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Effects of Remedial Grouting on the Ground-Water Flow System at Red Rock Dam near Pella, Iowa

Water-Resources Investigations Report 00–4231

U.S. Department of the Interior
U.S. Geological Survey

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By S. Mike Linhart and Bryan D. Schaap

U.S. GEOLOGICAL SURVEY

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ROCK ISLAND DISTRICT
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Iowa City, Iowa
2001

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter

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

$$°F = (1.8 \times °C) + 32$$

Abbreviated water-quality units used in this report: Chemical concentration is given in milligrams per liter (mg/L) and micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. Micrograms per liter is a unit expressing the concentration of chemical constituents in solution as weight (micrograms) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Per mil: A unit expressing the ratio of stable-isotopic abundances of an element in a sample to those of a standard material. Per mil units are equivalent to parts per thousand. Stable-isotopic ratios are computed as follows (Kendall and Caldwell, 1998):

$$\delta X = \left(\frac{R(\text{sample})}{R(\text{standard})} - 1\right) \times 1,000$$

where

X is the heavier isotope and

R is the ratio of the heavier, less abundant stable isotope to the lighter, stable isotope in a sample or standard.

The δ values for oxygen, hydrogen, and sulfur stable isotopic ratios discussed in this report are referenced to the following standard material:

Ratio (R)	Standard identity and reference
hydrogen-2:hydrogen-1	Vienna Standard Mean Ocean Water (VSMOW)
oxygen-18:oxygen-16	Vienna Standard Mean Ocean Water (VSMOW)
sulfur-34:sulfur-32	Vienna Canyon Diablo Troilite (VCDT), defined by assigning a value of –0.3 per mil exactly to IAEA–S–1 silver sulfide

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

Water year: The 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends. Thus, the year ending September 30, 1996, is called water year 1996.

Effects of Remedial Grouting on the Ground-Water Flow System at Red Rock Dam near Pella, Iowa

By S. Mike Linhart *and* Bryan D. Schaap

Abstract

Previous studies have shown direct evidence of underseepage at Red Rock Dam on the Des Moines River near Pella, Iowa. Underseepage is thought to occur primarily on the northeast side of the dam in the lower bedrock of the St. Louis Limestone, which consists of discontinuous basal evaporite beds and an overlying cavity zone. Because of concerns about the integrity of the dam, the U.S. Army Corps of Engineers initiated a remedial grouting program in September 1991. To assess the effectiveness of the remedial grouting program and to evaluate methods for future assessments, a study was conducted by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers.

Potentiometric surface maps of the overburden and bedrock indicate that the direction of ground-water flow on the northeast side of the dam has changed little from pre-grout to post-grout periods. A comparison of water levels, between a pre-grout date and a post-grout date, shows that water levels decreased but that the decrease may be more attributable to changes in dam operations than to remedial grouting. Water-level data for the same two dates indicate that a more gradual potentiometric surface exists on the northeast side of the dam than on the southwest side of the dam, which suggests that the hydraulic connection between Lake Red Rock and downgradient bedrock wells still is greater on the northeast side of the dam than on the southwest side. Hydrographs for some wells on the northeast side of the dam indicated a departure from pre-grout trends at approximately the same time grouting was initiated. To varying degrees, hydrographs for the same wells then appear to return to a trend similar to pre-grout years, possibly as a result of new flow paths developing over time after remedial grouting. Spearman correlation coefficients computed for water levels in wells, pool, and tailwater indicate that some areas on the northeast side of the dam appear to be less under the influence of changing pool elevations after grouting than before grouting. This suggests that the hydraulic connection between the Red Rock pool and some downgradient areas has decreased.

Analysis of water samples collected from selected wells on the northeast side of the dam shows significant increases in sulfate concentrations beginning about the same time remedial grouting was done upgradient from the wells, possibly indicating that flow paths were cut off to these wells, thereby reducing the amount of mixing with fresh reservoir water. Observable changes in chloride concentrations or trends as a result of remedial grouting were not apparent. Analysis results for hydrogen and oxygen stable isotope samples collected since 1995 indicate large seasonal fluctuations of isotope ratios in the tailwater (assumed representative of the reservoir). Similar but more subdued fluctuations were observed at some wells, but other wells appeared to have little seasonal change. Stable sulfur isotope results indicate the presence of distinct water types between Lake Red Rock and in ground water from downgradient bedrock wells.

Sulfur isotope values from samples from a bedrock well located upgradient from the grout curtain indicate a mixture of pool and ground water, whereas samples from downgradient overburden wells have values similar to the pool. Samples from the bedrock wells downgradient from the grout curtain have sulfur isotope values similar to a value obtained from analysis of a gypsum and anhydrite core sample.

Hydrographs, statistical analysis of water-level data, and water-chemistry data suggest that underseepage on the northeast side of the dam has been reduced but not completely eliminated. Some areas appear to have been affected to a greater degree and for a longer period of time than other areas. Future monitoring of water levels, water chemistry, and stable isotopes can aid in the evaluation of the long-term effectiveness of remedial grouting.

INTRODUCTION

In 1991, a cooperative study by the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (COE) (Lucey, 1991) found direct evidence of seepage through the bedrock foundation of Red Rock Dam near Pella, Iowa (fig. 1), which could have threatened the integrity of the dam. The evidence for underseepage included correlation between water levels and chloride concentrations in Lake Red Rock with water levels and chloride concentrations in bedrock observation wells downstream from the dam (Lucey, 1991). The COE initiated a remedial grouting program at the dam in September 1991. The purpose of the remedial grouting program was to decrease the permeability of the bedrock on the northeast side of the dam and limit underseepage. Grouting was completed along approximately 3,000 feet of the axis of the dam, from 1991 through 1997 (fig. 1). A second study was conducted in 1999 by the USGS in cooperation with the COE to assess the effects of the remedial grouting on the ground-water flow system. The study involved comparisons of pre-grouting and post-grouting relations in water-level and water-chemistry data. Knowledge will be gained about the application of stable isotope techniques that could be used to assess and monitor ground-water flow systems in other regions of the country.

Purpose and Scope

This report presents the results of the study to evaluate the effects of the remedial grouting program conducted by the COE from 1991 to 1997 on the ground-water flow system at Red Rock Dam.

The report includes descriptions of (1) the geology in the vicinity of Red Rock Dam; (2) the ground-water flow system in the vicinity of Red Rock Dam prior to the remedial grouting program; and (3) the effects of the remedial grouting program on the ground-water flow system. Changes in the time correlation and absolute differences between water levels, sulfate concentrations, and chloride concentrations in Lake Red Rock and the observation wells are discussed. The effect of the remedial grouting program on ground-water flow and chemistry (indicators of underseepage) is described. Stable isotope (hydrogen, oxygen, and sulfur) data from samples collected since December 1995 at several observation wells in the study area and from the Lake Red Rock tailwater are evaluated as a possible tool for assessing underseepage at Red Rock Dam in the future.

Previous Studies

There have been several studies investigating underseepage at Red Rock Dam. The U.S. Army Corps of Engineers (1970) detected higher water levels in observation wells on the northeast side of the dam than in wells on the southwest side. Large calcium and sulfate concentrations were detected below the dam in water flowing in the old river channel and drainage ditches on the northeast side of the valley, providing evidence of underseepage through underlying bedrock. The effect on the municipal water supply of Pella as a result of the formation of Lake Red Rock was reported by W.L. Steinhilber (U.S. Geological Survey, written commun., 1971), who cited increased concentrations of sulfate, dissolved solids, and hardness as a result of the upward movement of ground water from the St. Louis Limestone into the alluvial aquifer. A U.S. Army Corps of Engineers (1975) study found that specific-conductance values were lower in observation wells at higher pool (reservoir) elevations, indicating mixing of reservoir water with ground water. Another U.S. Army Corps of Engineers (1984) study found further evidence of underseepage from temperature data; a zone of colder water in glacial sands and upper

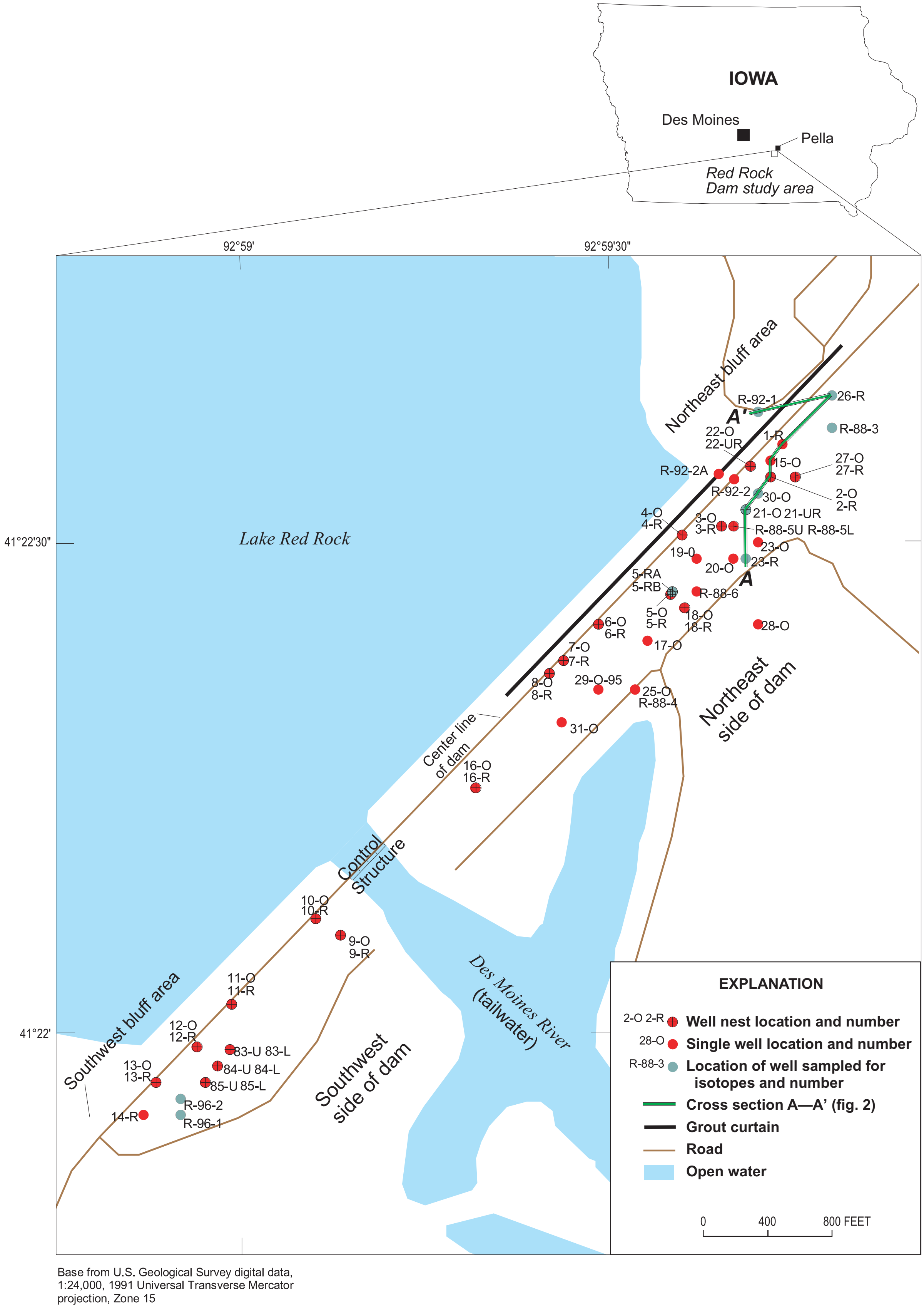

Figure 1. Red Rock Dam study area and location of observation wells.

bedrock in the northeast abutment indicated a possible flow path of colder reservoir water. During very high reservoir levels in 1984 (U.S. Army Corps of Engineers, 1984), mapping of the potentiometric surface showed a more gradual gradient at the northeast side of the dam when compared to the southwest side of the dam for both overburden and bedrock zones, implying the existence of a hydraulic connection between Lake Red Rock and ground water at the northeast side of the dam. Lucey (1991), using chloride concentration data as a tracer, found peak concentrations in both the overburden and bedrock observation wells 1 to 4 months after peak chloride concentrations occurred in Lake Red Rock, furthering evidence of underseepage. In the same study, higher correlation coefficients between pool-elevation changes and water-level changes in observation wells were found in data from the northeast abutment than in areas closer to the tailwater (on the northeast side of the dam) or on the southwest side of the dam. After remedial grouting in 1991–94, potentiometric surfaces appeared to be lower for both the overburden and bedrock at the northeast side of the dam than during pre-grout periods (B.D. Schaap, U.S. Geological Survey, written commun., 1995). At one well, water levels were determined to be less influenced by pool elevations after the remedial grouting than water levels before the grouting, and analysis of water quality showed less correlation to reservoir concentrations after grouting than before grouting (B.D. Schaap, U.S. Geological Survey, written commun., 1995). At a nested well site, water levels decreased, while pool elevations increased or stayed the same, and the water chemistry changed from a bicarbonate to sulfate water type, indicating less mixing with reservoir water (B.D. Schaap, U.S. Geological Survey, written commun., 1995).

Acknowledgments

The authors thank Vern Greenwood of the U.S. Army Corp of Engineers for providing water-level and water-chemistry data as well as technical assistance. The authors also thank Donna Lutz of Iowa State University, Department of Civil and Construction Engineering, for collection of water-quality and stable isotope samples and responses to inquiries regarding interpretations of isotope data.

DESCRIPTION OF STUDY AREA

Red Rock Dam is located on the Des Moines River, 30 miles southeast of Des Moines, Iowa (fig. 1). The study area is located in section 19 in township 76 north and range 18 west (T. 76 N., R. 18 W., sec. 19) in Marion County and covers approximately 1 mi^2. The crest of the dam extends 5,841 ft between the bluffs in the Des Moines River valley and is 100 ft high with an elevation at the top of the dam of 797 ft above sea level. The land surface of the alluvial valley ranges from 702 to 708 ft above sea level, and bluffs rise to 850 ft above sea level along both sides of the valley. The reservoir (Lake Red Rock) formed by Red Rock Dam has a maximum storage capacity of 1,489,900 acre-ft at a full flood-control level of 780 ft above sea level (May and others, 1999). The current conservation pool level is 742 ft above sea level.

Hydrogeology

Bedrock units of the Des Moines River valley within the study area include the Warsaw Limestone of Mississippian age, which consists of dolomitic shales and argillaceous shales. The Warsaw Limestone is overlain by the St. Louis Limestone of Mississippian age, which forms the bedrock surface in the Des Moines River valley and consists of alternating beds of limestone, sandstone, dolomite, and discontinuous basal evaporite beds. The alternating beds of limestone, sandstone, and dolomite are hereinafter referred to as the “upper bedrock” of the St. Louis Limestone. The discontinuous basal evaporite beds of the St. Louis Limestone consist of gypsum and anhydrite beds, overlain by a cavity zone. Gypsum is the predominant evaporite mineral present in the evaporite beds within the study area. The cavity zone formed from dissolution of evaporites and resultant slumping of the overlying bedrock and consists of numerous fractures and cavities. The cavities are either open or are filled with clay, silt, sand, and rock fragments. The discontinuous basal evaporite beds and overlying cavity zone of the St. Louis Limestone is hereinafter referred to as the “lower bedrock.” Within the valley, the bedrock is overlain by Quaternary-age alluvium and glacial outwash deposits (Lucey, 1991).

In the valley bluffs, the St. Louis Limestone is overlain by rocks of the Cherokee Group of Pennsylvanian age, which consist primarily of black shales with occasional interbedded siltstone, sandstone, limestone, and coal. Overlying the Pennsylvanian strata is Pleistocene pre-Illinoian glacial till consisting mainly of clay with fine, clayey sands and occasional fine- to medium-grained sand layers. Along the center line of the dam, glacial till is present primarily in the northeast bluff area (see fig. 1 for location of northeast and southwest bluff areas), whereas dam fill material and Pennsylvanian-age strata predominate in the southwest bluff area (Lucey, 1991). A layer of loess approximately 10 to 20 ft thick overlies the glacial till on the bluffs (U.S. Army Corps of Engineers, 1984). The unconsolidated glacial and alluvial deposits and dam fill overlying the bedrock units throughout the study area are hereinafter referred to as the "overburden."

Figure 2 shows elevations of the land surface, bedrock surfaces, potentiometric surfaces, and well-screen depths at the northeast side of the dam.

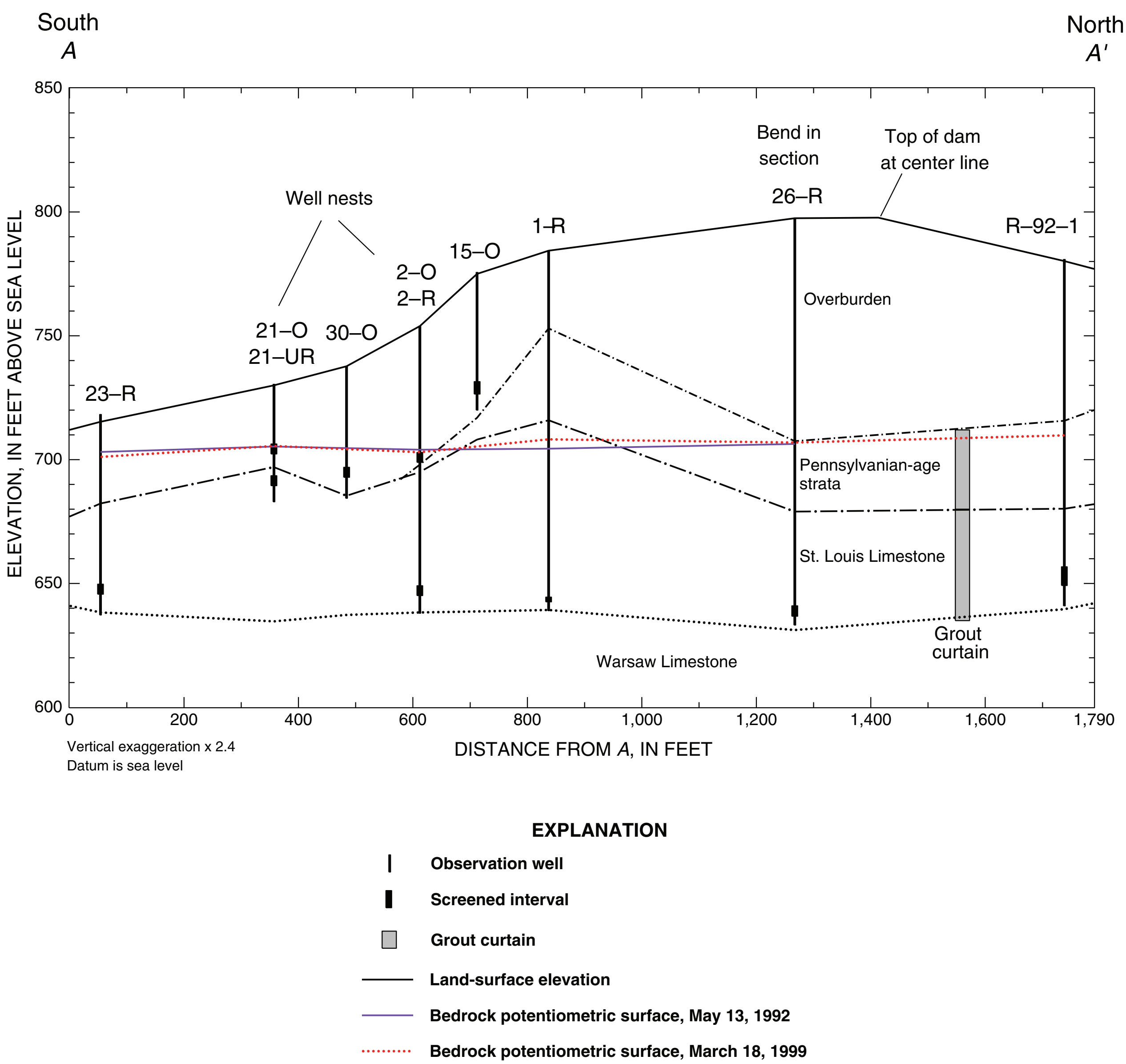

Figure 2. Hydrogeologic section through the northeastern part of Red Rock Dam; trace of section shown in figure 1.

Locations of wells and trace of section used to construct section *A–A*' are shown in figure 1. The overburden along this section ranges in thickness from about 35 to 90 ft. The Pennsylvanian-age strata is as much as 40 ft thick and the St. Louis Limestone ranges from about 38 to 75 ft in thickness. Bedrock water levels on two different dates ranged from about 710 to 701 ft above sea level. The grout curtain extends from the bottom of the St. Louis Limestone to the top of the bedrock surface.

The Warsaw Limestone is the lower confining unit at the Red Rock Dam study area and has limited permeability, which retards movement of ground water. The St. Louis Limestone contains two water-bearing parts, referred to as the lower bedrock and upper bedrock. Where overlying consolidated units are absent, unconfined conditions are present in the St. Louis Limestone. Where present, overlying consolidated units produce confined conditions in the St. Louis Limestone. The Pennsylvanian-age strata are generally confining units and contain interspersed sandstone water-bearing units, but the units are not extensive. The overburden contains glacial and alluvial sands that are water-bearing units. Regional flow in the St. Louis Limestone is generally in a southwesterly direction (Lucey, 1991).

Ground-Water Flow System Prior to Remedial Grouting

Water levels measured on February 23, 1984, July 13, 1984, and July 9, 1990, indicate that, in general, the gradient of the potentiometric surface of the overburden was from the topographic highs of the valley bluffs toward the Des Moines River (Lucey, 1991). Potentiometric maps indicated that the direction of ground-water movement in the overburden at the northeast side of the dam is approximately at a 45-degree angle (toward the south) to the axis of the dam and the river regardless of pool levels (Lucey, 1991). Ground-water flow in the evaporite zone of the St. Louis Limestone also was generally toward the river. At lower pool elevations, ground-water flow in the lower bedrock of the St. Louis Limestone was more parallel to the axis of the dam, whereas at higher pool elevations, ground-water flow had a slightly more downstream direction. Potentiometric-surface elevations for nested well pairs indicate that ground-water movement is in an upward direction in the river valley where confining conditions exist in the evaporite beds of the St. Louis Limestone. Ground-water movement was found to be in a downward direction in the northeast bluff area as the St. Louis Limestone is recharged from the overburden (Lucey, 1991).

Differences in hydraulic connectivity between the reservoir and the ground water were evident from potentiometric-surface gradients on the southwest and northeast sides of the dam. A very steep gradient was observed along the southwest side of the dam between the reservoir and the downstream wells, indicating restricted hydraulic connectivity. A more gradual gradient was observed on the northeast side of the dam, indicating the presence of underseepage from the reservoir through bedrock to the wells downstream from the dam axis. Correlations between water-level changes in the reservoir and wells, along with observations of peak chloride concentrations in the reservoir and wells, provided further evidence that, prior to remedial grouting beginning in 1991, water was flowing from the reservoir through the basal evaporite zone and overlying cavity zone of the St. Louis Limestone (Lucey, 1991).

Based on comparisons of observed changes in water levels (during a period when the pool elevation increased 28.2 ft) between wells in the northeast bluff area and wells located at a far enough distance and in a completion interval high enough (completed in shale bedrock of Pennsylvanian age) to reflect water-table conditions above the zone of influence of the reservoir, water-level increases in wells in the northeast bluff area were thought to be primarily a result of the hydraulic connection to Lake Red Rock rather than from climatological effects (Lucey, 1991).

REMEDIAL GROUTING PROGRAM

The COE began the remedial grouting program in September 1991. The grouting program was intended to reduce the permeability of the St. Louis Limestone at the northeast side of the dam and to decrease underseepage through the evaporite zone. Grouting was completed over a 3,000-ft length, parallel (northwest of the center line of the dam) to the axis of the dam. Grouting was completed in two stages (stage I and stage II) (U.S. Army Corps of Engineers, 1998).

Figure 3 shows the amount of grout required at different locations along the grout curtain. The grouting during the initial phase (1991 and 1992, stage I) included stations 2500 to 3600 (distance from a reference point, in feet; reference point not shown in fig. 3). Hole spacing for the primary grouting was on 20-ft centers with secondary holes placed in between primary holes on 10-ft centers. Tertiary holes at 5-ft centers and quaternary holes on 2.5-ft centers also were placed in regions where large volumes of grout were required (U.S. Army Corps of Engineers, 1998).

Stage II grouting began in 1994 and continued through 1997. This stage of the grouting included stations 3550 to 5500. The primary holes were placed on 10-ft centers, and secondary and tertiary holes were placed on 5-ft and 2.5-ft centers, respectively. Quaternary holes also were placed in regions where large volumes of grout were required. Grout was pumped into the holes until refusal. Multiple rows of holes were grouted in regions of high grout volumes. No grouting was done in 1993 because of high pool elevations (U.S. Army Corps of Engineers, 1998).

In 1996 (fig. 3), significant amounts of grout were required between stations 4400 and 5200; more than 3,000 ft^3 of grout was placed at station 4760. Between stations 4600 and 4900, large volumes of grout were needed, even in some tertiary and quaternary holes, indicating the complexity and irregularity of the geology. Many other stations, however, required very little grout in tertiary and quaternary holes, indicating closure of the grout curtain. Total volume of grout placed during remedial grouting (stages I and II) was approximately 77,650 ft^3. Most grout was pumped at a 3-to-1 water-to-cement mix (U.S. Army Corps of Engineers, 1998).

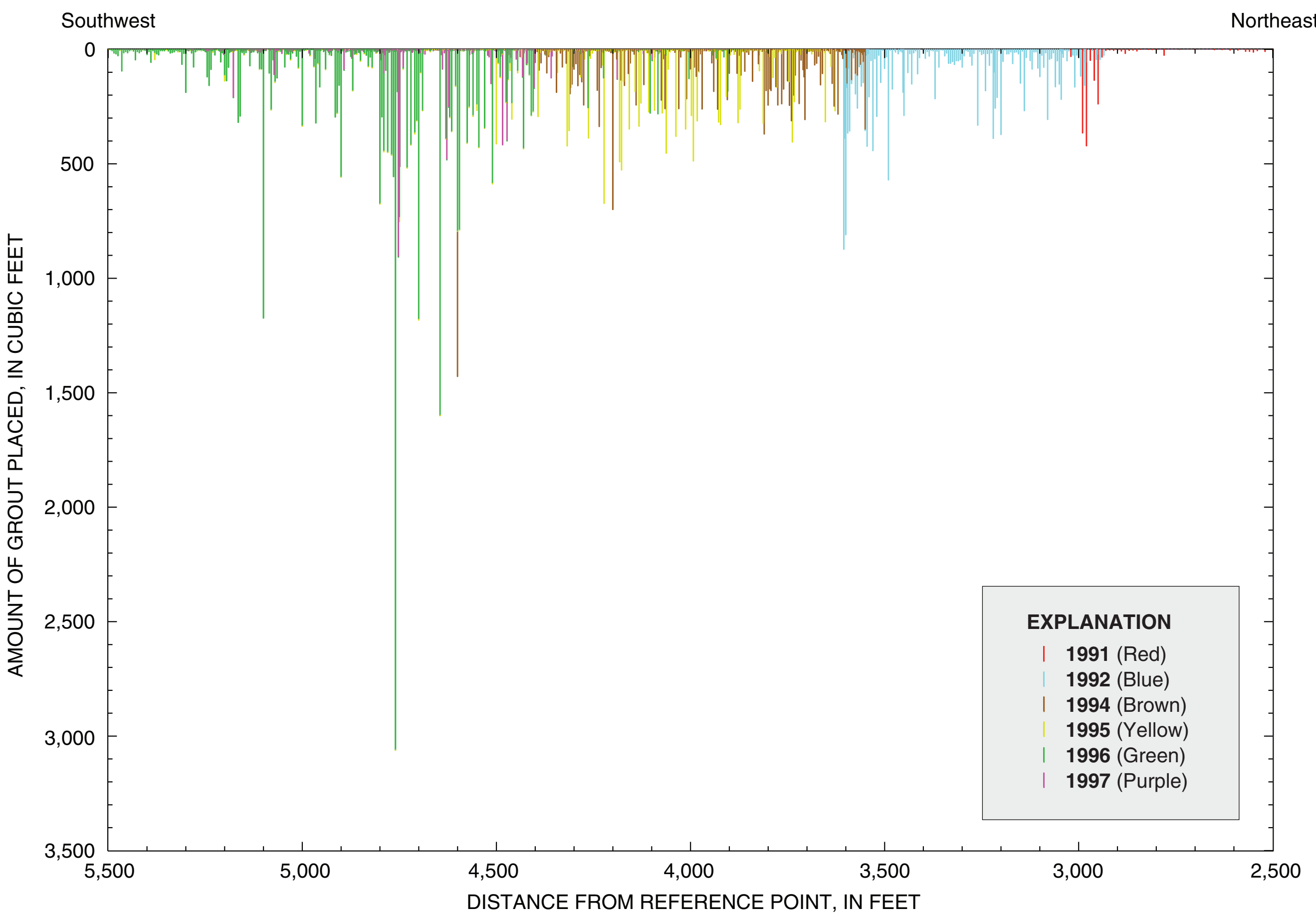

Figure 3. Amount of grout placed during remedial grouting at Red Rock Dam.

DESCRIPTION OF OBSERVATION WELLS AND METHODS OF STUDY

Observation Wells

Currently (2000) there are about 85 observation wells in the Red Rock Dam study area. The locations of selected bedrock wells and overburden wells are shown in figure 1. Selected wells are those for which accurate location information is available. Wells designated "–O" are completed in the overburden materials, either alluvium, glacial till, or dam fill material. Wells completed in the evaporite zone or the cavity zone of the St. Louis Limestone are designated by "–R" (lower bedrock), "–RA" (evaporite zone), "–RB" (cavity zone), or "–L" (lower bedrock). Wells designated "–U" are completed in sandstone in the upper bedrock of the St. Louis Limestone, and "–UR" designates wells completed in limestone in the upper bedrock of the St. Louis Limestone. Wells labeled "R–" generally are completed in the lower bedrock of the St. Louis Limestone. Exceptions to wells designated "R–" include well R–88–3, which is completed in the bedrock of the Cherokee Group in the bluff on the northeast side of the dam, and well R–88–4, which is completed in extremely fractured and weathered limestone of the St. Louis Limestone in the former Des Moines River channel. Observation well nests (for example, 2–O, 2–R) were installed by nesting two separate pipe assemblies in a single well bore and isolating the well screens at different depths (Lucey, 1991).

Tables 1 and 2 list observation well numbers, station, distance offset from the center line on top of the dam, elevations at the top of the wells, and elevations at the bottom of the well screens. Station numbers indicate that station 3120 is 3,120 ft southwest (following the center line of the dam) of a reference point, station 0000, located in the bluff area to the northeast of the dam. Direction of offset is designated as either upstream (U/S) or downstream (D/S) from the center line of the dam. Distances between wells along the center line of the dam and offset distances to wells may not necessarily agree between figure 1 and tables 1 and 2. Stations and offsets in tables 1 and 2 were obtained by the COE using conventional surveying techniques, whereas well locations in figure 1 were obtained by the USGS using a handheld global positioning system (GPS). Elevations at the top of the wells (tables 1 and 2) were obtained by the COE using conventional surveying techniques.

Water-Level Data Collection and Analysis

Since Red Rock Dam was completed in 1969, the COE has collected water-level data from observation wells. Water levels were measured at 62 observation wells from July 1988 to July 1990, before remedial grouting began (Lucey, 1991). Since that time, additional wells have been added to the network and some wells have been removed from the network. Currently (2000), there are about 85 observation wells in the water-level measuring network. Water levels are measured monthly or bimonthly by COE personnel. Water levels also are measured monthly at a selected subset of the observation wells by Iowa State University at the same time water-quality samples are collected. Since 1969, elevation for Lake Red Rock has been measured at a water-stage recorder (COE station 05488100 Lake Red Rock near Pella, Iowa) at the outlet works on the upstream side of the dam. From 1968 to 1992, tailwater elevation was measured at water-stage recorders at COE stations located at various sites downstream from Red Rock Dam. Since 1992, tailwater elevation is measured at a water-stage recorder (USGS station 05488110 Des Moines River near Pella, Iowa) located 0.4 mi downstream from the dam (May and others, 1999).

Potentiometric-surface maps are used to determine ground-water flow directions and gradients and to evaluate any changes in flow direction that may result from remedial grouting. Data used to construct potentiometric maps are from wells on the northeast side of the dam for which accurate location information is available. Wells completed in the upper bedrock of the St. Louis Limestone were not used to construct potentiometric maps. Also, for wells with similar water levels and with similar locations, only one of the water levels was used in construction of the potentiometric map. In addition, two points in time, a pre-grout day and a post-grout day, at similar pool elevations, were compared to evaluate changes in relations between water levels in selected observation wells, Lake Red Rock elevation, and tailwater elevation. Some wells had not been drilled prior to the pre-grout day; however, post-grout water levels for these wells are presented in table 2 for reference to the potentiometric maps. Comparisons of water levels and water-level changes through time, between selected observation wells, tailwater, and the pool, were made using time-series plots. Statistical analysis of water-level data for selected bedrock wells using Spearman correlation coefficients was used to detect possible changes in the response of ground-water levels

Table 1. Data pertaining to selected bedrock wells in the Red Rock Dam study area

[D/S, downstream; U/S, upstream; shaded rows indicate wells located on the southwest side of dam]

Well number (fig. 1)	Station (distance from reference point in northeast bluff along center line of dam) (feet)[1]	Offset from center line of dam (feet)	Elevation of top of well (feet above sea level)	Elevation of bottom of well screen (feet above sea level)
1–R	3120	85 D/S	784.40	642.60
2–R	3403	192 D/S	753.90	645.10
3–R	3802	230 D/S	730.10	643.40
4–R	4001	17 D/S	797.40	646.10
5–R	4279	229 D/S	729.30	645.40
5–RA	4264	229 D/S	733.40	651.10
5–RB	4264	229 D/S	732.30	659.20
6–R	4550	19 D/S	797.30	643.90
7–R	5040	19 D/S	796.90	648.10
8–R	5201	18 D/S	796.30	647.00
9–R	7247	237 D/S	723.90	640.60
10–R	7249	21 D/S	795.70	639.60
11–R	8001	22 D/S	796.60	633.00
12–R	8400	22 D/S	796.90	633.20
13–R	8700	23 D/S	796.90	633.50
14–R	8904	113 D/S	777.30	630.80
16–R	6000	230 D/S	724.60	639.60
18–R	4281	378 D/S	715.90	649.60
21–UR	3580	241 D/S	730.30	689.50
22–UR	3404	19 D/S	797.10	683.70
23–R	3817	371 D/S	718.20	645.70
26–R	2750	58 D/S	797.50	636.80
27–R	3250	375 D/S	774.90	642.60
83–L	8300	240 D/S	723.60	635.70
83–U	8300	240 D/S	723.90	654.00
84–L	8400	240 D/S	723.80	632.50
84–U	8400	240 D/S	723.70	652.00
85–L	8500	240 D/S	723.50	631.30
85–U	8500	240 D/S	723.80	656.20
R–88–3	2870	256 D/S	792.00	740.60
R–88–4	4924	503 D/S	701.90	652.80
R–88–5L	3786	230 D/S	731.90	639.70
R–88–5U	3786	230 D/S	732.00	650.40
R–88–6	4199	385 D/S	714.00	639.70
R–92–1	3092	200 U/S	780.80	649.20
R–92–2A	3440	25 U/S	797.40	647.00
R–92–2	3540	18 D/S	797.10	647.00
R–96–1	8686	289 D/S	751.00	641.80
R–96–2	8683	299 D/S	751.00	633.80

[1]Station numbers indicate that station 3120 is 3,120 ft southwest (following the center line of the dam) of a reference point, station 0000, located in the bluff area to the northeast of the dam.

Table 2. Data pertaining to selected overburden wells in the Red Rock Dam study area

[D/S, downstream; U/S, upstream; shaded rows indicate wells located on the southwest side of dam]

Well number (fig. 1)	Station (distance from point in northeast bluff along center line of dam) (feet)[1]	Offset from center line of dam (feet)	Elevation of top of well (feet above sea level)	Elevation of bottom of well screen (feet above sea level)
2–O	3403	192 D/S	753.90	698.90
3–O	3802	230 D/S	730.40	692.20
4–O	4001	17 D/S	797.50	685.80
5–O	4279	229 D/S	729.30	688.30
6–O	4550	19 D/S	797.40	677.00
7–O	5040	19 D/S	797.10	673.50
8–O	5201	18 D/S	796.50	673.70
9–O	7247	237 D/S	724.10	678.80
10–O	7249	21 D/S	795.90	679.80
11–O	8001	22 D/S	796.90	677.40
12–O	8400	22 D/S	797.20	672.70
13–O	8700	23 D/S	797.20	714.60
15–O	3251	108 D/S	775.60	726.50
16–O	6000	230 D/S	724.60	673.60
17–O	4600	319 D/S	715.90	693.70
18–O	4281	378 D/S	715.90	692.60
19–O	4051	261 D/S	728.90	686.60
20–O	3903	375 D/S	717.50	683.70
21–O	3580	241 D/S	730.40	702.30
22–O	3404	19 D/S	797.30	710.00
23–O	3717	371 D/S	717.70	690.30
25–O	4855	480 D/S	709.00	691.00
27–O	3250	375 D/S	775.00	741.50
28–O	3946	698 D/S	713.40	690.40
29–O–95	5099	355 D/S	706.30	676.30
30–O	3532	185 D/S	737.70	692.90
31–O	5368	359 D/S	704.80	677.50

[1]Station numbers indicate that station 3403 is 3,403 ft southwest (following the center line of the dam) of a reference point, station 0000, located in the bluff area to the northeast of the dam.

to changes in pool and tailwater elevations between pre-grout and post-grout periods. The Spearman rank order correlation coefficient is a measure of the degree to which two variables increase (or decrease) monotonically, even though the relation may not necessarily be linear (Ott, 1993). Correlation coefficients closer to 1 indicate better correlation to, and possibly better hydraulic connection with, the pool. Wells selected for the Spearman statistical analysis were those which were thought to be representative of the spatial distribution of wells within the study area to enable comparisons between the northeast and southwest sides of the dam.

Water-Quality Data Collection and Analysis

Water-quality samples are collected monthly from seven observation wells (5–RA, 5–RB, 23–R, 30–O, R–96–1, R–96–2, and 29–O–95), the tail water, and the pool, by Iowa State University. Onsite measurements include specific conductance, pH, temperature, and alkalinity. The wells are pumped, and once the onsite measurements stabilize, samples are collected. Samples are analyzed for major cations, major anions, nitrate, total hardness, carbon dioxide, suspended solids, total solids, and dissolved silica. Saturation indices are calculated for calcite, dolomite, and gypsum. The Analytical Services Laboratory at the Department of Civil and Construction Engineering of Iowa State University provided the analytical services.

Time-series plots were used to compare concentrations of selected ions in water sampled from selected observation wells and the tailwater (assumed to be representative of water from Lake Red Rock). These concentrations are assumed to reflect the mineralogy of the adjacent geologic formations. Any changes in water chemistry, excluding naturally occurring fluctuations, from pre-grout periods to post-grout periods may indicate changes in flow paths or residence time and, therefore, a change in underseepage conditions.

Boxplots of water-quality data (sulfate concentrations) were used to illustrate differences between pre- and post-grout years. Wilcoxon rank-sum nonparametric statistical tests (Ott, 1993) were used to evaluate the statistical significance of differences between pre- and post-grout sulfate concentrations. Values were generated by the tests to describe the probability that observed differences between pre- and post-grout periods occurred by chance. A probability (p) value of 0.05 indicates a 95-percent confidence that observed differences are not the result of chance occurrence. Differences with probability values of 0.05 or less were considered significant.

Since December 1995, samples for stable isotope analysis of oxygen, hydrogen, and sulfur ($^{18}O/^{16}O$, $^{2}H/^{1}H$, and $^{34}S/^{32}S$) have been collected from selected wells by Iowa State University. These wells are the same ones used for the regular water-quality sampling with the exception of well 29–O–95 (fig. 1). Samples for isotope analysis also are collected from the tailwater, which is assumed to be representative of water from Lake Red Rock. Samples are collected bimonthly from wells 23–R and R–96–2 and the tailwater. The remaining wells are sampled two or three times per year. In addition to the wells sampled by Iowa State University, USGS personnel collect samples for isotope analysis once a year from wells 21–O, 21–UR, 26–R, R–88–3, and R–92–1. These samples are analyzed by the USGS Stable Isotope Laboratory in Reston, Virginia.

The use of natural stable isotopes and their relative abundance can be a useful tool for studying the characteristics and origins of ground water (Gat and Gonfiantini, 1981). The heavy isotopes of oxygen (^{18}O) and hydrogen (^{2}H) and their relative abundance can act as tracers for meteoric water (precipitation derived from the atmosphere) and, therefore, be indicators of the degree to which reservoir water is mixing with ground water. Because there are significant sources of sulfur in the evaporite zone on the northeast side of the dam, sulfur (^{34}S) isotopes also can be useful for determining the degree of mixing of reservoir water and ground water. Time-series plots of these isotopes for selected wells and the tailwater are used to show their relative abundance and to monitor changes. As sampling for stable isotopes at Red Rock Dam has been done only since December 1995, a comparison of pre-grout and post-grout periods is not possible.

EFFECTS OF REMEDIAL GROUTING ON THE GROUND-WATER FLOW SYSTEM

Flow Patterns

A potentiometric surface map of the overburden for March 18, 1999, is shown in figure 4. The pool elevation this day was 742.79 ft above sea level. In the northeast bluff area, ground-water flow in the overburden is in a southeasterly direction. Farther to the southwest along the axis of the dam, the flow through the overburden is approximately parallel to the axis of the dam, in a southwesterly direction. The potentiometric surface around well 21–O (fig. 4) is higher than the surrounding wells (with the exception of well 22–O). The nested well pair, 21–O and 21–UR, had water levels of 706.6 ft and 705.5 ft, respectively, on this day, indicating a downward component of flow at this location. This pattern also is consistent with historical data at this location, as the water level in well 21–O is most often higher than in 21–UR and the surrounding wells. The general flow direction through the overburden in the northeast bluff area appears very similar to that described by Lucey (1991) for the overburden on February 23, 1984, at what then was a conservation pool elevation of 731.1 ft and tailwater elevation of 697.4 ft. However, flow farther southwest along the axis of the dam, closer to the Des Moines River, is more similar to the flow direction described by Lucey (1991) on July 13, 1984, when the pool elevation was 773.4 ft and tailwater elevation was 699.7 ft. Flow direction in this area of dam on July 13, 1984, was more parallel to the axis of the dam compared to February 23, 1984, when flow direction was more southerly away from the axis of the dam. Similarly, the lower tailwater elevation (690.72) on March 18, 1999 (fig. 4), compared to February 23, 1984 (697.4 ft), resulting in a greater head difference between the reservoir and the tailwater (52.07 ft on March 18, 1999, and 33.70 ft on February 23, 1984) appears to result in a change in flow direction in the overburden to a more southwesterly (parallel to the axis of the dam) direction in this part of the dam site. It appears that there has been little change in the general flow direction in the overburden since remedial grouting.

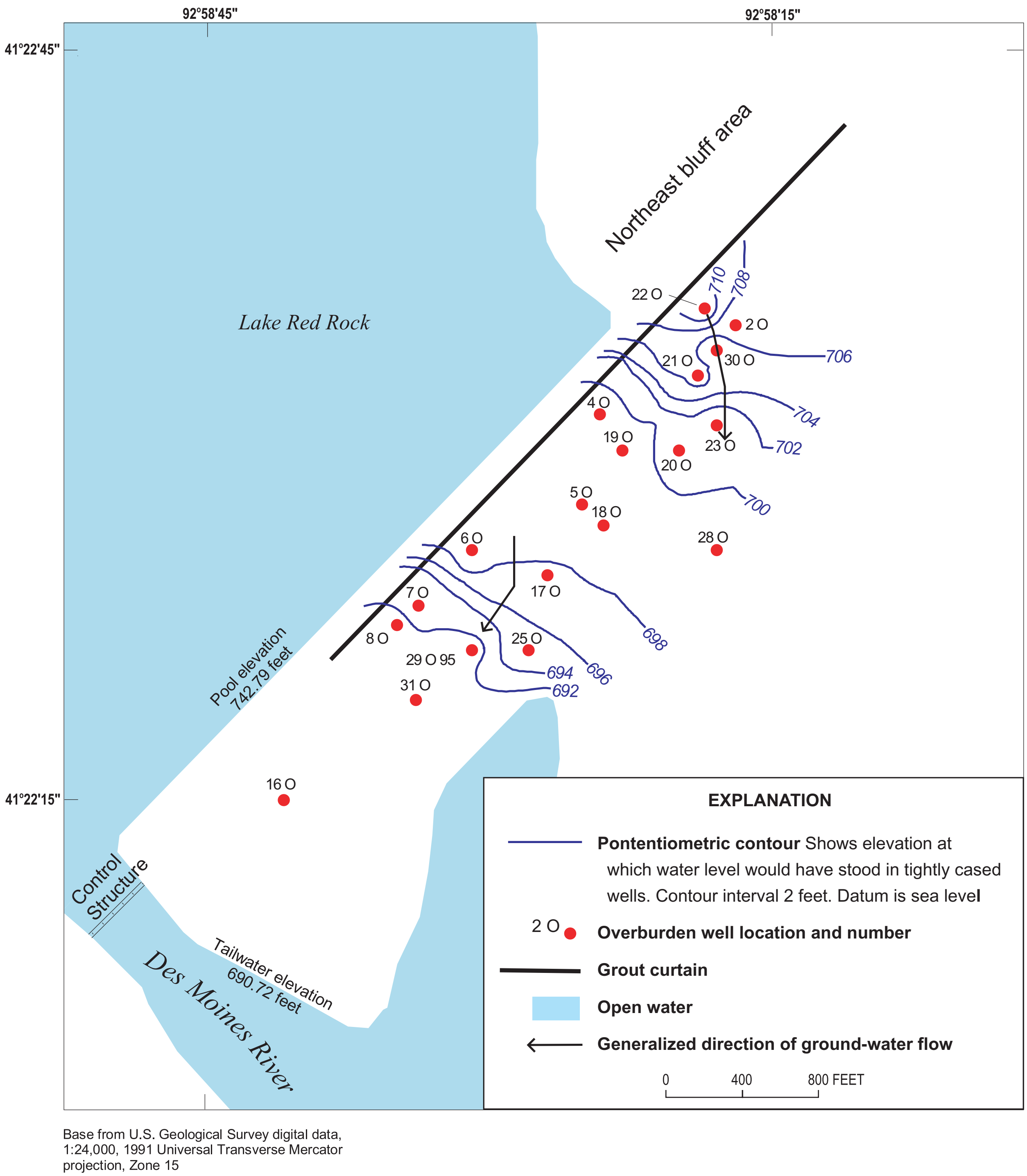

Figure 4. Potentiometric surface of the overburden, March 18, 1999.

Ground-water flow in the bedrock (fig. 5) closest to the northeast bluff is primarily in a southeasterly direction, with flow occurring in a southwesterly direction farther downstream from the dam axis. The flow changes to a more southerly direction as one moves toward the southwest along the dam axis. This also is very similar to the flow patterns described by Lucey (1991) on July 9, 1990 (at a pool conservation level of 764.4 ft above sea level), on the northeast side of the dam. Comparisons of potentiometric gradients for two days (February 23, 1984, and July 9, 1990) indicated that when higher pool elevations exist, ground-water flow in the bedrock becomes more parallel to the axis of the dam (primarily in the

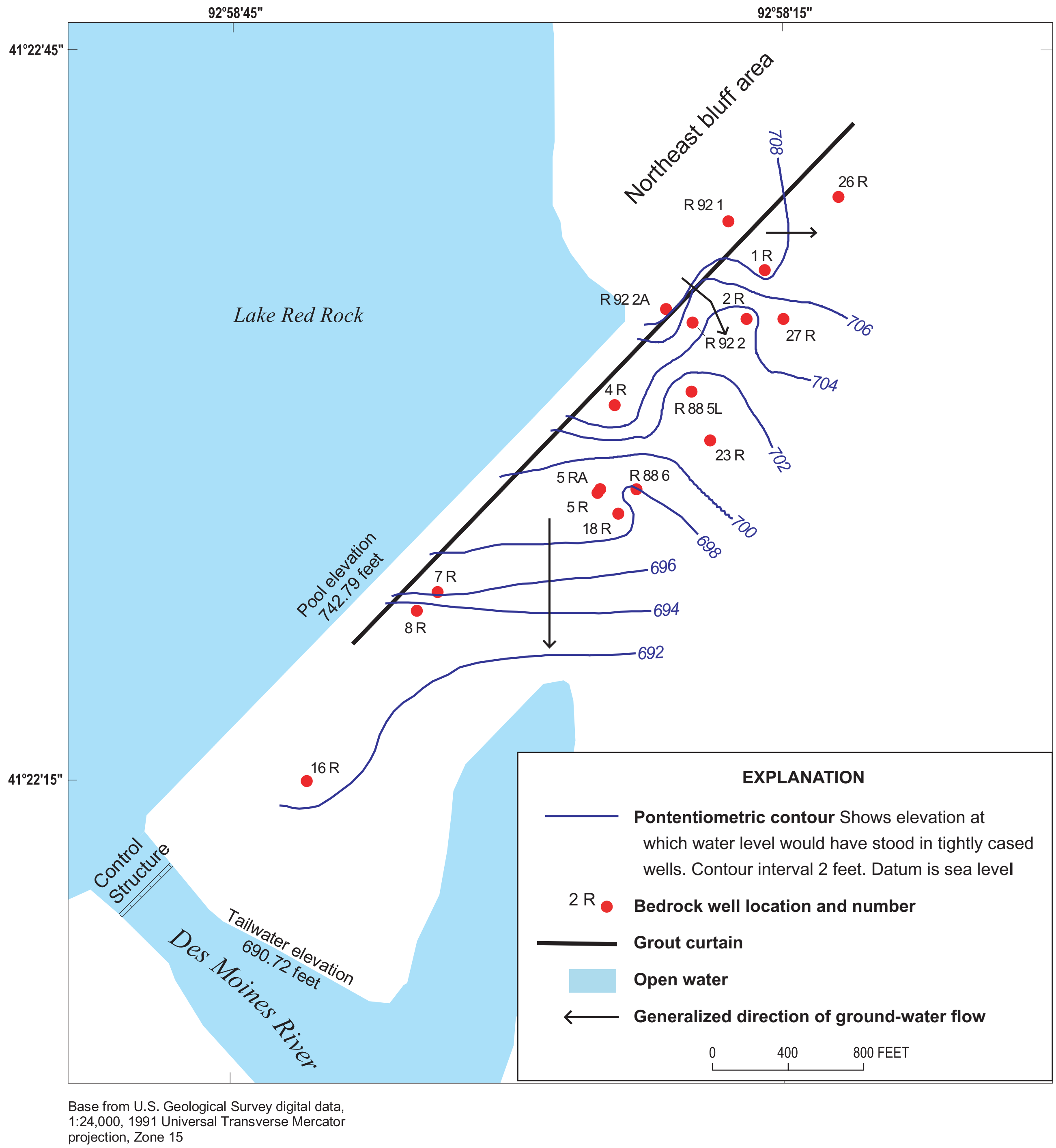

Figure 5. Potentiometric surface of the bedrock, March 18, 1999.

area to the southwest along the axis of the dam toward the Des Moines River), as was the case within the overburden. At lower pool elevations, ground-water flow was more perpendicular to the dam axis (Lucey, 1991). The direction of ground-water flow in the bedrock on March 18, 1999 (pool elevation 742.79 ft), suggests flow patterns more consistent with higher pool elevations, at least compared to flow patterns described by Lucey (1991) on February 23, 1984, when the pool elevation was 731.1 ft. Based on the potentiometric surface on March 18, 1999, it appears that the general direction of ground-water flow in the bedrock has changed little since pre-grout periods. A potentiometric high still exists in the northeast bluff area, suggesting that seepage through the overburden down into the bedrock and underseepage through bedrock and the grout curtain may still be occurring, at least to some degree.

Relation Between Water-Level Changes in the Reservoir, Tailwater, and Observation Wells

A comparison of water-level elevations for selected bedrock wells for pre-grout and post-grout conditions (May 13, 1992, and March 18, 1999, respectively) is given in table 3. These dates were selected because of similar pool and tailwater elevations. May 13, 1992, was the earliest date at which the pool elevation was near the conservation level of 742 ft above sea level to enable comparison to a post-grout day with a similar conservation pool elevation. Grouting in 1992 began in late March at station 2935 and did not proceed very far along the axis of the dam by May 13, 1992; therefore, hydrologic conditions represent a pre-grout date for the majority of wells. Grouting occurred immediately upstream from well 26–R in 1991 (fig. 3).

For most of the wells along the length of the dam, water levels decreased between May 1992 and March 1999 (table 3). Relatively large decreases occurred in wells 16–R (–4.0 ft), 8–R (–3.7 ft), and 7–R (–3.3 ft). These three wells are closest to the Des Moines River on the northeast side of the control structure. Well 11–R on the southwest side of the dam had a water-level decrease of –3.9 ft. Closer to the northeast bluff area, water levels for some of the bedrock wells increased between the two days. This occurred for wells 1–R, 4–R, 21–UR, 26–R, and 27–R. The closer to the northeast bluff, the greater the increase in water levels, with the exception of well 26–R. Increases of 3.8 ft (1–R), 1.4 ft (27–R), and 0.6 ft (4–R) were larger than the increase in pool elevation (0.39 ft) between the two days. There were no increases in water levels on the southwest side of the dam between the two days. Because pool elevations in the months prior to May 13, 1992, were lower (fig. 6) than pool elevations preceding March 18, 1999, the increase in water levels at these wells may indicate a response to the higher conservation pool elevations during the post-grout period. These results indicate that there may still be a greater hydraulic connection between the bedrock in the vicinity of these wells and the reservoir compared to other areas on the northeast side of the dam (that is, farther to the southwest along the dam axis) and the southwest side of the dam. Lucey (1991) observed that these same wells (with the exception of 4–R) had significant responses (increase in water levels) to changing reservoir levels, indicating greater hydraulic connectivity compared to other areas downgradient from the dam. Median changes in water levels for the two dates are very similar between the two sides of the dam (northeast –2.25 ft and southwest –2.10 ft).

Most of the overburden wells along the length of the dam showed a decrease in water levels between the two dates (table 4). Most decreases were very similar among these wells; however, well 30–O in the northeast bluff area had the smallest decrease of –0.3 ft. Overburden wells 9–O, 10–O, 11–O, and 12–O on the southwest side of the dam had somewhat larger decreases than those on the northeast side of the dam. The largest decreases on the northeast side of the dam were in those wells closest to the river, (7–O, –3.9 ft), (8–O, –3.7 ft) and, (16–O, –3.4 ft). The larger decreases observed in these wells (compared to those closer to the northeast bluff area) may be related to their better hydraulic connection to the tailwater. Pre-grout tailwater elevations were higher for several months prior to water-level measurements on May 13, 1992, than for the preceding months before water levels were measured on March 18, 1999 (see tailwater elevations in fig. 6).

On the northeast side of the dam, the highest water levels observed were in wells 22–O (711.3 ft), 21–O (706.6 ft), 2–O (706.5 ft), and 30–O (704.4 ft). These wells are located in the northeast bluff area and may indicate that ground-water flow in this area is moving down through the overburden from

Table 3. Water levels for selected bedrock wells, Red Rock pool, and Red Rock tailwater on May 13, 1992, and March 18, 1999, and the differences between the two days

[--, no data; shaded rows are those wells located on the southwest side of the dam]

Well number or surface-water body	May 13, 1992, water level (feet above sea level)	March 18, 1999, water level (feet above sea level)	Difference (feet)
1–R	704.4	708.2	+3.8
2–R	704.0	703.0	–1.0
3–R	703.4	701.2	–2.2
4–R	704.9	705.5	+0.6
5–R	702.4	699.5	–2.9
5–RA	701. 9	699.3	–2.6
5–RB	701.9	699.3	–2.6
6–R	No reading	No reading	--
7–R	699.7	696.4	–3.3
8–R	697.0	693.3	–3.7
9–R	692.1	690.9	–1.2
10–R	700.4	698.0	–2.4
11–R	703.6	699.7	–3.9
12–R	695.7	693.6	–2.1
13–R	696.5	693.9	–2.6
14–R	696.0	694.0	–2.0
16–R	696.3	692.3	–4.0
18–R	701.8	699.5	–2.3
21–UR	705.3	705.5	+0.2
22–UR	705.6	705.5	–0.1
23–R	703.1	701.2	–1.9
26–R	706.3	706.9	+0.6
27–R	704.4	705.8	+1.4
83–L	694.1	692.3	–1.8
83–U	694.1	692.7	–1.4
84–L	694.9	692.8	–2.1
84–U	694.7	693.6	–1.1
85–L	695.9	693.5	–2.4
85–U	695.9	693.7	–2.2
R–88–4	No reading	695.2	--
R–88–5L	703.4	701.0	–2.4
R–88–5U	703.2	701.1	–2.1
R–88–6	700.3	698.0	–2.3
R–92–1	No reading	709.8	--
R–92–2A	No reading	708.2	--
R–92–2	No reading	704.2	--
Red Rock pool	742.40	742.79	+0.39
Red Rock tailwater	690.50	690.72	+0.22

the reservoir. Water levels in the overburden wells on the southwest side of the dam (with the exception of well 13–O, 715 ft) were lower than those measured in overburden wells on the northeast side of the dam, probably due to the absence of permeable glacial material on the southwest side of the dam and the presence of lower hydraulic conductivity dam fill material (Lucey, 1991). Water levels in wells 21–O and 22–O increased between May 13, 1992, and March 18, 1999. This may be a result of higher conservation pool elevations preceding the post-grout day compared to lower conservation pool elevations preceding the pre-grout day (fig. 6). The effects on water levels in the overburden, as a result of remedial grouting, are probably minimal and may likely be more related to dam operations and the geology of the overburden material.

For the nested pairs of wells, almost all of the water levels were higher in the bedrock wells compared to the overburden wells for both the pre-grout and post-grout days, indicating an upward component of ground-water flow. Therefore, there was little change in direction of the vertical component of flow between the two days. Changes in the direction of the vertical component of flow, from upward to downward, did occur between the two dates in the area around the well nest 21–O and 21–UR. However, when considering water levels in wells 21–O and 21–UR over time (data not shown), which includes both pre-grout and post-grout periods, water levels are typically higher in well 21–O, indicating that the vertical component of ground-water flow in this area is most often downward. The change in flow direction is probably a result of the lower pool elevations in the months preceding May 13, 1992, when the overburden in the vicinity of 21–O was not being recharged from the reservoir. Water levels in well nest 2–O and 2–R and well nest 22–O and 22–UR indicate downward flow components on March 18, 1999; however, water levels were not available on May 13, 1992, as 2–O was not measured and 22–O was dry. Based on the two comparison dates, it

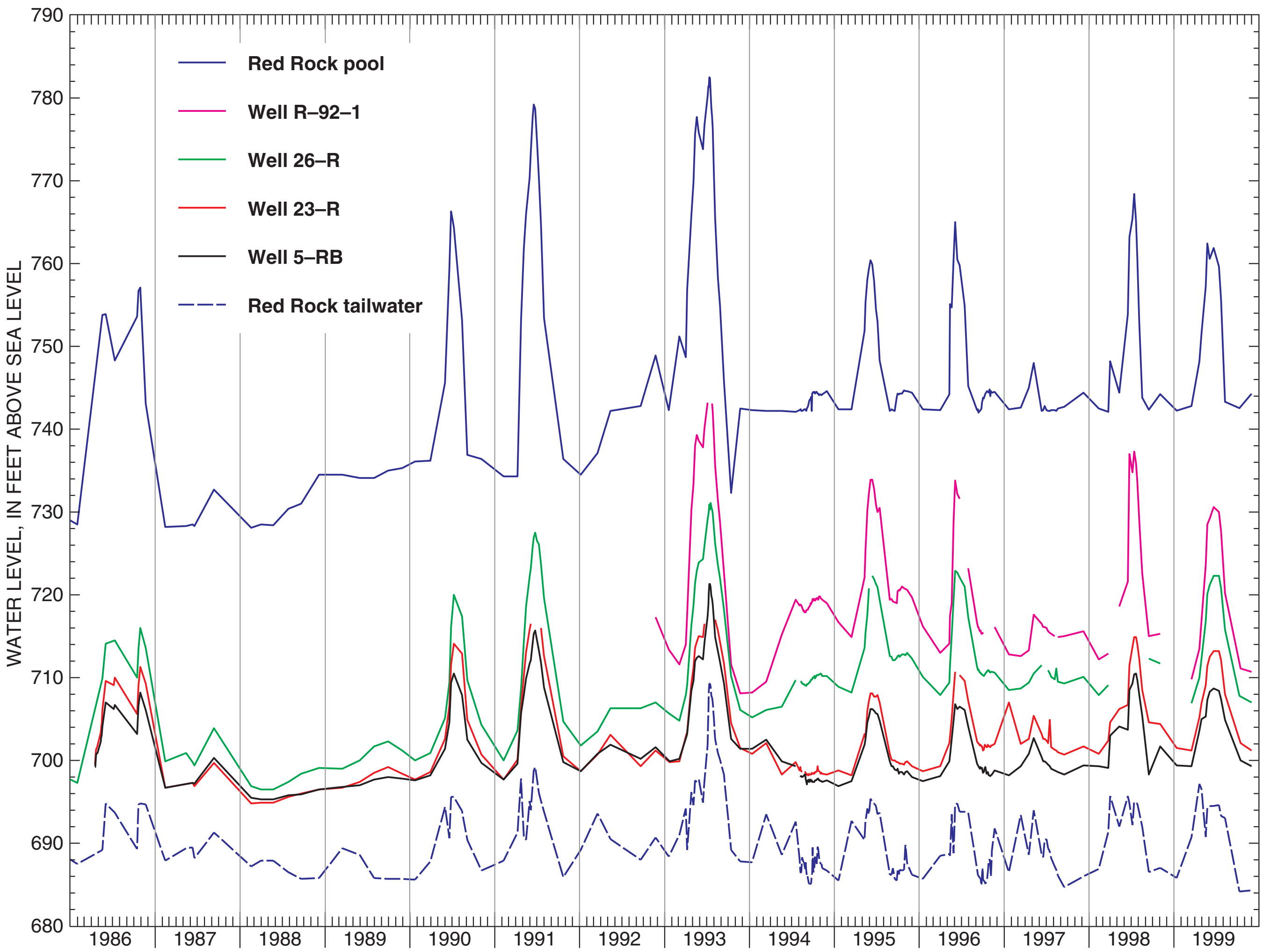

Figure 6. Water levels for Red Rock pool, tailwater, and selected bedrock wells on the northeast side of Red Rock Dam.

Table 4. Water levels for selected overburden wells, Red Rock pool, and Red Rock tailwater on May 13, 1992, and March 18, 1999, and the differences between the two days

[--, no data; shaded rows are those wells located on the southwest side of the dam]

Well number or surface-water body	May 13, 1992, water level (feet above sea level)	March 18, 1999, water level (feet above sea level)	Difference (feet)
2–O	No reading	706.5	--
3–O	702.9	700.8	–2.1
4–O	702.5	699.5	–3.0
5–O	701.4	698.5	–2.9
6–O	702.2	699.2	–3.0
7–O	696.3	692.4	–3.9
8–O	695.5	691.8	–3.7
9–O	693.8	690.4	–3.4
10–O	694.8	690.8	–4.0
11–O	694.4	689.9	–4.5
12–O	694.7	690.2	–4.5
13–O	Dry	715.0	--
15–O	Dry	No reading	--
16–O	694.3	690.9	–3.4
17–O	700.4	697.9	–2.5
18–O	701.2	698.8	–2.4
19–O	701.4	699.0	–2.4
20–O	702.7	700.6	–2.1
21–O	Dry	706.6	--
22–O	Dry	711.3	--
23–O	702.8	700.7	–2.1
25–O	698.3	695.9	–2.4
27–O	Dry	Dry	--
28–O	701.7	699.0	–2.7
29–O–95	694.3	691.7	–2.6
30–O	704.7	704.4	–0.3
31–O	693.6	691.0	–2.6
Red Rock pool	742.40	742.79	+0.39
Red Rock tailwater	690.50	690.72	+0.22

appears there has been little observable change in the vertical component of ground-water flow on either the southwest or the northwest side of the dam. Wells in which measured water levels indicated a downward flow component (with the exception of well pair 13–O and 13–R) on March 18, 1999, are wells that are located closest to the northeast bluff area, possibly indicating, as was previously mentioned, flow down through the overburden from the reservoir. On May 13, 1992, on the southwest side of the dam, there was only one well nest (9–O and 9–R) where water levels indicated a downward component of flow. Water levels measured in wells 9–O and 9–R on March 18, 1999, then indicate that the vertical component of flow in the vicinity of these wells changed between the two dates from downward to upward. While the direction of the vertical component of flow remained much the same at nested well sites for the two dates, three nested well sites exhibited larger increases in head difference between the bedrock and the overburden, indicating an increased upward flow component. This occurred at well nests 12–O, 12–R and 10–O, 10–R on the southwest side of the dam with increased differences of 2.4 ft and 1.6 ft, respectively. Nested well site 4–O and 4–R on the northeast side of the dam had an increased head difference of 3.6 ft, indicating an increased upward component of flow at this site. These increases in head difference at nested well sites are largely due to the large decreases in water levels in the overburden. Although not a nested well site, the increased water level (3.8 ft) at bedrock well 1–R, in an area of the dam where there is primarily a downward component of flow, might suggest an increase in flow downward from the overburden into the bedrock or an increase in flow through the grout curtain and bedrock as result of continued hydraulic connectivity to the reservoir. Overall, the majority of well nest sites along the dam indicated an upward component of flow, which is consistent with the description by Lucey (1991), and there has been little change between the two comparison dates. In addition, when comparing the water levels for the two dates between the southwest side of the dam and the northeast side of the dam, water levels remain somewhat higher in wells on the northeast side of the dam, indicating that more gradual gradients from the pool to the downstream wells probably still exist on the northeast side of the dam. This may reflect a combination of flow from the reservoir downward through the overburden into the bedrock and continuing hydraulic connection between the pool and the bedrock.

Some evidence for the effectiveness of the grout curtain is the observable difference in water levels between wells R–92–2A and R–92–2. Well R–92–2A is upstream from the grout curtain and well R–92–2 is downstream from the grout curtain, both on the northeast side of the dam (fig. 1). At the March 18, 1999, pool elevation of 742.79 ft above sea level, the difference in water levels (R–92–2A, 708.2 ft and R–92–2, 704.2 ft) of 4.0 ft indicates a steep hydraulic gradient within a relatively short distance (approximately 43 ft) across the grout curtain. This same condition has been observed repeatedly by the COE since the wells were installed (V. Greenwood, U.S. Army Corps of Engineers, oral commun., 2000). Because these wells did not exist prior to remedial grouting, it is impossible to compare pre- and post-grout water levels and determine the magnitude of the gradient between these wells that might have existed prior to remedial grouting.

Several water-level trends were observed in selected bedrock wells for the period of record (fig. 6). Hydrographs for wells 23–R and 5–RB indicate a departure from pre-grout trends (as early as 1992) when compared to hydrographs for Red Rock Lake and wells R–92–1 (upstream from the grout curtain) and 26–R. Water levels in 23–R and 5–RB also appear to trend downward early in 1994 (the same year in which grouting took place immediately upstream from these wells), while water levels in R–92–1 and 26–R continued to rise and the pool elevation remained steady. There was then a continuing separation of water levels through time between wells 23–R, 5–RB, and well 26–R compared to pre-grout periods when water levels in these wells tracked each other more closely. This separation then appears to narrow somewhat (more so for well 23–R) starting in 1996. This suggests that the grouting may have reduced the hydraulic connection between the reservoir and areas in the vicinity of these wells, especially initially. This narrowing may be a result of the ground-water flow system coming to an equilibrium after grouting or, in the case of wells 23–R and 5–RB, the water levels in the bedrock in this area of the dam responding much slower (as a result of remedial grouting) to the increase in the conservation pool elevation. This same trend, to varying degrees, can be seen for water levels in other bedrock wells on the northeast side of the dam (figs. 7 and 8). In figure 7, hydrographs for both wells 1–R and 2–R initially (1992) show a departure from pre-grout trends compared to well 26–R; however, water levels in well 1–R then appear to again track water levels in well 26–R (possibly as result of new flow paths developing after high pool elevations in 1993). The greater separation for the water level in well 2–R may indicate that hydraulic connectivity from the reservoir to the area in the vicinity of well 2–R has been reduced to a greater degree compared to the area in the vicinity of well 1–R. The hydrograph for well 2–R then also shows a slight narrowing in the late 1990's when water levels in well 2–R begin to track water levels observed in wells 1–R and 26–R more closely. Well 13–R, located on the southwest side of the dam, has much lower water levels and very little increase over time in response to the increased conservation pool elevation, indicating that the hydraulic connectivity on the northeast side of the dam, from the reservoir to the bedrock downgradient, is probably still greater than that on the southwest side of the dam, although it appears that remedial grouting has had some effect. The hydrographs (fig. 8) for wells R–92–2A (upstream from grout curtain) and R–92–2 (downstream from grout curtain) also show similar trends. Grouting between these wells was done in 1992, with additional grouting

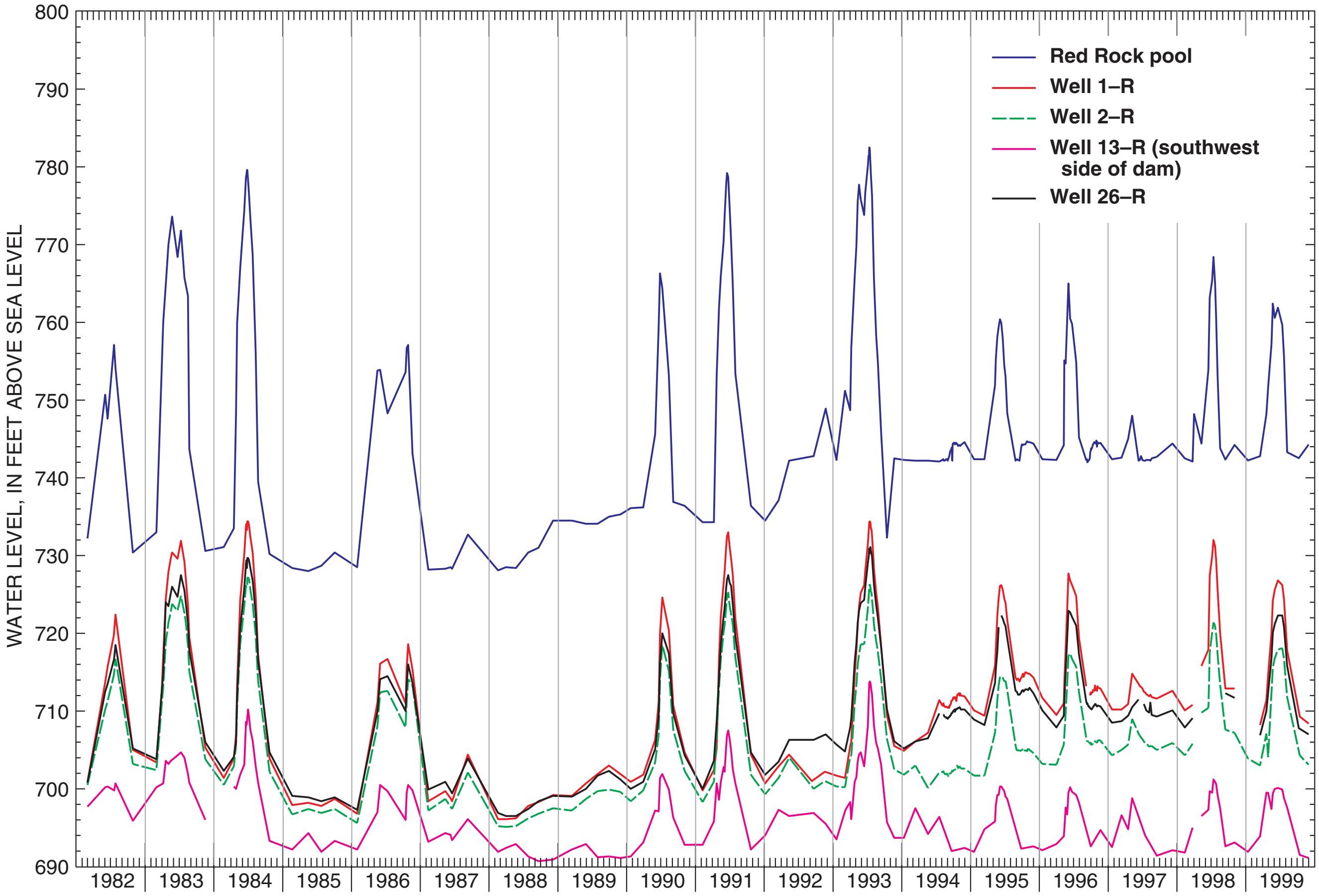

Figure 7. Water levels for Red Rock pool and selected bedrock wells on the northeast and southwest sides of Red Rock Dam.

being done 10 ft farther to the southwest (fig. 3) again in 1994. These wells did not exist prior to initiation of remedial grouting. There is greater separation in water-level elevations early (1994), possibly in response to remedial grouting, and then a narrowing as water levels in R–92–2A trend downward and water levels in R–92–2 trend upwards. Several other wells (data not shown) on the northeast side of the dam, 3–R, 4–R, 21–UR, and 27–R, also show similar water-level trends of large initial responses to remedial grouting and then varying degrees of narrowing over time. The narrowing effect may be a result of the ground-water flow system coming to an equilibrium as new flow paths develop in response to development of the grout curtain. Hydraulic gradients across the grout curtain are evident (figs. 6 and 8), with water levels in wells upgradient from the grout curtain (R–92–1 and R–92–2A) ranging from approximately 10 to 4 ft higher than water levels in wells downgradient from the grout curtain.

Pre- and post-grout Spearman correlation coefficients were calculated between water levels in selected bedrock wells, pool elevations, and tailwater elevations to determine if correlations between water levels have changed. Pre-grout and post-grout periods were based on grouting periods upgradient from the well location. If a well location is such that it is near the middle of the stations grouted during a given year, then that year was considered the dividing line between pre-grout and post-grout periods, with the grouting year removed, to avoid any question as to whether grouting had any effect on the well in that year. If the well is located along the axis of the dam such that it is near the boundary between different grouting years, then both years were removed to separate pre-grout and post-grout periods. In some instances wherein the well is located near the boundary of the 1992 and 1994 grouting years, a 3-year period divides pre- and post-grout years. No grouting was done in 1993 due to the unusually high pool levels. Wells selected for analysis

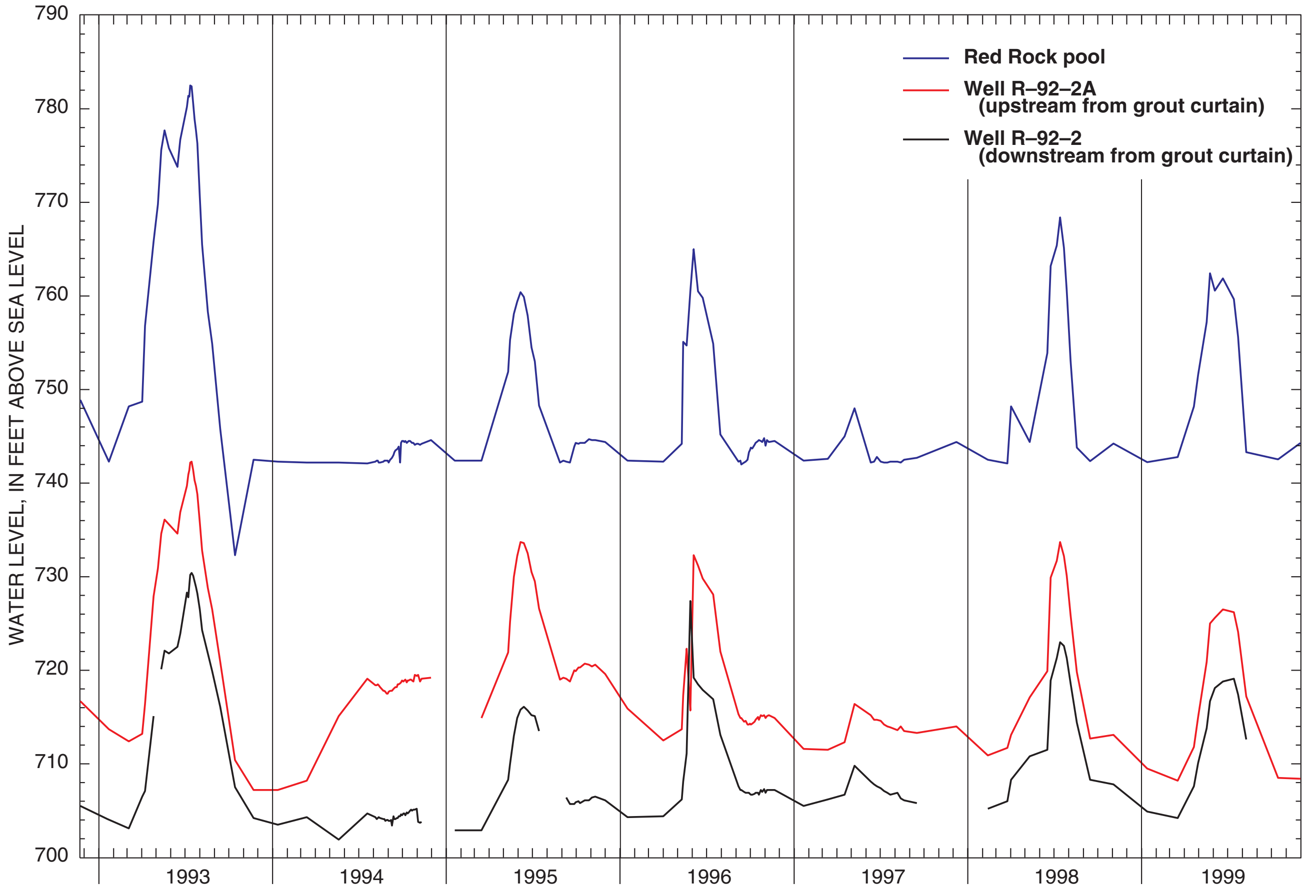

Figure 8. Water levels for Red Rock pool and bedrock wells R–92–2 and R–92–2A on the northeast side of Red Rock Dam.

include (1) wells located closest to and in the northeast bluff area where underseepage is thought be greatest; (2) wells that spatially represent hydrologic conditions present in other areas of Red Rock Dam—namely, the northeast side of the dam closer to the Des Moines River, the area upgradient from the grout curtain, and the southwest side of the dam where underseepage is thought to be minimal; and (3) wells having accurate location information. For comparison purposes, the selected wells on the southwest side of the dam, where no remedial grouting took place, were similarly divided into pre-grout and post-grout periods by eliminating 1993 water-level data. This provides similar timeframes for which pre- and post-grout comparisons between water levels in wells on the southwest side of the dam and the northeast side of the dam can be made. The pre-grout and post-grout periods, along with the calculated Spearman correlation coefficients, are listed in table 5.

Water levels in bedrock wells 1–R, 2–R, 3–R, 4–R, 5–RB, 23–R, 26–R, R–88–5L, and R–88–6, all on the northeast side of the dam, had lower correlation coefficients with pool elevations during post-grout periods than during pre-grout periods (fig. 9). The largest decrease was for well 4–R, from 0.93361 during pre-grout years to 0.58642 during post-grout years. Well 16–R, located on the northeast side of the dam closest to the tailwater, also had a lower correlation coefficient. Wells R–92–1, R–92–2, and R–92–2A essentially had no pre-grout water levels as they were constructed in 1992. Correlation coefficients for post-grout years for these wells were very similar and a little higher than other northeast wells with the exception of well 1–R. Wells R–92–1 and R–92–2A are upgradient from the grout curtain, whereas R–92–2 is downgradient from the grout curtain.

The water level in overburden well 30–O in the northeast bluff area also had a lower post-grout correlation coefficient compared to the pre-grout period.

Table 5. Spearman correlation coefficients for water levels in selected bedrock wells, well 30–O, Red Rock pool, and Red Rock tailwater

[--, no data; shaded rows indicate wells located on the southwest side of dam]

Well number	Pre-grout dates	Post-grout dates	Red Rock pool pre-grout	Red Rock pool post-grout	Red Rock tailwater pre-grout	Red Rock tailwater post-grout
1–R	03/01/82 to 10/23/91	01/19/93 to 08/09/99	0.95396	0.76081	0.80005	0.61742
2–R	03/01/82 to 04/09/91	01/19/95 to 08/09/99	0.93417	0.68411	0.84536	0.68889
3–R	03/01/82 to 10/23/91	01/19/95 to 08/09/99	0.94634	0.66181	0.82198	0.76162
4–R	03/01/82 to 11/22/93	01/19/95 to 08/09/99	0.93361	0.58642	0.82618	0.67046
5–RB	04/17/86 to 11/22/93	01/19/95 to 08/09/99	0.95223	0.63585	0.89508	0.76516
10–R	03/01/82 to 09/20/92	01/12/94 to 08/09/99	0.91857	0.83439	0.90889	0.93529
11–R	03/01/82 to 11/23/92	01/12/94 to 08/09/99	0.93221	0.85094	0.89264	0.87599
13–R	03/01/82 to 11/23/92	01/12/94 to 08/09/99	0.88175	0.79625	0.94272	0.93368
16–R	03/01/82 to 09/20/92	01/12/94 to 07/14/99	0.85853	0.58125	0.93055	0.77520
21–UR	03/01/82 to 10/23/91	01/19/95 to 08/09/99	0.89777	0.57081	0.79931	0.59346
22–UR	03/02/83 to 10/23/91	01/19/93 to 08/09/99	0.94537	0.73020	0.82265	0.65906
23–R	04/17/86 to 10/23/91	01/19/95 to 08/09/99	0.93922	0.64445	0.74371	0.74739
26–R	03/01/82 to 11/05/90	01/19/93 to 08/09/99	0.92804	0.71051	0.82318	0.55106
83–L	03/01/82 to 11/23/92	01/12/94 to 08/09/99	0.83865	0.74490	0.96554	0.94250
83–U	03/01/82 to 11/23/92	01/12/94 to 08/09/99	0.83258	0.75113	0.96589	0.94235
85–L	03/01/82 to 09/20/92	01/12/94 to 08/09/99	0.84966	0.79485	0.94985	0.92983
85–U	03/01/82 to 11/23/92	01/12/94 to 08/09/99	0.84270	0.78730	0.95171	0.93103
R–88–5L	07/27/88 to 11/22/93	01/19/95 to 08/09/99	0.91426	0.66009	0.89905	0.75497
R–88–6	07/27/88 to 11/22/93	01/19/95 to 08/09/99	0.92315	0.63866	0.91885	0.75964
R–92–1	Non-existing	11/23/92 to 08/09/99	--	0.74540	--	0.52868
R–92–2A	Non-existing	01/19/95 to 08/09/99	--	0.73032	--	0.52979
R–92–2	Non-existing	01/19/95 to 08/09/99	--	0.73795	--	0.72934
30–O	04/17/86 to 10/23/91	01/19/95 to 08/09/99	0.92513	0.68241	0.74974	0.68953
Red Rock tailwater	03/01/82 to 11/23/92	01/12/94 to 07/14/99	0.73013	0.52302	--	--

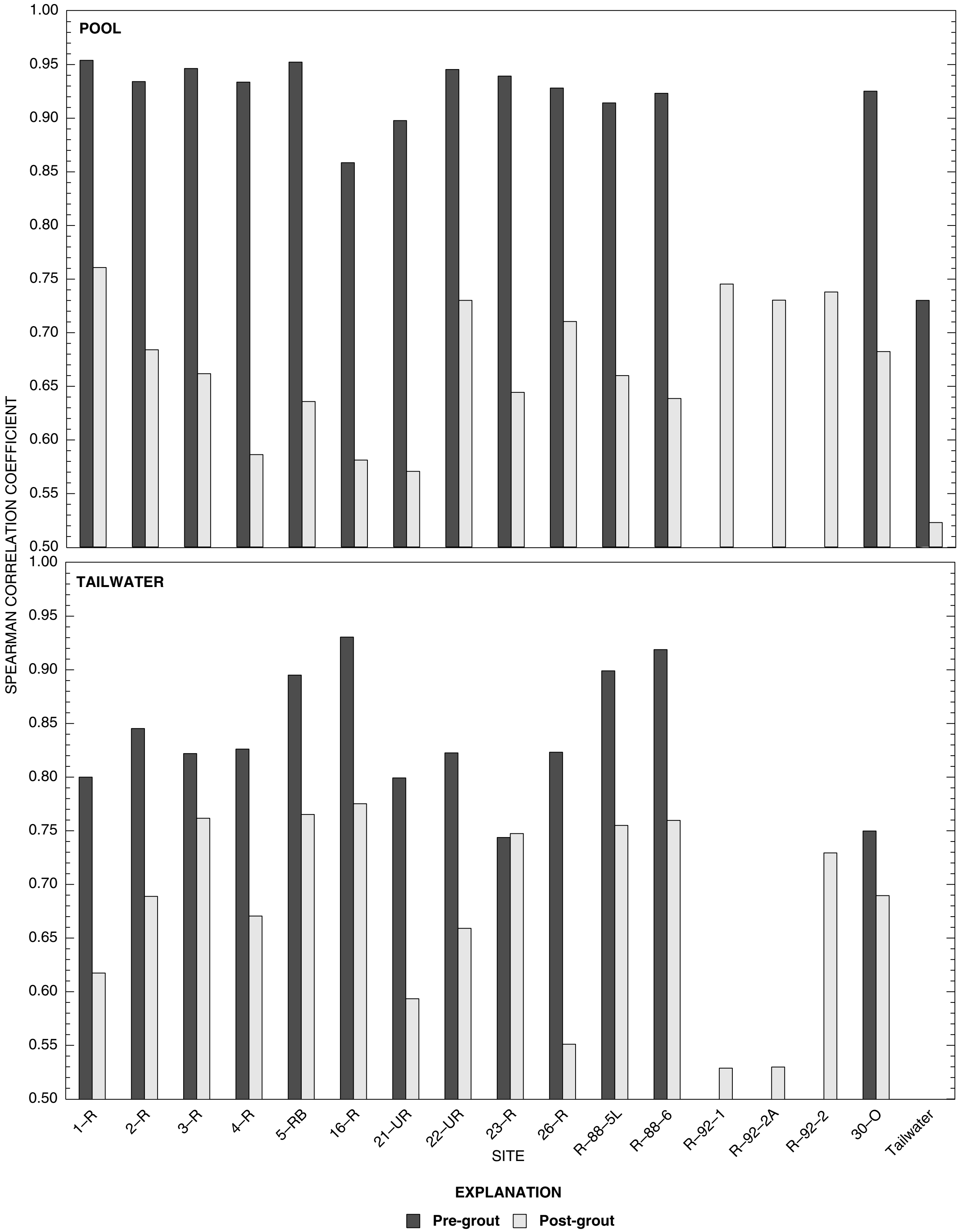

Figure 9. Correlation coefficients between water levels in selected bedrock wells, well 30–O, pool, and tailwater elevations during pre-grout and post-grout periods on the northeast side of the dam.

This well is in an area of the dam where the vertical component of ground-water flow is thought to be primarily downward (based on hydrographs for the period of record for overburden wells located at well nest sites in the same vicinity of well 30–O, data not shown) through the overburden, and therefore, should be less affected by remedial grouting. The lower correlation coefficient for well 30–O during post-grout years might be a result of dam operations—that is, smaller but more frequent rises in pool levels (fig. 6), or possibly, the development of longer flow paths to this well. If dam operations are at least partially responsible for the lower correlation coefficient at well 30–O during post-grout years, then it is possible that the decreases in correlation observed for water levels in bedrock wells on the northeast side of the dam may also be due, at least in part, to dam operations. Other overburden wells (2–O, 15–O, 21–O, and 22–O) in the same vicinity as well 30–O, where there is predominantly downward component of flow, were often dry during pre-grout years before pool conservation levels were increased; therefore, reliable pre-grout correlation coefficients for those wells could not be calculated.

Water levels in selected wells (fig. 9), with the exception of well 23–R, also had lower correlation coefficients with the tailwater between pre-grout and post-grout periods. Water levels in well 23–R had a slightly higher post-grout correlation coefficient with the tailwater. The correlation coefficient for the pool and tailwater was lower for the post-grout period compared to the pre-grout period, with 1993 acting as the boundary. Therefore, it is possible that the lower post-grout correlation coefficients between the water levels in the wells and the tailwater may be due, at least in part, to the greater fluctuations in outflow from the dam control structure (fig. 6) beginning in 1994.

On the southwest side of the dam, correlation coefficients between water levels in wells and pool elevations (fig. 10) also were lower for post-grout years compared to pre-grout years, although the decreases were not as large as those occurring on the northeast side of the dam. Correlation coefficients between water levels in all selected wells (with the exception of well 10–R) on the southwest side of the dam and the tailwater also slightly decreased from pre-grout to post-grout periods. Again, this may be related to the greater fluctuations in pool elevations and outflow from the dam control structure (fig. 6) beginning in 1994.

During pre-grout periods, water levels in selected wells on the northeast side of the dam (fig. 9) had higher correlation coefficients with pool elevations than with tailwater elevations, suggesting that these wells were more under the influence of changing pool levels than changing tailwater elevations. The exception is the water level in well 16–R, which had a higher correlation coefficient with the tailwater than with the pool. This well is located closest to the Des Moines River. Then, during post-grout years, water levels in wells 2–R, 3–R, 4–R, 5–RB, 21–UR, 23–R, R–88–5L, and R–88–6 have higher correlation coefficients with tailwater levels than with pool levels. This suggests that these wells are now more under the influence of the tailwater than the pool. For wells 1–R, 22–UR, and 26–R, although correlation coefficients were lower during post-grout years, their relation between the pool and tailwater did not change and appears still to be more under the influence of changing pool elevations. The relation between water levels in well 16–R, the pool, and the tailwater also remained the same from pre-grout to post-grout years, with a higher correlation coefficient with the tailwater than with the pool.

Water levels in wells on the southwest side of the dam (fig. 10) also had lower correlation coefficients with pool levels for post-grout periods. However, correlation coefficients with the tailwater remained higher when compared to the pool, suggesting that changes in tailwater elevations still have a greater influence on ground-water levels on that side of the dam. This is in contrast to some of the selected wells on the northeast side of the dam where the relation between water levels in wells, pool, and tailwater has changed. Of the selected wells, 10–R and 11–R are the only wells on the southwest side of the dam where there was a change in the relation between water levels in wells, pool, and tailwater. Wells 2–R, 3–R, 4–R, 5–RB, 16–R, 21–UR, 22–UR, 23–R, 26–R, R–88–5L, and R–88–6 on the northeast side of the dam had lower well/pool correlation coefficients during post-grout years than did the well (83–L) on the southwest side of the dam with the lowest well/pool correlation coefficient. This differs from pre-grout years when wells on the northeast side of the dam had higher well/pool correlation coefficients than did wells on the southwest side of the dam. This suggests that grouting along the northeast side of the dam has reduced the hydraulic connection relative to the southwest side of the dam where no remedial grouting was

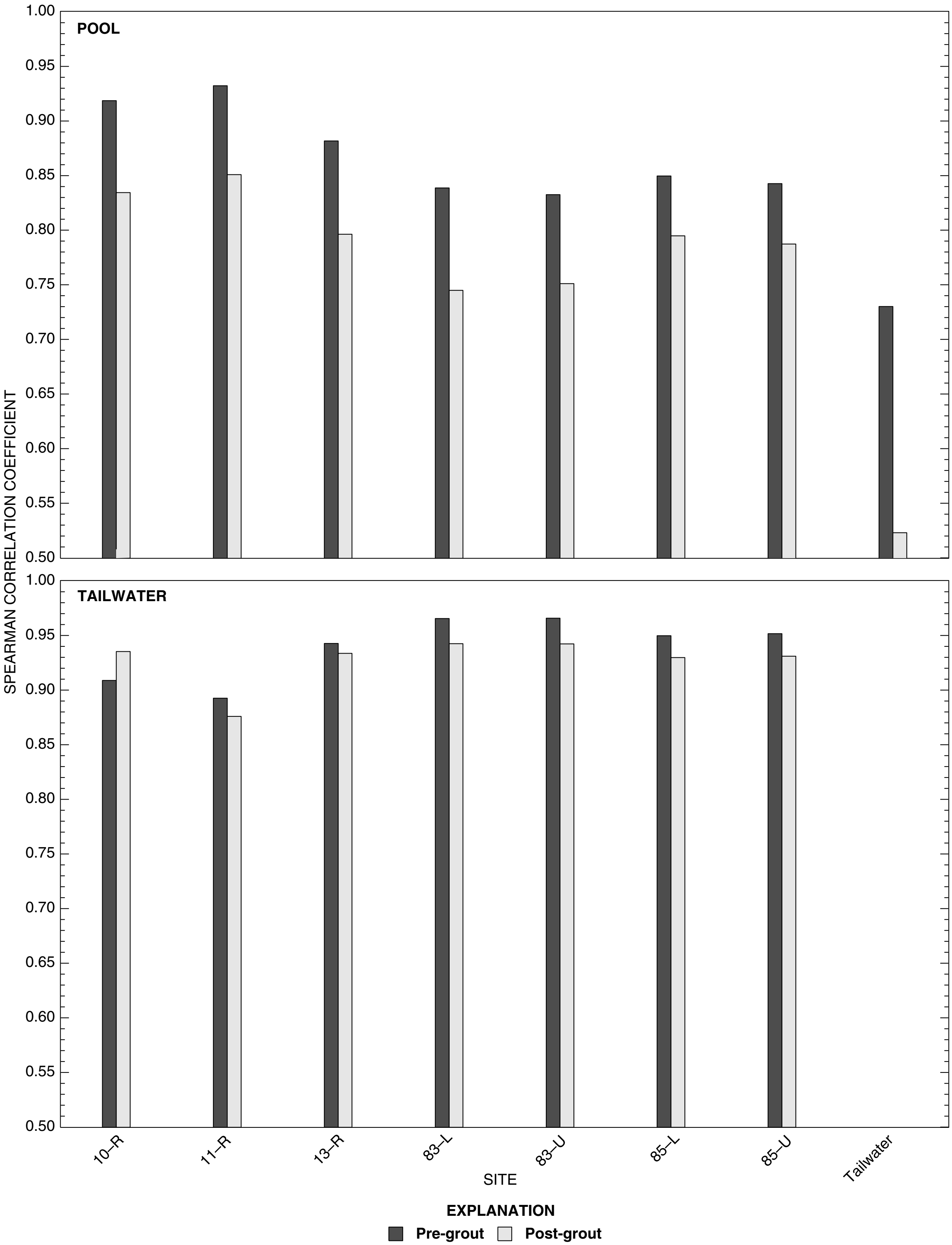

Figure 10. Correlation coefficients between water levels in selected bedrock wells, pool, and tailwater elevations during pre-grout and post-grout periods on the southwest side of the dam.

done. Although there is a hydraulic gradient across the grout curtain from the upgradient well, R–92–2A, to the downgradient well, R–92–2, correlation coefficients with the pool for water levels in these two wells are very similar. This suggests that remedial grouting may not have been as effective in this area of the northeast side of the dam.

Comparison of the relative changes in correlation coefficients for pre- and post-grouting periods between the northeast and southwest sides of the dam, and the observed change in relations between water levels in wells, pool, and tailwater on the northeast side of the dam, suggests that remedial grouting has had some effect in decreasing the overall hydraulic connection between the reservoir and downgradient wells. However, the wells in the extreme northeast bluff area (1–R, 22–UR, R–92–2, and 26–R) had well/pool correlation coefficients during the post-grout period similar to the upgradient wells (R–92–1 and R–92–2A) on the other side of the grout curtain, suggesting that this area still has a greater hydraulic connection. Grouting may have had some effect, however, on the northeast side of the dam, as observable decreases in correlation coefficients are evident, especially for wells 3–R, 4–R, 5–RB, 21–UR, 23–R, R–88–5L, and R–88–6. The underseepage to the area of well 23–R, thought to be the area with the greatest hydraulic connection to the reservoir prior to remedial grouting, based on chloride tracer data (Lucey, 1991), appears to have been reduced as a result of remedial grouting.

Water Chemistry

Sulfate Concentrations

Sulfate concentrations in samples collected from selected wells and the Red Rock tailwater are shown in figure 11 along with grouting periods. Tailwater concentrations are used because the monthly sampling record is more complete than the pool sampling record (due to ice formation during the winter months on Lake Red Rock), and concentrations of constituents of interest in same-day samples of the pool and tailwater are similar. After the 1992 grouting began, sulfate concentrations in well 23–R increased while Red Rock tailwater concentrations remained relatively stable. For example, increases in pool elevations in 1990 and 1991 (fig. 6) were associated with smaller sulfate concentrations at 490 and 428 milligrams per liter (mg/L), respectively, than in 1993, during even higher pool elevations when the smallest sulfate concentration was 608 mg/L. The sulfate concentration peak in 23–R during 1992 (1,007 mg/L) may have occurred because the primary connection to the reservoir was cut off and residence time increased compared to ground water that was there prior to 1992. As other pathways developed or the flow system equilibrated to the grout barrier, sulfate concentrations decreased slightly and then began to increase again in 1996, possibly as a result of more grouting upgradient from 23–R during 1994 and 1995. When sulfate concentrations for well 23–R are divided into pre-grout and post-grout periods (fig. 12), as was done in calculating Spearman correlation coefficients for water-level data, sulfate concentrations are greater during the post-grout period (Wilcoxon rank-sum test, $p=0.0017$). This suggests that there is less flow through the grout curtain and mixing of reservoir water and that ground-water residence time at well 23–R may have increased, allowing water to stay in contact with the gypsum for a longer period of time. Decreased inflow and storage in Lake Red Rock during post-grout years (fig. 6), and therefore less mixing of reservoir and ground water, may also be a factor in the greater sulfate concentrations observed during post-grout years. It is unknown to what extent the grout material is a contributor of sulfate to the ground water. Sulfur trioxide (SO_3) was the only sulfur-bearing compound in the grout material and constituted approximately 2.6 percent of the grout material. Calcium oxide (CaO) and silicon dioxide (SiO_2) made up the largest proportions of the grout material, approximately 63.1 percent and 20.5 percent, respectively (L. Cook, Lafarge Corporation, written commun., 1994).

Sulfate concentrations in samples collected from well 5–RB prior to 1994 were similar to the Red Rock tailwater sulfate concentrations (fig. 11). As the grouting in 1994 proceeded, sulfate concentrations in well 5–RB increased significantly while the Red Rock tailwater sulfate concentrations remained stable. There has, however, been a slight decrease in sulfate concentrations in well 5–RB since early 1998. When sulfate concentrations are divided into pre-grout and post-grout periods (fig. 12), post-grout sulfate concentrations in well 5–RB are greater than the sulfate concentrations during the pre-grout period ($p=0.0001$). This may indicate that flow from the reservoir to the cavity zone or evaporite zone across the axis of the dam was

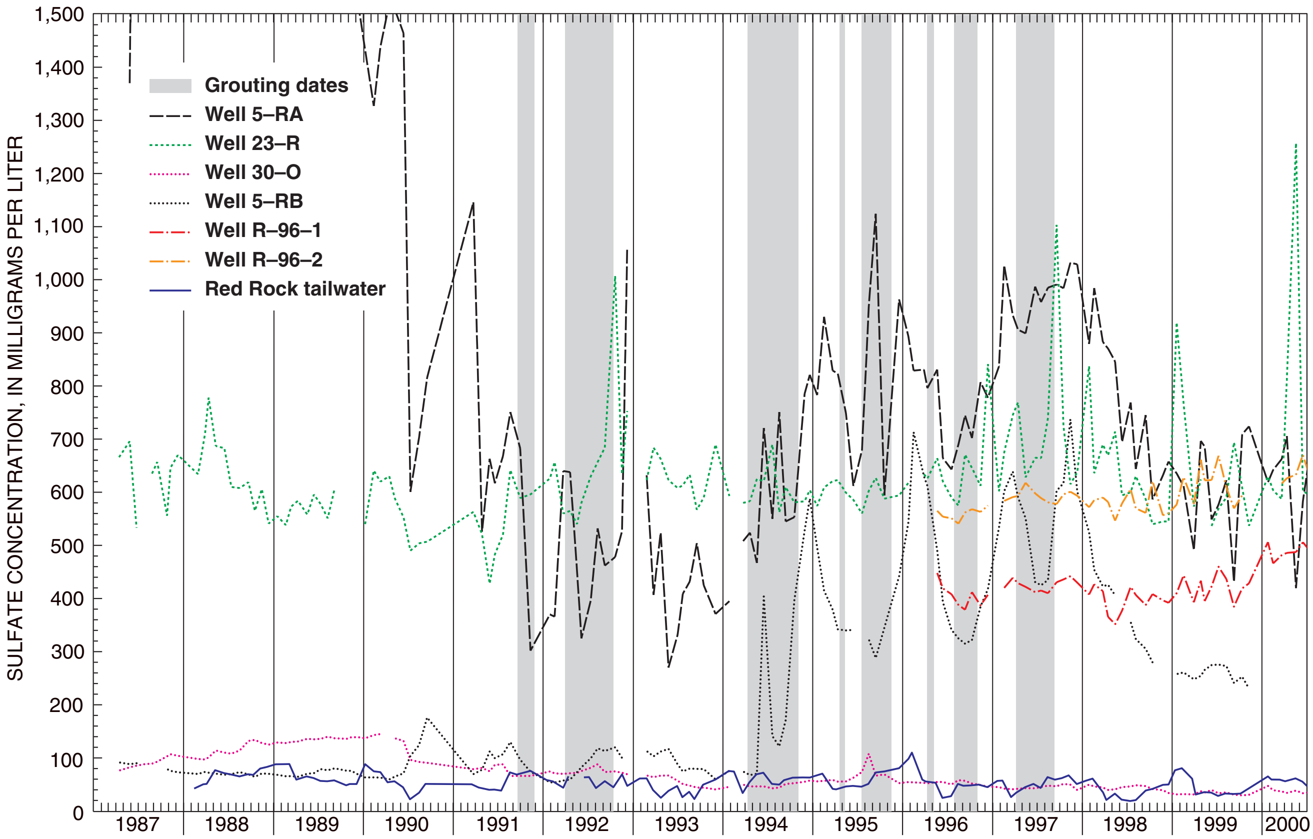

Figure 11. Sulfate concentrations in the tailwater and selected observation wells through time.

cut off by the initial grouting and less Red Rock pool water was mixing with water in the area of well 5–RB. In turn, this may allow greater mixing of deeper waters as an upward component of flow occurs from the evaporite zone to the cavity zone. Sulfate concentrations for wells 5–RB and 23–R are similar to those for wells R–96–1 and R–96–2 on the southwest side of the dam. There is, however, less fluctuation in sulfate concentrations for wells on the southwest side of the dam, indicating that less hydraulic connectivity probably still exists between Lake Red Rock and the bedrock wells on the southwest side of the dam.

A peak concentration of 3,390 mg/L in October 1988 was observed for well 5–RA (data not shown). The large decrease in sulfate concentrations observed for well 5–RA beginning in late 1988 may have been due to the development of a solution channel from adjacent strata, allowing breakthrough from a more permeable zone and consequently permitting mixing of water types (Lucey, 1991). Sulfate concentrations then began to increase again in 1994 and continued to increase until 1998 when sulfate concentrations began to decrease, following a similar pattern to well 5–RB.

Chloride Concentrations

Chloride concentration data from tailwater samples are used to represent reservoir water samples because samples from the tailwater have been collected on a consistent basis. It was not always possible to collect samples from the reservoir due to ice formation during winter months. In addition, chloride concentrations in same-day samples of the pool and tailwater are similar. Chloride concentrations in the tailwater vary seasonally, and peak concentrations typically occur during late winter and early spring (fig. 13). Sources of chloride are thought to be from application of road salt upstream in the drainage basin of the Des Moines River and possibly from application of potash fertilizer to agricultural lands in the drainage basin (Lucey, 1991). Prior to the initial grouting in 1991, chloride concentrations in selected wells appeared to be correlated to changes in reservoir chloride concentrations (fig. 13) and were thought to be due to underseepage in the lower bedrock of the St. Louis Limestone and not through downward movement of water through the overburden because potentiometric surfaces for nested well pairs indicated an upward component of flow for the majority of wells along the dam axis (Lucey, 1991). The vertical component of ground-water flow is similar for the post-grout years, as was discussed earlier.

Throughout the grouting period, the variations in chloride concentrations in the Red Rock tailwater are evident. Chloride concentrations for selected wells appear to vary to a greater degree prior to grouting, especially during 1991. Then, chloride concentrations remain relatively stable during periods of peak chloride concentrations in the tailwater throughout the grouting period. This may indicate that the grout curtain had some effect on underseepage to these wells during the grouting period. However, in late 1997, a large peak in chloride concentration in the Red Rock tailwater was detected along with large concentrations in all wells. It is unclear why this occurred, although a new analytical method for chloride was implemented at about the same time (D. Lutz, Iowa State University, written commun., 1998). Those data are considered

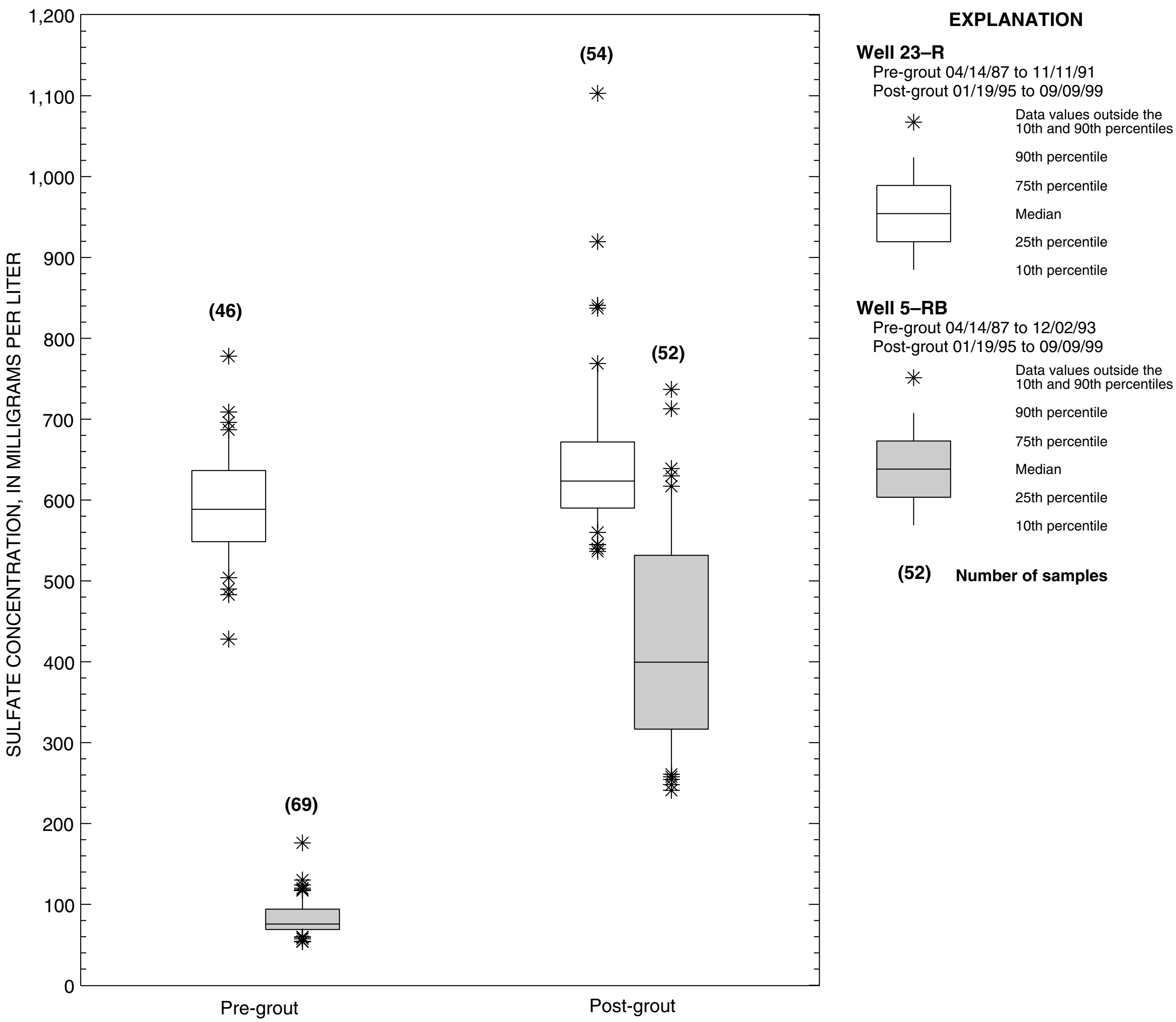

Figure 12. Pre-grout and post-grout sulfate concentrations for wells 23–R and 5–RB.

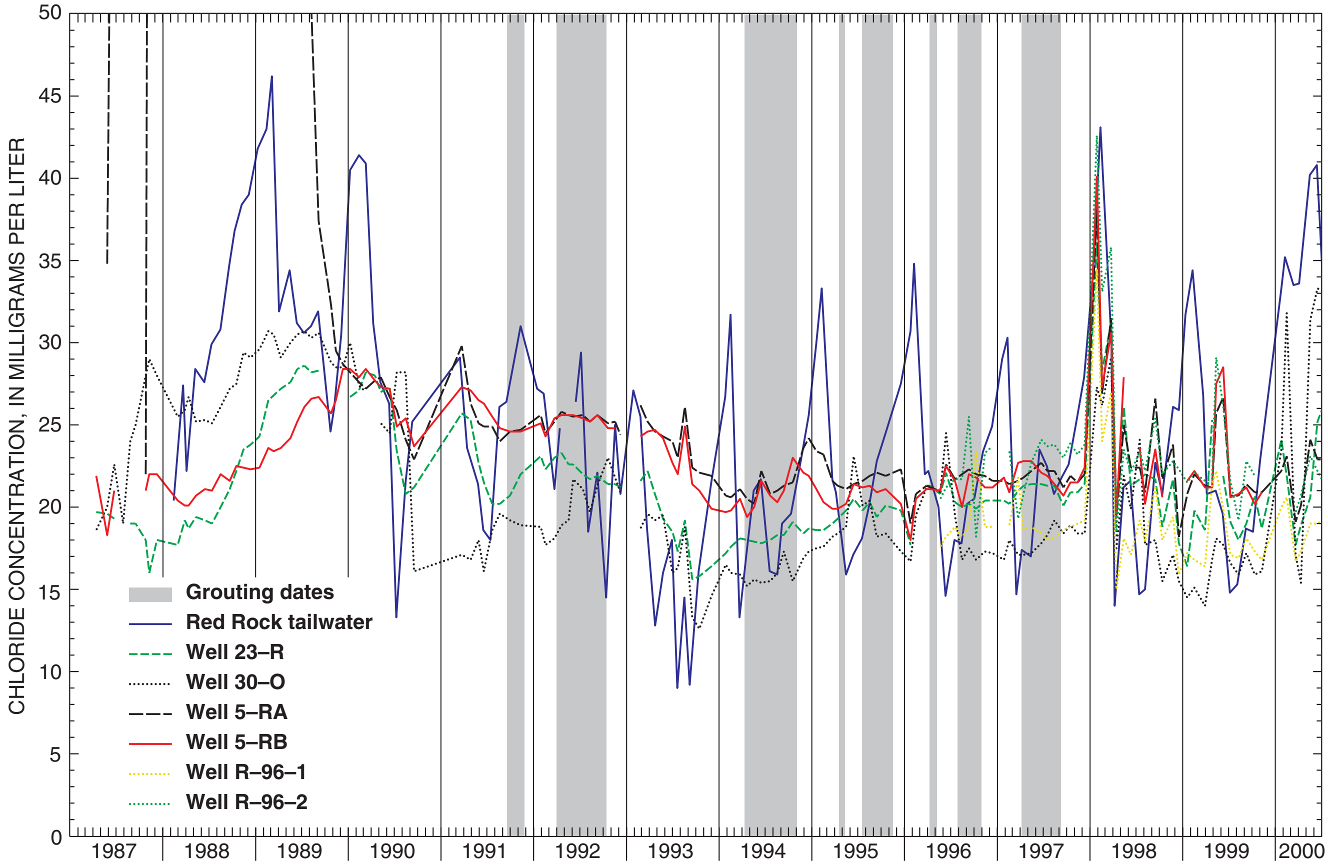

Figure 13. Chloride concentrations in the tailwater and selected observation wells through time.

outliers, as chloride concentrations for previous and subsequent samples are similar for all wells and tailwater. Large chloride concentrations also were detected in late 1997 for wells R–96–1 and R–96–2 on the southwest side of the dam where all previous hydrologic data indicate minimal underseepage. In general, differences in trends for chloride concentrations between pre-grout and post-grout periods are difficult to discern and, therefore, inconclusive.

Stable Isotopes

Hydrogen and Oxygen

The locations of the wells sampled for stable isotopes are shown in figure 1. Figures 14 and 15 show the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ isotope ratios for the wells and tailwater (assumed to be representative of reservoir water) sampled by Iowa State University from December 1995 to April 2000. Results are reported in parts per thousand (per mil or $\delta^{2}H$ and $\delta^{18}O$) and are defined as the relative enrichment or impoverishment relative to the VSMOW (Vienna Standard Mean Ocean Water), where $\delta^{2}H$ and $\delta^{18}O$ equal zero and are normalized on scales such that the oxygen and hydrogen isotopic values of SLAP (Standard Light Antarctic Precipitation) are –55.5 per mil and –428 per mil, respectively. There is a 2-sigma (2 standard deviations) uncertainty for oxygen and hydrogen isotopic results of 0.2 per mil and 2 per mil, respectively (Coplen, 1996). A positive δ value indicates that the sample contains more of the heavy isotope than the standard, and a negative δ value indicates that the sample contains less of the heavy isotope than the standard. For example, a $\delta^{2}H$ of –40 per mil means that there are 40 parts per thousand or 4 percent less ^{2}H in the sample relative to the standard (Kendall and Caldwell, 1998). A $\delta^{2}H$ value of –40 per mil in a sample contains more of the heavier isotope than does a sample with a $\delta^{2}H$ value of –50 per mil, even though both samples contain less ^{2}H relative to the standard.

In figure 14, δ^2H for the tailwater varies over time with the heavier isotopes becoming relatively enriched in the summer months and relatively depleted in the spring. A similar pattern is observed for $\delta^{18}O$ in the tailwater (fig. 15). This variability does not appear to be due to fractionation caused by evaporation. Plots (fig. 16) of tailwater δ^2H and $\delta^{18}O$ values along the GWML (Global Water Meteoric Line) are very close to the same slope as the GWML, indicating little effect on isotopic composition due to evaporation. The seasonal variability in δ^2H values may be due to the different sources of water for winter and summer precipitation. The low-temperature, high-latitude winter precipitation travels west to east over the Rocky Mountains and is depleted in heavy isotopes, whereas the high-temperature, low-latitude precipitation from the Gulf of Mexico in the summer is enriched in heavy isotopes (Simpkins, 1995). The seasonal depletion of δ^2H (in the spring) for the tailwater seems to have trended toward enrichment since 1997. Simpkins (1995) also suggests that local temperatures also may play a role in determining isotopic composition in precipitation. In any case, because of the large observable variability in the tailwater for both δ^2H and $\delta^{18}O$, if water from the Red Rock pool is mixing with the ground water in downgradient areas, then similar observable trends in variability in the ground water might be indicative of a hydraulic connection.

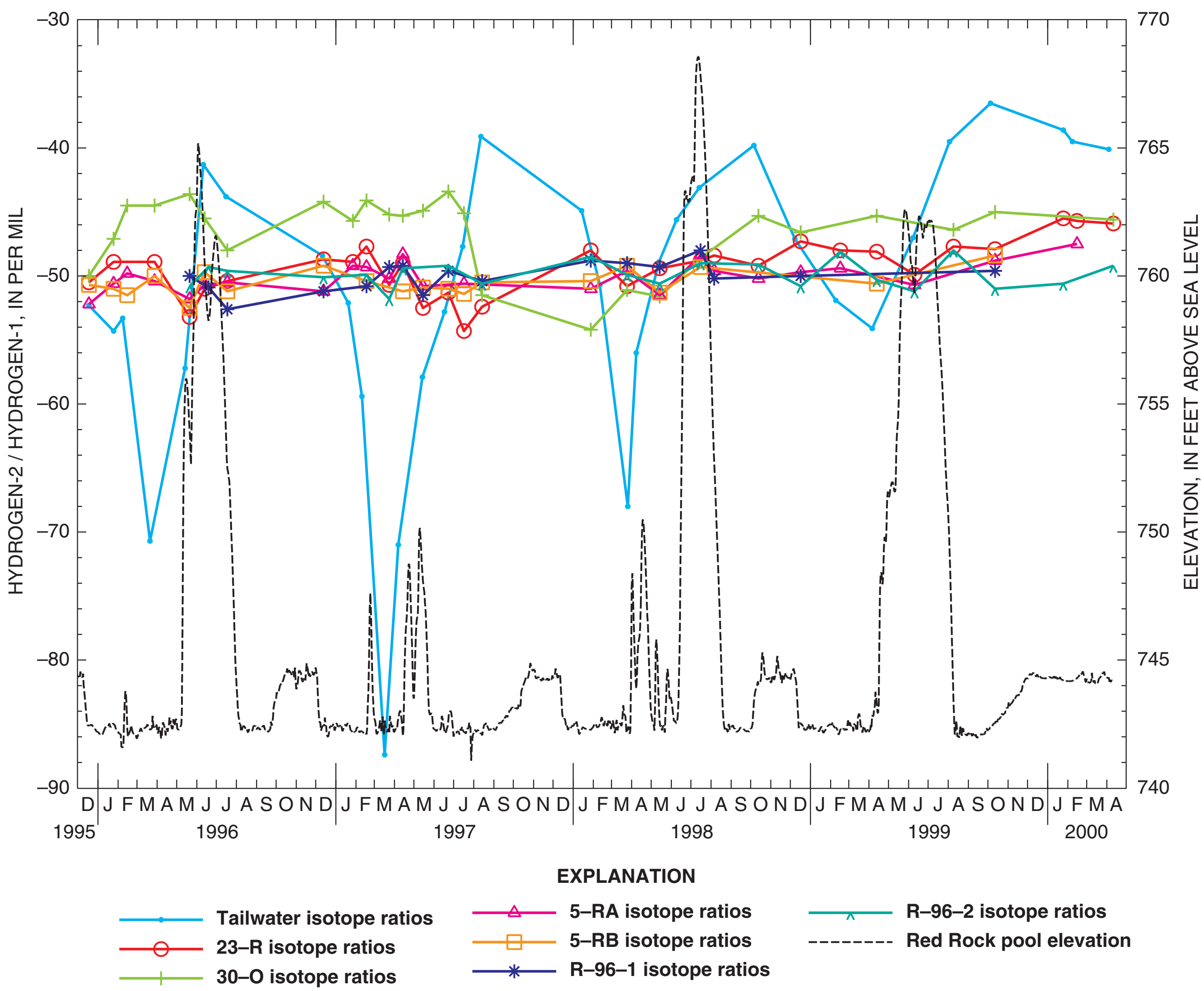

Figure 14. Hydrogen isotope ratios for the tailwater and selected observation wells.

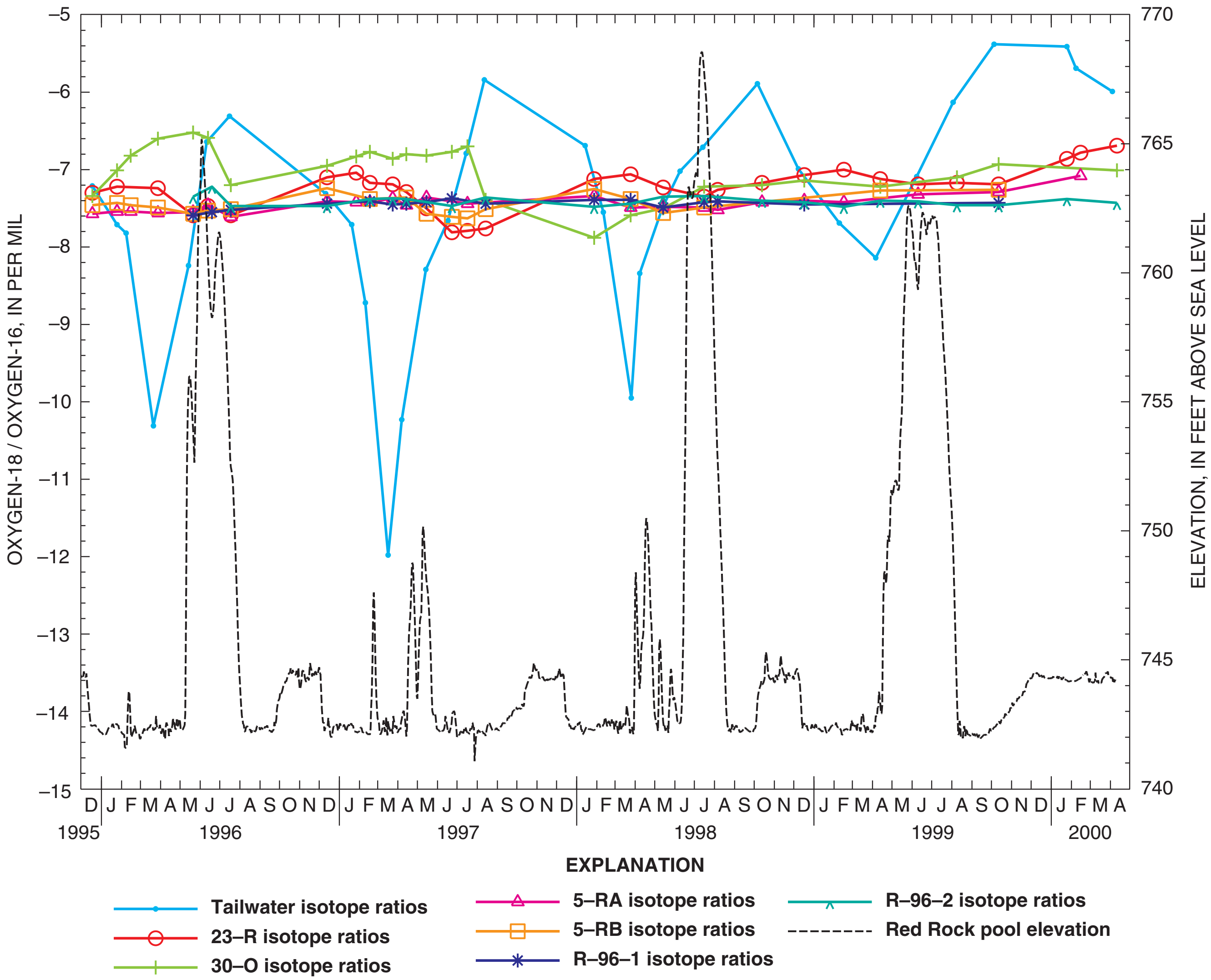

Figure 15. Oxygen isotope ratios for the tailwater and selected observation wells.

The δ^2H and $\delta^{18}O$ in samples from wells R–96–1 and R–96–2 on the southwest side of the dam, which are believed to be relatively unaffected by underseepage, are relatively stable compared to the tailwater and the other wells on the northeast side of the dam (figs. 14 and 15). When considering the variability of the analytical methods for hydrogen and oxygen isotopes, the isotopic ratios observed at most of the wells are essentially straight lines, although they do vary somewhat more than at wells R–96–1 and R–96–2, especially in the case of oxygen isotopes. The exceptions are wells 5–RA and 5–RB, which also are relatively stable over time. There is evidence that the seasonal fluctuations seen in precipitation are attenuated to a certain degree as the water moves through the unsaturated zone into the ground water (Simpkins, 1995). Hydrogen and oxygen isotope ratios for samples from well 30–O, allowing for a lag period, appear to show some seasonal variability (figs. 14 and 15). Precipitation and seepage from Lake Red Rock through the overburden are probably contributing to the relatively greater variability observed in samples from well 30–O. Beginning in 1998, less variability is observed at well 30–O, which may be related to the decreased variability over time observed in the tailwater, or possibly to decreased seepage from the reservoir through the overburden. Results for well 23–R also show some seasonal variability similar to well 30–O, although more subdued (figs. 14 and 15). This well was in the area of the dam thought to have the greatest amount of underseepage prior to remedial grouting (Lucey, 1991). No relation is apparent between variations in ground-water isotope ratios and changes in Lake Red Rock elevation.

Sulfur

Figure 17 shows the relative abundance of $^{34}S/^{32}S$ isotope ratios for ground-water samples collected from wells and the tailwater by Iowa State University and the USGS. Results are reported as parts per thousand (per mil or $\delta^{34}S$) relative to the standard VCDT (Vienna Canyon Diablo Troilite), defined by assigning a value of –0.3 per mil to IAEA-S-silver sulfide (Coplen and Krouse, 1998). There is a 2-sigma (2 standard deviations) uncertainty of 0.4 per mil for $\delta^{34}S$. Positive and negative δ values correspond to the enrichment or depletion, respectively, relative to the standard as was discussed for the ^{2}H and ^{18}O isotope ratios. A modern meteoric water value of +5 per mil for $\delta^{34}S$ (R. Carmody, U.S. Geological Survey, oral commun., 1997) is plotted in figure 17 as a visual reference and for comparison to $\delta^{34}S$ values obtained from tailwater and ground-water samples.

The $^{34}S/^{32}S$ isotope ratios are probably more related to the composition of the bedrock (that is, gypsum and anhydrite layers), whereas the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ isotopic ratios are more indicative of sources of water in the system. Therefore, sulfur isotopes may be a useful tool in distinguishing the different water types and the degree of mixing that may be occurring.

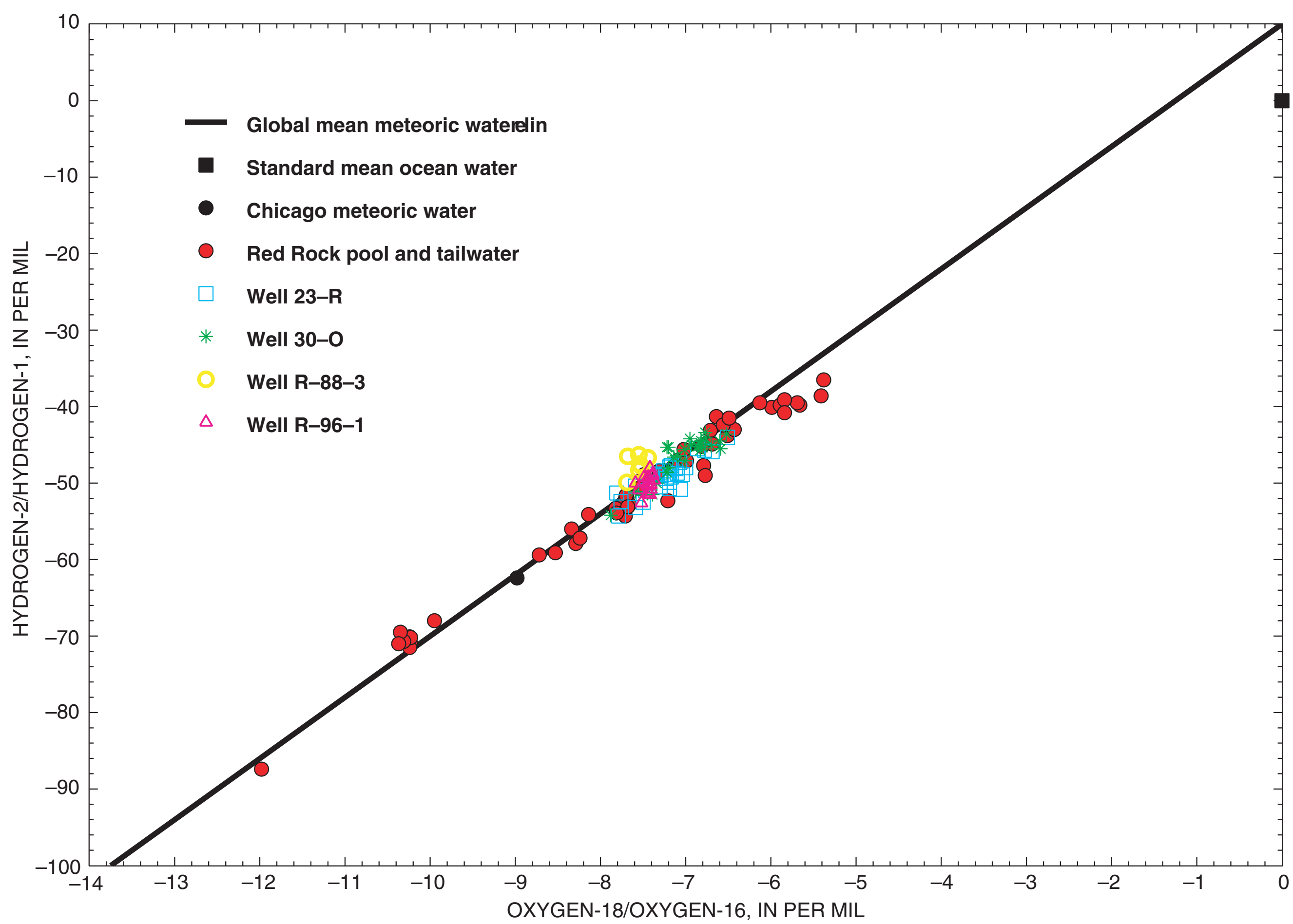

Figure 16. Plot of oxygen-18/oxygen-16 relative to hydrogen-2/hydrogen-1 for stable isotope sampling events at Red Rock Dam.

The sulfur isotope data to date suggest that the water samples from Lake Red Rock and the bedrock wells are much different. Ground-water samples from bedrock wells (5–RA, 5–RB, and 23–R) on the northeast side of the dam have similar $\delta^{34}S$ values compared to samples collected from wells (R–96–1 and R–96–2) on the southwest side of the dam where mixing of water from the reservoir with the ground water is thought to be minimal. These values also are very close to the $\delta^{34}S$ value (16.7 per mil) determined for a core sample of gypsum and anhydrite obtained in 1994 from an exploratory hole, P–58–X, located at station 3620 (approximately 200 ft southwest of well R–92–2A) and 15 ft upstream from the dam center line (unpublished data on file at the U.S. Geological Survey, Iowa City, Iowa). The $\delta^{34}S$ values for samples collected from the overburden well 30–O on the northeast side of the dam are very similar to those for the tailwater, which supports interpretations of other hydrologic data collected from well 30–O. Ground-water samples collected from wells 21–O, 21–UR, and R–88–3 on the northeast side of the dam have enriched $\delta^{34}S$ values compared to the tailwater but are still quite different than those samples collected from bedrock wells thought to be in the area of greatest

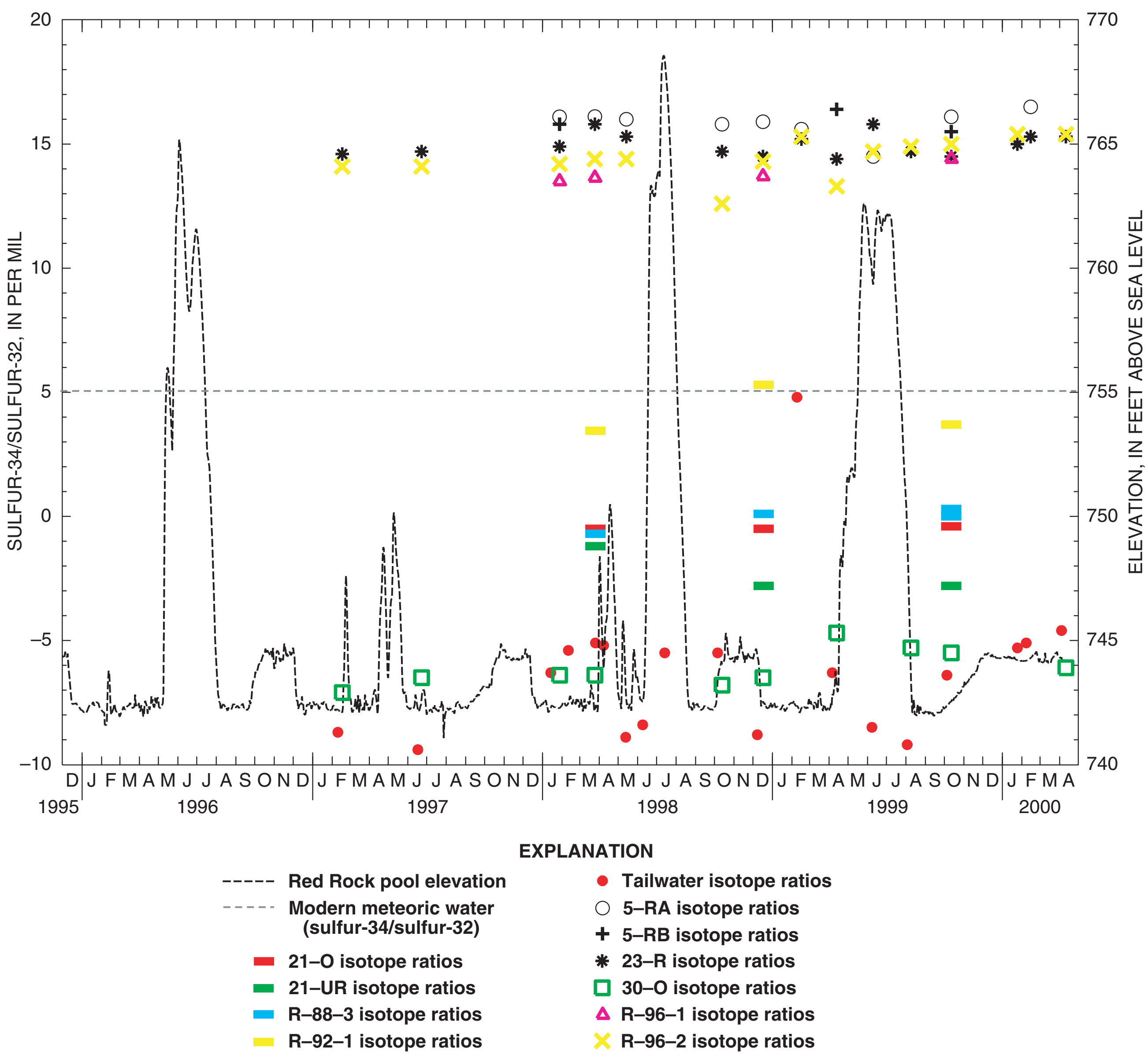

Figure 17. Sulfur isotope ratios for the tailwater and selected observation wells.

underseepage. Well R–92–1 is located in the northeast bluff area but is upgradient from the dam and grout curtain. The $\delta^{34}S$ values for samples collected from this well suggest that there is mixing of water from the reservoir with ground water that contains dissolved sulfur from the evaporites. Similar values might be expected in samples from other bedrock wells if a greater mixing of reservoir water and ground water was occurring. These results suggest that currently, there appear to be distinct water types associated with the tailwater (and overburden) and with the bedrock, indicating that seepage, therefore mixing, through the overburden is occurring to a greater degree than in the bedrock, at least in the vicinity of the wells sampled for stable isotopes. It is possible that this is a result of remedial grouting but without pre-grout sulfur isotope data, the relative degree of change is not known. Based on $\delta^{34}S$ values, the proportion of reservoir water in the overburden and the bedrock appears to be relatively constant over time since the initiation of stable isotope data collection in 1997.

The sulfur isotope data collected so far provide additional evidence that distinct water types are present on the northeast side of the dam in ground water in bedrock and in the tailwater and overburden, and that mixing of fresh reservoir water does not appear to be depleting the $^{34}S/^{32}S$ ratios determined for water in the bedrock. A downward trend in $\delta^{34}S$ values from samples collected from bedrock wells would indicate an increase in the amount of underseepage. This is still a relatively short period of time for detecting changes, but additional monitoring could aid an evaluation of what, if any, changes are occurring. Because the $\delta^{34}S$ values for the tailwater (Lake Red Rock) are quite depleted compared to the modern meteoric water value, as well as ground water in bedrock, any increase in mixing and therefore changes in isotopic composition of water from the northeast bedrock wells, might be readily detected using sulfur isotopes. It is possible that the negative $\delta^{34}S$ values in the tailwater, relative to the modern meteoric water value of +5 per mil, possibly may be from oxidized pyrite associated with coal mining or burning upstream from Lake Red Rock (R. Carmody, U.S. Geological Survey, oral commun., 1997) or possibly from naturally occurring sources such as evaporites in north-central Iowa (D. Lutz, Iowa State University, written commun., 1998).

SUMMARY AND CONCLUSIONS

Previous studies have shown direct evidence of underseepage at Red Rock Dam located on the Des Moines River near Pella, Iowa. Because of concerns about the integrity of the dam, the U.S. Army Corps of Engineers initiated a remedial grouting program in September 1991 to decrease the permeability and limit the underseepage in the underlying bedrock on the northeast side of the dam. Underseepage is thought to occur primarily on the northeast side of the dam in the lower bedrock of the St. Louis Limestone, which consists of discontinuous basal evaporite beds and an overlying cavity zone. The discontinuous basal evaporite beds are made up primarily of gypsum and anhydrite. To assess the effectiveness of the remedial grouting program and to evaluate methods for future assessments, a study was conducted by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers.

Potentiometric-surface maps of the overburden and bedrock indicate little change has occurred in the general flow directions between pre-grout (Lucey, 1991) and post-grout periods. Flow in the overburden is generally in a southeasterly direction in the northeast bluff area and, farther to the southwest along the axis of the dam, flow is approximately parallel to the axis of the dam in a southwesterly direction. Flow in the bedrock is primarily in a south and southeasterly direction in the extreme northeast bluff area and then appears to be in a more southerly direction farther along the axis of the dam toward the Des Moines River. Changes in flow direction as a result of remedial grouting are not apparent.

Water-level data for two dates (May 13, 1992, and March 18, 1999) at similar pool and tailwater elevations indicate that, at least for the two dates, the water levels decreased in the vicinity of Red Rock Dam. However, this may be more related to the hydrologic conditions (that is, dam operations) in Lake Red Rock and the tailwater that preceded the comparison dates than to any reduction in underseepage as a result of remedial grouting. All overburden wells had a decrease in water levels, with wells on the southwest side of the dam showing a somewhat larger decrease. Well 30–O had the smallest decrease of –0.3 ft. Most of the bedrock wells also had decreased water levels between the two dates. Some wells, however, had increased water levels; the largest increase (3.8 ft) occurred at well 1–R. These wells are all in or near the northeast bluff area. Comparison of water levels between the southwest side of the dam (where underseepage in thought to be minimal) and the northeast side of the dam on the post-grout date indicates that more gradual potentiometric gradients from the pool to the areas in the vicinity of the downstream wells still exist on the northeast side of the dam (in particular the northeast bluff area), indicating a greater hydraulic connection there, from flow downward through the overburden into the underlying bedrock and(or) from underseepage through the bedrock. Water levels at well nest sites indicate that the vertical component of ground-water flow is essentially unchanged between the two dates with downward flow occurring in the northeast bluff area and upward flow occurring farther southwest along the axis of the dam closer to the Des Moines River. Based on just water-level data between the two comparison dates, the effects of remedial grouting are not apparent, but water-level data do seem to indicate a continued difference between the southwest side of the dam and the northeast side of the dam.

Hydrographs show that water levels in wells 5–RB and 23–R showed a departure, after initiation of remedial grouting, from pre-grout trends when these water levels tracked water levels for well 26–R much more closely. Hydrographs for wells 1–R and 2–R also showed the same trend with a departure in correlation with water levels in well 26–R from pre-grout periods to post-grout periods. Similar trends were observed for water levels in other wells. Hydrographs for many of the wells on the northeast side of the dam indicate what is probably an initial response to remedial grouting as the hydraulic connection to the reservoir was reduced. For some wells, over a period of time, there was then a narrowing in water-level differences until water levels again were tracking water levels in well 26–R similar to pre-grout periods. This narrowing may be the result of the ground-water flow system coming to an equilibrium as new flow paths develop after the initial response to remedial grouting. This was particularly the case for wells 1–R, 4–R, and 27–R. Narrowing of water-level differences occurred to a lesser degree for wells 2–R, 3–R, 5–RB, and 23–R as a greater water-level difference, compared to pre-grout periods, was maintained over time, implying that remedial grouting had a greater effect in reducing the hydraulic connectivity between Lake Red Rock and areas in the bedrock in the vicinity of these wells. While it appears, based on hydrographs, remedial grouting reduced underseepage to varying degrees at different areas on the northeast side of the dam, the hydraulic connection is still probably greater on the northeast side of the dam as the hydrograph for well 13–R (completed in evaporite material on the southwest side of the dam) indicates, showing lower water levels through time than wells on the northeast side of the dam.

Statistical analysis of bedrock water levels, pool levels, and tailwater elevations suggest that for wells on the northeast side of the dam, the correlation between ground-water levels and pool levels has decreased from pre-grout periods to post-grout periods, indicating some degree of reduced hydraulic connectivity as a result of remedial grouting. Water levels in many wells on the northeast side of the dam now appear to be less affected by changes in pool elevations. However, the observed lower correlation coefficients during post-grout years may be due in part to differences in dam operations and differences in defining pre- and post-grout periods. Water-level data and the hydrograph (fig. 7) of well 13–R plotted with wells 1–R and 2–R still indicate a more gradual potentiometric gradient on the northeast side of the dam. Although the statistical analysis indicates some reduced hydraulic connectivity, the degree (based on changes in the Spearman correlation coefficient from pre-grout to post-grout years) of change and the implied change in the influence of the tailwater and pool upon ground-water levels in the bedrock should be regarded with caution. Therefore, in general, water-level data in conjunction with statistical analysis suggest that underseepage to the areas of wells 2–R, 3–R, 5–RB, and 23–R appears to have been decreased to a greater degree as a result of remedial grouting than to the areas of wells 1–R, 4–R, 26–R, and 27–R, where remedial grouting probably had lesser effect.

Sulfate data also suggest that the observed changes in water chemistry at wells 5–RA, 5–RB, and 23–R may indicate less underseepage and, therefore, less mixing of reservoir and ground water in the vicinity of these wells. Significant increases in sulfate concentrations for wells 5–RB and 23–R occurred at the same time grouting occurred, which may indicate flow paths from the reservoir were cut off to these wells. Chloride concentrations (with the exception in late 1997) have decreased at these same wells since pre-grout years; however, the effect of remedial grouting is not as apparent.

Although pre-grout and post-grout comparisons were not possible, sulfur isotope data since 1995 show distinct isotopic values for water from bedrock wells compared to that from tailwater and overburden wells. Samples collected from bedrock well R–92–1, located upgradient from the grout curtain, had sulfur isotope values indicating a greater mixture of reservoir and ground water. This suggests a lesser degree of mixing in the bedrock downgradient from the grout curtain, where sulfur isotope ratios in samples collected from those wells are more similar to those determined from a gypsum and anhydrite core sample. This suggests that the grout curtain restricts ground-water flow from the reservoir to the St. Louis Limestone downgradient from the dam to some degree. Seasonal fluctuations in δ^2H and δ^{18}O values for the tailwater are large enough that some fluctuation also is observed in water from some wells (30–O and 23–R), even when one accounts for the analytical variability. Peak enrichment of hydrogen and oxygen isotope ratios in the tailwater have remained very similar from year to year; however, peak enrichment observed at wells 30–O and 23–R appears to have decreased over time, especially for the oxygen isotopes. There appears to be an overall dampening over time at these wells, but it may be a result of the dampening also observed for the tailwater.

Hydrographs, statistical analysis of water-level data, and water-chemistry data suggest that underseepage on the northeast side of the dam has been reduced as a result of remedial grouting, with some areas affected to a greater degree and for a longer period of time than other areas on the northeast side of the dam. Comparisons between the southwest side of the dam and the northeast side of the dam also indicate that there is still a greater hydraulic connection between Lake Red Rock and downgradient bedrock wells on the northeast side of the dam and that underseepage is probably still occurring there, but to a lesser degree since completion of remedial grouting.

Continued measurement and evaluation of water-level data along with isotope sampling that possibly includes some of the newer wells (for example, R–92–2A and the PX–97 series), located upgradient from the dam, would provide further insight into the long-term effects of remedial grouting on underseepage along the northeast side of the dam. Because there was no pre-grout isotope sampling, inclusion of these existing additional wells on the upgradient side of the dam for isotope sampling would enable further comparisons between upgradient and downgradient bedrock waters to assess the effectiveness of the grout curtain. Continuing monthly water-quality monitoring would add to the data base in support of the hydraulic and isotope data. In addition, the use of tracer tests could be used to determine potential flow paths and travel times.

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