Effect of the Paradox Valley Unit on the Dissolved-Solids Load of the Dolores River near Bedrock, Colorado, 1988–2001

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Prepared in cooperation with the Bureau of Reclamation

Abstract

Discharge of brine with an average dissolved-solids concentration of about 256,000 milligrams per liter from alluvium in Paradox Valley, a collapsed salt anticline, substantially increases the dissolved-solids load of the Dolores River. In 1996, the Bureau of Reclamation began operation of the Paradox Valley Unit, a series of brine-withdrawal wells completed in alluvium along the Dolores River and a deep-injection well for the brine, to decrease flow of brine into the river. This report presents the findings of a study to determine the effectiveness of the Paradox Valley Unit from 1988 through September 2001.

Differences in dissolved-solids load of the Dolores River between two gaging stations, one upstream and one downstream from the Paradox Valley Unit, indicate that an average dissolved-solids load of about 313 tons per day (an annual average of about 115,000 tons) was contributed by brine inflow to the Dolores River before operation of the Paradox Valley Unit began in July 1996. By September 30, 2001, the dissolved-solids load contributed by brine had declined to an average of about 29 tons per day—a decrease of about 90 percent. This decrease might have been facilitated by a decrease in precipitation and streamflow into the Paradox Valley during the last few years of the assessed period.

INTRODUCTION

Discharge of saline ground water (brine) to the Dolores River, as it crosses the Paradox Valley (fig. 1), substantially increases the dissolved-solids load of this river, a tributary of the Colorado River. Increases in concentrations of dissolved sodium and chloride account for most of the increase in salinity. According to water-quality data (Andrew Nicholas, Bureau of Reclamation, written commun., 2002), the brine has an average dissolved-solids concentration of about 256,000 milligrams per liter (mg/L) in alluvium in the vicinity of the Dolores River. 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 (BOR) as one of the projects implemented to control salinity in the Colorado River Basin.

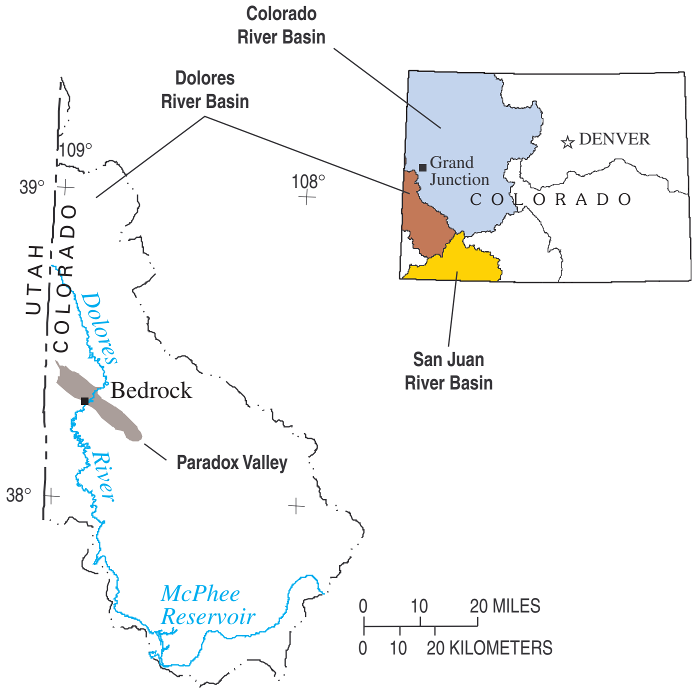

Figure 1. Location of the study area (from Watts, 2000).

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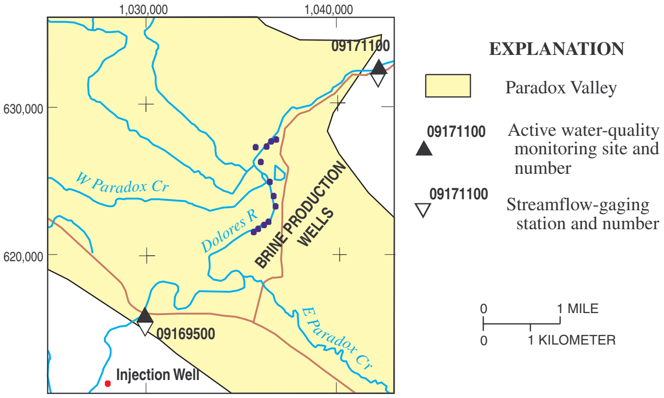
The Paradox Valley Unit, as described by Watts (2000), consists of 12 shallow (less than 80 feet deep) production wells, a pipeline connecting the wells to a treatment facility, and a deep injection well (fig. 2). The well field is located along the Dolores River and is designed to intercept brine before it flows to the river. The brine is injected into rocks of Precambrian and Paleozoic age, primarily the Leadville 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.

During 1999, the U.S. Geological Survey (USGS), in cooperation with the BOR, studied the effect of the Paradox Valley Unit on dissolved solids, sodium, and chloride in the Dolores River. The study evaluated changes in water quality from October 1987 through September 1998. The resulting report (Watts, 2000) estimated that, during nonpumping periods, about 76 percent of the dissolved solids, about 86 percent of the dissolved sodium, and about 90 percent of the dissolved chloride in the Dolores River near Bedrock (station 09171100; fig. 2) probably was derived from ground-water flow of brine in the Paradox Valley. Watts (2000) also concluded that decreases in median concentrations of dissolved solids (from 1,570 to 1,115 mg/L), sodium (480 to 294 mg/L), and chloride (760 to 470 mg/L) at that station between nonpumping and pumping periods indicate that the Paradox Valley Unit captured part of the brine that would have otherwise flowed into the Dolores River. Watts (2000) estimated that operation of the Paradox Valley Unit reduced the dissolved-solids load to the Dolores River by about 32 percent, the dissolved-sodium load by about 36 percent, and the dissolved-chloride load by about 37 percent.



Base from U.S. Geological Survey digital line graphs, 1:100,000
Colorado state plane coordinate system, southern zone.
North American datum 1927

Figure 2. Locations of U.S. Geological Survey gaging stations and Paradox Valley Unit brine-withdrawal wells and injection well (modified from Watts, 2000).

Since 1998, BOR modified operation of the Paradox Valley Unit to optimize interception of brine flowing into the Dolores River. Early in 2002, BOR requested that the USGS reevaluate the effect of the Paradox Valley Unit on removal of dissolved solids from the Dolores River.

Purpose and Scope

This report reevaluates the effectiveness of the Paradox Valley Unit in decreasing dissolved-solids load to the Dolores River by evaluating the entire period of the water-quality record through September 30, 2001 (at the time, the latest date for quality-assured, continuous data in USGS databases). This reevaluation is based on estimates of dissolved-solids loads at water-quality stations upstream and downstream from the Paradox Valley and on brine-withdrawal data for the Paradox Valley Unit.

Geohydrologic Setting

The following description of the geohydrologic setting is modified from Watts (2000). 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.

Approach

Dissolved-solids loads contributed to the Dolores River by seepage of brine were estimated by water-quality records for two USGS gaging stations (fig. 2): (1) Dolores River at Bedrock (station 09169500), upstream from Paradox Valley; and (2) Dolores River near Bedrock (station 09171100), downstream from Paradox Valley. Loads at these sites were estimated only for days in the record for which data were available for both sites (that is, matched-pair observations).

Dissolved-solids loads at these two gaging stations were estimated with the following approach: (1) dissolved-solids concentrations for discrete water-quality samples were estimated as the sum of the concentrations of major ions; (2) a linear equation was developed to predict dissolved-solids concentrations from specific-conductance measurements; (3) daily dissolved-solids loads were estimated as the product of mean-daily discharge and estimated mean-daily dissolved-solids concentration; and (4) dissolved-solids concentrations from discrete water-quality samples were used to estimate mean-daily dissolved-solids concentrations for some days without specific-conductance data.

Water-quality records include 315 discrete water-quality analyses (159 for station 09169500 and 156 for station 09171100), which were collected approximately monthly between January 4, 1978, and February 27, 2002. Because these analyses did not include concentration of alkalinity, alkalinity (as CO_3^{2-} ion) was calculated as the mass required to balance the sum of charges of major ions in the sample. Masses of major ions, including alkalinity, were then summed to provide an estimate of dissolved-solids concentration for each sample. Linear regression was used to determine the relation between specific conductance and dissolved-solids concentration for all samples at both sites (fig. 3). This strong relation (R^2=0.995, indicating the fraction of the variation in dissolved-solids concentration that is explained by variation in specific conductance) was then used to estimate dissolved-solids concentration for days when only specific conductance was measured for salinity (as described in the next paragraph).

Most water-quality data for stations 09169500 and 09171100 consist of mean-daily streamflow and mean-daily specific conductance, as determined by continuous measurements (generally every 15 minutes) from water-quality monitors. The usable

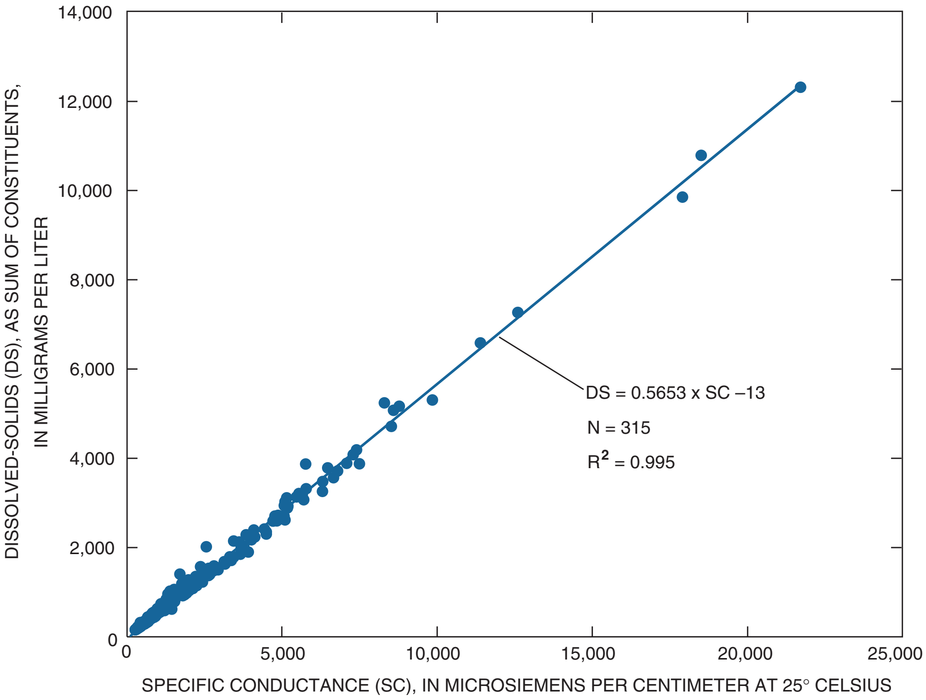


Figure 3. Relation between specific conductance and dissolved-solids concentration at gaging stations 09169500 and 09171100, January 1988–February 2002

record began on August 1, 1991, and consists of 3,714 days for which dissolved-solids loads could be estimated at both stations. Mean-daily specific conductance and the relation between specific conductance and dissolved-solids concentration (fig. 3) were used to estimate mean-daily dissolved-solids concentration at both stations on those days. Because of missing data in the specific-conductance record, 57 estimates of mean-daily dissolved-solids loads based on the sum of ionic concentrations for discrete water-quality analyses (as described in the preceding paragraph) were used to supplement the dissolved-solids-load data through September 30, 2001. Of these estimates, 36 were for January 13, 1988–July 26, 1991 (before the usable record from water-quality monitors), and 21 were for missing days in the water-quality-monitor record. In total, the water-quality record had 3,771 days (ending September 30, 2001) for which dissolved-solids concentration could be estimated from specific conductance at the upstream and downstream stations. For these days, dissolved-solids load at these stations was computed by multiplying dissolved-solids concentration by mean-daily streamflow and a conversion factor.

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

Daily dissolved-solids load of brine withdrawn by the Paradox Valley Unit (fig. 4) was estimated from monthly brine-withdrawal volumes (Andrew Nicholas, Bureau of Reclamation, written commun., 2000) and the average dissolved-solids concentration for brine (256,000 mg/L, based on samples collected from brine-withdrawal wells in December 1997, eight wells; February 1998, seven wells; June 1998, six wells; and July 2001, six wells). Although an average of about 300 tons per day of dissolved solids was withdrawn during January 1980 through September 1987, data for this withdrawal period are not shown in figure 4 because it precedes the scope of this study and was followed by a 6-year hiatus in withdrawal. This hiatus probably allowed ground-water levels to recover to ambient conditions. The BOR withdrew an average of about 186 tons of dissolved solids per day from October 1993 through February 1994; an average of about 262 tons per day from August 1994 through April 1995; an average of about 233 tons per day from July 1996 through April 1997; and an average of about 315 tons per day from July 1997 through April 2000. Withdrawals decreased to an average of about 205 tons per day from May 2000 through September 2001. Withdrawals were insignificant or nonexistent between these periods.

LOWESS, or LOcally WEighted Scatterplot Smoothing (Cleveland, 1979; Helsel and Hirsch, 1992), was used to average (smooth) the extreme seasonal fluctuation in dissolved-solids loads at the upstream and downstream gaging stations (fig. 5). Smoothing was done with the computer-based statistics package S-Plus Professional

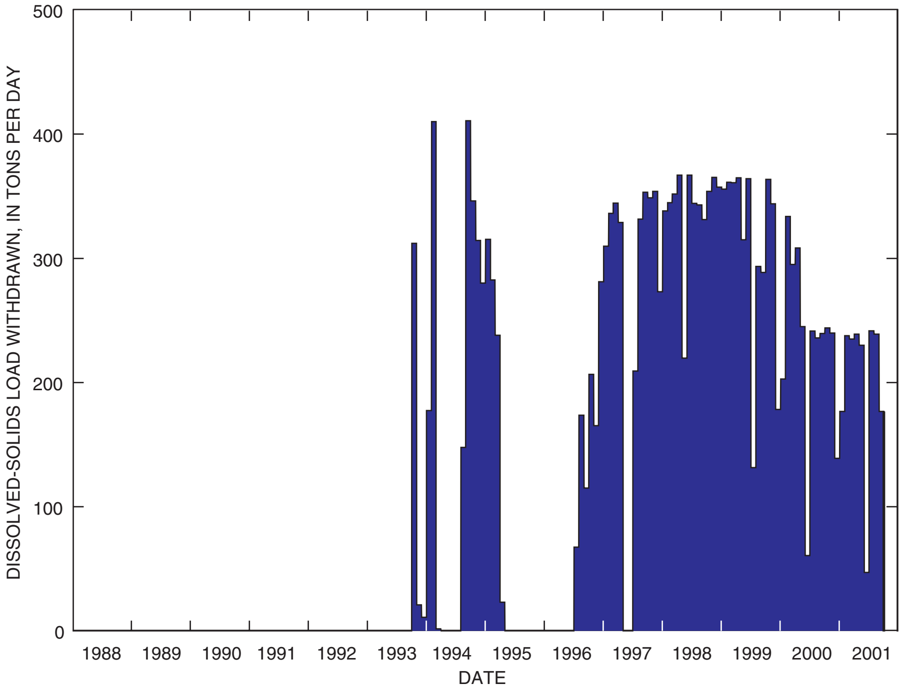


Figure 4. Dissolved-solids load withdrawn by the Paradox Valley Unit, January 1988–September 2001.

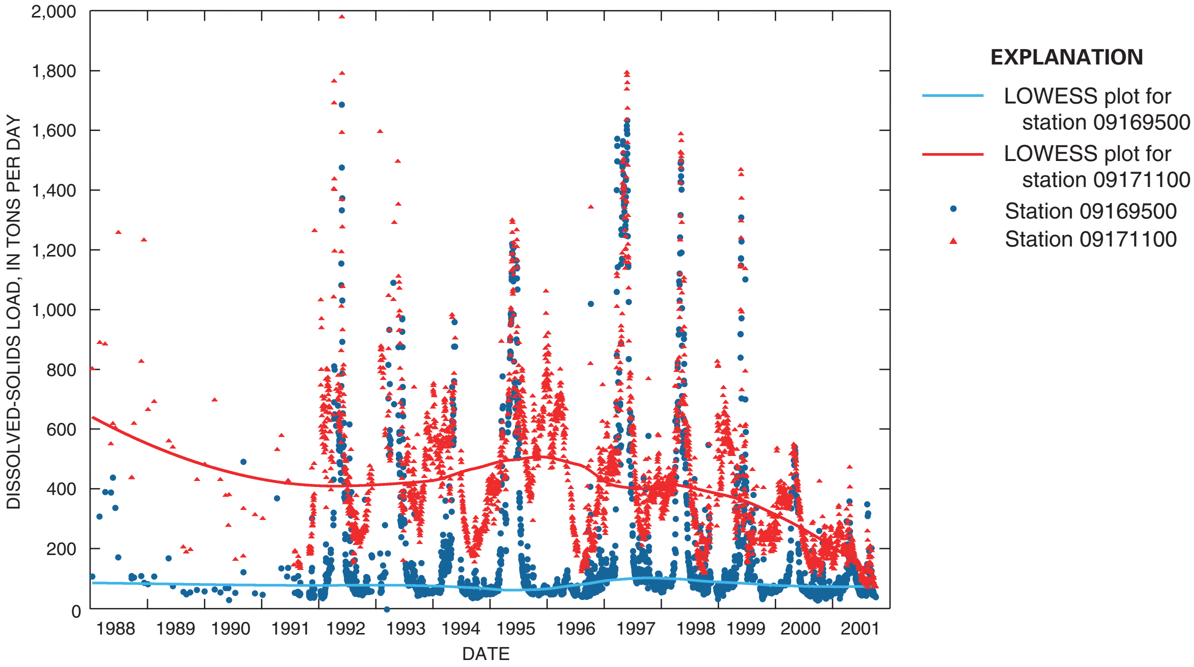


Figure 5. Daily dissolved-solids load at gaging stations 09169500 (upstream) and 09171100 (downstream), January 1988–September 2001.

Release 2000 (MathSoft, Inc., 1999)[1]; parameters were set to give symmetric, second-degree smoothing with a span of 0.5 for intermediate smoothing. The gradual decline in the difference in dissolved-solids load between the two stations since the onset of regular brine withdrawal in July 1996 (fig. 4) is evident. The LOWESS curves for the two gaging stations show that most of the difference in dissolved-solids load had been eliminated by September 30, 2001 (fig. 5).

The long-term change in dissolved-solids load between the upstream and downstream gaging stations can be estimated with a LOWESS plot (with the same parameters as for the plots in fig. 5) of the daily, matched-pair difference in dissolved-solids load between the two stations (fig. 6). The large negative load differences probably are largely the result of streamflow losses that recharge the alluvial aquifer of the Paradox Valley during the rise in river stage accompanying early spring, lowland melting of ice and snow; errors in measurement of streamflow and specific conductance may contribute to negative load differences but, because these errors probably are randomly distributed, they probably do not affect load differences on average. This plot illustrates the gradual decline in the difference in dissolved-solids load between the two stations since regular withdrawals of brine began in July 1996. Before July 1996, the long-term median gain between the two stations was about 313 tons per day, indicating an annual average of about 115,000 tons. At the end of September 2001, the gain in dissolved-solids load between the two stations had declined to 29 tons per day, indicating that about 90 percent of the gain in load had been eliminated. It should be noted, however, that the substantial decrease in dissolved-solids-load gain between upstream station 09169500 and downstream station 09171100 might have been facilitated by the regional decrease in precipitation during the last few relatively dry years of the record. Decrease in precipitation and streamflow into the Paradox Valley could have decreased the flux of brine in the alluvium of Paradox Valley along the Dolores River, thus decreasing the amount of brine that needed to be intercepted by the Paradox Valley Unit before it could flow into the river as base flow. The decrease in dissolved-solids load withdrawn by the Paradox Valley Unit from May 2000 through September 2001 (fig. 4) supports this hypothesis.

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[1] The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

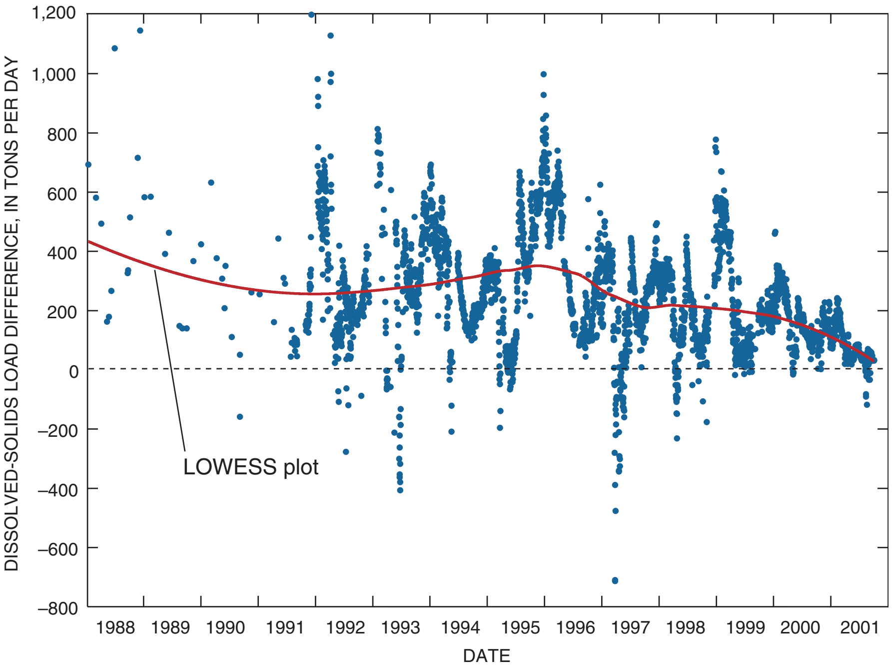

Figure 6. Difference (downstream minus upstream) in daily dissolved-solids load between gaging stations 09169500 (upstream) and 09171100 (downstream), January 1988–September 2001.

SUMMARY

Discharge of brine with an average dissolved-solids concentration of about 256,000 milligrams per liter from alluvium in Paradox Valley, a collapsed salt anticline, substantially increases the dissolved-solids load of the Dolores River. In 1996, the Bureau of Reclamation began operation of the Paradox Valley Unit, a series of brine-withdrawal wells completed in alluvium along the Dolores River and a deep-injection well for the brine, to decrease the flow of brine into the river. In 1999, the U.S. Geological Survey assessed the effectiveness of the Paradox Valley Unit and concluded that a substantial fraction of the brine had been intercepted by September 1998. In 2002, the effectiveness of the Paradox Valley Unit was reevaluated through September 2001.

Differences in dissolved-solids load of the Dolores River between two gaging stations, one upstream and one downstream from the Paradox Valley Unit, indicate that an average of about 313 tons per day (an annual average of about 115,000 tons) of dissolved solids was contributed to the Dolores River by inflow of brine before operation of the Paradox Valley Unit began in July 1996. By the end of September 2001, the contribution had declined to an average of about 29 tons per day—indicating a decrease of about 90 percent compared to the period before operation of the Paradox Valley Unit. This decrease, however, might have been facilitated by the relatively dry conditions during the last few years of the assessment, which could have decreased the amount of brine to be intercepted by the Paradox Valley Unit.

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