ions (calcium, magnesium, potassium, sodium, chloride, fluoride, nitrite plus nitrate, silica, and sulfate). Water-quality data were retrieved from the USGS water-quality data base.

Streamflow

Streamflow at the upstream station is affected by diversions for irrigation of about 5,000 acres upstream from the station in the Dolores River Basin and about 74,760 acres in the San Juan River Basin (fig. 1). Since March 19, 1984, streamflow has been regulated by McPhee Reservoir (fig. 1). During WY 1988–98, streamflow (daily mean flow) of the Dolores River at Bedrock, near where it enters the Paradox Valley, ranged from 4 to 4,230 cubic feet per second (ft^3/s), with a mean of about 302 ft^3/s. Streamflow at the downstream gaging station, in addition to regulation by McPhee Reservoir and upstream diversions for irrigation, also is affected by gains from and losses to the ground-water system, occasionally by tributary inflow and, slightly, by pumping of the well field. Tributary inflow includes runoff from storms and irrigation return flow. During WY 1988–98, daily mean flow of the Dolores River near Bedrock, where it leaves the valley, ranged from 7.1 to 4,390 ft^3/s, with a mean of about 304 ft^3/s.

Although the hydrographs (fig. 3A–B) of daily mean flow of the upstream and downstream gaging stations for WY 1988–98 appear similar, the difference between daily mean outflow and inflow (fig. 3C) indicates substantial differences (gains and losses) in streamflow in the valley. The difference between daily mean flow at the downstream and the upstream gaging stations ranged from an apparent loss of about 450 to an apparent gain of 290 ft^3/s (fig. 3C), with a mean difference (gain) of about 2.7 ft^3/s. These differences between outflow and inflow primarily are losses to and gains from ground water but also include occasional gains from tributary inflow and errors in estimating flow at the gaging stations. Stage (depth of water above a reference datum) is measured continuously at gaging stations, and flow is predicted (estimated) from the relation of flow with stage.

Selected Water-Quality Characteristics

The salinity (concentration of dissolved solids) of the Dolores River increases substantially as it crosses the valley. The inflow of a relatively small volume (less than 1 ft^3/s) of sodium-chloride brine, with a dissolved-solids concentration of about 250,000 mg/L, results in an estimated dissolved-solids load of as much as about 205,000 tons per year. Specific conductance is monitored continuously at the upstream and downstream stations to estimate the salinity of the river.

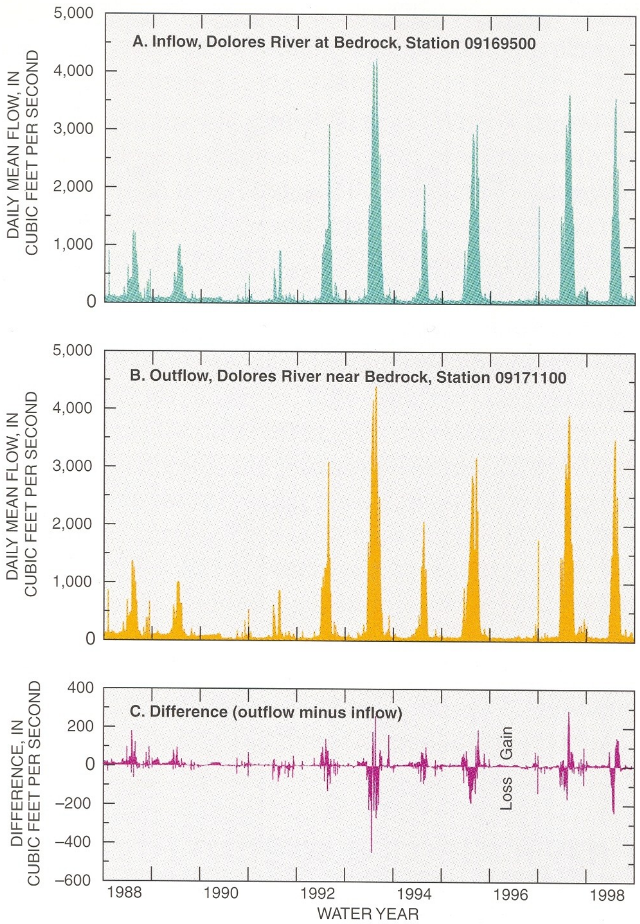

Figure 3. Daily mean flow of Dolores River at Bedrock (A), near Bedrock (B), and the difference (C), water years 1988–98.

Specific Conductance

Specific conductance of water is an electrical measurement of the conductivity of water, which is a function of total ionic concentrations in water (Hem, 1985). Therefore, specific conductance can be used to estimate the concentration of dissolved solids in the river. During WY 1988–98, daily mean specific conductance at the upstream gaging station ranged from 133 to 2,860 microsiemens per centimeter at 25 degrees Celsius (μS/cm), with a mean of 784 μS/cm and a median of 726 μS/cm; at the downstream gaging station, daily mean specific conductance ranged from 262 to 33,200 μS/cm, with a mean of 3,734 μS/cm and a median of 3,100 μS/cm.

Relation of Specific Conductance to Streamflow

The specific conductance of the water is inversely related to daily mean flow of the Dolores River. Generally, specific conductance of the river is least when daily mean flow is largest and greatest when streamflow is smallest (fig. 4A–B). Specific conductance of the river, particularly at the downstream station, is highly variable when daily mean flow is less than about 100 ft^3/s. The large variation in specific conductance in the river at smaller flow rates may result from variations in rates of ground-water flow to the river, in concentrations of dissolved solids in brine that flows to the river, and from intermittent contributions from unmeasured tributary flow. The volume and concentration of dissolved solids in ground-water flow to the river are likely affected by pumping of the well field. Tributary flow may substantially affect specific conductance of the river, particularly when there is little flow in the Dolores River; however, the long-term effects of tributary flow on specific conductance in the river are likely negligible in comparison with effects of relatively steady discharge of brine.

Because there was missing record for daily mean specific conductance for some periods during WY 1988–98, missing values were estimated by linear regression for 445 of 4,018 days for the upstream station and 380 of 4,018 days for

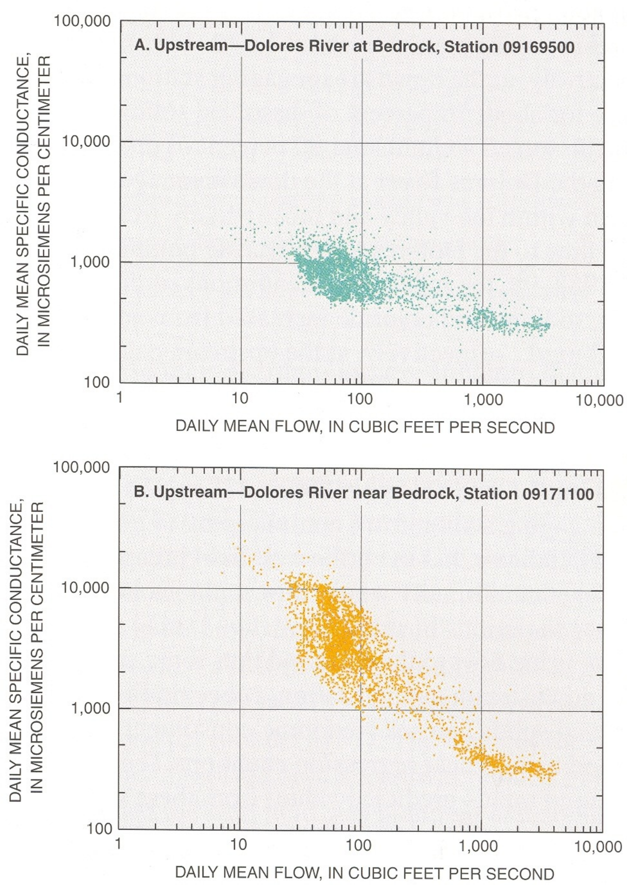

Figure 4. Relation of daily mean specific conductance to daily mean flow of the Dolores River at Bedrock (A) and near Bedrock (B), water years 1988–98.

the downstream station. The linear regressions of the logarithm (base 10) of daily mean specific conductance with the logarithm of daily mean flow had R-square statistics (a measure of the fit of a linear equation) of 0.51 and 0.79, for the upstream and downstream stations, respectively. This indicates that 51 and 79 percent of the variation in daily mean specific conductance at the upstream and downstream stations, respectively, can be explained by variation in daily mean flow. The larger R-square statistic for the linear equation for the downstream station probably is a result of the dominant effect of brine inflow on the specific conductance of the Dolores River near Bedrock, gaging station 09171100.

Dissolved Solids, Sodium, and Chloride

The distributions of the concentrations of dissolved solids, sodium, and chloride of the river, upstream (station 09169500) and downstream (station 09171100) from the Paradox Valley Unit, for non-pumping and pumping periods, are shown in the figure 5 boxplots. During non-pumping periods of WY 1988–98, the median concentrations of dissolved solids, sodium, and chloride increased from about 370, 66, and 78 mg/L, respectively, at the upstream gaging station to about 1,570, 480, and 760 mg/L, respectively, at the downstream gaging station. Thus, the source for about 76 percent of dissolved solids, 86 percent of the dissolved sodium, and 90 percent of dissolved chloride in the Dolores River at the downstream gaging station is from within the valley and mostly likely from groundwater flow to the Dolores River. During pumping periods of WY 1988–98, the median concentrations of dissolved solids, sodium, and chloride increased from about 326, 57, and 72 mg/L, respectively, at the upstream gaging station to about 1,115, 294, and 470 mg/L, respectively, at the downstream gaging station. The decreases in median concentrations of dissolved solids (1,570 to 1,115 mg/L), sodium (480 to 294 mg/L), and chloride (760 to 470 mg/L) at the downstream gaging station from non-pumping to pumping periods, indicate that the brine well field is capturing part of the brine that normally would flow to the Dolores River. Because variations in streamflow (fig. 3) may also affect rates of brine flow to the river and thus ionic concentrations at the downstream gaging station, concentrations of dissolved solids and selected ionic constituents were flow adjusted using linear regression equations.The residuals (measured minus predicted value) from these regression equations are referred to as flow-adjusted concentrations and are the variation in measured concentration that is independent of the rate of streamflow. Boxplots (fig. 5) show small variability in concentrations of dissolved solids, sodium, and chloride between non-pumping and pumping periods for the upstream gaging station; however, there are

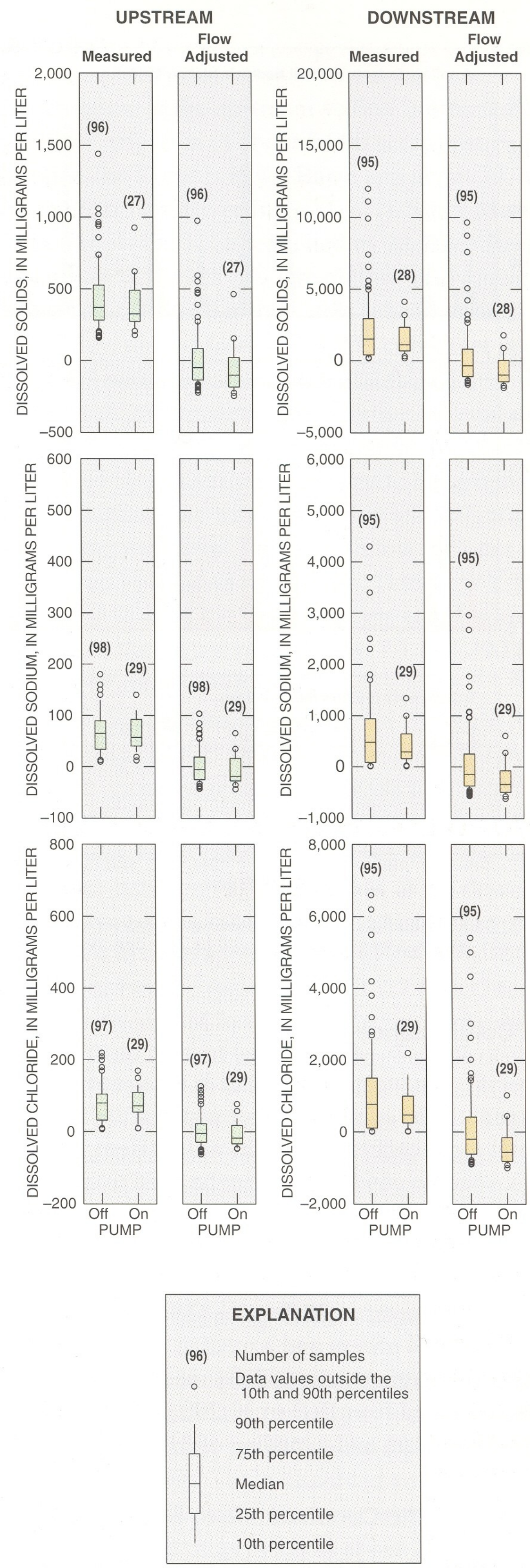

Figure 5. Measured and flow-adjusted concentrations of dissolved solids, sodium, and chloride in the Dolores River, upstream and downstream from the Paradox Valley Unit well field during pumping and non-pumping periods, water years 1988–98.

noticeable reductions in the median and ranges of concentrations between the non-pumping and pumping periods for the downstream gaging station.

Non-parametric statistical tests (Wilcox signed-rank tests) were done to evaluate the effect of withdrawals by the well field on measured and flow-adjusted concentrations of dissolved solids and selected ions at the downstream gaging station (09171100). Based on the Wilcox signed-rank tests, concentrations of dissolved solids, sodium, and chloride in the river were not significantly different at 0.05 exceedance level during non-pumping and pumping periods; however, flow-adjusted concentrations were significantly different at 0.05 exceedance level during non-pumping and pumping periods. Flow-adjusted concentrations were smaller during pumping periods than during non-pumping periods, which implies that withdrawals by the well field reduced concentrations of dissolved solids, sodium, and chloride in the Dolores River near Bedrock. Flow-adjusted concentrations of other selected dissolved ions (calcium, fluoride, magnesium, potassium, and sulfate) also were significantly different during non-pumping and pumping periods.

ESTIMATED LOADS OF DOLORES RIVER

Regression equations were developed to estimate concentrations of dissolved solids, sodium, and chloride in the Dolores River at Bedrock (station 09169500) and near Bedrock (station 09171100) for WY 1988–98. The equations were based on the relation between the logarithm (base 10) of concentrations of dissolved solids, sodium, and chloride and the logarithm (base 10) of specific conductance measured at the time of sample collection. Daily mean concentrations of dissolved solids, sodium, and chloride were then estimated for WY 1988–98, using the regression equations and the logarithm of daily mean specific conductance. Figure 6 show the relations of dissolved solids (figs. 6A and 6B), sodium (figs. 6C and 6D), and chloride (figs. 6E and 6F) concentrations with specific conductance for both stations.

Daily dissolved-solids loads, expressed in tons of solute per day, at the upstream and downstream gaging stations were calculated as the product of estimated daily mean concentrations and daily mean flow for WY 1988–98. The daily mean loads were summed by month, and the differences between monthly outflow and inflow loads were calculated. The difference in monthly dissolved-solids loads between the downstream and upstream gaging stations (fig. 7) is assumed to be caused by inflow of brine in the Paradox Valley. Estimated monthly dissolved-sodium and dissolved-chloride loads are not shown in

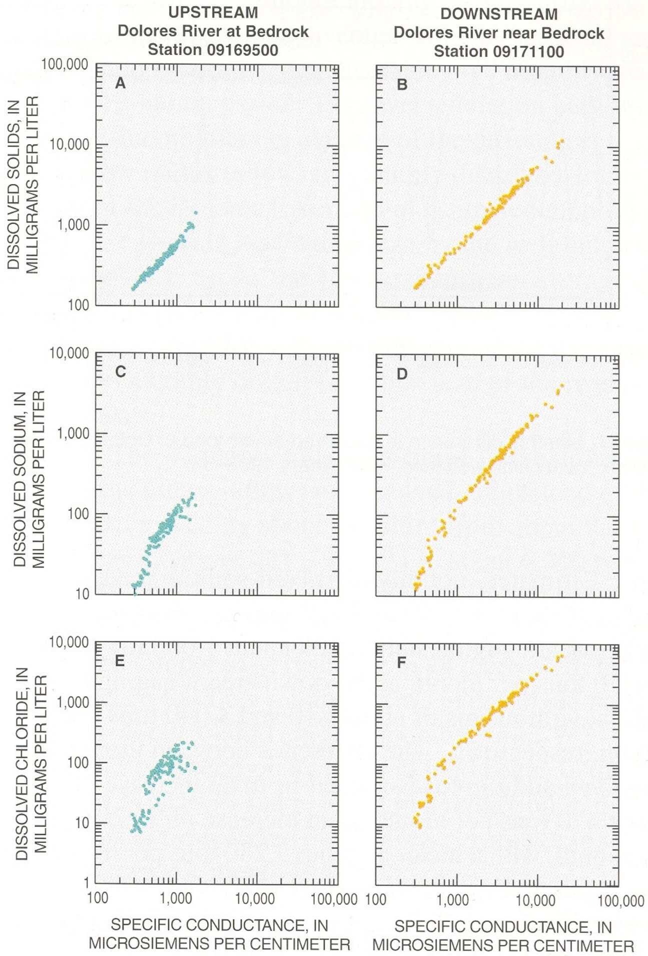

Figure 6. Relations between specific conductance and concentrations of dissolved solids, sodium, and chloride in the Dolores River, upstream and downstream of the well field, water years 1988–98.

figure 7 because their distributions are similar to that of estimated monthly dissolved-solids load.

Monthly dissolved-solids loads ranged from about 1,340 to 46,010 tons per month at the upstream gaging station and 5,070 to 51,220 tons per month at the downstream gaging station, with means of about 6,280 and 15,800 tons per month, respectively. The difference (outflow minus inflow) in monthly dissolved-solids loads ranged from a decrease in load of about 690 tons per month to an increase of about 26,250 tons per month, with a mean increase of about 9,230 tons per month (fig. 7). The mean of the difference in monthly dissolved-solids load was about 6,950 tons per month when the well field was pumping and about 10,190 tons per month when the well field was not pumping. Assuming that the mean load of 10,190 tons per month for non-pumping periods represents the natural increase in dissolved-solids load of the Dolores River as it crosses the Paradox Valley, a 32-percent reduction in dissolved-solids load occurred when the well field was pumped.

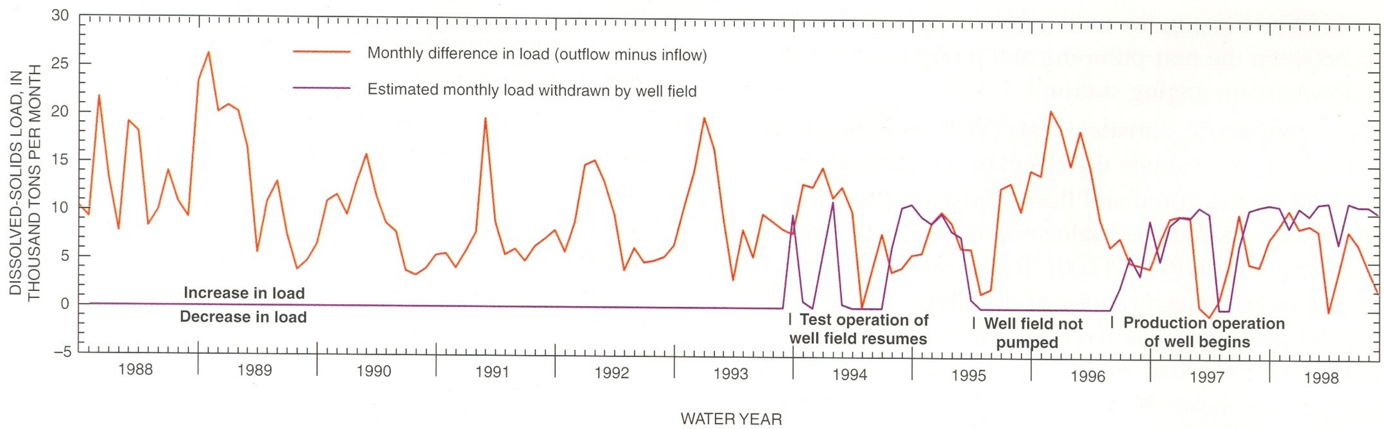

Figure 7. Monthly difference in dissolved-solids load of Dolores River (outflow-inflow) and estimated dissolved-solids load withdrawn by the Paradox Valley Unit well field, water years 1988–98.

Estimated monthly dissolved-sodium loads ranged from about 180 to 4,480 tons per month at the upstream gaging station and about 1,060 to 10,350 tons per month at the downstream gaging station, with means of about 810 and 4,040 tons per month, respectively. The difference between monthly dissolved-sodium loads ranged from an increase of about 470 tons per month to an increase of 9,820 tons per month, with a mean of about 3,230 tons per month. The mean of the difference in monthly dissolved-sodium loads was about 2,320 tons per month when the well field was pumping and about 3,610 tons per month when the well field was not pumping. Assuming that the mean load of 3,610 tons per month for non-pumping periods represents the natural increase in dissolved-sodium load, a 36-percent reduction in dissolved-sodium load occurred when the well field was pumped.

Estimated monthly dissolved-chloride loads ranged from about 190 to 4,360 tons per month at the upstream gaging station and about 1,450 to 17,430 tons per month at the downstream gaging station, with means of about 870 and 6,280 tons per month, respectively. The difference between monthly dissolved-chloride loads ranged from an increase of about 750 tons per month to an increase of 16,840 tons per month, with a mean of about 5,410 tons per month. The mean of the difference in monthly dissolved-chloride loads was about 3,810 tons per month when the well field was pumping and about 6,080 tons per month when the well field was not pumping. Assuming that the mean load of 6,080 tons per month for non-pumping periods represents the natural increase in dissolved-chloride load, a 37-percent reduction in dissolved-chloride load occurred when the well field was pumped.

DISSOLVED-SOLIDS LOAD WITHDRAWN BY THE WELL FIELD

Daily dissolved-solids loads of brine withdrawn by the well field were estimated as the product of reported pumping rate (Andrew Nicholas, Bureau of Reclamation, 1999, written commun.) and an assumed dissolved-solids concentration for the brine of 250,000 mg/L. Monthly dissolved-solids loads of brine withdrawn by the brine well field were computed by summing the daily dissolved-solids load for each month and ranged from 0 to about 11,125 tons per month, with a mean of about 2,450 tons per month during WY 1988–98 (fig. 7).

EFFECTS OF THE PARADOX VALLEY UNIT ON DISSOLVED-SOLIDS LOAD OF DOLORES RIVER

Test operation of the Paradox Valley Unit well field resumed in WY 1993, after about 7 years of minimal withdrawals, and ended in WY 1995. Production operation began in WY 1996 and except for a brief period in WY 1997 has been relatively continuous. The difference (outflow minus inflow) in monthly dissolved-solids load generally is largest during periods when the well field is not pumped and smallest during periods when the well field is in relatively continuous use. Figure 7 shows the temporal variation in the difference in monthly dissolved-solids load of the Dolores River as it crosses the Paradox Valley and the estimated monthly dissolved-solids load withdrawn by the well field. Seasonal and year to year variations in monthly dissolved-solids loads are apparent during WY 1988–93 and in WY 1995–96, when there were no reported withdrawals by the well field. Annual peak monthly dissolved-solids loads were generally larger during WY 1988–93 and WY 1995–96, when there was little or no reported withdrawal by the well field, and generally smaller during WY 1994–95 and WY 1996–98, when the well field was in operation (fig. 7). During the periods when the well field was not in use, the differences in monthly dissolved-solids load of the river ranged from increases of about 130 to 26,250 tons per month; when the well field was in use, the differences in monthly dissolved-solids load ranged from a decrease of about 690 tons per month to an increase of about 14,600 tons per month (fig. 7). In addition to the effects of brine withdrawals by the well field, the monthly differences of load of the river also may result from variation in rates of streamflow into the valley, concentrations of dissolved solids in the inflow, and tributary flow within the valley.

Because of the temporal variability of differences in monthly dissolved-solids load of the river, the effects of operation of the well field are more apparent when shown as 12-month moving averages (fig. 8). The 12-month moving average smooths seasonal variation and is computed by averaging the monthly loads for a 12-month period. The inverse relation between the 12-month moving average of the difference (outflow minus inflow) of monthly dissolved-solids load of the Dolores River and of estimated monthly dissolved-solids load withdrawn by the well field is obvious (fig. 8). As the 12-month moving average of dissolved-solids load withdrawn by the well field increases, the 12-month moving average of the difference in monthly dissolved-solids load of the river decreases.

The 12-month moving average of the difference (outflow minus inflow) in dissolved-solids load of the river decreased by about one-third from about 9,000 tons per month in WY 1992–94 to about 6,000 tons per month during WY 1995 (fig. 8). During the last half of WY 1995, withdrawals by the well field were stopped temporarily, resulting in an increase in the difference (outflow minus inflow) in dissolved-solids load to about 14,000 tons per month by mid-WY 1996. Production operation by the well field began in the last half of WY 1996 and resulted in a reduction in the difference from about 14,000 tons per month to about 6,000 tons per month (fig. 8).

Annual dissolved-solids loads in the Dolores River near Bedrock (outflow), at Bedrock (inflow), the difference in annual dissolved-solids loads between

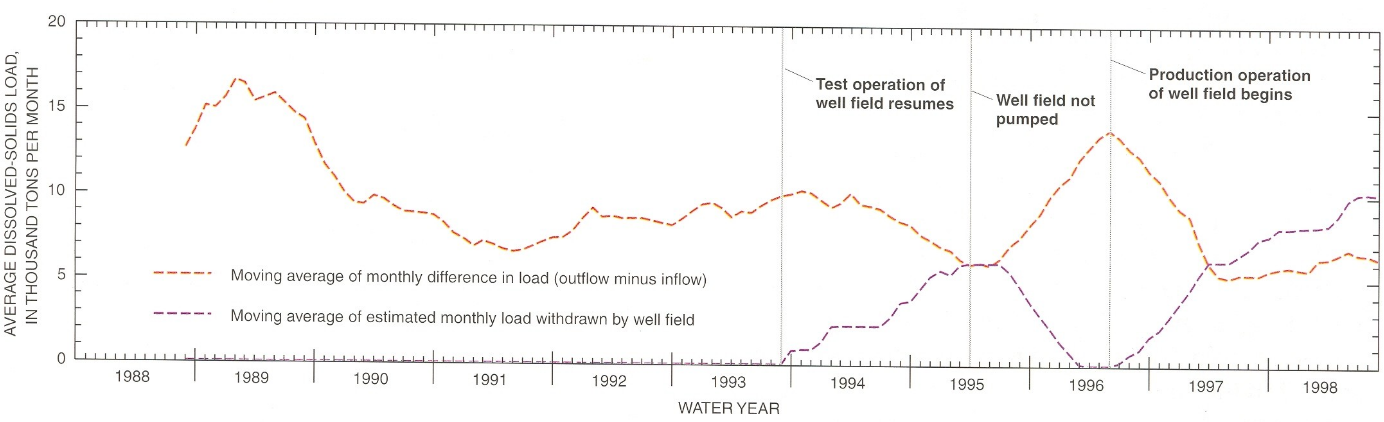

Figure 8. Twelve-month moving average of monthly difference (outflow minus inflow) of dissolved-solids load of Dolores River and estimated dissolved-solids load withdrawn by the Paradox Valley Unit well field, water years 1988–98.

these two gaging stations (outflow minus inflow), and the estimated annual dissolved-solids load withdrawn by the well field are listed in table 1. Dissolved-solids load from brine inflow to the river in the Paradox Valley is approximately equal to the difference (outflow minus inflow) in dissolved-solids load of the river and was previously estimated to be about 205,000 tons per year (Bureau of Reclamation, 1997). The increase in annual dissolved-solids load of the Dolores River as it crosses the Paradox Valley ranged from about 86,000 to 172,000 tons per year during WY 1988–93 when the well field was not pumped and from 64,000 to 149,000 tons per year during WY 1994–98 when the well field was pumped. Assuming that the dissolved-solids load withdrawn by the well field would have discharged to the river, then the difference (outflow minus inflow) in dissolved-solids load was reduced by an equivalent amount. The percent reduction in the increase in dissolved-solids load as the Dolores River crosses the Paradox Valley is equivalent to the ratio of dissolved-solids load withdrawn by the well field to the sum of the difference in dissolved-solids load in the river plus the dissolved-solids load withdrawn by the well field. During WY 1994–98, cumulative withdrawals by the Paradox Valley Unit well field are estimated to have reduced the increase in the dissolved-solids load of the Dolores River as it crosses the Paradox Valley by about 40 percent [322,000/(483,000 + 322,000) = 0.40]. The increases in annual dissolved-solids load of the Dolores River as it crosses the Paradox Valley were relatively small in WY 1995, 1997, and 1998 when withdrawals by the brine well field were at relatively steady rates (table 1).

Table 1. Annual dissolved-solids load in Dolores River near Bedrock (outflow) and at Bedrock (inflow), difference in dissolved-solids load, and estimated dissolved-solids load withdrawn by well field, water years 1988–98

Water year	Annual dissolved-solids load in Dolores River (thousand tons)			
	Outflow (Dolores River near Bedrock)	Inflow (Dolores River at Bedrock)	Difference (outflow minus inflow)	Estimated withdrawal by well field[1]
1988	222	70	152	0
1989	231	59	172	0
1990	130	24	106	0
1991	125	39	86	0
1992	175	75	100	0
1993	253	133	120	0
1994	162	60	102	44
1995	195	104	91	55
1996	173	24	149	11
1997	213	149	64	90
1998	169	92	77	122

[1]Dissolved-solids load withdrawn by well field estimated as the product of reported pumping rates and an assumed dissolved-solids concentration of 250,000 milligrams per liter; where estimated withdrawal equals zero, no withdrawals were reported.

References

Bureau of Reclamation, 1997, Paradox Valley Unit—Final supplemental definite plan report and environmental assessment: Bureau of Reclamation, Salt Lake City, 6 numbered chapters.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

—By Kenneth R. Watts

Information about this study can be obtained from:
Subdistrict Chief
U.S. Geological Survey
Water Resources Division
764 Horizon Drive, Room 125
Grand Junction, CO 81506
Telephone: (970) 245–5257 ext. 14
FAX: (970) 245–1026
E-mail: pbvongue@cronos.usgs.gov

Printed on recycled paper

☆ U.S. GOVERNMENT PRINTING OFFICE: 2000 — 573-082 / 47028 Region No. 8