ANALYSIS OF THE GROUND-WATER FLOW SYSTEM, GEOCHEMISTRY, AND UNDERSEEPAGE IN THE VICINITY OF THE RED ROCK DAM NEAR PELLA, IOWA

By Keith J. Lucey

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Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
foot (ft)	0.3048	meter
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
pound (lb)	0.00454	gram
gallon (gal)	0.264	liter
gallons per minute (gpm)	0.631	liters per second
foot per mile (ft/mi)	0.189	meter per kilometer
pound per square inch (lb/in^2)	6.895	kilopascal
foot per day (ft/d)	0.3048	meter per day

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

°C = 5/9 (°F - 32)

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.

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ABSTRACT

The U.S. Army Corps of Engineers operates the Red Rock Dam on the Des Moines River in Marion County, Iowa. The dam consists of a gravity concrete control structure between two earthen embankments and has an impoundment storage capacity of 1,700,000 acre-feet. Since the impoundment of Lake Red Rock commenced during 1969, water seepage beneath the dam has been significant enough to cause continuing investigation by the Corps of Engineers of its source and implications.

The St. Louis Limestone, which consists of interbedded sandstones and carbonates with solution collapse features resulting from partial removal of a basal evaporite zone, forms the bedrock foundation of the dam in the river valley. The soluble gypsum and anhydrite in the evaporite zone have the potential to be removed in greater quantity with increasing seepage velocities and volumes. Solution channels may develop as material is removed from the bedrock foundation, which could result in the collapse of overlying strata, thereby threatening the integrity of the earthen dam.

The potentiometric surface in the overburden on the southwest side of the dam has an extremely steep hydraulic gradient from the reservoir through the dam to the downstream observation wells, which implies expected small permeability and minimal seepage through the dam and embankment materials. A lesser hydraulic gradient exists on the northeast side of the dam, which could indicate excessive seepage through embankment material from larger than expected hydraulic conductivity or underseepage through bedrock. Statistical analysis of water-level changes in the reservoir and in observation wells completed in the evaporite stratigraphic horizon on the northeast side of the dam indicates a hydraulic connection between the reservoir and the wells.

Direct evidence of the existence of a connection between the reservoir and the ground-water system is provided by chloride concentration data. Maximum chloride concentrations occurred in the reservoir water in the early spring of 1989. Chloride concentrations reached a maximum in ground water from bedrock and overburden observation wells on the northeast side of the dam 1 to 4 months after their maximum in the reservoir. Underseepage of reservoir water occurs through the basal evaporite zone of the St. Louis Limestone and through the glacial sands in the northeast bluff between the bedrock surface and the base of the dam fill.

The increased hydraulic head imposed on the system by the impounded waters of Lake Red Rock causes recharge and flow to the deeper bedrock aquifers in the immediate vicinity of the dam. This effect is manifested in the observation wells along and downstream from the dam axis, implying flow through the grout curtain in the bedrock foundation of the dam. There is potential for dissolution of the gypsum and anhydrite in the bedrock foundation, because reservoir water and shallow ground water in the vicinity of the dam are undersaturated with respect to these evaporite minerals.

INTRODUCTION

The Rock Island District of the U.S. Army Corps of Engineers (COE) operates the Red Rock Dam on the Des Moines River in Marion County, Iowa. The dam is 5,841 ft (feet) long and approximately 100 ft high and has an impoundment storage capacity of 1,700,000 acre-ft (acre-feet). The dam was constructed during the 1960's and consists of a gravity concrete control structure between two earthen embankments. Although limited water seepage is expected at dams of earth-fill construction (Freeze and Cherry, 1979), seepage at Red Rock Dam since the impoundment of Lake Red Rock began during 1969 has been significant enough to cause continuing investigation by the COE of its source and implications.

During construction of the dam, a grout curtain was installed in the upper 70 ft of bedrock to control underseepage. After evaluation of observation well levels and geologic and water-quality data, the COE became concerned that excessive underseepage occurs through the bedrock foundation at the dam site. Part of the bedrock foundation is composed of gypsum and anhydrite, which are potentially soluble by ground water that is undersaturated with respect to these evaporites. As material is removed from the bedrock foundation, solution channels may develop resulting in the collapse of overlying strata, and thereby threatening the integrity of the earthen dam. To address concerns about the potential effects of the seepage, the U.S. Geological Survey (USGS), in cooperation with the COE, conducted an investigation of the ground-water flow system and its associated geochemistry.

Purpose and Scope

This report presents the findings of the investigation of the ground-water flow system and its associated geochemistry in the vicinity of the Red Rock Dam and provides an analysis of underseepage. The study is based on a review of available hydrologic and geologic data.

The COE has been collecting hydrologic data at the dam site from observation wells since reservoir impoundment (Lake Red Rock) began during 1969. This analysis is based on hydrologic data collected by the COE from observation wells at the dam site from March 1982 through July 1990. Geologic information collected from exploratory borings by the COE since dam construction began during 1960 also was incorporated in the study. Limited water-quality data were collected by USGS personnel during 1990.

Location of Study Area

The Red Rock Dam is located on the Des Moines River, 4 mi (miles) southwest of Pella, Iowa. The study area covers approximately 1 mi^2 (square mile) in section 19 in township 76 north and range 18 west (T76N-R18W), in Marion County (fig. 1). The dam site with the network of observation wells discussed in this report is depicted on plate 1. The topography of the area varies from the relatively flat alluvial valley of the Des Moines River with an elevation range of 702 to 708 ft above sea level to the dissected bluffs on either side of the valley that rise to 850 ft.

Geology

The geologic units in the study area include the Warsaw Limestone of Mississippian age, the St. Louis Limestone of Mississippian age, Pennsylvanian age rocks, Pleistocene glacial till, Pleistocene outwash deposits, and Holocene alluvial deposits (table 1). Unconsolidated glacial deposits overlie bedrock in highland areas, while alluvium and glacial outwash deposits cover bedrock in the Des Moines River valley. Only unconsolidated deposits and shallow bedrock units related to the foundation of the dam will be discussed. In this report, overburden refers to the unconsolidated glacial and alluvial deposits and dam fill overlying the shallow bedrock units.

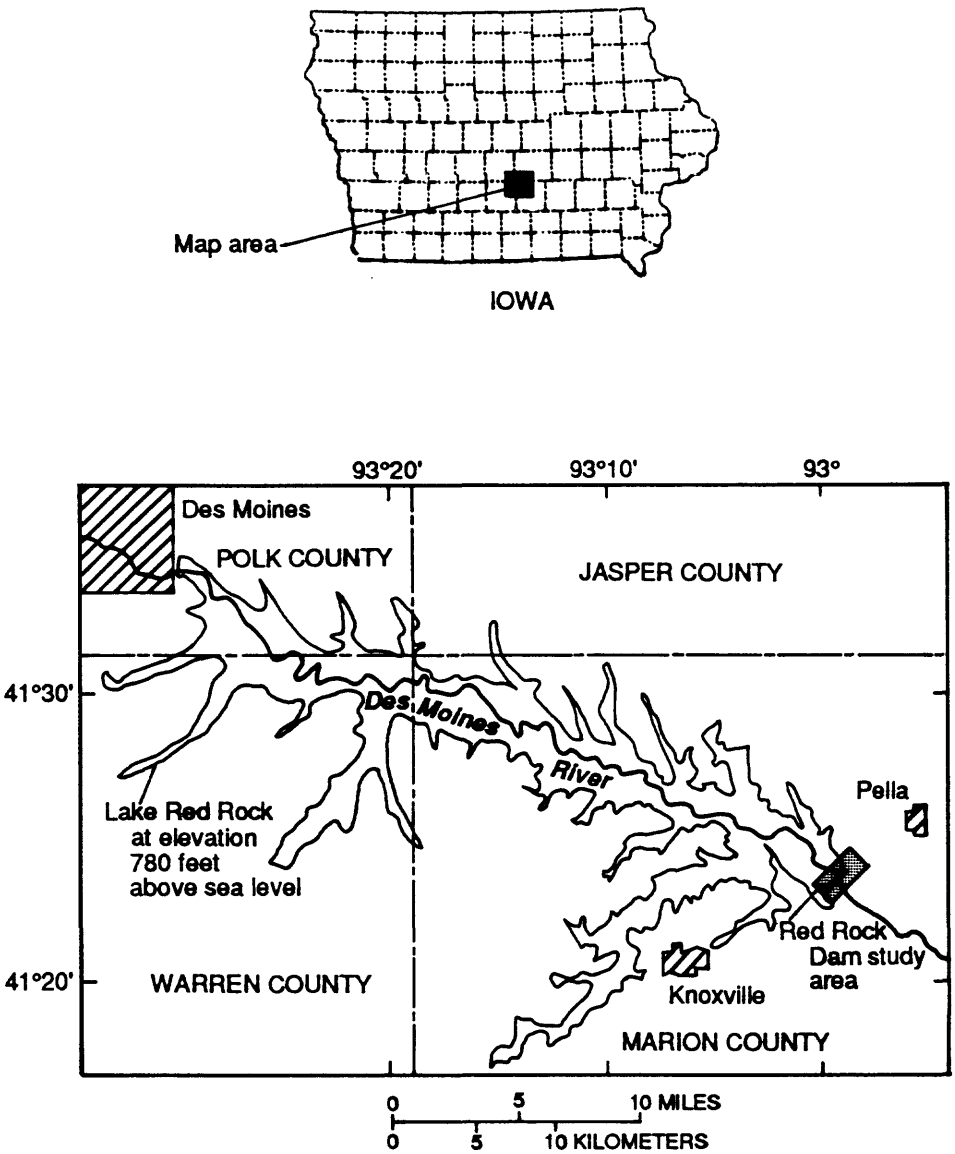


Figure 1.--Location of study area.

Table 1.--*Geologic units and their water-bearing characteristics at the Red Rock Dam site*

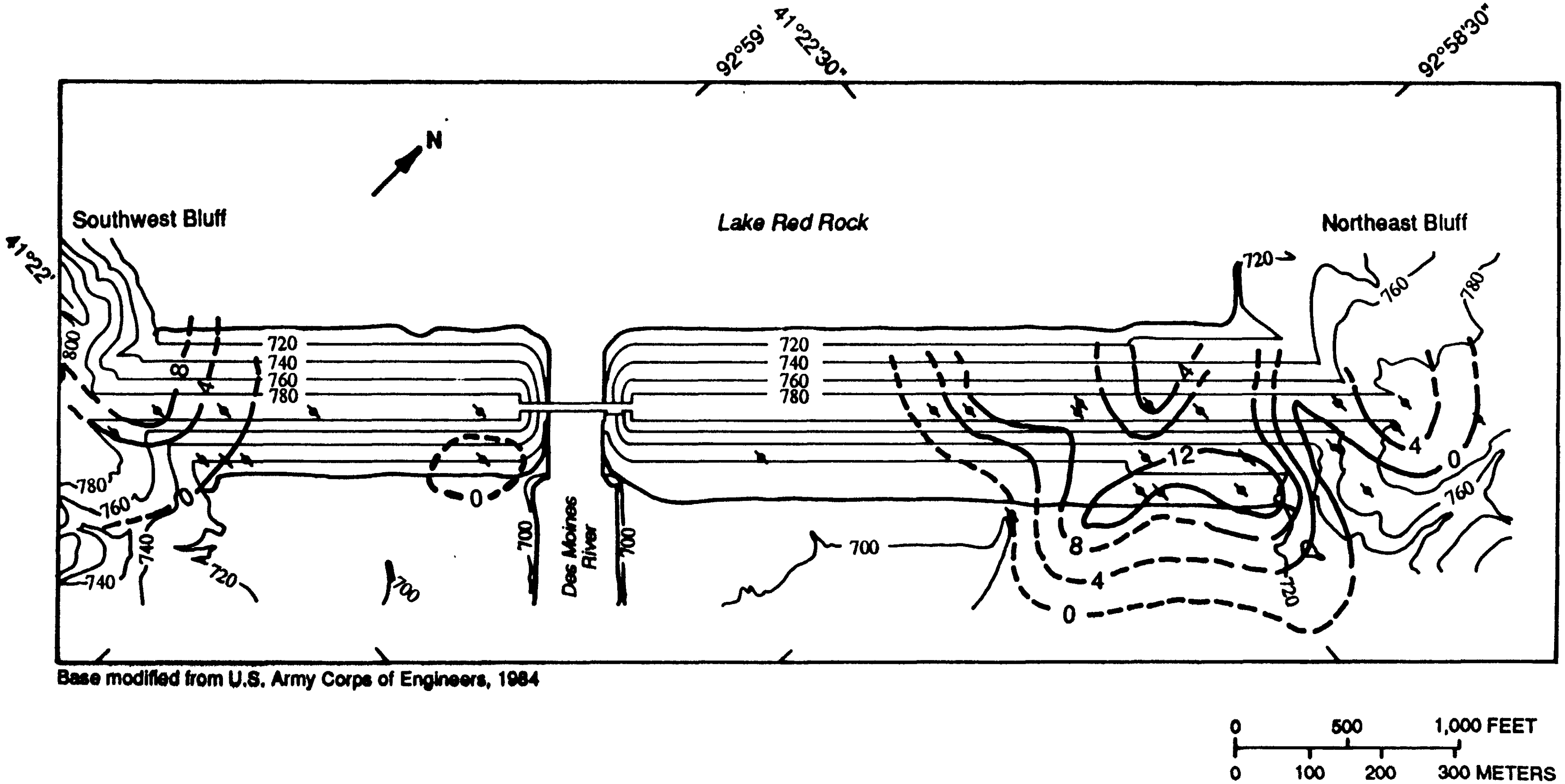
[undiff., undifferentiated; gpm, gallons per minute; yield data under water-bearing characteristics from Cagle and Heinitz (1978)]

System	Series	Geologic unit	Lithology	Water-bearing characteristics
Quaternary	Holocene	undiff.	Clay, silt, sand (dam fill)	Limited permeability; internal sand drain for seepage control
		undiff.	Sand, silt, clay (alluvium)	Yields 150-500 gpm
	Pleistocene	undiff.	Clay, silt, sand, (glacial till, loess) and gravel (outwash)	Sands in till can yield 1-5 gpm; outwash 150-500 gpm
Pennsylvanian	Desmoinesian	undiff.	Shale, occasional sandstone, siltstone, limestone, coal	Limited permeability; discrete sands yield 3-10 gpm
Mississippian	Meramecian	St. Louis Limestone	Interbedded limestone, sandstone, dolomite; solution-collapse features overlying gypsum-anhydrite beds in lower part	Yields 5-60 gpm, higher where unit is bedrock surface overlain by permeable surface material
		Warsaw Limestone	Shale and dolomite	Limited permeability

The locations of the geologic sections presented in this report are shown on plate 1. Geologic section A-A' (plate 1) illustrates the stratigraphy along the axis of the dam from the northeast bluff through the river valley to the southwest bluff. The relatively impermeable dolomitic shales and argillaceous dolomites of the Warsaw Limestone are used to anchor the grout curtain of the dam. Exploratory holes drilled during the construction of the dam detected no lithology change in the top 70 ft of the Warsaw Limestone (U.S. Army Corps of Engineers, 1968).

The St. Louis Limestone overlies the Warsaw Limestone and forms the bedrock surface in the Des Moines River valley. It varies from 40 to 85 ft thick in the study area because of an erosional surface at the top of the formation. Consisting of alternating limestone, sandstone, and dolomite with a discontinuous, basal evaporite bed, the unit is locally intensely fractured and contains open cavities. Gypsum is the predominant evaporite mineral present in the evaporite beds at the dam site. The composition of evaporite material was determined from X-ray diffraction studies of core samples obtained from four exploratory borings at the dam site (George Mech, Rock Island District, U.S. Army Corps of Engineers, written commun., 1990). In samples from two of the borings, the mineral composition of the evaporite beds is typically two parts gypsum to one part anhydrite with trace amounts of other evaporite minerals. In the remaining two borings, the evaporite material was determined to be composed essentially of gypsum with no anhydrite detected.

Over geologic time, weathering processes have removed parts of the basal evaporite bed of gypsum and anhydrite, causing slumping and collapse of the overlying bedrock. As a result, there is a zone of intense fracturing and cavity development immediately above and adjacent to the evaporites. Strata fractured to a lesser degree exist throughout the overlying bedrock. Cavities are either open or are filled with clay, silt, sand, and rock fragments. There are remnants of evaporite material up to 15 ft thick in the discontinuous evaporite bed (fig. 2).



Base modified from U.S. Army Corps of Engineers, 1984

EXPLANATION

—— 4 – – LINE OF EQUAL THICKNESS OF EVAPORITE DEPOSITS IN ST. LOUIS LIMESTONE--Dashed where approximately located. Interval is 4 feet

— 720 — TOPOGRAPHIC CONTOUR--Shows elevation of land surface in feet above sea level. Contour interval is 20 feet

WELL LOCATION--Control point

Figure 2.--Thickness of evaporite deposits in the St. Louis Limestone.

Throughout this report, the following terminology will be used in discussions of the St. Louis Limestone. The "lower bedrock" is up to 25 ft thick and contains an "evaporite zone" of anhydrite and gypsum beds, or its stratigraphic equivalent, overlain by a "cavity zone" of extremely fractured bedrock with open and filled cavities and solution channels. The "upper bedrock" refers to the alternating limestone, sandstone, and dolomite above the "lower bedrock" and can be as much as 60 ft thick.

In the valley bluffs, rocks of Pennsylvanian age overlie the St. Louis Limestone. The Desmoinesian Series of the Pennsylvanian primarily are black shales with occasional interbedded siltstone, sandstone, limestone, and coal. In the bluff comprising the southwest abutment of the dam, the Pennsylvanian rocks are nearly 100 ft thick, whereas in the northeast abutment they are only 40 ft thick (U.S. Army Corps of Engineers, 1984).

The unconsolidated deposits in the Des Moines river valley include Pleistocene glacial outwash and Holocene alluvium up to 30 ft thick. The sands, silts, and clays of the alluvium overly the sands and gravels of the outwash deposits (W.L. Steinhilber, U.S. Geological Survey, written commun., 1971).

The overburden on the valley bluffs is Pleistocene pre-Illinoian glacial till primarily consisting of clay with fine, clayey sands and occasional fine to medium sand layers. Thickness ranges from a few feet on the southwest bluff to nearly 100 ft on the northeast bluff. A layer of loess 10 to 20 ft thick caps the bluffs (Anderson, 1983; U.S. Army Corps of Engineers, 1984).

Regional dip of the bedrock units is approximately 10 ft/mi (feet per mile) to the south-southwest. Locally, dip direction and magnitude will vary within the collapse features of the St. Louis Limestone (U.S. Army Corps of Engineers, 1984).

Description of Dam

The Red Rock Dam extends 5,841 ft between the bluffs of the Des Moines River valley and is approximately 100 ft high. The top of the dam is at an elevation of 797 ft. The control structure of the dam is southwest of the center of the valley, whereas the former Des Moines River channel is northeast of the valley center (plate 1). As a result, there is an oxbow on the northeast side of the valley formed from the cutoff river channel. The conservation pool elevation of the reservoir is 735 ft and stands about 35 ft above the downstream valley. The maximum pool elevation for Lake Red Rock is 780 ft; the record pool elevation was recorded during June 1984 at 779.6 ft. Dam operation maintains a minimum downstream flow of 300 ft^3/s (cubic feet per second).

From exploratory borings during the construction of the Red Rock Dam, the COE (1965, 1968, 1969, 1971) determined that the shallow bedrock in the river valley at the dam site consists of fractured limestones and sandstones of the St. Louis Limestone. To decrease permeability and control underseepage, a grout curtain was installed in the upper 70 ft of the bedrock foundation of the dam to the base of the evaporite horizon. Impermeable, competent dolomitic shales of the Warsaw Limestone underlie the evaporite zone.

The grout curtain was installed through holes that were drilled on 20-ft centers. Grout was pumped until refusal into the holes in three zones, beginning at the bottom of the St. Louis Limestone and terminating at the bedrock surface. In areas of extensive open cavities or numerous fractures, spacing of the holes was decreased to 10, 5, or 2.5-ft centers and the number of lines of grout holes was increased to 2 or 3 to augment the integrity of the curtain. Generally, the grout curtain consists of a single line of grout holes extending from the southwest abutment to the abandoned oxbow of the old Des Moines River channel in the northeast river valley (plate 1). Three lines of grout holes spaced 10 ft apart comprise the grout curtain in the northeast part of the river valley from the oxbow to the base of the northeast bluff. Two lines of grout holes extend the curtain for a 300-ft reach and a single line of grout holes completes the grout curtain to a point about 100 ft southwest of well location 26-R in the northeast bluff (plate 1). The grout curtain is located approximately 35 ft upstream from the dam axis in the river valley and straddles the dam axis in the bedrock beneath the bluffs (U.S. Army Corps of Engineers, 1971).

The base of the earth-fill dam, the core trench, was cut into the bedrock from the southwest side of the dam through the valley to the base of the bluff on the northeast side of the dam. The bluffs on the southwest side of the dam are composed of consolidated shales of Pennsylvanian age, while unconsolidated glacial materials in the bluffs on the northeast side comprise a part of the abutment of the dam. Auger and rotary borings were drilled on 100-ft centers to evaluate the glacial materials in the northeast abutment. A fine-grained sand was recovered from materials along the dam axis; 6 to 10 percent passed through a 200-mesh [0.075 (mm) millimeter], silt-sized sieve. Upstream from the dam axis, up to 15 percent of sand samples would pass through the 200-mesh sieve. Relatively impervious material was collected from the first 4 ft in all borings.

Sixteen observation wells were installed initially at the dam site in the overburden materials and in the bedrock (U.S. Army Corps of Engineers, 1970). After the first year of operation, an additional eight observation wells were installed on the northeast side of the dam in the valley and abutment. To monitor dam operation, the observation well network was expanded to its present total of 69 wells during the next two decades (plate 1).

Previous Investigations

During the first operational year of the dam, the COE (1970) detected higher water levels in observation wells on the northeast side of the dam than in wells on the southwest side. Large concentrations of calcium and sulfate were detected in water flowing in the old river channel and drainage ditches on the northeast side of the valley, indicating a probable source from the underlying bedrock.

The effects of the Red Rock Dam on the alluvial wells supplying water to the city of Pella, Iowa, were analyzed by W. L. Steinhilber (written commun., 1971). The increased hydraulic head resulting from Lake Red Rock on the confined St. Louis Limestone caused sulfate concentrations to increase in the Pella water supply wells as highly mineralized water was discharged upward into the alluvium in the Des Moines River valley.

Selected overburden observation wells and drainage weirs on the northeast side of the dam were sampled during an investigation at the Red Rock Dam during the early 1970's by the COE (1975). Results of this study indicated that specific conductance of the ground water decreased with increasing pool levels. Ground-water levels were higher in both the overburden and bedrock observation wells in the northeast abutment area than in the southwest abutment area.

Temperature studies at the Rod Rock Dam by the COE (1984) from May to July 1983 detected a zone in the glacial sands and upper bedrock in the northeast abutment that was 1 to 3 degrees colder than the surrounding materials. This was interpreted as evidence of a seepage path for colder reservoir water.

During the record reservoir level at an elevation of 779.6 ft in June 1984, the COE (1984) mapped the potentiometric surface in the overburden with a gentler gradient from the reservoir to the toe of the dam in the area of the northeast abutment than in the area of the southwest abutment. A similar gradient existed for the potentiometric surface in the St. Louis Limestone. Decreasing specific conductance values were measured in water samples from both overburden and bedrock wells during rising pool levels during 1983, implying mixing with fresher reservoir waters.

Examples of investigations of ground-water systems where the dissolution of evaporite material causes concern for dam safety include James and Lupton (1978) and Claassen (1981). Both studies were concerned with the accelerated dissolution rates of anhydrite and gypsum in dam foundations resulting from increased hydraulic head caused by reservoirs.

METHODS OF INVESTIGATION

Well Nomenclature and Construction

The present (1990) network of 69 observation wells (plate 1) at the dam site monitors ground-water levels at various depths within the overburden and the bedrock. Wells designated "-O" or "GW-" are completed in the overburden materials, either alluvium (at an elevation between 673 ft and 694 ft) or glacial till sands (at an elevation between 693 ft and 742 ft); wells completed in the evaporite zone or in a stratigraphic equivalent cavity zone at an elevation between 630 and 648 ft are annotated by "-R" (lower bedrock), "-RA" (evaporite zone), or "-L" (lower bedrock); "-U" designates wells monitoring water levels in sandstones in the upper bedrock of the St. Louis Limestone at an elevation between 652 and 656 ft; and "-UR" represents wells completed in limestone in the upper bedrock of the St. Louis Limestone at an elevation between 680 and 690 ft. Generally, wells labeled "R-" monitor water levels in the lower bedrock of the St. Louis Limestone or will have a modifier "U" or "L" to designate the cavity zone or evaporite zone.

The following wells are exceptions to the previously described annotation system. R-88-1, R-88-2, and R-88-3 are completed in the bedrock of Pennsylvanian age in the bluff on the northeast side of the dam. R-88-1, located about 1,150 ft north of well 26-R, is not located on the base map but will be referred to in table 2. R-88-4 is completed in extremely fractured and weathered limestone of the former Des Moines River channel at the approximate elevation of the lower cavity zone. R-87-2U is completed in limestone in the upper bedrock of the St. Louis Limestone. Well 5-RB is completed in the fractured, cavity zone above the evaporite horizon at an elevation of 654 ft.

In general, observation wells were installed as 0.75 in.(inch)- to 2 in.-diameter galvanized or PVC (polyvinyl chloride) pipe, the annulus back-filled with sand to an elevation above the top of the well point or well screen, the completion zone isolated by a bentonite seal, and the annulus then back-filled with sand, cement, and bentonite. Observation well pairs were prepared in a similar manner by nesting two separate pipe assemblies in a single well bore and isolating the well points or well screen with bentonite layers (U.S. Army Corps of Engineers, 1970; Terracon Consultants, 1987, 1988).

Data Collection

The COE has measured water levels from several observation wells at the Red Rock Dam since impoundment of water began during 1969. Water levels from the present (1990) observation well network (plate 1) were measured on a monthly or bimonthly basis.

The current (1990) ground-water monitoring program for collecting and analyzing water samples on a monthly basis at five water-quality wells (23-R, 5-RB, 5-RA, 30-O, and 29-O) was begun in April 1987 (plate 1). Well R-87-4 was added to the program in October 1989. Since March 1988, samples also have been collected from the tailwater downstream from the dam and from the reservoir. Iowa State University, under contract from the Rock Island District of the COE, collects the water samples and measures field specific conductance, pH, temperature, and alkalinity. Wells were pre-pumped and samples collected when parameters measured onsite stabilized. The Analytical Services Laboratory (U.S. Environmental Protection Agency-certified) at the Department of Civil and Construction Engineering of Iowa State University analyzed the samples for major cations and anions, nitrate, iron, and manganese.

Table 2--*Range of water-level changes in observation wells, reservoir, and tailwater at the Red Rock Dam from July 27, 1988-July 9, 1990*

[Completion elevation, elevation of the base of the completion interval, in feet above sea level; reading, water-level elevation, in feet; --, not applicable]

Well or reservoir location (plate 1)	Completion elevation (feet)	Lowest reading (feet)	Highest reading (feet)	Number of readings	Range of readings (feet)
R-88-3	740.6	744.5	749.2	12	4.7
31-O	677.5	691.1	698.4	13	7.3
16-O	673.6	690.7	698.3	13	7.6
29-O	675.7	692.0	700.0	13	8.0
8-O	673.7	692.5	700.8	13	8.3
16-R	639.6	692.4	701.2	13	8.8
R-88-1	750.0	782.3	791.1	11	8.8
25-O	691.0	693.2	702.0	13	8.8
7-O	673.5	693.1	702.1	13	9.0
8-R	647.0	693.5	702.7	13	9.2
9-O	678.8	688.5	697.8	13	9.3
9-R	640.6	687.9	697.3	13	9.4
10-O	679.8	689.9	699.6	13	9.7
11-O	677.4	688.9	698.6	13	9.7
Tailwater	--	685.7	695.6	13	9.9
12-O	672.7	689.1	699.1	13	10.0
83-L	635.7	689.6	699.7	13	10.1
GW-1	690.8	693.5	703.7	13	10.2
R-88-4	652.8	693.5	703.8	12	10.3
83-U	654.0	689.2	699.6	13	10.4
84-U	652.0	690.0	700.4	13	10.4
85-L	631.3	690.0	700.5	13	10.5
85-U	656.2	690.1	700.6	13	10.5
84-L	632.5	689.9	700.6	13	10.7
14-R	630.8	690.7	701.8	13	11.1
13-R	633.5	690.7	701.9	13	11.2
7-R	648.1	695.2	706.4	13	11.2
12-R	633.2	690.3	701.6	13	11.3
R-88-2	761.2	768.2	780.0	12	11.8
17-O	693.7	694.5	707.2	13	12.7
10-R	639.6	695.2	708.1	13	12.9
18-O	692.6	695.1	708.4	13	13.3
6-O	677.0	695.9	709.7	13	13.8
5-O	688.3	695.3	709.2	13	13.9
19-O	686.6	695.3	709.3	13	14.0
28-O	690.4	694.4	708.6	13	14.2
11-R	633.0	696.6	710.8	13	14.2
4-O	685.8	696.1	710.5	13	14.4
5-RB	654.3	695.8	710.5	13	14.7
5-R	645.4	695.9	710.7	13	14.8

Table 2--*Range of water-level changes in observation wells, reservoir, and tailwater at the Red Rock Dam from July 27, 1988-July 9, 1990*--Continued

Well or reservoir location (plate 1)	Completion elevation (feet)	Lowest reading (feet)	Highest reading (feet)	Number of readings	Range of readings (feet)
R-88-6	639.7	693.8	709.0	12	15.2
20-O	683.7	695.1	710.8	13	15.7
18-R	649.6	694.4	710.4	13	16.0
23-O	690.0	695.3	711.3	13	16.0
3-O	692.2	695.3	711.6	13	16.3
21-O	702.3	719.0	719.0	1	[1]16.7
R-87-4	640.1	696.0	713.3	13	17.3
23-R	645.7	695.6	714.1	13	18.5
R-88-5U	650.4	696.0	714.5	12	18.5
R-88-5L	639.7	696.1	714.7	12	18.6
4-R	646.1	697.4	716.1	13	18.7
3-R	643.4	694.8	714.7	13	19.9
21-UR	689.5	697.1	718.2	13	21.1
2-R	645.1	696.2	718.5	13	22.3
26-R	636.8	697.4	720.0	13	22.6
30-O	687.8	697.7	720.7	13	23.0
27-R	642.6	696.6	720.2	13	23.6
22-UR	683.7	697.0	721.5	13	24.5
22-O	710.0	734.5	734.5	1	[1]24.5
1-R	642.6	697.8	724.6	13	26.8
R-87-1	638.0	697.6	726.6	13	29.0
R-87-2L	642.3	696.5	726.3	13	29.8
R-87-2U	684.3	697.0	732.7	13	35.7
Reservoir	--	730.4	766.3	13	35.9

[1] Range of readings is a minimum, because the well was dry before the July 9, 1990, measurement.

Correlation of Geologic Units

Drillers' logs for exploratory and observation wells at the Red Rock Dam site contain geologic information and are available from files stored at the Rock Island District of the COE. Bedrock cores cut by Terracon Consultants during drilling programs in 1987 and 1988 are available for wells R-87-1 through R-87-4 and wells R-88-1 through R-88-6 (Terracon Consultants, 1987, 1988). Using this information, geologic cross-sections at a 5:1 vertical exaggeration were constructed to correlate permeable zones in the bedrock and glacial till, and as an aid in visualizing the spatial relation of observation wells to the geology.

Hydrogeologic Mapping and Statistical Analysis of Water-Level Changes

In addition to areal maps of the potentiometric surface in the overburden and the potentiometric surface in the evaporite zone of the St. Louis Limestone, maps were prepared comparing the changes in water levels for observation wells and the reservoir. Maps showing the difference between the potentiometric surface in the bedrock and the potentiometric surface in the overburden also were prepared.

A data base containing more than 4,000 water-level measurements for the reservoir, the tailwater, and all observation wells at the dam from March 1982 through July 1990 was created on the USGS computer. The change in water levels in each observation well between two monthly measurements and the change in the reservoir or tailwater levels for the same period was calculated using the relational data base INFO[1]. A correlation coefficient was calculated for the monthly or bimonthly change in water levels in each well and the corresponding change in reservoir level or tailwater level using the statistical package P-STAT. For this statistical analysis, only those wells with at least 50 water-level readings covering the entire 8 years were used.

Analysis of Geochemistry

By expressing concentrations of major ions in meq/L (milliequivalents per liter) and subsequently calculating the percent of major cations (calcium, magnesium, sodium, and potassium) and anions (bicarbonate, carbonate, sulfate, and chloride), trilinear (Piper) diagrams were used to distinguish water types in the vicinity of the dam and possible mixing relations (Hem, 1985). Saturation indices for calcite, dolomite, and gypsum were calculated using the USGS chemical equilibrium program WATEQ4F (Plummer and others, 1976), which models the thermodynamic speciation of inorganic ions and complex species in solution.

For water-quality analysis in this study, water samples collected from the observation wells are assumed to represent the formation waters at the elevation of the well screen. It is expected that well completion techniques, described in the "Well Nomenclature and Construction" section of this report, provide an effective seal in the well bore, isolating the well screen interval from adjacent formation waters.

Determination of Hydraulic Conductivity and Ground-Water Velocity

Hydraulic conductivity for the evaporite zone and the cavity zone in the St. Louis Limestone was calculated from water pressure test data obtained by Terracon Consultants during drilling programs at the dam site during 1987 and 1988 (Terracon Consultants, 1987, 1988). For each test interval of 5 to 10 ft, gauge pressure was recorded in lb/in^2 (pounds per square inch), water loss in ft^3/s, and elapsed time (5 minutes in each case). Hydraulic conductivity (K), or permeability, in ft/d (feet per day) per unit gradient is calculated from equation 1:

$$K = [Q/(C_s + 4)rH] \times 86,400 \qquad (1)$$

where
- K = hydraulic conductivity, in feet per day;
- Q = flow into well, in cubic feet per second;
- C_s = conductivity coefficient for semispherical flow in saturated material;
- r = radius of well bore, in feet;
- H = effective hydraulic head; and
- 86,400 converts feet per second to feet per day.

C_s is graphically determined from a plot against A/r where A is length of aquifer exposed in the well bore, in feet. H is determined from $h_1 + h_2 - L$, where h_1 is the distance between the gauge and the water table; h_2 is the applied pressure at the gauge, in feet of water; and L is the head loss in the pipe, in feet, from friction. A detailed explanation of this method of calculating hydraulic conductivity from in-situ water pressure tests is contained in Bureau of Reclamation (1985).

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

Ground-water velocities were determined from tracer information. Road salt application upstream from Lake Red Rock during the winter months probably caused peak chloride ion concentrations in the reservoir during March 1989 and February 1990. After a time lag of 1 to 4 months, chloride concentrations peaked in observation wells at the dam site. An average ground-water velocity was then calculated by assuming a flow path:

$$V = D/T \quad (2)$$

where V = average velocity, in feet per day;
D = distance, in feet; and
T = time, in days.

Ground-water velocities also were measured in two bedrock wells completed near the grout curtain on the northeast side of the dam during June 1990, with a K-V Associates Groundwater Flowmeter System, Model 40. A point source of heat is produced at the center of the tool, which is sensed by four pairs of thermistors arranged in a circular pattern. From the magnitude and direction of the thermal rise, the velocity and direction of horizontal flow can be calculated from vector resolution. The tool is fitted with a packer assembly, which isolates the probe in the interval of interest, and is lowered into the well casing on a rod assembly. To eliminate instrument bias, two separate sets of measurements are taken at a given well depth. After the initial set of measurements, the tool and rod assembly is rotated 180 degrees and a second set of measurements is obtained (K-V Associates, 1983).

HYDROGEOLOGY

The hydrogeology of south-central Iowa is described in Cagle and Heinitz (1978). The Warsaw Limestone is the lower confining unit in the area. The St. Louis Limestone contains two water-bearing parts, referred to as the lower bedrock and upper bedrock. Rocks of Pennsylvanian age are generally confining units with interspersed water-bearing strata. Water-bearing units within the overburden include glacial sands and alluvial sands.

The Warsaw Limestone is the lower confining unit at the Red Rock Dam site. The shale and dolomite have limited permeability and retard movement of ground water.

Water is confined in the St. Louis Limestone, where it is overlain by consolidated units. Where overlying units are absent, ground water is under water-table conditions. Mapping of the potentiometric surface indicates that the water in the St. Louis Limestone discharges to the Des Moines River and alluvium (W.L. Steinhilber, written commun., 1971). The regional flow gradient in the St. Louis Limestone generally is toward the southwest.

Regionally, extremely mineralized water occurs in the St. Louis Limestone. Dissolved solids averaged about 3,000 mg/L (milligrams per liter). Where the aquifer is the bedrock surface, or near the bedrock surface, dissolved solids averaged about 700 mg/L. Sulfate concentrations ranged from 50 to 3,500 mg/L and the higher concentrations occurred in ground water near the evaporite beds (Cagle and Heinitz, 1978).

Strata of Pennsylvanian age are mostly confining units. A few water-bearing sandstone units are within these strata, but are generally thin and not areally extensive.

The potentiometric surface in the shallow glacial material of the overburden generally slopes from topographic highs toward the stream valleys, where water is discharged to the alluvial deposits. Water moves toward the streams in the valley within the alluvium. At high stream levels, there may be a reversal of flow in the alluvium as water moves toward the valley walls from the stream.

The gradient of the potentiometric surface in the overburden at the Red Rock Dam site is from the valley bluffs toward the Des Moines River. The potentiometric surface on February 23, 1984 (fig. 3), when the reservoir level was 731 ft, indicates that shallow ground-water generally flows from the bluffs on either side of the dam with a down-valley component away from the dam in the river valley. The potentiometric surface in the evaporite zone of the St. Louis Limestone on February 23, 1984, indicates flow away from the dam on both sides of the valley (fig. 4). Ground water in the evaporite zone is under confined conditions in the river valley, because the top of the potentiometric surface, at an elevation of approximately 700 ft (fig. 4), is above the top of the St. Louis Limestone, which is at an elevation of less than 690 ft (geologic section A-A' on plate 1).

The difference in elevation between the potentiometric surface in the evaporite zone and the potentiometric surface in the overburden on February 23, 1984, is indicated by the observation well-pairs installed by the COE throughout the valley and northeast bluff (fig. 5). At the Red Rock Dam site, water in the St. Louis Limestone is being discharged upward to the overburden in the river valley. The St. Louis Limestone is being recharged by water from the overburden in the northeast bluff.

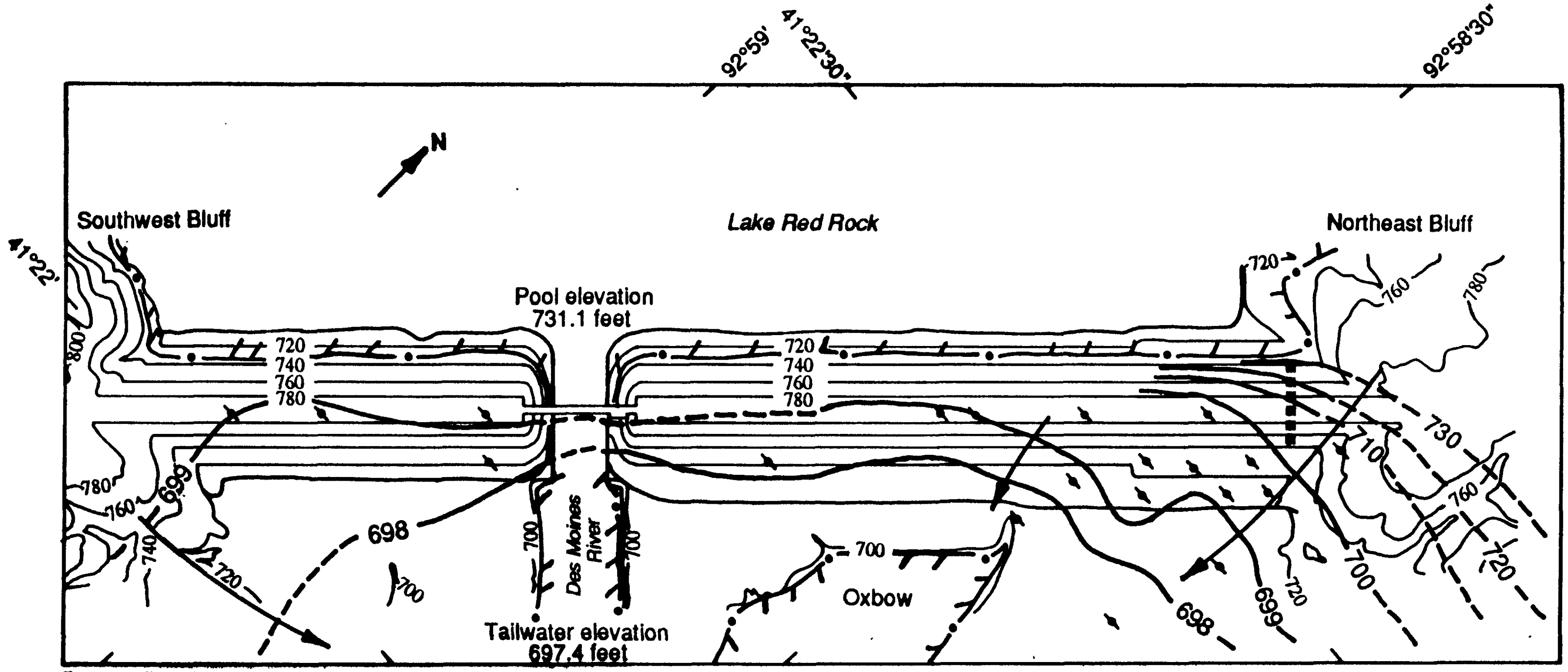
Despite the small hydraulic conductivity of dam fill material, large hydraulic head differences between the reservoir and the toe of the dam cause extremely steep potentiometric gradients that result in natural seepage. When the reservoir level was 773.4 ft on July 13, 1984, the configuration of the potentiometric surface in the overburden (fig. 6) had changed compared to February 23, 1984, with flow becoming more parallel to the axis of the dam. The potentiometric surface had an extremely steep hydraulic gradient from the reservoir through the dam and southwest bluff to the downstream observation wells, which implies expected small permeability and minimal seepage through the dam and embankment materials. A lesser hydraulic gradient from the reservoir to the downstream observation wells existed on the northeast side of the dam, which could indicate excessive seepage through embankment material from larger than expected hydraulic conductivity, underseepage through bedrock, or a recharge area unconnected to the reservoir located northeast of the dam site. The potentiometric surface of the evaporite zone had a similar configuration in the river valley on the southwest side of the dam on July 13, 1984 (fig. 7), to that on February 23, 1984. On the northeast side of the dam, flow generally paralleled the axis of the dam with a strong down-valley component.

A similar relation of the potentiometric surface of the evaporite zone to the potentiometric surface in the overburden on July 13, 1984, to February 23, 1984 was evident (fig. 8). Higher water levels occur in the overburden than in the bedrock aquifer in the area of the northeast bluff. If vertical hydraulic conductivity is large enough, water from the overburden can move downward and recharge the bedrock.

GEOCHEMISTRY

Three primary types of water are present in the ground-water system in the vicinity of the Red Rock Dam on the basis of a classification of major ion percentages with a trilinear diagram (fig. 9). The most prevalent is a calcium bicarbonate water (type I), which occurs in the cavity zone of the St. Louis Limestone, in the overburden (both alluvial and glacial deposits), the Des Moines River, and in Lake Red Rock. Water samples collected and analyzed by the USGS in June 1990 from wells R-88-2 and R-88-3 indicate a calcium bicarbonate water occurs in the shale and other fine-grained deposits of Pennsylvanian age in the bluffs on the northeast side of the dam. A calcium sulfate water (type II) occurs in the lower evaporite zone of the St. Louis Limestone.

A sodium sulfate water (type III) has been sampled from the lower evaporite zone in well 5-RA during the current (1990) water-quality monitoring program and in well 3-R during previous water-quality studies at the dam (U.S. Army Corps of Engineers, 1984). These wells were initially completed in a thick, impermeable evaporite bed; therefore, the large sodium concentration (800-1,200 mg/L) could be caused by the existence of associated sodic-minerals in the evaporite sequence or water from deeper rock units being discharged upward into the well bore.



Base modified from U.S. Army Corps of Engineers, 1984

0 500 1,000 FEET

0 100 200 300 METERS

EXPLANATION

—700— — POTENTIOMETRIC CONTOUR--Shows elevation, in feet, at which water level would have stood in tightly cased wells. Dashed where approximately located. Interval variable. Datum is sea level

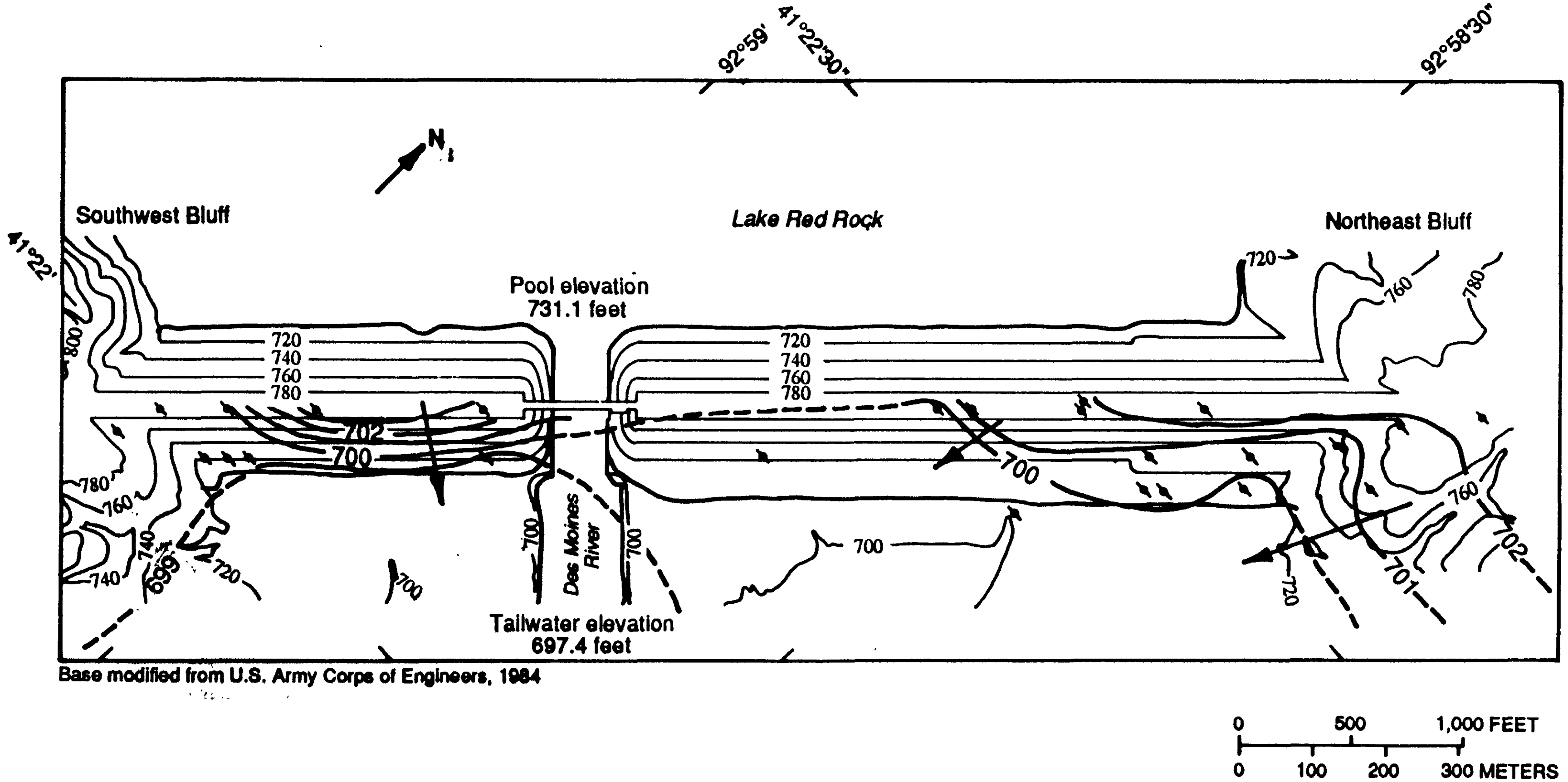
CONTACT BETWEEN BEDROCK SURFACE AND DAM FILL

SURFACE-WATER LIMIT--Hachures toward surface water

GENERALIZED DIRECTION OF GROUND-WATER FLOW

OBSERVATION WELL

Figure 3.--Potentiometric surface in the overburden, February 23, 1984.



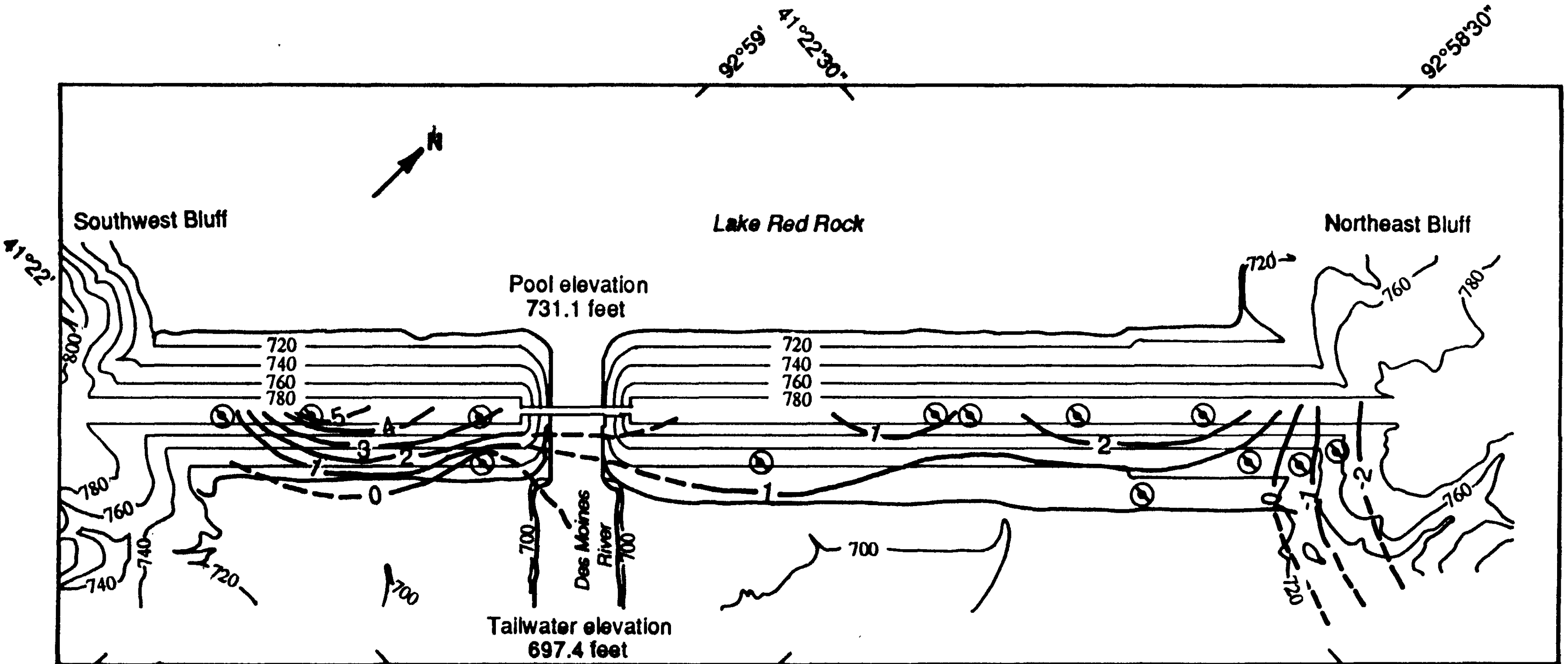
EXPLANATION

—700— — POTENTIOMETRIC CONTOUR--Shows elevation, in feet, at which water level would have stood in tightly cased wells. Dashed where approximately located. Interval is 1 foot. Datum is sea level

GENERALIZED DIRECTION OF GROUND-WATER FLOW

OBSERVATION WELL

Figure 4.--Potentiometric surface in the evaporite zone of the St. Louis Limestone, February 23, 1984.



Base modified from U.S. Army Corps of Engineers, 1984

0 500 1,000 FEET

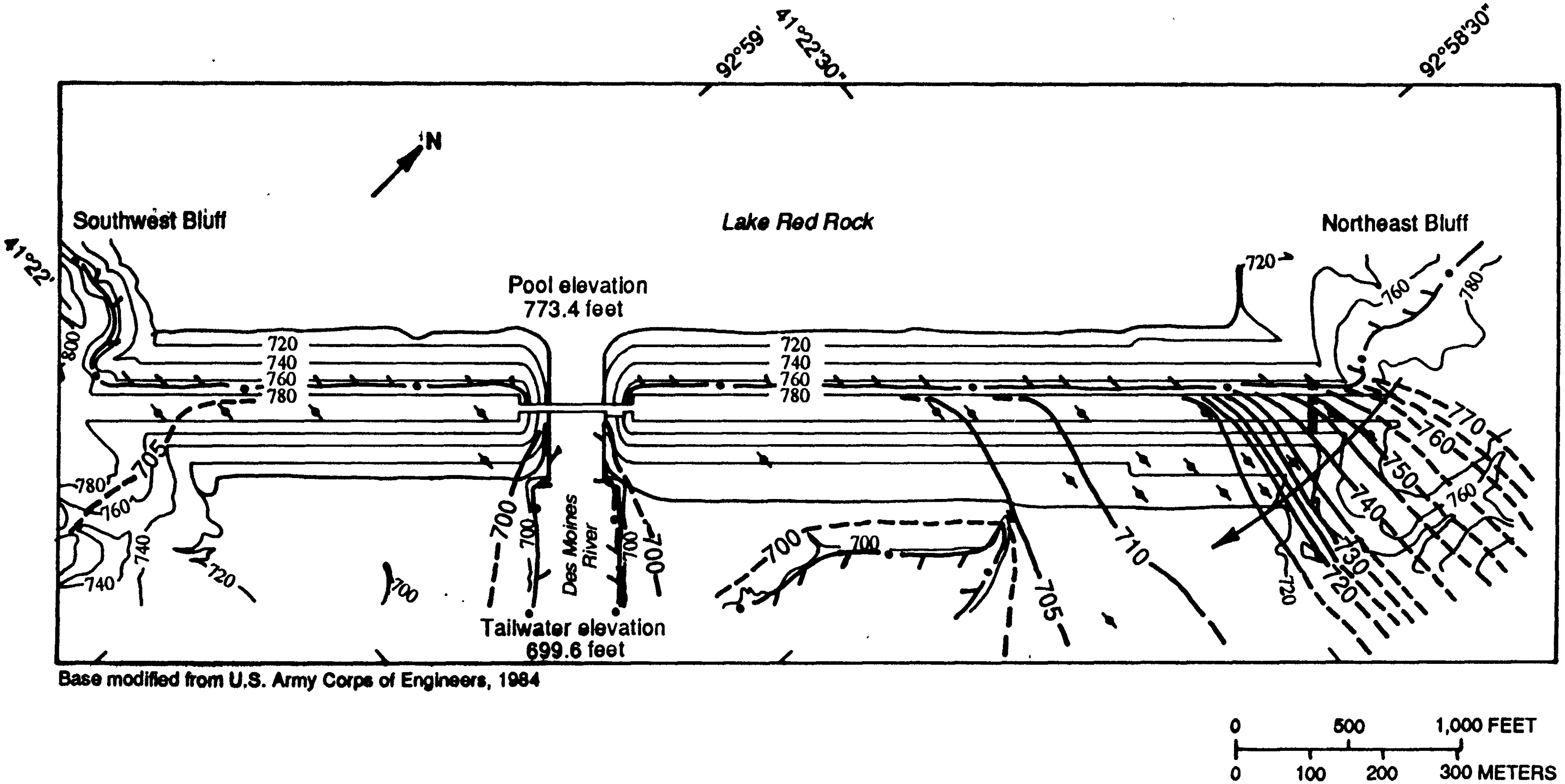
0 100 200 300 METERS

EXPLANATION

—2— — LINE OF EQUAL DIFFERENCE BETWEEN THE POTENTIOMETRIC SURFACE IN THE EVAPORITE ZONE OF THE ST. LOUIS LIMESTONE AND THE POTENTIOMETRIC SURFACE IN THE OVERBURDEN--Negative number indicates potentiometric surface in the overburden is greater than the potentiometric surface in the evaporite zone. Dashed where approximately located. Interval is 1 foot

⊗ OBSERVATION WELL NEST--Screened intervals in overburden and evaporite zone

Figure 5.--Difference between the potentiometric surface in the evaporite zone of the St. Louis Limestone and the potentiometric surface in the overburden, February 23, 1984.



EXPLANATION

—700 – – POTENTIOMETRIC CONTOUR--Shows elevation, in feet, at which water level would have stood in tightly cased wells. Dashed where approximately located. Interval is 5 feet. Datum is sea level

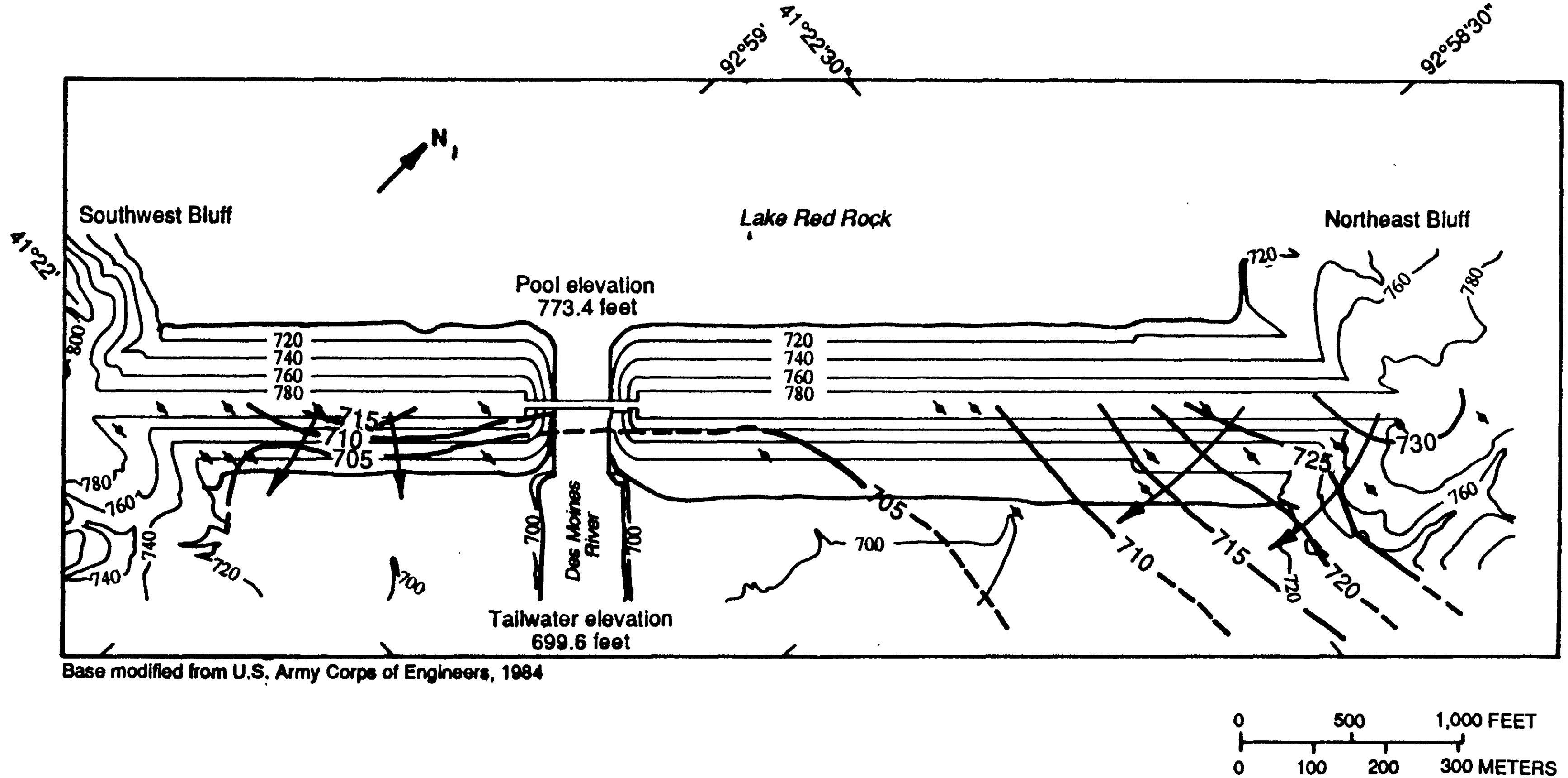
CONTACT BETWEEN BEDROCK SURFACE AND DAM FILL

SURFACE-WATER LIMIT--Hachures toward surface water

GENERALIZED DIRECTION OF GROUND-WATER FLOW

OBSERVATION WELL

Figure 6.--Potentiometric surface in the overburden, July 13, 1984.



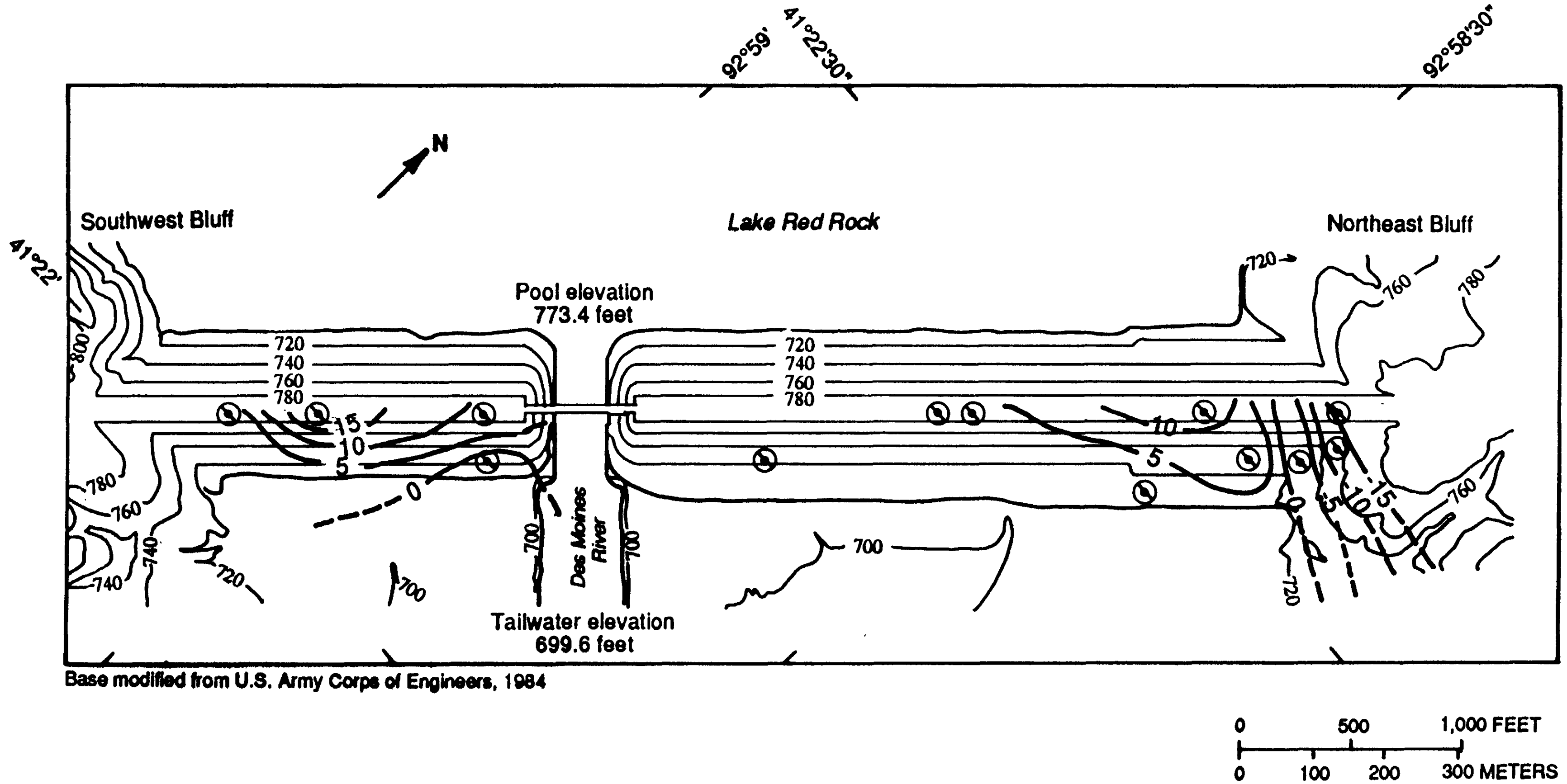
EXPLANATION

—710— — POTENTIOMETRIC CONTOUR--Shows elevation, in feet, at which water level would have stood in tightly cased wells. Dashed where approximately located. Interval is 5 feet. Datum is sea level

GENERALIZED DIRECTION OF GROUND-WATER FLOW

OBSERVATION WELL

Figure 7.--Potentiometric surface in the evaporite zone of the St. Louis Limestone, July 13, 1984.



EXPLANATION

—— 5 – – LINE OF EQUAL DIFFERENCE BETWEEN THE POTENTIOMETRIC SURFACE IN THE EVAPORITE ZONE OF THE ST. LOUIS LIMESTONE AND THE POTENTIOMETRIC SURFACE IN THE OVERBURDEN--Negative number indicates potentiometric surface in the overburden is greater than the potentiometric surface in the evaporite zone. Dashed where approximately located. Interval is 5 feet

⊗ OBSERVATION WELL NEST--Screened intervals in overburden and evaporite zone

Figure 8.--Difference between the potentiometric surface in the evaporite zone of the St. Louis Limestone and the potentiometric surface in the overburden, July 13, 1984.

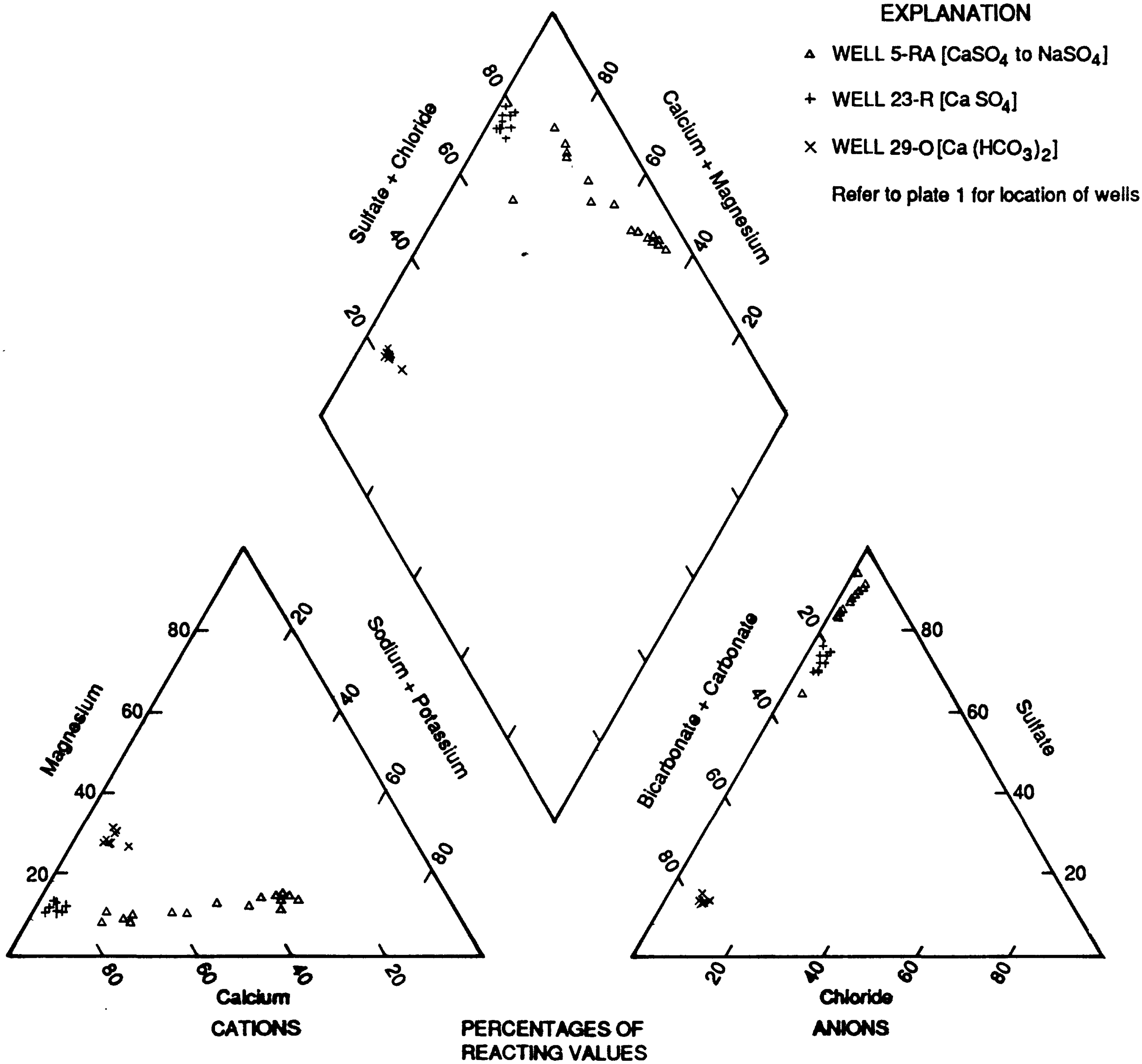


Figure 9.--Trilinear diagram showing water types present in wells 5-RA, 23-R, and 29-O.

On the trilinear diagram in figure 9, data from wells 29-O, 23-R, and 5-RA represent the calcium bicarbonate, calcium sulfate, and sodium sulfate water types. Water samples from these wells have been analyzed monthly from April 1987 through July 1990. The trend in the data from well 5-RA indicates a change from the sodium sulfate water to the calcium sulfate water occurring in well 23-R. When well 5-RA initially was completed in the impermeable evaporite bed, it was isolated from the more permeable parts of the St. Louis Limestone. The high sodium concentration in well 5-RA subsequently decreased dramatically during 1989 (fig. 10). Before May 1989, waters with a large sodium concentration from the underlying Warsaw Limestone possibly were being discharged to the well bore and constituted a large part of the pumped water samples. As the evaporite bed was stressed by subsequent sampling operations, a pathway was opened to the more permeable part of the formation and calcium sulfate water began to mix with the sodium sulfate water. A water analysis obtained from the USGS national water-quality data base (WATSTORE) for a well completed in the Warsaw Limestone, located approximately 40 mi southeast of the dam site in Monroe County, indicates that sodium sulfate water occurs in the Warsaw Limestone.

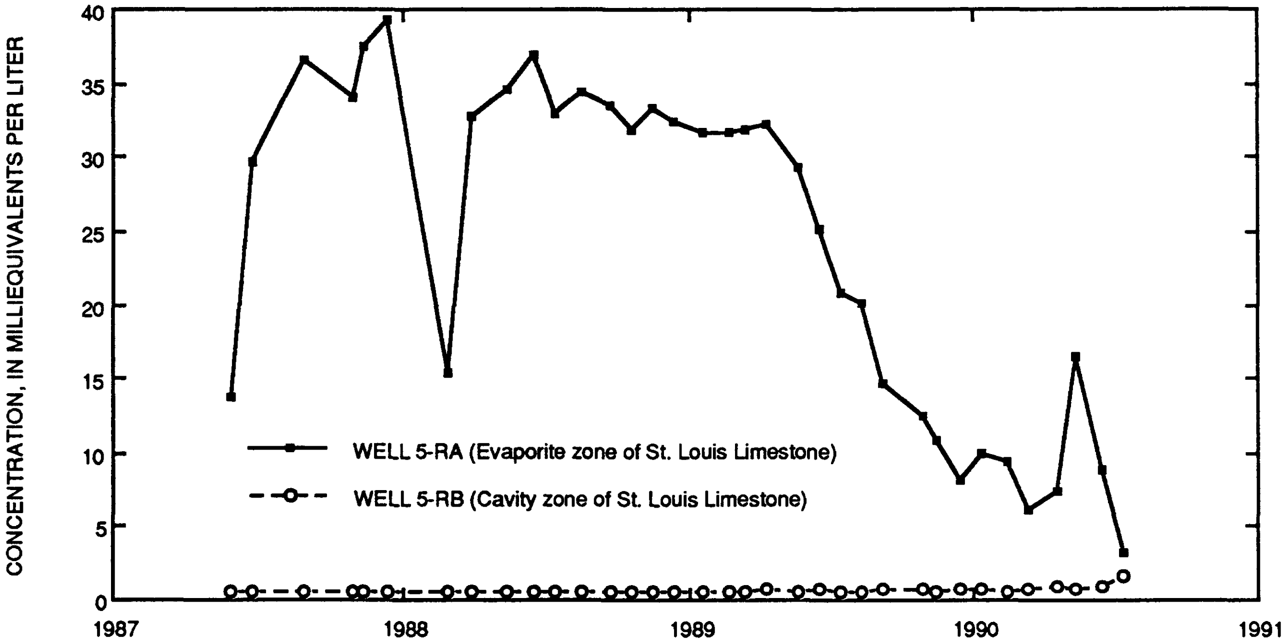


Figure 10.--Sodium concentration in samples from wells 5-RA and 5-RB, April 1987- July 1990.

An alternative explanation for the trend toward a calcium bicarbonate water type in well 5-RA is that dissolution of the evaporite minerals occurred during the sampling period because of in-situ processes in the ground-water system. Downward movement of ground water from overlying strata or development of a solution channel from adjacent strata could have caused a breakthrough from a more permeable zone, allowing mixing of the two water types. If the sampling interval is not isolated from the well bore, leakage from overlying strata also could explain the change in water chemistry.

EVIDENCE OF UNDERSEEPAGE

Evidence for excessive underseepage of reservoir water through the overburden (glacial sands) and the St. Louis Limestone beneath the dam on the northeast side of the dam site will be presented. Topics include comparing the water-level changes in observation wells with corresponding changes in reservoir levels, mapping the potentiometric surfaces in the overburden and in the St. Louis Limestone in the vicinity of the dam, evaluating the geochemistry of the ground-water system using data from analyses of water samples collected from observation wells at the dam site, and presenting results of ground-water flow measurements.

Relation Between Water-Level Changes in Reservoir and Observation Wells

The range in water-level measurements for all observation wells at the dam site from July 27, 1988, through July 9, 1990, is listed in table 2. Data for well 5-RA are not included because water levels did not always recover to the potentiometric surface between water-level measurements after samples were pumped from the well. Ranges of reservoir and tailwater elevations and the elevation of the base of the completion interval of each well are included for reference. Tailwater elevation is measured in a stilling basin located in the concrete control structure of the dam and represents river elevation immediately downstream from the dam spillway. This comparison of water-level changes indicates that varying hydrogeologic conditions exist near Red Rock Dam. Of the observation wells completed in the evaporite zone of the St. Louis Limestone, those having the widest range in water-level measurements (R-87-2L, R-87-1, 1-R, 27-R, 26-R, and 2-R) are located on the northeast side of the dam (plate 1), whereas wells on the southwest side of the dam (12-R, 13-R, and 14-R) have a much smaller range in their water-level measurements. Wells completed in the upper bedrock of the St. Louis Limestone located on the northeast side of the dam (R-87-2U, 22-UR, and 21-UR) (plate 1) also exhibit large fluctuations in water levels. Of the overburden observation wells, the largest water-level fluctuations occurred in wells 30-O and 22-O, which are completed in glacial sands in the overburden of the northeast bluff (plate 1).

Large fluctuations in hydraulic head were observed on the northeast side of the dam in the bedrock and in the overburden. The ranges in water-level measurements from July 27, 1988, to July 9, 1990, in wells R-87-2U, R-87-2L, R-87-1, 1-R, and 30-O represent more than 75 percent of the 35.9 ft that the level of Lake Red Rock varied during this period.

Time-series plots comparing monthly water elevations of the reservoir, observation wells, and tailwater from March 1982 to July 1990 indicate hydrogeologic conditions differ on the two sides of the river valley. Well 14-R (fig. 11), located in the southwest bluff (plate 1), has a more subdued response to reservoir level changes than does well 1-R (fig. 12), which is located in the northeast bluff (plate 1). Both wells are located immediately downstream from the dam axis and are completed in the evaporite zone of the St. Louis Limestone. The magnitude of water-level changes in well 1-R correlates better with changes in reservoir levels. This difference in response between observation wells on the two sides of the dam has been noted by the COE since dam operations began. For this reason, and because the distribution of evaporite beds is more extensive on the northeast side of the river valley than on the southwest side (fig. 2), hydrogeologic data collection has been focused on the northeast valley and bluff.

Time-series plots for water levels in observation wells completed in the overburden of the northeast bluff also show a correlation with changes in reservoir levels from March 1982 to July 1990. Until the piezometer became inoperative, water-level data for well 2-O (fig. 13) show a similar response to changes in reservoir levels as data for well 1-R. Water-level measurements for well 21-O (fig. 14) also show a relation to high reservoir levels. There seems to be a time lag of 1 month or less between a maximum reservoir level reading and the maximum water-level measurement in wells 2-O and 21-O, which are completed in the same glacial sand package of the overburden (geologic section B-B' on plate 1).

The time-series data for well 21-UR (fig. 15) indicate a relation between water-level changes in an observation well completed in the upper bedrock of the St. Louis Limestone and changes in reservoir levels. This well is located in the northeast bluff and is completed in fractured limestone just below the top of the uneven, erosional bedrock surface (geologic section B-B').

Time-series data indicate a relation between pool-level changes and water-level changes in observation wells on the northeast side of the dam site. A correlation coefficient between the monthly or bimonthly changes in water levels in each of the observation wells and the corresponding changes

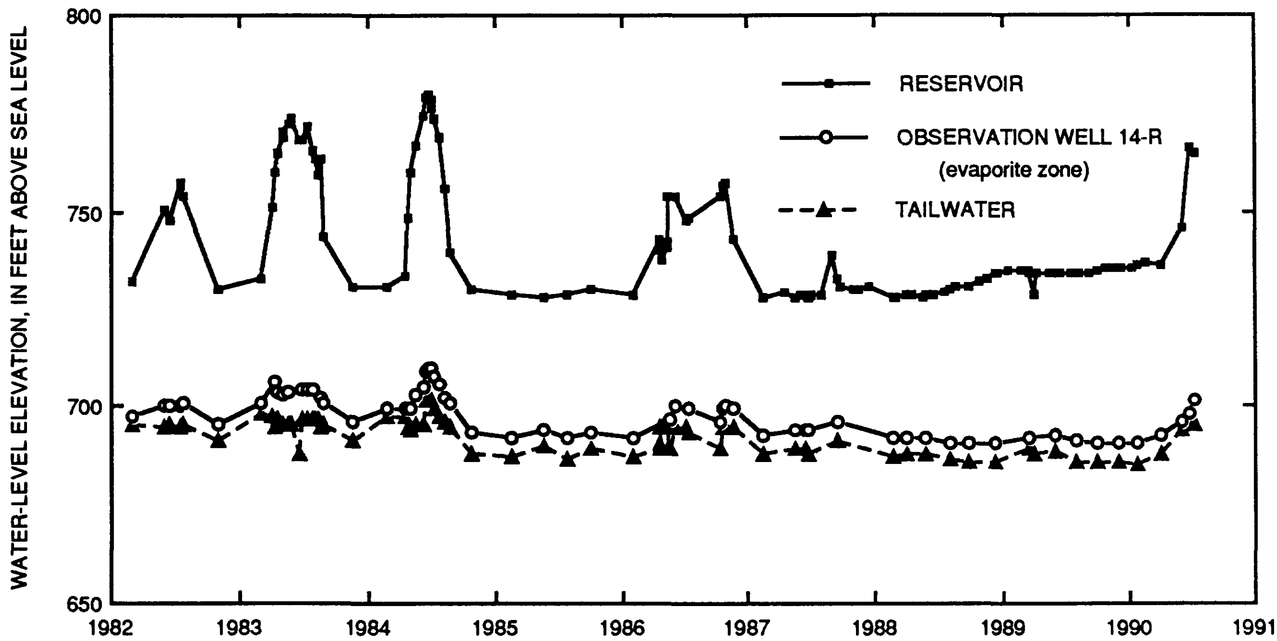


Figure 11.--Water-level elevations of reservoir, observation well 14-R, and tailwater, March 1982 - July 1990.

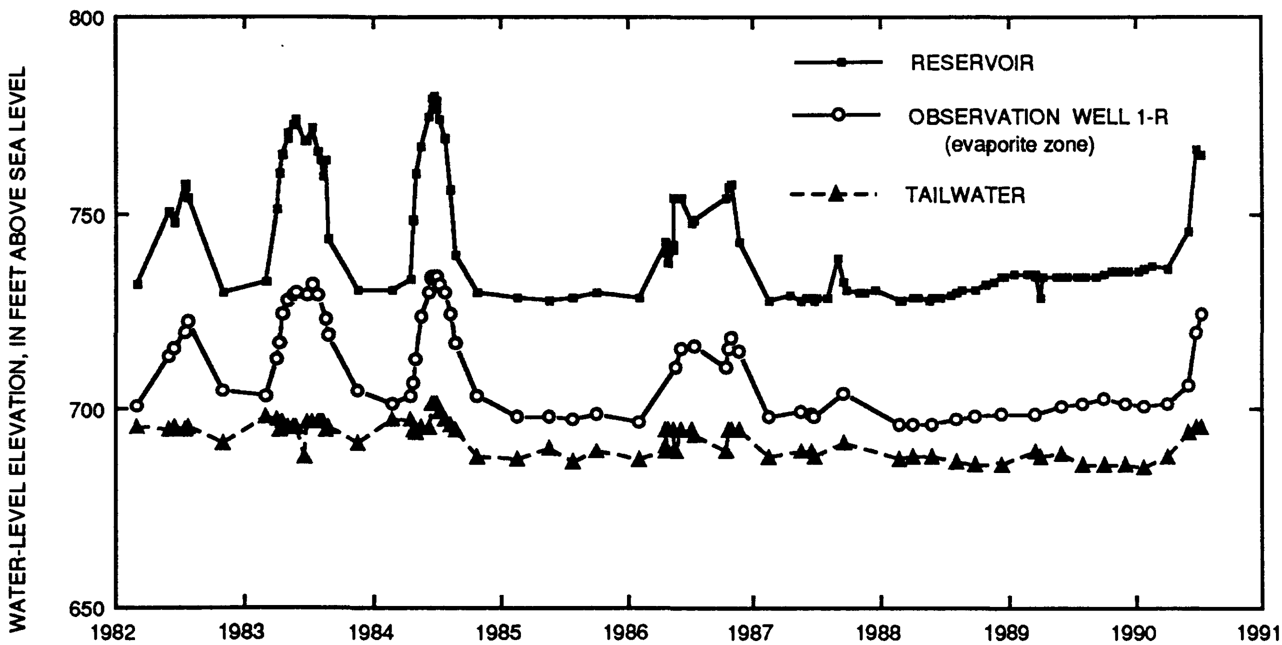


Figure 12.--Water-level elevations of reservoir, observation well 1-R, and tailwater, March 1982 - July 1990.

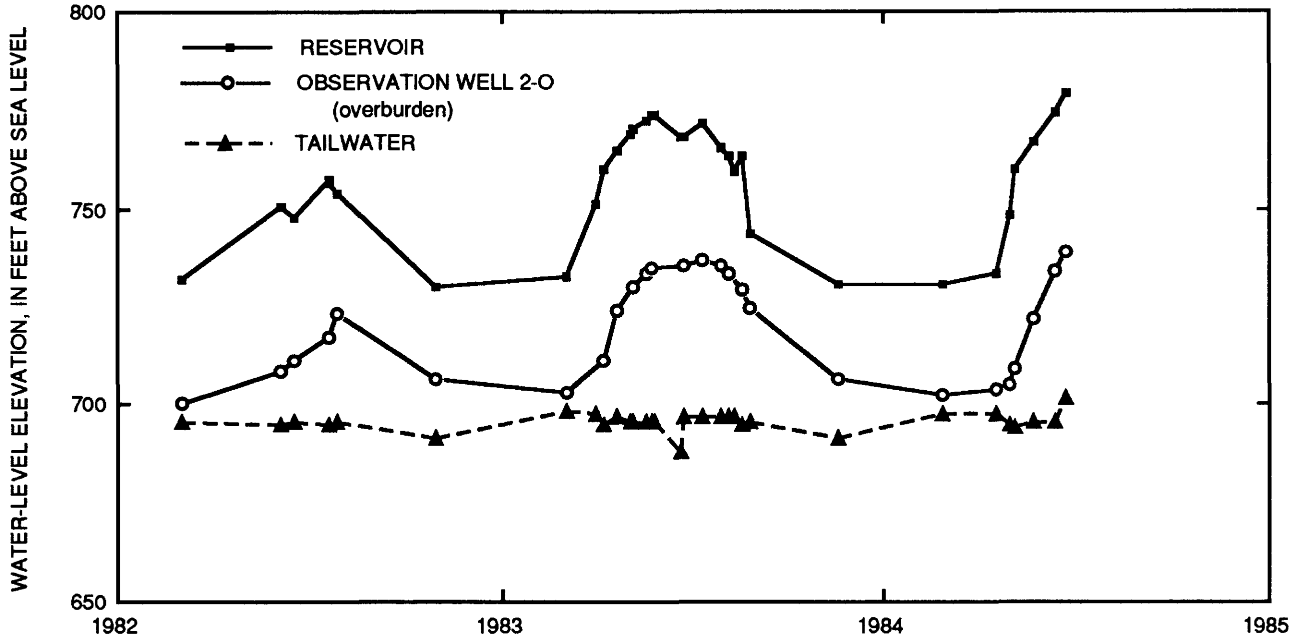


Figure 13.-- Water-level elevations of reservoir, observation well 2-O, and tailwater, March 1982 - June 1984.

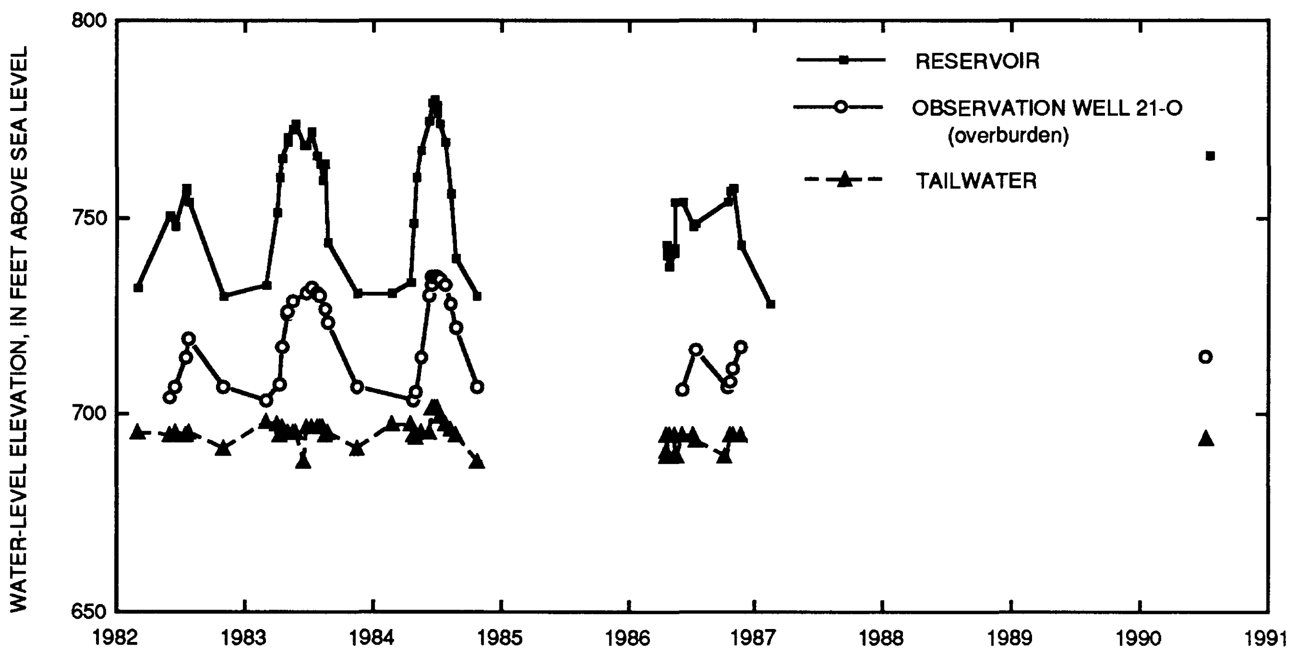


Figure 14.--Water-level elevations of reservoir, observation well 21-O, and tailwater, March 1982 - July 1990.

in reservoir levels was calculated from June 1982 to July 1990. The correlation coefficient should be near unity in proximity to an area of good hydraulic connection between the reservoir and the observation wells or of pressure response without flow caused by loading on confined units. Low correlation to reservoir level changes should indicate areas with an effective barrier to downstream flow minimizing underseepage.

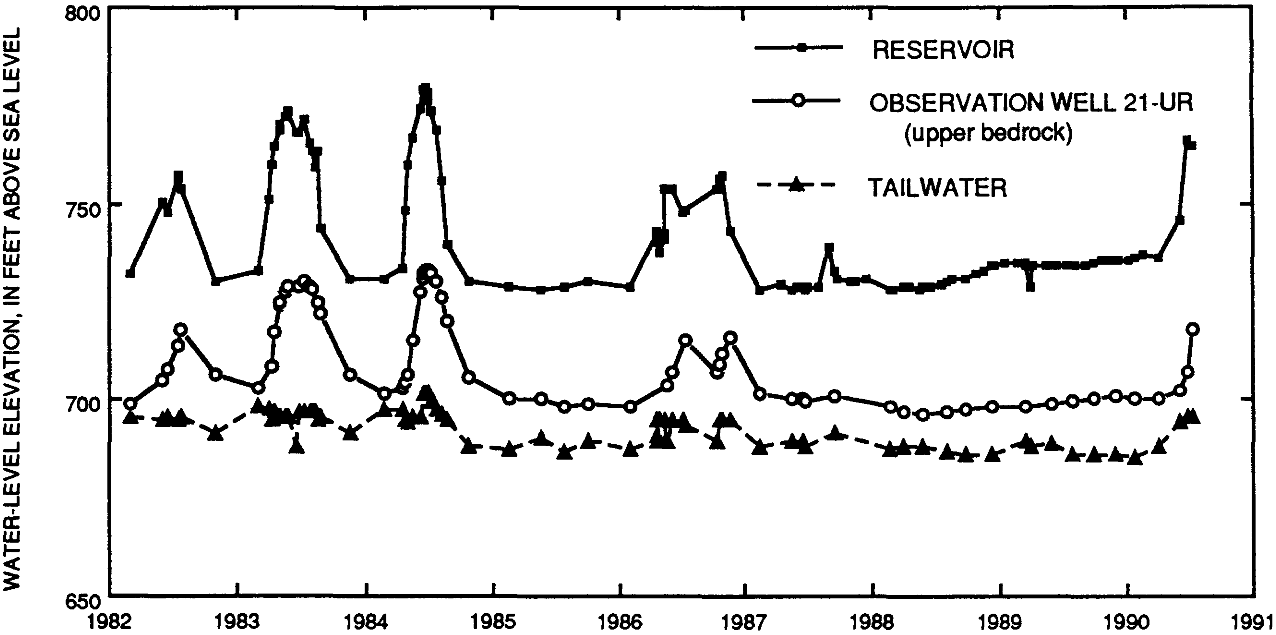


Figure 15.--Water-level elevations of reservoir, observation well 21-UR, and tailwater, March 1982 - July 1990.

A contour map of the correlation coefficients for observation wells completed in the evaporite zone at the dam site (fig. 16) shows values greater than 0.80 for wells in the northeast bluff and river valley, while correlation coefficients generally are less than 0.70 for wells on the southwest side of the dam. A contour map of the correlation coefficients for observation wells completed in the overburden (fig. 17) shows a similar relation between the two sides of the dam site, although the correlations are lower for the overburden well data than for the bedrock well data.

Lower correlation to reservoir level changes in the overburden wells than in the bedrock wells is probably caused by frequent changes in the level of the water-table resulting from short-term climatic variations or dam operations affecting tailwater levels. Time lags associated with ground-water flow paths and varying rock properties (such as hydraulic conductivity) also affect the correlation between water-level changes in the reservoir and in the various observation wells. Greater correlation coefficients occurring on the northeast side of the dam site indicate the existence of different hydrogeologic conditions from those on the southwest side of the dam. This statistical treatment of the water-level data indicates that fluctuations in reservoir level probably have a greater effect on the hydrogeologic system on the northeast side of the dam site.

Computing a correlation coefficient for the monthly change in tailwater levels and the corresponding change in water levels in observation wells from June 1982 to June 1990 provides an opposite relation between the two sides of the dam site compared to correlations with reservoir level changes. For bedrock wells, correlation coefficients on the southwest side of the dam site have values ranging from 0.80 to 0.90, while on the northeast side of the dam site these values are less than 0.80 (fig. 18). Similar values of correlation coefficients and a similar relation between the two sides of the dam occur for overburden wells (fig. 19).

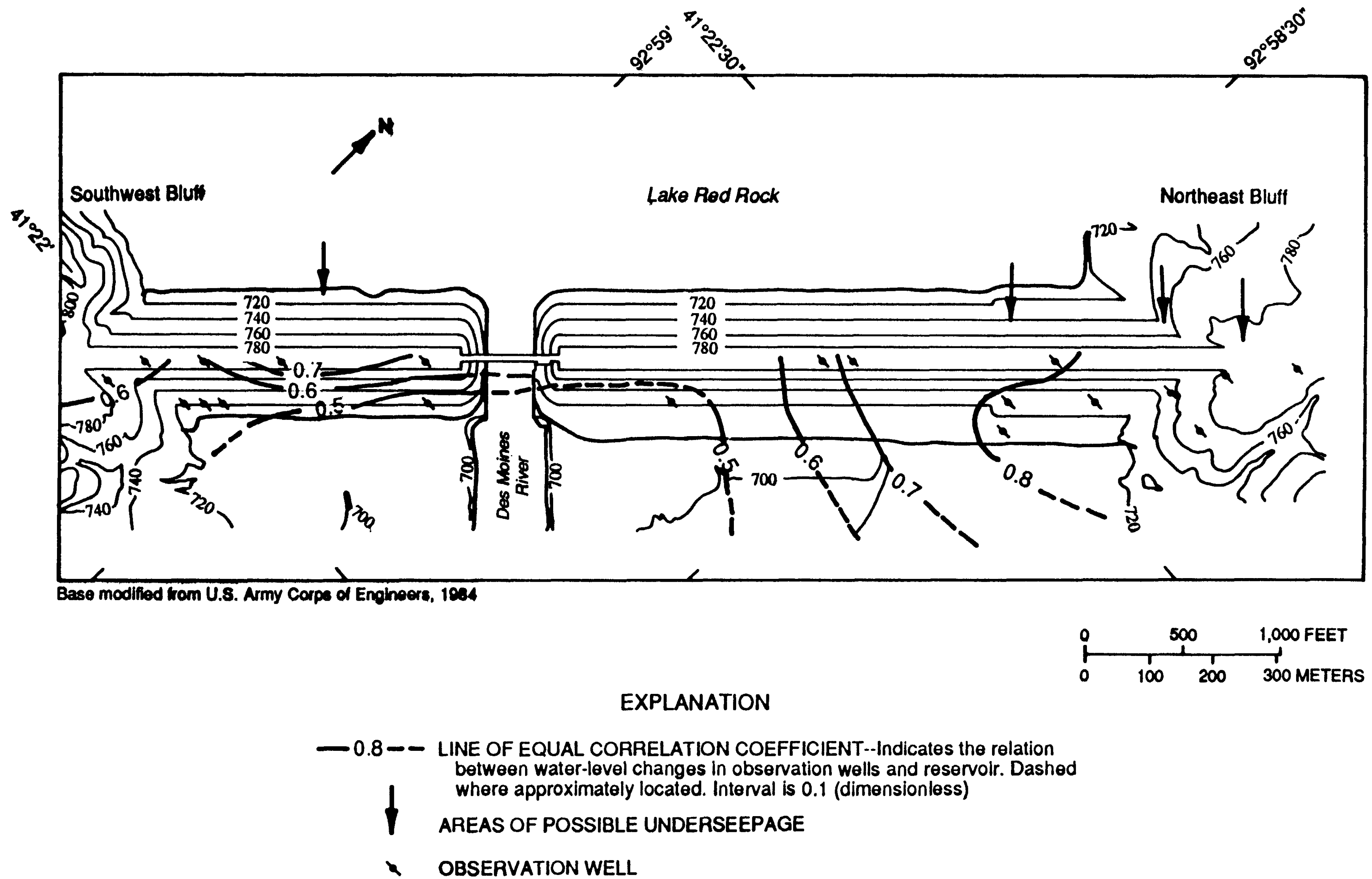
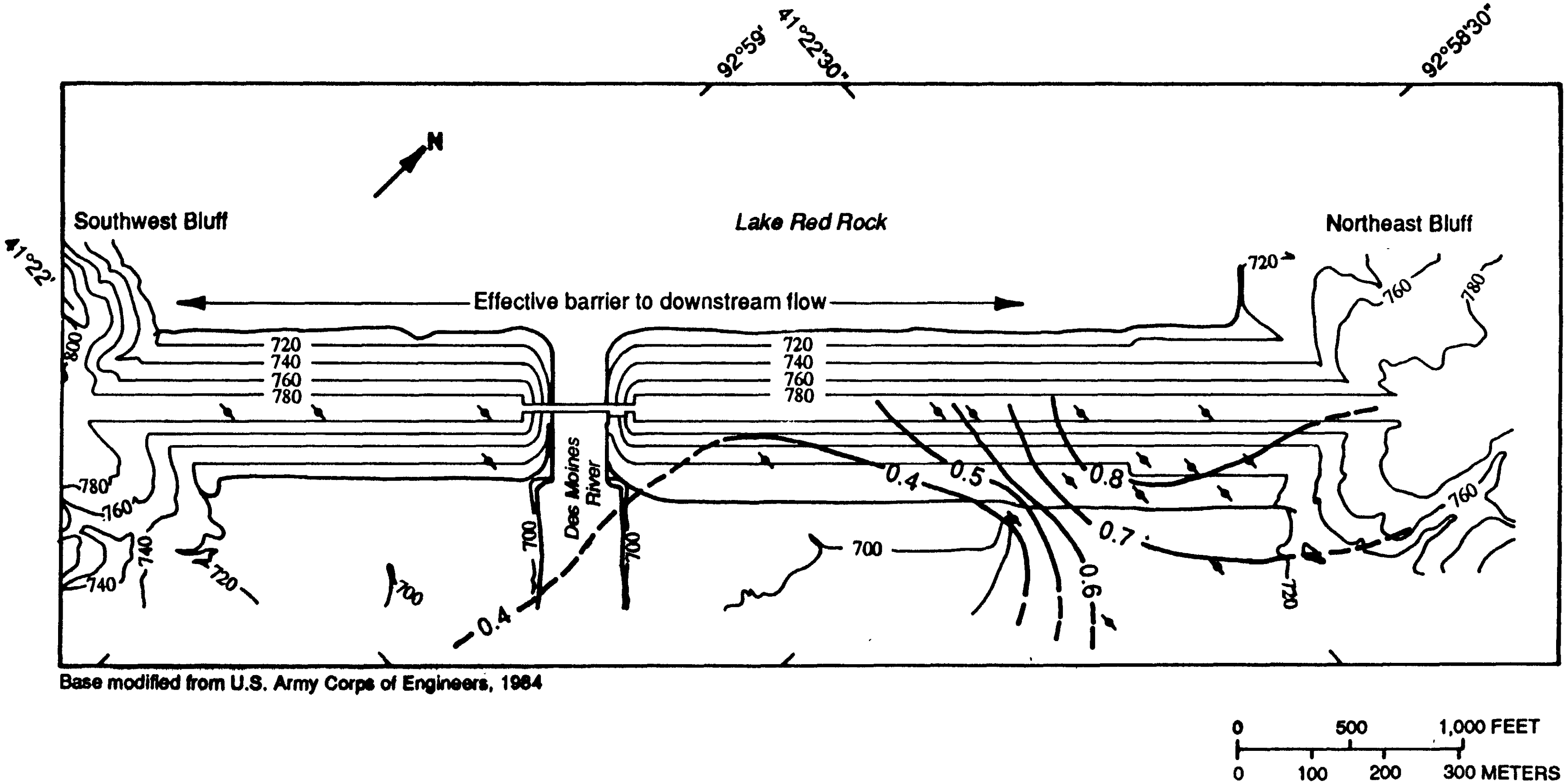


Figure 16.--Correlation coefficients for the relation between water-level changes in the evaporite zone of the St. Louis Limestone and the reservoir, March 1982-July 1990.

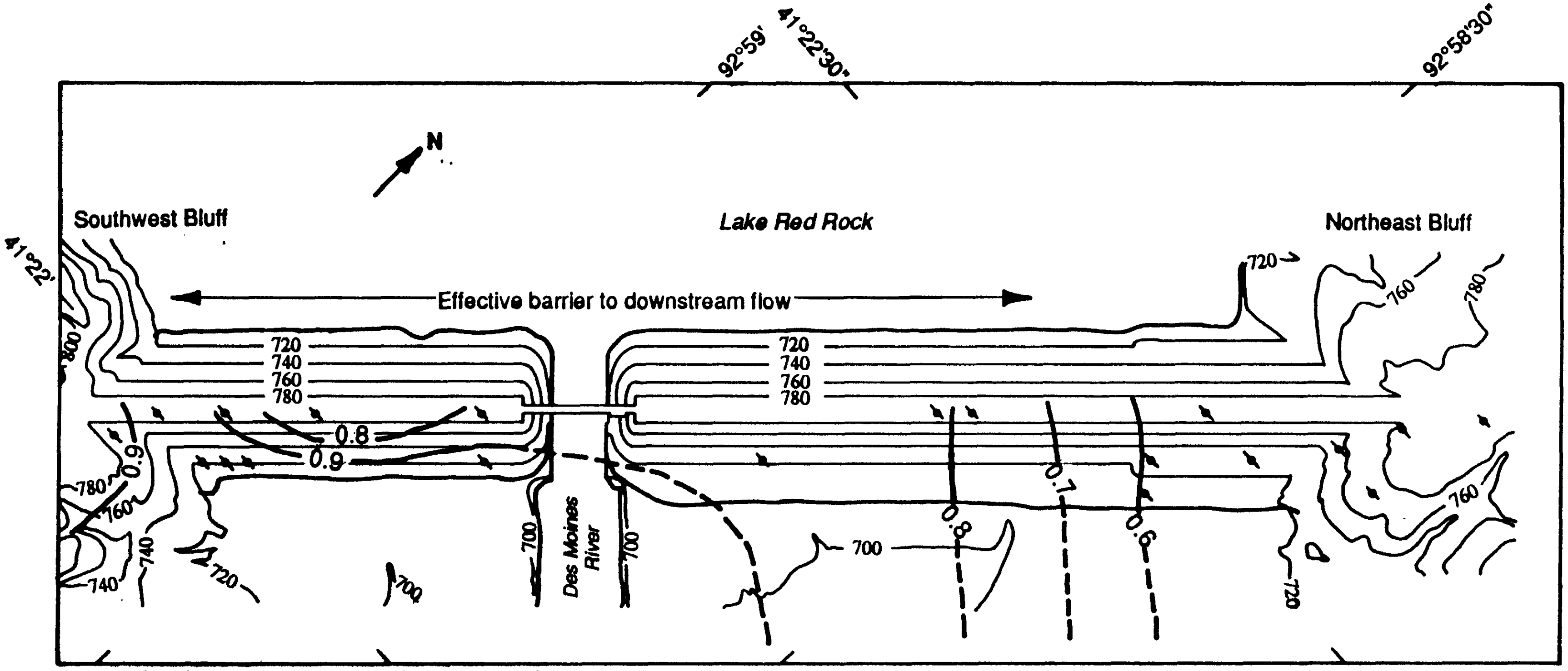


EXPLANATION

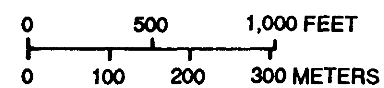
—0.8 – – LINE OF EQUAL CORRELATION COEFFICIENT--Indicates the relation between water-level changes in observation wells and reservoir. Dashed where approximately located. Interval is 0.1 (dimensionless)

OBSERVATION WELL

Figure 17.--Correlation coefficients for the relation between water-level changes in the overburden and the reservoir, March 1982-July 1990.



Base modified from U.S. Army Corps of Engineers, 1984

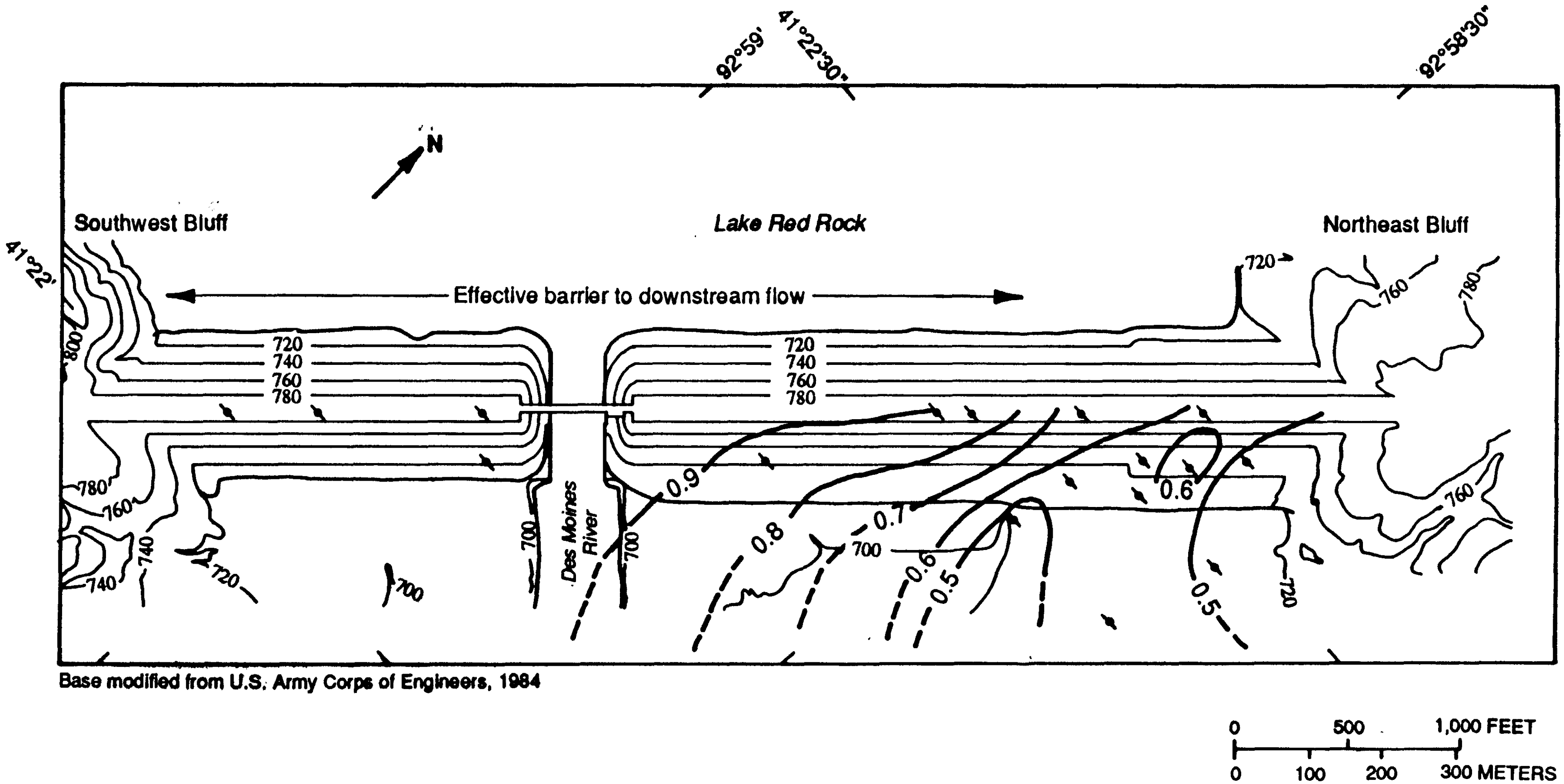


EXPLANATION

—— 0.8 — — LINE OF EQUAL CORRELATION COEFFICIENT--Indicates the relation between water-level changes in observation wells and tailwater. Dashed where approximately located. Interval is 0.1 (dimensionless)

OBSERVATION WELL

Figure 18.--Correlation coefficients for the relation between water-level changes in the evaporite zone of the St. Louis Limestone and tailwater, March 1982-July 1990.



EXPLANATION

—— 0.8 – – LINE OF EQUAL CORRELATION COEFFICIENT--Indicates the relation between water-level changes in observation wells and tailwater. Dashed where approximately located. Interval is 0.1 (dimensionless)

OBSERVATION WELL

Figure 19.-- Correlation coefficients for the relation between water-level changes in the overburden and tailwater, March 1982-July 1990.

Areas with a high correlation to changes in tailwater levels and a low correlation to changes in reservoir levels indicate an effective barrier to underseepage. Water levels in wells closer to the river channel below the control structure will be effected to a greater degree by changes in tailwater levels than those in wells located farther away. Effects of underseepage through the bedrock can be masked by tailwater changes in wells located near the river channel, but the overall pattern of correlation coefficients between water-level changes in wells and tailwater provides an indication of the different hydrogeologic influences affecting the northeast and southwest sides of the river valley. The high correlation of water-level changes in the bedrock (fig. 18) and in the overburden (fig. 19) to tailwater-level changes on the southwest side of the valley demonstrates lesser influence by reservoir level fluctuation.

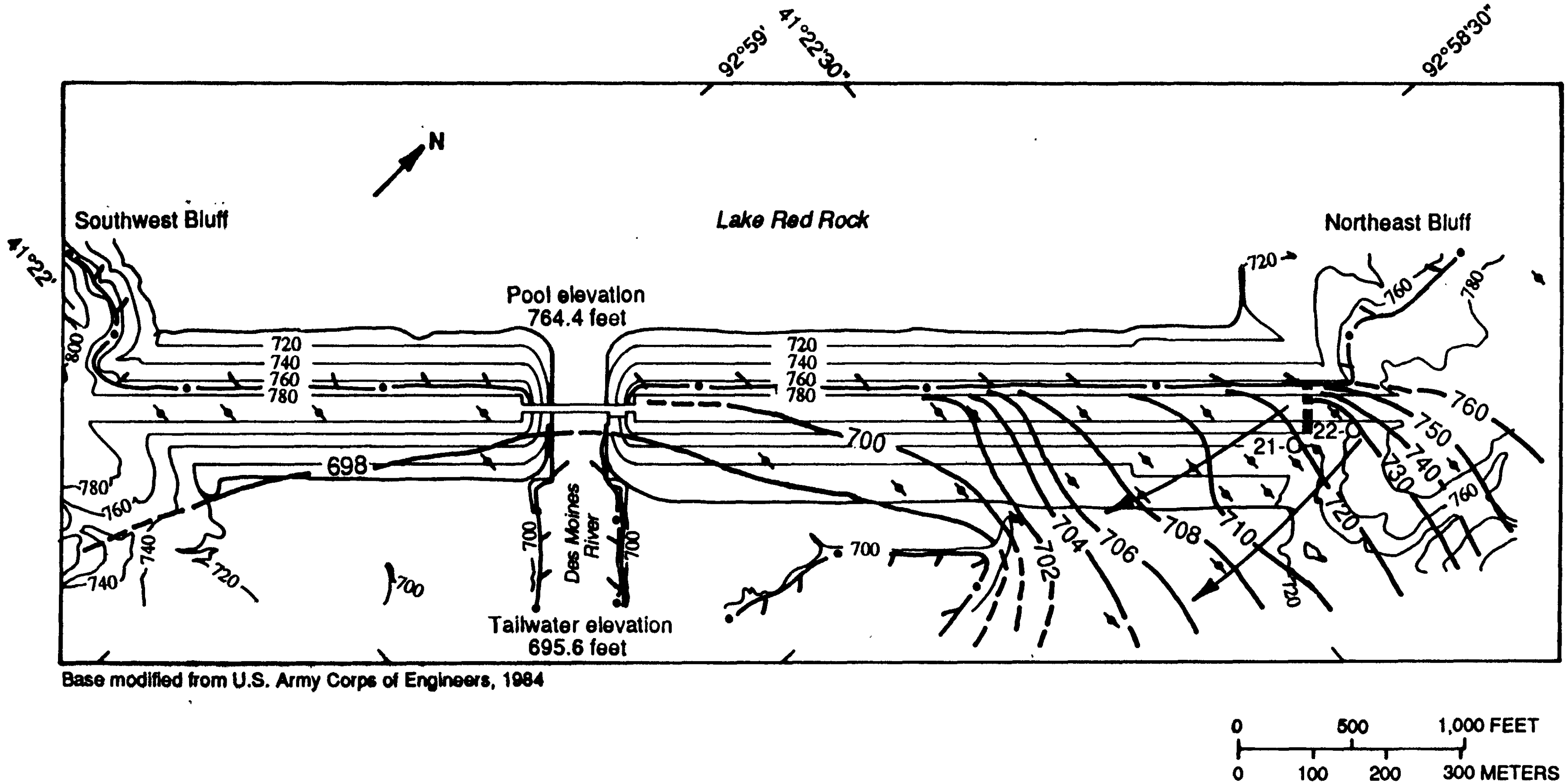
The results of the statistical analysis computing correlation coefficients indicate that the Red Rock Dam is an effective barrier to downstream flow from the reservoir from a point between wells 7-R and R-87-4 in the northeast embankment of the dam across the valley to the southwest abutment. There is a high correlation to tailwater level changes and low correlation to reservoir level changes throughout this reach, which indicates an effective grout curtain. There may be limited underseepage in the vicinity of well 11-R in the southwest embankment because its correlation to reservoir level changes is greater than adjacent wells. However, there are no evaporite beds in the bedrock foundation of the dam in this area (fig. 2).

Geologic sections A-A' and B-B' (plate 1) illustrate the relation of the observation wells to the geologic units. The evaporite beds vary in thickness and are overlain by a permeable zone of fractured limestone containing open and filled cavities. The locally extensive, permeable cavity zone at this stratigraphic horizon could provide good hydraulic connection between some observation wells. Several adjacent wells can have a similar response (such as large water-level fluctuations) to reservoir level changes from a localized source of underseepage.

The elevation of the reservoir was 764.4 ft and the elevation of tailwater was 695.6 ft on July 9, 1990. Considering the potentiometric surface in the overburden, there was a much steeper hydraulic gradient across the dam on the southwest side of the dam than on the northeast side, as expected from an effective barrier to downstream flow caused by materials in the bluff and the dam. The gentler hydraulic gradient on the northeast side of the dam results either from greater hydraulic conductivity of the dam materials or greater upward flow from the bedrock (fig. 20). At a reservoir elevation of 773.4 ft on July 13, 1984 (fig. 6), the configuration of the potentiometric surface in the overburden was similar to that on July 9, 1990, except that water levels generally were 4 ft higher in the observation wells during the higher reservoir level.

Up to 90 ft of overburden in the northeast bluff constitutes an integral part of the extreme northeast section of the embankment of the dam (geologic section A-A') and contains clayey, fine- to medium-grained sands. Samples of these glacial sands from borings along the axis of the dam are slightly permeable, as 6 to 10 percent passed a 200-mesh, silt-sized sieve (U.S. Army Corps of Engineers, 1969). As discussed previously, observation well 21-O is completed in these sands (geologic section B-B') and demonstrates a response to high reservoir levels (fig. 14).

Wells 21-O and 22-O, with well screens installed to elevations of 702 and 710 ft, in the overburden of the northeast bluff, were dry on June 27, 1990, when the elevation of the reservoir was 766.3 ft. The water-level elevation in well 22-O was 734.5 ft on July 9, 1990, which means the potentiometric surface at this location rose at least 24.5 ft during the 13 days since the last measurement on June 27, 1990. Similarly, the water levels at the location of well 21-O rose at least 17 ft during the same 13 days. A time lag of at most 13 days for ground water to follow a seepage path through the overburden and charge these glacial sands in response to extended, high reservoir levels is inferred, because the elevation of the reservoir was essentially the same on the two dates that the wells were read (766.3 ft on June 27 and 764.4 ft on July 9). The configuration of the potentiometric surface in the overburden in the northeast bluff (fig. 20) demonstrates that these materials are more permeable than the earth-



EXPLANATION

—— 700 – – POTENTIOMETRIC CONTOUR--Shows elevation, in feet, at which water level would have stood in tightly cased wells. Dashed where approximately located. Interval is variable. Datum is sea level

CONTACT BETWEEN BEDROCK SURFACE AND DAM FILL

SURFACE-WATER LIMIT--Hachures toward surface water

GENERALIZED DIRECTION OF GROUND-WATER FLOW

OBSERVATION WELL

Figure 20.--Potentiometric surface in the overburden, July 9, 1990.

fill embankment of the dam. The time lag associated with the observation well response to increases in reservoir levels could be caused by expected seepage conditions through the embankment and overburden (glacial till) or to the intersection of a permeable layer within the overburden by ground-water flow at reservoir elevations greater than 750 ft.

Geologic section C-C' (plate 1) depicts a possible seepage path for reservoir water to charge the glacial sands of the overburden along the dam axis in the northeast bluff. If the surficial overburden upstream from the northeast abutment does not provide an effective permeability barrier during high reservoir levels (greater than 750 ft in elevation), sand (1) on geologic section C-C' could provide a permeable flow path for seepage waters, which in turn would charge sand (2). The entire glacial sand package on the valley side of the erosional remnant of shale of Pennsylvanian age could become a flow path for seepage waters. Geologic section B-B' intersects geologic section C-C' at well 15-O and illustrates the downstream continuity of the glacial sands from the northeast bluff toward the alluvium in the river valley.

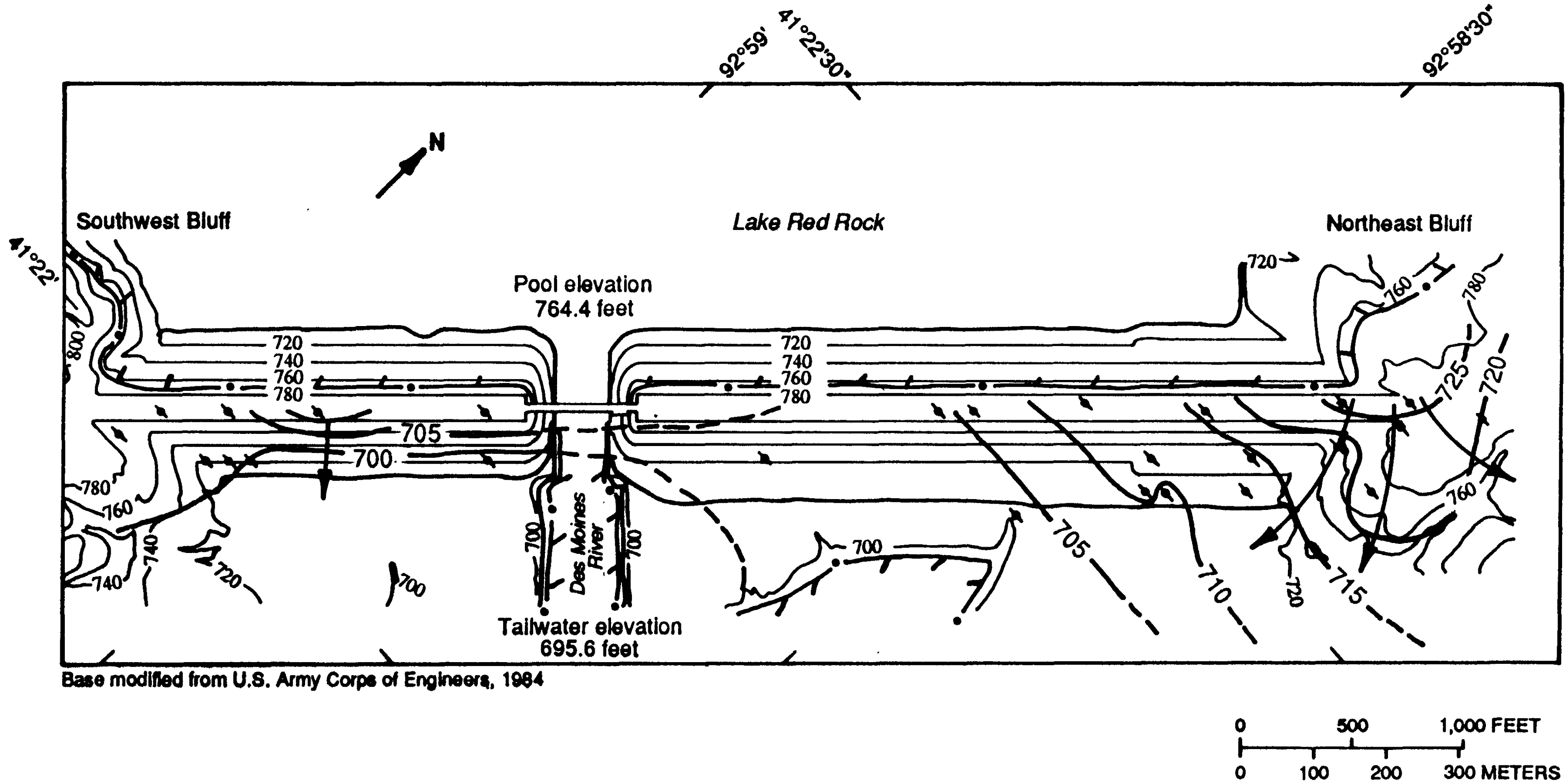
The ground-water flow lines superimposed on the potentiometric surface of the evaporite zone of the St. Louis Limestone on July 9, 1990 (fig. 21), indicates flow away from the dam axis in the area of the northeast bluff and extreme northeast side of the river valley. A potentiometric high, or recharge area, is defined by wells R-87-1, R-87-2L, and 1-R causing flow directions to the east and southeast--counter to the regional southwest gradient. Further, the elevations of the water levels in these wells is greater than 724 ft, which is more than 13 ft higher than the water level measured in the evaporite zone in any well on the southwest side of the dam. The grout curtain of the dam foundation terminates immediately southwest of well 26-R; therefore, the configuration of the recharge area in the northeast bluff demonstrates that ground-water flow in the lower bedrock is through the grout curtain rather than around the extreme northeast terminus of the grout curtain. The potentiometric surface on the southwest side of the dam also has a down-valley gradient perpendicular to the dam axis. This may be evidence for underseepage through the grout curtain, although the lower water level elevations compared to the northeast side indicate less hydraulic connection.

A component of water-level increases and decreases in the evaporite zone is caused by loading on the confined St. Louis Limestone by the volume of water in Lake Red Rock. However, loading is considered to have a minimal impact on observation well water-level analysis in this study. During the 28-ft increase in the level of Lake Red Rock from March 30 to July 9, 1990, the range in water levels measured in observation wells completed in the evaporite zone along the axis of the dam was 7.1 to 25.1 ft (fig. 22). Assuming uniform loading on the unit, the maximum ratio (ΔL) of water-level increase measured in bedrock observation wells caused by the loading effect to the total water-level increase of the reservoir can be calculated:

$$\Delta L = (\Delta Wm / \Delta R) \quad (3)$$

where ΔWm is the minimum measured water-level increase in a bedrock observation well along the axis of the dam during the period (7.1 ft) and ΔR is the increase in reservoir level during the period (28 ft). In this example, loading from the 28-ft increase in reservoir level causes a water-level increase in a bedrock observation well of not more than 7.1 ft, and water-level increases greater than this value represent hydraulic connection and leakage from Lake Red Rock. Actual loading efficiency is between 0 and 0.25, because reservoir leakage could be causing some or all of the 7.1-ft water-level change that occurs. In the absence of comprehensive rock properties for the limestone unit or daily hydrographs for the observation wells to monitor detailed reservoir level effects, the approximation of 0.25 for loading efficiency of the competent limestone unit is a reasonable estimate.

A contour map of the change in water levels from March 30, 1990, to July 9, 1990, in observation wells completed in the evaporite zone indicates areas of hydraulic connectivity to the reservoir (fig. 22). Observation wells in proximity to a source of underseepage should have the largest magnitudes of water level changes. The rise in the reservoir level during this period was 28.2 ft; more than 90 percent



EXPLANATION

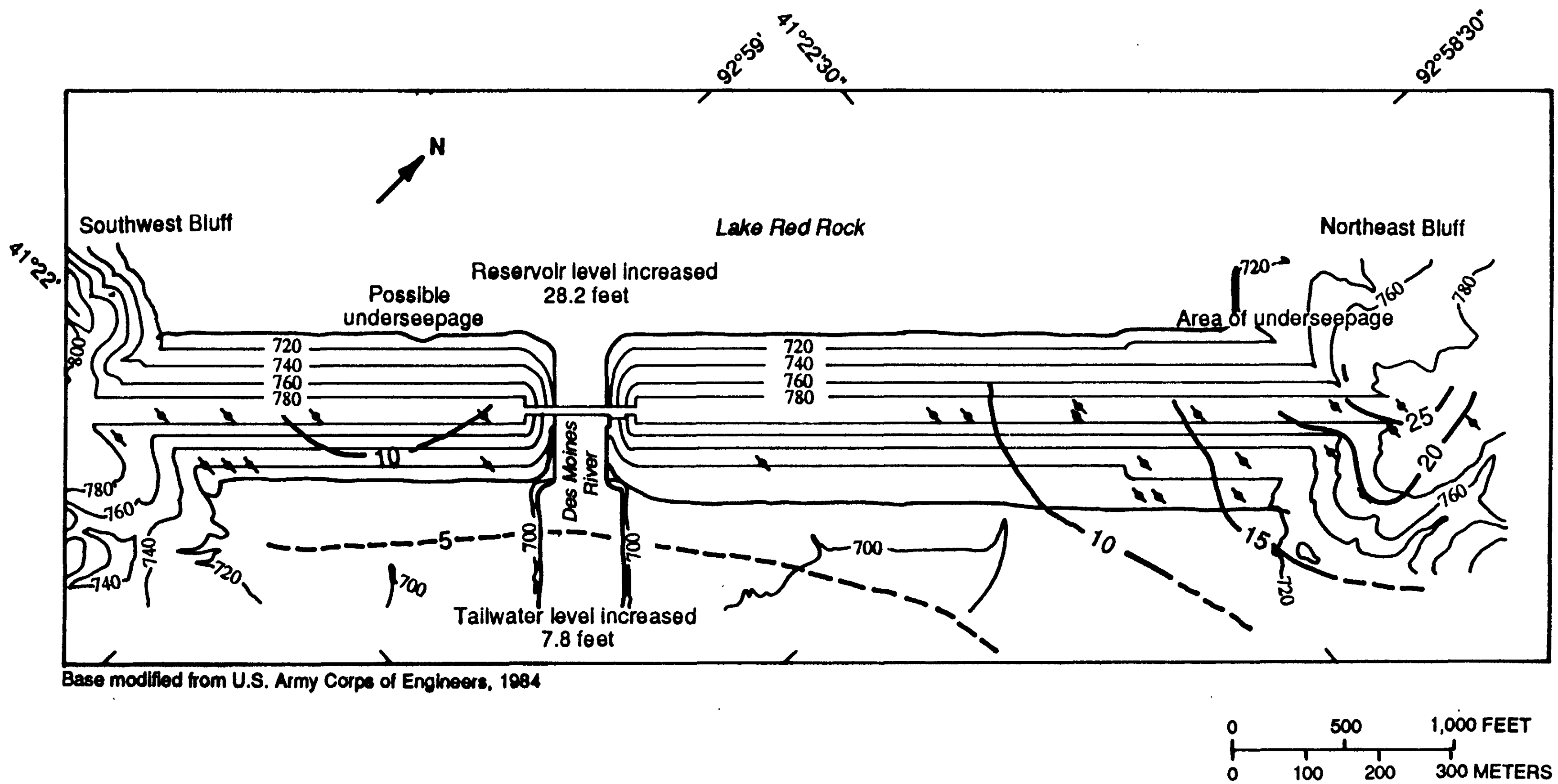
700 — POTENTIOMETRIC CONTOUR--Shows elevation, in feet, at which water level would have stood in tightly cased wells. Dashed where approximately located. Interval is 5 feet. Datum is sea level

SURFACE-WATER LIMIT--Hachures toward surface water

GENERALIZED DIRECTION OF GROUND-WATER FLOW

OBSERVATION WELL

Figure 21.--Potentiometric surface in the evaporite zone of the St. Louis Limestone, July 9, 1990.



EXPLANATION

—10 — — LINE OF EQUAL WATER-LEVEL CHANGE--Dashed where approximately located. Interval is 5 feet

OBSERVATION WELL

Figure 22.--Change in water level from March 30-July 9, 1990, in the evaporite zone of the St. Louis Limestone.

of this change (26 ft) occurred in wells R-87-1, R-87-2L, and 1-R. Well 1-R is located downstream from the grout curtain of the dam, whereas wells R-87-1 and R-87-2L are located upstream from the dam axis in proximity to the grout curtain. The largest water-level change on the southwest side of the dam was only 11.1 ft in well 11-R. Water-level changes increase in a northeast direction from well R-87-4 to well 1-R, providing further evidence that the grout barrier may be ineffective on the extreme northeast side of the dam.

The contour map of the change in water levels in overburden wells for March 30, 1990, to July 9, 1990, illustrates the largest changes occurring on the northeast side of the dam (fig. 23). Water levels in well 30-O and well 22-O, located on the northeast side of the dam, increased 20.6 ft and at least 24.5 ft, while the largest change on the southwest side of the dam was 6.9 ft. The tailwater change during this period was 7.8 ft. Water levels in overburden observation wells located on the southwest side of the river valley or on the northeast side of the valley near the control structure likely are affected by tailwater level changes, because this is the area of highest correlation to changes in tailwater.

The anomalous changes in water levels in bedrock and overburden observation wells on the northeast side of the dam appear to result from a hydraulic connection to Lake Red Rock rather than to climatological effects. Wells R-88-2 and R-88-3 are completed in the shale bedrock of Pennsylvanian age in the northeast bluff updip of the reservoir and experienced water-level changes of -9.5 ft and 3.8 ft from March 30, 1990 to July 9, 1990. The water levels in these shallow observation wells reflect climatological effects more than the other bedrock observation wells. Well R-88-2 is located at a ground-surface elevation of 799.7 ft with the base of its well screen at an elevation of 761.2 ft. Well R-88-3 is located at a ground surface elevation of 790.6 ft with the base of its well screen at an elevation of 740.6 ft. Locations of both wells are distant enough and completion interval elevations are high enough to be indicative of water-table conditions above the zone of influence of the reservoir.

The magnitude of the changes in water levels in the overburden wells generally is less than that in the evaporite-zone wells in the river valley; the magnitude of changes is similar between the overburden and evaporite-zone wells in the northeast bluff. The potential for upward movement of ground water in the river valley from the bedrock aquifer to the overburden becomes greater with increased reservoir levels. Conversely, in the northeast bluff, the potential for downward ground-water movement from the overburden to the bedrock aquifer becomes greater with increased reservoir levels.

By subtracting the value of the potentiometric surface in well R-87-2L (completed in the evaporite zone) from the value of the potentiometric surface in well R-87-2U (completed in the upper bedrock) and comparing to reservoir elevation (fig. 24), a relation between reservoir levels and potential ground-water flow direction can be shown. When elevations of water levels in the evaporite zone are greater than those in the upper bedrock at low reservoir levels, ground-water flow is upward (positive values in fig. 24); when elevations of water levels in the upper bedrock zone are greater than those in the evaporite zone, ground-water flow is reversed downward (negative values in fig. 24).

At high reservoir levels in the vicinity of wells R-87-2L and R-87-2U in the northeast bluff, shallow ground water moves downward into the evaporite zone of the St. Louis Limestone. Hydrogeologic section D-D' (plate 1) traverses the northeast bluff from the reservoir side of the dam through the dam axis and terminates downstream from the dam in the river valley. The idealized ground-water flow system is depicted on the northeast side of the dam on July 9, 1990, when the reservoir elevation was 764.4 ft. On the upstream side of the dam, there is downward flow from the overburden into the bedrock and through the grout curtain. Downstream from the dam in the river valley, the ground-water flow system converts to upward flow from the bedrock into the overburden.

The downward flow of ground water from the glacial sands into the bedrock demonstrates a flow path for reservoir water to enter the deep ground-water system in the northeast bluff and contribute to the formation of the anomalous recharge area evident on the potentiometric surface of the evaporite

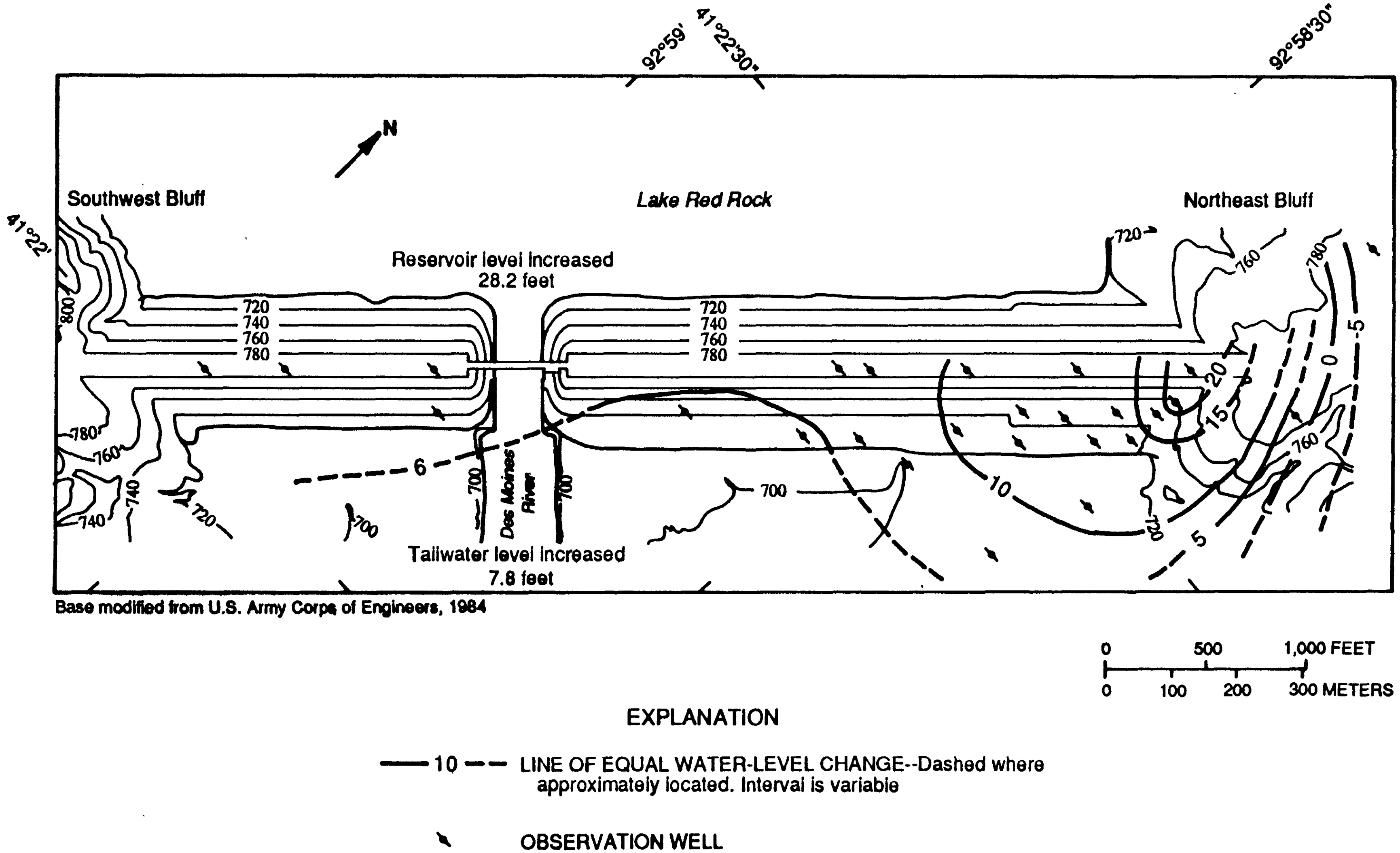


Figure 23.--Change in water level from March 30-July 9, 1990, in the overburden.

zone in this area (fig. 21). However, the distribution of anomalous changes in water levels in the evaporite-zone wells between March 30, 1990, and July 9, 1990, in the northeast part of the river valley as well as the northeast bluff (fig. 22) indicates that there are additional areas of hydraulic connection between the reservoir and the evaporite zone, in addition to the path through the glacial materials in the northeast bluff.

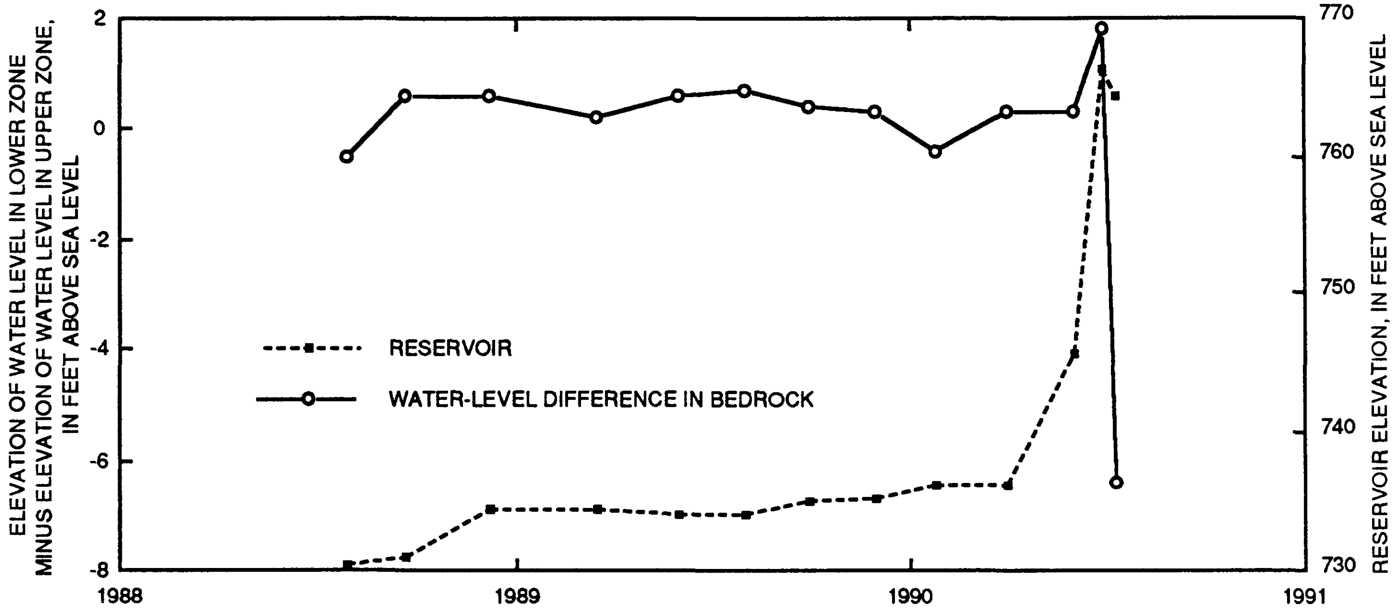


Figure 24.--Differences between water-level elevations in the lower and upper bedrock zones of the St. Louis Limestone, with the elevation of the reservoir, July 1988 - July 1990.

Geochemistry

Increases and decreases in water-levels observed in wells on the northeast side of the dam site are thought to be caused by fluctuations in reservoir levels rather than by short-term climatic conditions or a simple pressure response to loading by Lake Red Rock on the ground-water system. Geochemical data are presented to demonstrate that ground-water flow is present in selected areas of the northeast side of the dam that likely results from underseepage of reservoir water through the shallow bedrock and grout curtain. Results of chemical analyses for water samples collected from selected observation wells, the reservoir, and tailwater from April 1987 through July 1990 are listed in table 3.

Water Composition

Trilinear diagrams were used to distinguish water types and to develop possible mixing relations among the various water sources in the area (Hem, 1985). Water types in the lower bedrock of the St. Louis Limestone and in the reservoir for the sampling period April 1987 to July 1990 are shown in figure 25. A calcium bicarbonate water occurs in the cavity zone above the basal evaporite zone in well 5-RB and a calcium sulfate water occurs in the basal evaporite zone in well 23-R. Water-quality data for the reservoir and tailwater samples indicate a calcium bicarbonate water type with a larger percent of chloride and magnesium ions than in the observation wells. The water-quality data for well R-87-4, which is completed in an evaporite bed (at a similar stratigraphic horizon as well 23-R) near the grout curtain of the dam foundation, plot between the two dominant water types on the trilinear diagram. The occurrence of a unique water type in the foundation of the dam indicates abnormal hydrogeologic conditions and the possibility of a complex mixing of water types.

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*

[Concentration data in milligrams per liter, except as indicated; Well, observation well; Temp, temperature, in degrees Celsius; Ca, calcium; Mg, magnesium; Na, sodium; K, potassium; HCO_3, bicarbonate; SO_4, sulfate; Cl, chloride; F, fluoride; RES-B, reservoir sample collected 1 meter above the bottom, RES-S, reservoir sample collected at a depth of 1 meter below the surface; TAILWTR, tailwater sample collected from the river 2,000 ft downstream from the control structure; reservoir samples are collected 100 meters upstream of the dam approximately 100 meters from the northeast shore; --, no data; to convert milligrams per liter to milliequivalents per liter, multiply Ca x 0.04990, Mg x 0.08229, Na x 0.04350, K x 0.02558, HCO_3 x 0.01639, SO_4 x 0.02082, Cl x 0.02821, F x 0.05264 (from Hem, 1989)]

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
23-R	4/15/87	13.0	7.20	320	30.5	17.2	3.2	268	666	19.7	0.36
	5/28/87	14.7	7.20	327	25.5	14.5	2.7	269	695	19.6	.51
	6/25/87	14.8	7.06	318	30.3	12.3	2.3	255	533	19.3	.40
	8/27/87	14.2	7.28	335	26.5	13.3	2.2	262	635	19.0	.34
	9/17/87	14.6	7.07	304	25.6	12.2	1.9	268	657	19.0	.34
23-R	10/27/87	13.3	7.22	286	27.2	11.7	2.0	262	556	18.0	.38
	11/10/87	13.2	7.24	326	26.8	12.1	1.9	262	646	16.0	.48
	12/10/87	12.9	7.15	328	24.1	13.4	2.1	270	670	18.0	.44
	3/01/88	12.8	6.84	312	29.1	12.3	2.1	271	634	17.7	.22
	4/13/88	13.2	7.15	418	30.3	13.6	2.3	276	778	18.7	.43
23-R	5/12/88	13.4	7.09	345	29.1	13.0	2.1	276	687	19.4	.36
	6/16/88	13.6	6.97	344	28.6	12.6	2.1	272	683	19.2	.31
	7/14/88	13.9	6.88	318	31.7	13.1	2.2	274	610	19.0	.31
	8/17/88	14.2	6.84	304	30.6	12.6	2.0	269	608	20.0	.44
	9/22/88	13.7	6.95	264	29.4	13.2	2.3	260	619	21.1	.39
23-R	10/18/88	12.9	6.82	275	29.4	13.3	2.3	256	565	22.2	.34
	11/15/88	13.4	6.81	300	28.2	13.6	2.7	257	606	23.5	.41
	12/13/88	12.6	6.81	290	28.3	14.0	2.2	253	541	23.8	.43
	1/17/89	12.6	6.79	280	26.4	14.1	2.0	254	555	24.3	.31
	2/21/89	12.3	6.87	293	29.1	15.5	3.0	249	538	26.5	.40
23-R	3/14/89	12.4	6.97	300	28.3	15.8	2.4	255	573	26.8	.39
	4/11/89	12.6	7.13	294	28.2	18.1	2.9	253	584	27.2	.47
	5/19/89	13.2	6.94	302	28.3	19.0	2.4	247	558	27.6	.50
	6/15/89	13.1	7.02	296	26.5	20.7	2.2	243	596	28.4	.41
	7/13/89	14.0	7.06	295	26.1	17.9	2.4	239	577	28.6	.39
23-R	8/10/89	14.0	7.03	274	25.4	18.1	2.4	232	551	28.2	.42
	9/07/89	15.4	6.89	308	24.1	18.4	2.6	225	608	28.3	.42
	11/14/89	13.1	6.95	288	25.4	16.5	2.6	224	551	26.5	.39
	1/09/90	12.8	6.89	266	21.5	15.4	--	231	540	26.7	.45
	2/13/90	12.6	7.00	313	21.6	15.8	2.1	238	641	27.1	.43

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*--Continued

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
23-R	3/12/90	13.6	7.02	322	23.7	16.3	2.1	218	620	28.2	0.40
	4/17/90	12.4	7.07	324	23.8	20.3	2.5	220	630	28.0	.44
	5/10/90	13.0	7.15	326	25.1	24.5	2.2	226	588	27.0	.40
	6/14/90	14.6	6.80	296	22.7	23.2	2.4	225	553	27.3	.42
	7/12/90	13.6	7.02	261	23.2	21.4	2.7	227	490	23.4	.40
29-O	5/28/87	14.2	7.11	123	32.2	13.1	2.2	406	64	22.9	.42
	6/25/87	13.8	7.18	130	32.9	13.6	2.2	390	60	22.1	.40
	8/27/87	13.4	7.18	129	33.2	13.7	2.5	409	60	22.0	.33
	10/27/87	12.2	7.09	126	33.5	13.2	2.6	411	58	22.0	.41
	12/10/87	11.9	7.24	128	33.1	14.5	2.6	413	55	21.0	.42
29-O	3/01/88	11.8	6.96	128	32.4	13.3	2.6	417	59	22.3	.24
	3/29/88	11.0	7.04	127	35.0	13.5	2.6	405	57	21.9	.34
	4/13/88	12.2	7.15	129	33.7	13.6	2.5	411	57	22.0	.48
	5/12/88	12.3	7.21	130	32.5	13.1	2.2	413	53	21.9	.39
	6/16/88	12.6	7.10	132	33.5	13.2	2.5	408	53	22.7	.31
29-O	7/14/88	12.8	6.97	132	33.2	13.7	2.5	400	53	22.4	.33
	8/17/88	13.3	6.88	125	32.4	13.3	2.3	393	52	22.2	.45
	9/22/88	13.2	7.01	126	32.7	13.0	2.7	401	53	22.7	.38
	10/18/88	12.4	6.96	126	33.4	13.2	2.6	393	48	22.5	.34
	11/10/88	12.2	7.12	131	33.2	13.6	2.7	392	57	23.0	.50
29-O	11/15/88	12.7	6.87	128	32.6	13.3	3.2	393	56	23.6	.40
	12/13/88	12.1	6.83	126	32.9	12.9	2.4	395	55	23.3	.41
	1/17/89	11.8	6.93	122	30.2	12.6	2.2	397	54	23.1	.28
	2/21/89	11.4	6.97	126	33.1	13.8	3.0	398	53	23.5	.37
	3/14/89	11.5	7.08	127	33.4	14.0	2.5	402	54	22.8	.37
29-O	4/11/89	11.5	7.00	125	32.9	14.3	3.1	401	54	24.1	.46
	5/19/89	12.0	6.95	125	38.0	14.2	2.5	393	55	23.7	.48
	6/15/89	12.0	6.93	125	32.5	15.9	2.5	388	56	25.4	.39
	7/13/89	13.0	7.04	125	32.9	14.4	2.6	388	57	26.1	.35
	8/10/89	13.2	6.98	125	32.9	14.6	2.9	390	56	26.1	.38
29-O	9/07/89	13.4	6.77	129	32.3	14.9	3.2	386	54	26.5	.39
	10/26/89	13.0	6.97	121	35.1	15.5	2.5	392	53	25.9	.35
	11/14/89	12.7	7.07	126	33.1	14.7	2.8	392	53	26.5	.37
	12/12/89	11.7	7.02	124	34.3	14.2	2.9	389	53	26.4	.38
	1/09/90	11.8	6.96	118	30.2	14.6	2.1	393	51	26.6	.42
29-O	2/13/90	11.4	6.91	106	31.8	13.9	2.8	413	53	26.6	.39
	3/12/90	12.2	6.88	120	30.7	14.9	2.3	363	49	27.0	.37
	4/17/90	10.4	7.11	116	31.4	21.2	2.7	368	50	26.3	.40
	5/10/90	11.7	7.12	127	32.9	17.0	2.4	388	52	26.0	.36
	6/14/90	13.3	6.89	122	30.6	19.6	2.9	385	54	27.8	.41

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*--Continued

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
29-O	7/12/90	13.1	6.84	116	30.6	25.1	2.8	379	52	28.2	0.44
30-O	4/15/87	12.2	6.80	68	33.0	9.0	0.7	198	76	18.6	.22
	5/28/87	14.6	6.78	71	33.3	8.2	0.5	212	82	20.0	.29
	6/25/87	14.9	6.76	76	35.2	9.0	0.7	209	85	22.6	.25
	7/30/87	15.2	6.77	79	37.6	9.5	0.6	217	88	19.0	.25
	8/27/87	13.0	6.81	79	37.0	8.9	0.6	215	89	24.0	.23
30-O	9/17/87	13.5	6.75	92	40.0	9.0	0.6	247	93	25.0	.22
	10/27/87	12.4	6.71	78	37.9	8.8	0.7	213	103	28.0	.25
	11/10/87	12.1	6.78	80	36.7	9.1	0.6	218	107	29.0	.29
	12/10/87	11.9	6.66	82	39.6	10.0	0.6	222	104	28.0	.28
	3/01/88	12.2	6.74	80	38.5	9.5	0.5	226	98	25.5	.14
30-O	3/29/88	11.5	6.65	79	37.7	9.4	0.6	228	97	25.9	.16
	4/13/88	12.8	6.75	84	40.4	9.7	0.6	228	101	26.7	.27
	5/12/88	12.7	6.71	88	40.7	10.2	0.6	228	114	25.2	.26
	6/16/88	12.8	6.60	87	41.4	10.3	0.5	228	110	25.3	.20
	7/14/88	12.8	6.36	89	42.9	10.3	0.6	229	108	25.1	.22
30-O	8/17/88	13.2	6.50	88	42.2	9.8	0.5	237	114	26.1	.32
	9/22/88	12.6	6.46	90	42.4	10.7	0.7	236	132	27.2	.25
	10/18/88	12.2	6.41	91	45.5	10.7	0.5	240	134	27.5	.21
	11/15/88	12.4	6.46	93	42.8	10.8	0.8	253	128	29.4	.22
	12/13/88	11.9	6.38	93	43.8	10.6	0.6	251	125	29.1	.26
30-O	1/17/89	12.0	6.23	100	42.3	9.9	0.5	249	129	29.6	.22
	2/21/89	11.4	6.51	98	45.8	10.7	0.7	248	128	30.7	.22
	3/14/89	11.9	6.48	100	46.2	10.4	0.6	255	130	30.5	.21
	4/11/89	12.2	6.78	98	46.1	10.8	0.6	255	131	29.1	.28
	5/19/89	12.8	6.59	100	47.0	10.0	0.6	257	136	30.0	.29
30-O	6/15/89	12.4	6.59	100	47.9	11.8	0.7	260	135	30.5	.23
	7/13/89	13.0	6.65	108	47.0	10.1	0.6	274	136	30.7	.21
	8/10/89	13.2	6.73	107	47.5	10.7	0.9	269	140	30.3	.23
	9/07/89	12.6	6.45	111	46.7	10.9	1.0	266	137	30.6	.23
	10/26/89	12.7	6.55	98	50.4	11.0	0.7	266	136	28.8	.19
30-O	11/14/89	12.4	6.46	106	48.7	10.9	0.9	253	139	28.5	.19
	12/12/89	12.2	6.61	96	49.0	10.0	1.0	262	139	28.5	.24
	1/09/90	11.8	6.91	98	44.1	11.0	0.7	274	137	30.0	.24
	2/13/90	11.4	6.45	82	48.0	8.7	0.7	282	143	27.4	.22
	3/12/90	13.2	6.49	104	46.9	9.9	0.6	250	145	27.0	.21
30-O	5/10/90	15.5	6.67	112	47.5	14.6	0.6	258	137	25.1	.21
	6/14/90	13.6	6.54	110	46.8	15.0	0.9	283	132	24.5	.24
	7/12/90	12.5	6.53	80	35.4	17.4	1.1	219	96	28.2	.22

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*--Continued

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
5-RA	5/28/87	14.2	7.16	307	38.2	316.0	5.8	185	1,370	34.8	0.57
	6/25/87	15.0	7.78	421	82.4	685.0	7.7	169	2,530	83.9	1.11
	8/27/87	13.6	7.98	428	114.0	840.0	9.4	183	3,180	106.0	1.18
	10/27/87	12.6	8.00	437	123.0	784.0	9.0	174	3,020	22.0	1.31
	11/10/87	12.6	7.92	446	123.0	861.0	9.8	157	3,089	105.0	1.86
5-RA	12/10/87	12.2	8.02	435	119.0	903.0	10.2	209	3,210	94.0	1.38
	3/01/88	11.8	7.17	297	66.0	355.0	6.4	187	1,860	74.0	.73
	3/29/88	11.5	7.53	415	115.0	755.0	8.8	197	2,910	98.3	1.28
	5/12/88	12.9	7.91	463	127.0	795.0	8.3	236	3,264	93.3	1.15
	6/16/88	13.4	7.62	519	124.0	848.0	8.9	223	3,177	93.2	1.38
5-RA	7/14/88	13.2	7.72	478	126.0	760.0	9.4	247	3,090	90.5	1.35
	8/17/88	13.4	7.43	444	122.0	793.0	9.0	237	3,110	88.8	1.60
	9/22/88	13.2	7.71	464	122.0	771.0	9.2	256	3,240	89.3	1.55
	10/18/88	12.3	7.58	436	125.0	734.0	9.1	246	3,390	107.0	1.40
	11/15/88	12.6	7.48	458	121.0	768.0	9.8	246	2,970	87.7	1.58
5-RA	12/13/88	11.8	7.44	458	117.0	747.0	9.0	251	2,920	84.6	1.65
	1/17/89	11.9	7.56	474	112.0	731.0	8.8	259	2,762	80.8	1.37
	2/21/89	11.6	7.52	468	117.0	731.0	9.7	258	2,842	81.2	1.63
	3/14/89	11.5	7.60	453	114.0	732.0	8.8	267	2,642	78.0	1.55
	4/11/89	12.1	7.66	481	114.0	740.0	9.7	278	2,689	73.1	1.75
5-RA	5/19/89	12.5	7.48	496	112.0	675.0	8.2	283	2,580	66.8	1.75
	6/15/89	12.4	7.36	487	86.8	581.0	8.1	299	2,320	52.3	1.30
	7/13/89	13.2	7.38	517	82.7	478.0	7.5	299	2,180	51.8	1.23
	8/10/89	12.9	7.24	533	86.1	463.0	7.1	302	2,122	50.0	1.17
	9/07/89	12. 7	6.99	536	63.0	339.0	6.5	304	1,830	37.4	.95
5-RA	10/26/89	12.8	7.30	516	57.1	288.0	5.6	303	1,685	32.3	.68
	11/14/89	12.0	7.18	544	50.1	252.0	5.0	303	1,591	29.5	.66
	12/12/89	12.1	7.26	526	47.9	186.0	3.2	302	1,518	28.7	.62
	1/09/90	11.8	7.13	352	40.1	228.0	3.7	310	1,432	28.2	.54
	2/13/90	11.6	7.03	519	40.8	215.0	4.7	320	1,327	27.6	.51
5-RA	3/12/90	12.6	7.06	609	40.6	141.0	3.9	278	1,438	27.2	.55
	4/17/90	11.8	7.10	536	42.4	170.0	4.5	290	1,520	27.7	.58
	5/10/90	12.4	7.08	574	43.2	378.0	4.2	299	1,508	27.9	.52
	6/14/90	13.0	7.18	572	40.9	202.0	4.5	306	1,464	26.7	.54
	7/12/90	12.2	7.01	322	29.4	73.5	6.8	365	601	25.9	.36
5-RB	4/16/87	12.7	6.92	117	27.6	13.4	3.5	335	92	21.9	.38
	5/28/87	14.6	7.06	114	27.6	13.0	3.4	339	88	18.3	.44
	6/25/87	14.2	7.14	122	28.0	13.4	2.8	314	90	21.0	.42
	8/27/87	14.0	7.11	124	28.2	13.1	3.0	338	87	22.0	.35
	10/27/87	12.5	6.98	122	29.5	13.2	3.0	341	79	21.0	.41

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*--Continued

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
5-RB	11/10/87	12.2	7.04	121	29.2	13.4	2.8	338	76	22.0	0.48
	12/10/87	12.2	7.06	122	28.4	14.5	3.0	346	73	22.0	.45
	3/01/88	12.2	6.93	114	27.2	13.3	2.5	337	70	20.4	.29
	3/29/88	11.6	6.96	114	29.6	13.3	2.8	326	74	20.1	.31
	4/13/88	12.6	7.02	115	28.5	13.4	2.6	333	72	20.1	.50
5-RB	5/12/88	12.8	7.13	120	27.5	13.6	2.9	331	70	20.7	.30
	6/16/88	12.9	6.99	120	28.7	12.9	2.7	328	69	21.1	.41
	7/14/88	12.7	6.90	122	28.8	13.5	2.8	334	70	21.0	.34
	8/17/88	13.2	6.79	118	29.0	13.0	2.2	337	73	22.0	.43
	9/22/88	13.0	6.94	120	28.4	12.8	3.0	346	69	21.6	.43
5-RB	10/18/88	12.3	6.85	121	29.7	13.3	2.9	341	64	22.5	.36
	11/15/88	12.6	6.88	121	30.2	13.3	3.3	342	71	22.4	.38
	12/13/88	12.1	6.74	120	29.6	13.2	2.9	342	70	22.3	.43
	1/17/89	12.2	6.78	117	28.2	13.1	2.8	343	68	22.4	.32
	2/21/89	11.8	6.80	121	30.5	14.0	3.6	351	66	23.6	.42
5-RB	3/14/89	12.0	6.97	120	30.0	13.4	2.8	353	66	23.4	.40
	4/11/89	12.2	7.06	120	30.1	15.1	3.4	351	66	23.6	.48
	5/19/89	12.4	6.85	130	34.2	14.5	2.9	356	70	24.2	.50
	6/15/89	12.4	6.84	126	30.4	16.5	3.0	357	71	25.2	.41
	7/13/89	12.9	6.88	125	31.0	14.4	3.2	364	79	26.1	.37
5-RB	8/10/89	13.0	6.83	131	31.0	14.5	3.1	366	77	26.6	.40
	9/07/89	12.7	6.62	132	30.8	15.2	3.3	358	80	26.7	.43
	10/26/89	12.8	6.81	128	32.5	16.0	3.1	367	76	25.7	.35
	11/14/89	12.4	6.90	131	31.0	14.5	3.3	366	76	26.5	.36
	12/12/89	12.3	6.89	135	31.9	16.0	2.0	361	69	28.4	.38
5-RB	1/09/90	12.0	7.02	122	28.1	15.4	2.2	366	63	28.4	.41
	2/13/90	11.6	6.74	105	28.5	13.6	3.5	378	63	27.9	.40
	3/12/90	12.8	6.79	128	28.7	15.5	2.6	340	63	28.4	.37
	4/17/90	12.2	6.84	124	29.4	20.0	3.1	358	60	27.7	.43
	5/10/90	12.5	7.20	139	30.6	17.8	2.8	360	65	27.3	.37
5-RB	6/14/90	13.4	7.22	130	28.5	19.2	3.1	372	71	27.2	.39
	7/12/90	12.3	6.68	151	29.4	37.4	3.7	387	104	24.9	.34
R-87-4	9/07/89	12.7	7.47	218	25.7	17.9	5.2	285	309	33.9	.34
	10/26/89	12.4	7.45	175	25.9	17.9	1.2	297	253	33.0	.32
	12/12/89	11.2	7.38	165	25.5	15.8	3.2	295	231	32.8	.36
	2/13/90	10.9	7.52	170	23.0	18.2	3.7	317	257	31.3	.38
	3/12/90	12.3	7.38	184	24.2	18.6	2.6	279	249	30.2	.36
R-87-4	6/14/90	12.8	7.40	186	22.8	21.9	3.6	298	242	30.9	.39
	7/12/90	12.1	6.73	196	28.0	18.9	3.0	310	275	31.6	.38

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*--Continued

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
R-88-2	6/14/90	15.5	7.80	67	35.0	42.0	4.1	333	120	11.0	--
R-88-3	6/14/90	13.7	7.50	130	30.0	12.0	4.2	433	100	18.0	--
R-88-4	7/12/90	12.5	6.94	114	30.8	17.4	2.6	360	53	27.9	0.44
RES-B	3/22/88	6.2	8.38	82	17.7	15.0	3.4	227	51	24.4	--
	4/05/88	10.9	8.25	78	24.6	15.4	2.7	231	51	22.0	--
	6/14/88	24.1	8.27	59	32.8	16.5	2.9	176	71	30.0	--
	7/12/88	25.2	7.60	66	32.3	18.6	3.0	192	69	30.1	--
	8/16/88	27.7	7.44	50	28.7	16.1	3.7	165	63	30.8	--
RES-B	9/20/88	19.4	7.40	53	28.6	26.9	5.2	172	71	35.1	--
	10/11/88	14.8	7.86	53	29.8	27.0	5.1	169	67	37.0	--
	11/08/88	6.7	8.15	61	28.7	28.0	6.3	184	80	38.8	--
	5/16/89	14.7	7.75	58	23.2	25.0	5.9	176	65	34.4	--
	6/13/89	20.6	7.67	56	22.2	22.0	5.4	159	62	31.1	--
RES-B	7/11/89	24.6	7.44	60	23.1	19.7	5.3	172	58	30.6	--
	8/08/89	24.9	7.99	48	23.0	21.7	6.1	156	57	31.7	--
	9/05/89	23.1	7.79	51	22.3	23.0	6.2	153	57	32.2	--
	10/24/89	11.3	8.30	47	19.0	18.9	3.6	143	49	25.2	--
	11/07/89	10.0	8.14	49	19.1	19.9	5.8	151	51	25.4	--
RES-B	4/10/90	7.5	7.86	78	23.9	22.4	4.6	186	55	30.4	.38
	5/08/90	15.7	8.08	66	22.6	18.8	4.5	164	55	28.2	--
	6/14/90	22.4	7.75	91	24.2	14.8	3.2	197	45	29.8	--
	7/12/90	23.0	7.00	48	12.8	6.2	4.4	127	--	12.0	--
RES-S	3/29/88	9.0	8.38	82	17.2	14.8	3.4	226	51	23.7	--
	4/13/88	13.7	8.41	81	25.4	15.0	2.6	227	52	23.3	--
	6/14/88	24.1	8.34	59	32.9	17.6	2.8	174	70	27.8	--
	7/12/88	27.5	8.20	64	32.2	18.6	3.2	187	69	30.1	--
	8/16/88	29.3	8.06	50	28.6	17.1	3.5	161	64	31.2	--
RES-S	9/20/88	19.8	7.81	53	28.6	24.7	4.9	168	69	34.7	--
	10/11/88	14.6	7.82	53	29.5	25.7	5.3	168	68	37.0	--
	11/08/88	7.5	8.14	61	29.5	28.1	6.1	186	78	38.6	--
	5/16/89	21.0	8.35	57	23.5	25.7	5.8	172	66	35.2	--
	6/13/89	22.1	7.88	56	22.4	22.3	5.4	159	63	30.5	--
RES-S	7/11/89	30.4	8.74	51	22.8	18.8	5.2	148	56	30.4	--
	8/08/89	25.8	8.5 8	49	22.9	20.3	5.5	148	56	30.3	--
	9/05/89	24.0	8.23	54	22.6	22.6	5.9	152	57	31.4	--
	10/24/89	13.0	8.50	46	18.7	19.5	3.8	141	48	24.9	--
	11/07/89	9.8	8.26	49	19.2	19.1	6.1	152	52	26.2	--

Table 3.--*List of chemical analyses for water samples collected from observation wells, reservoir, and tailwater at the Red Rock Dam, April 1987-July 1990*--Continued

Well or reservoir location	Date	Temp °C	pH (standard units)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F
RES-S	4/10/90	7.6	7.86	80	24.1	23.6	5.1	186	54	29.2	0.37
	5/08/90	16.4	8.18	82	22.4	21.2	4.3	162	56	27.9	--
	6/14/90	23.0	7.90	86	24.3	14.6	3.5	198	45	25.8	--
	7/12/90	26.7	7.49	54	14.4	6.7	4.3	137	--	13.8	--
TAILWTR	3/01/88	3.1	7.67	64	20.6	13.6	--	195	42	20.4	--
	3/22/88	8.2	8.28	82	18.3	15.7	3.4	227	50	27.4	--
	4/05/88	11.4	8.30	80	25.7	15.0	3.1	228	51	22.2	--
	5/09/88	21.1	8.26	72	32.7	16.4	2.6	198	77	28.4	--
	6/14/88	24.3	8.16	59	32.9	16.5	2.6	176	72	27.6	--
TAILWTR	7/12/88	27.0	8.14	66	31.7	18.4	3.4	191	69	29.9	--
	8/16/88	31.4	8.22	51	28.8	19.7	3.2	164	65	30.8	--
	9/20/88	20.8	8.08	53	28.4	25.3	5.0	167	69	34.7	--
	10/11/88	15.2	8.08	53	29.6	26.5	5.0	169	68	36.8	--
	11/08/88	7.9	8.29	60	29.1	28.2	6.4	184	80	38.4	--
TAILWTR	12/06/88	4.8	7.98	60	29.5	29.3	5.6	183	83	39.0	--
	1/10/89	1.8	7.96	68	30.0	28.4	5.3	208	88	41.8	--
	2/14/89	1.5	7.98	69	31.5	32.6	6.3	208	88	43.0	--
	3/07/89	2.4	7.57	74	30.5	35.0	6.3	222	89	46.2	--
	4/04/89	7.9	7.94	56	21.9	25.1	6.9	168	59	31.9	--
TAILWTR	5/16/89	16.5	7.94	57	23.8	24.8	5.7	174	65	34.4	--
	6/13/89	21.7	7.76	56	21.9	23.0	5.9	159	62	31.2	--
	7/11/89	26.5	7.77	65	23.0	19.8	5.5	174	57	30.6	--
	8/08/89	26.2	8.22	48	23.0	21.3	5.5	154	56	31.0	--
	9/05/89	25.0	8.06	61	23.2	23.2	6.1	155	58	31.9	--
TAILWTR	10/24/89	14.1	8.27	45	17.0	18.6	5.3	145	49	24.6	--
	11/07/89	10.1	8.16	49	19.2	18.8	5.7	146	51	26.0	--
	12/05/89	2.8	8.40	55	21.2	21.0	5.5	159	51	30.5	--
	1/09/90	6.0	7.85	63	23.9	32.4	5.8	204	88	40.5	--
	2/13/90	3.8	7.74	50	24.4	31.4	5.9	200	75	41.4	.43
TAILWTR	3/06/90	5.4	7.70	59	22.5	34.6	5.5	169	73	40.9	.37
	4/10/90	8.0	7.90	74	24.5	22.4	4.9	185	54	31.2	.36
	5/08/90	16.0	8.07	69	21.6	19.0	4.2	162	56	27.6	--
	6/14/90	22.4	7.69	85	24.1	16.9	3.5	198	45	26.3	--
	7/12/90	25.9	7.24	54	14.2	6.6	4.5	135	--	13.3	--

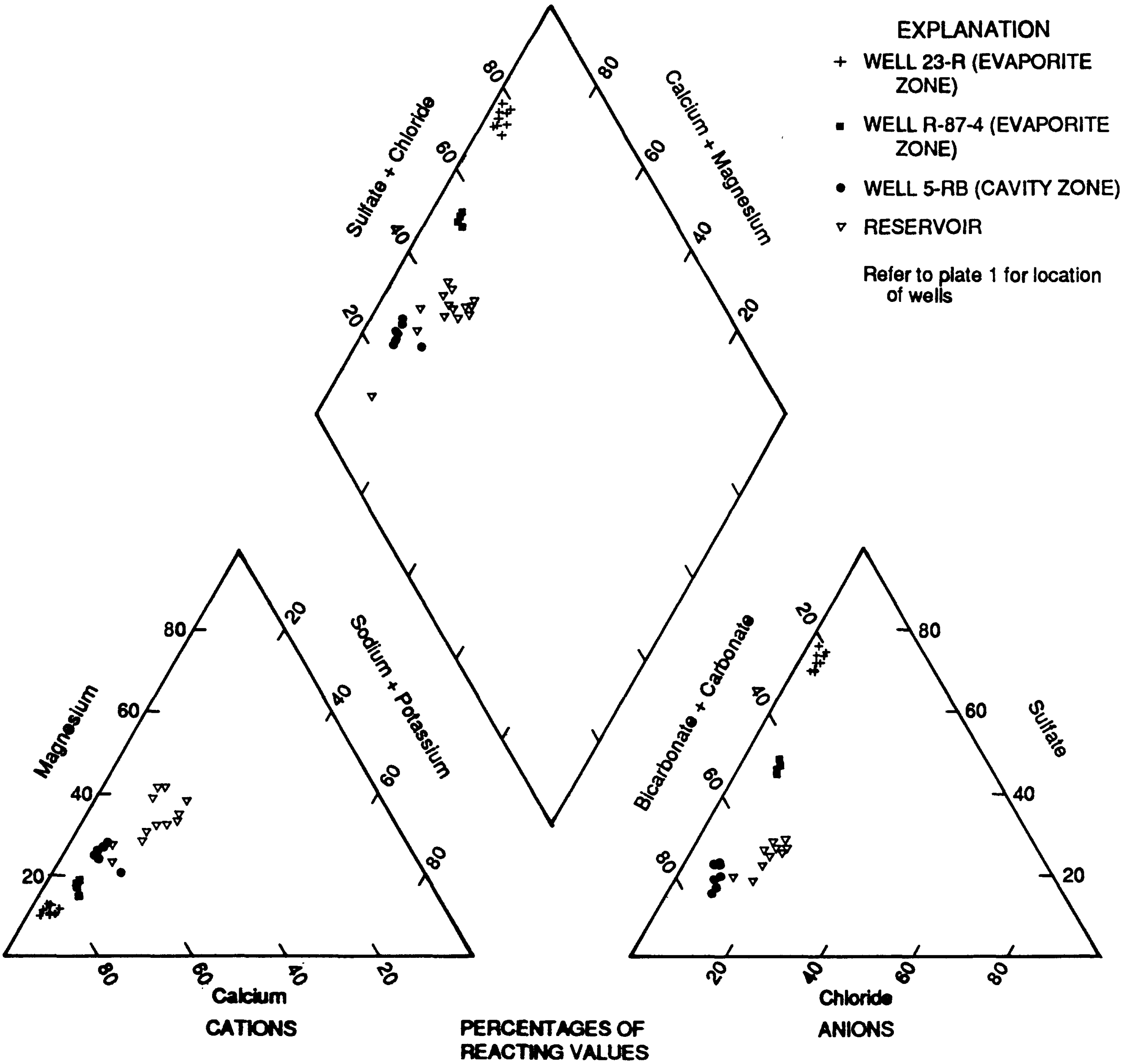


Figure 25.--Trilinear diagram showing water-quality data in samples from wells 23-R, R-87-4, and 5-RB, and reservoir sampled from April 1987-July 1990.

Water-composition data for the overburden wells and the reservoir sampled from April 1987 to July 1990 are presented in figure 26. Well 29-O is completed in the alluvial sand on the northeast side of the Des Moines River valley and well 30-O is completed in the glacial sands near the base of the bluff on the northeast side of the valley. Data for well R-88-3, completed in the shales of Pennsylvanian age of the northeast bluff at an elevation of 740.6 ft, are presented on this plot because the well is located upgradient from all bedrock and overburden observation wells. Water-quality data from well R-88-3 is important in determining if variations in water quality in observation wells on the northeast side of the dam are caused by downgradient movement of shallow ground water through the shales of Pennsylvanian age.

Hydrogeologic section E-E' (plate 1), which is constructed using water-quality wells sampled during June 1990, extends across the northeast side of the dam. The various water types that exist in the vicinity of the Red Rock Dam and their relation to the geologic units are illustrated. A calcium bicarbonate water (type I) occurs in the overburden, bedrock of Pennsylvanian age, and the cavity zone of the St. Louis Limestone, while a calcium sulfate water (type II) occurs in the basal evaporite zone of the St. Louis Limestone. Another water type, different from these two major types, exists in the vicinity of well R-87-4 in the basal evaporite zone near the grout curtain of the dam and is similar in composition to a mixture of the type I and type II waters. Either there could be a connection between the overlying cavity zone and the evaporite zone in the immediate area, or there could be a connection and flow of calcium bicarbonate water from a source some distance from the well bore.

The increased pressure head caused by the reservoir upstream from the dam could be forcing calcium bicarbonate waters into the lower evaporite zone of the St. Louis Limestone and subsequently through an ineffective grout curtain in the vicinity of well R-87-4. The ground-water flow system would have a downward flow component from the upper bedrock to the lower evaporite zone similar to that depicted on hydrogeologic section D-D' (plate 1) for the northeast bluff in the vicinity of wells R-87-2L and R-87-2U.

Although water-quality data for overburden wells indicate a calcium bicarbonate water type, there is a higher percent of magnesium and sulfate ions in well 30-O than in well 29-O during the sampling period (fig. 26). Magnesium and sulfate concentrations in water samples from well 30-O generally have increased since the water-quality monitoring program was initiated in April 1987 until July 1990 (fig. 27). Water from the bedrock of Pennsylvanian age apparently is not the source of increasing magnesium and sulfate ions at well 30-O. Well R-88-3, completed in the shale upgradient from well 30-O, has smaller concentrations (table 3) and percentages (fig. 26) of magnesium and sulfate than well 30-O.

The increasing sulfate and magnesium ion concentrations in the glacial sands of the overburden throughout the April 1987 to June 1990 water-quality sampling period are caused by upward movement of highly mineralized water from the bedrock. In the absence of a companion observation well monitoring bedrock water-levels at the location of well 30-O, the elevation of the water levels in the upper bedrock is estimated from the potentiometric gradient between upper bedrock wells 21-UR and 22-UR. By comparing the elevation of the reservoir (fig. 15) with the difference between the elevation of the potentiometric surface in the upper bedrock and that in the overburden for the period April 1987 to July 1990 (fig. 28), it is evident that the potentiometric surface in the upper bedrock generally is lower than the potentiometric surface in the overburden during high reservoir levels and is higher during low levels.

Low sulfate and magnesium concentrations in water samples collected from well 30-O in April 1987 probably resulted when highly mineralized ground water was flushed out of the overburden during the high reservoir levels in late 1986 (fig. 15), when the potentiometric surface in the overburden was higher than that in the bedrock (fig. 28) before the start of the water-quality sampling program. Drought conditions during 1988 and 1989 and subsequent consistently low reservoir levels resulted in highly mineralized water being continually discharged from the upper bedrock to the

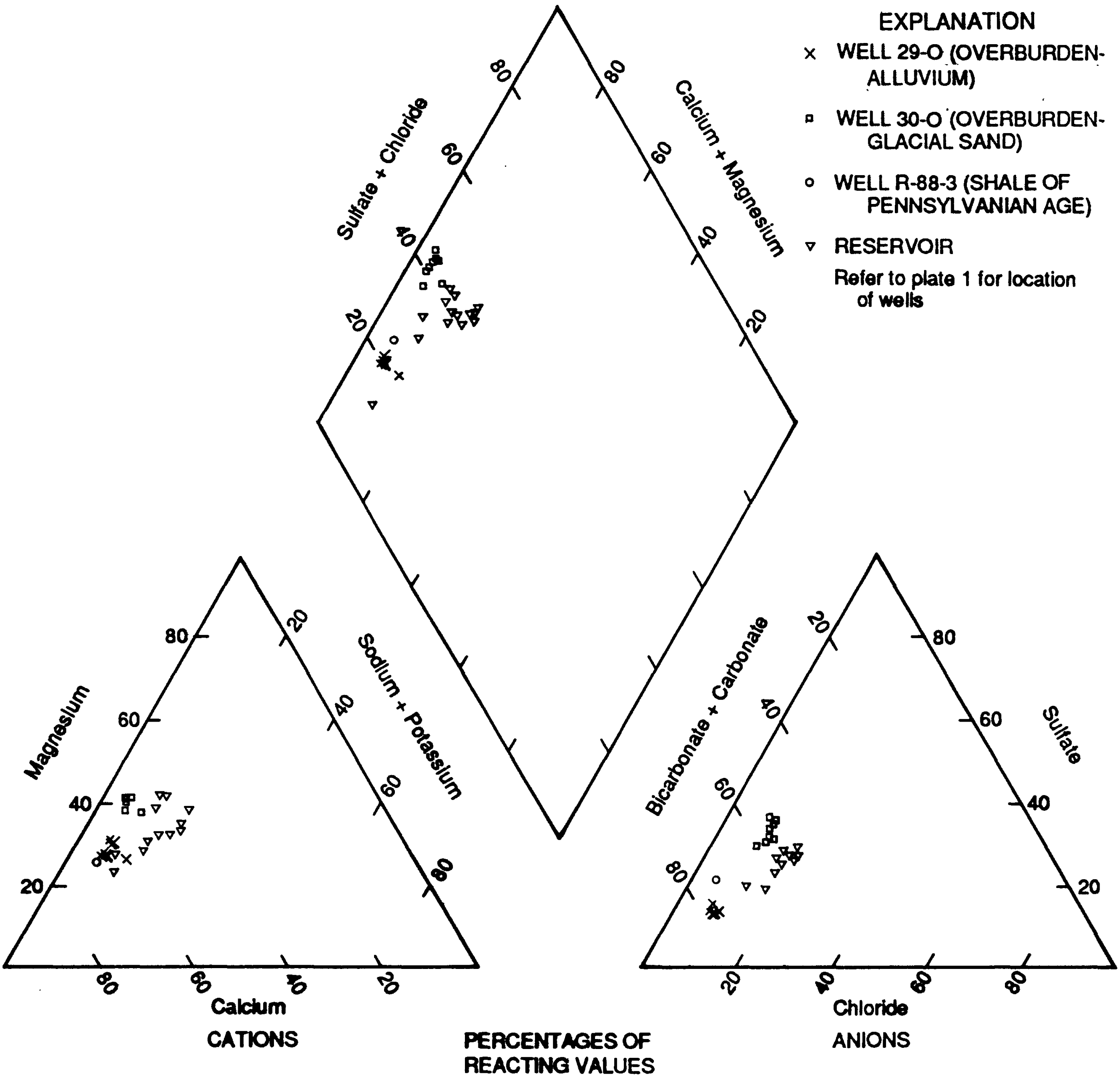


Figure 26.--Trilinear diagram showing water-quality data in samples from wells 29-O, 30-O, and R-88-3, and reservoir sampled from April 1987-July 1990.

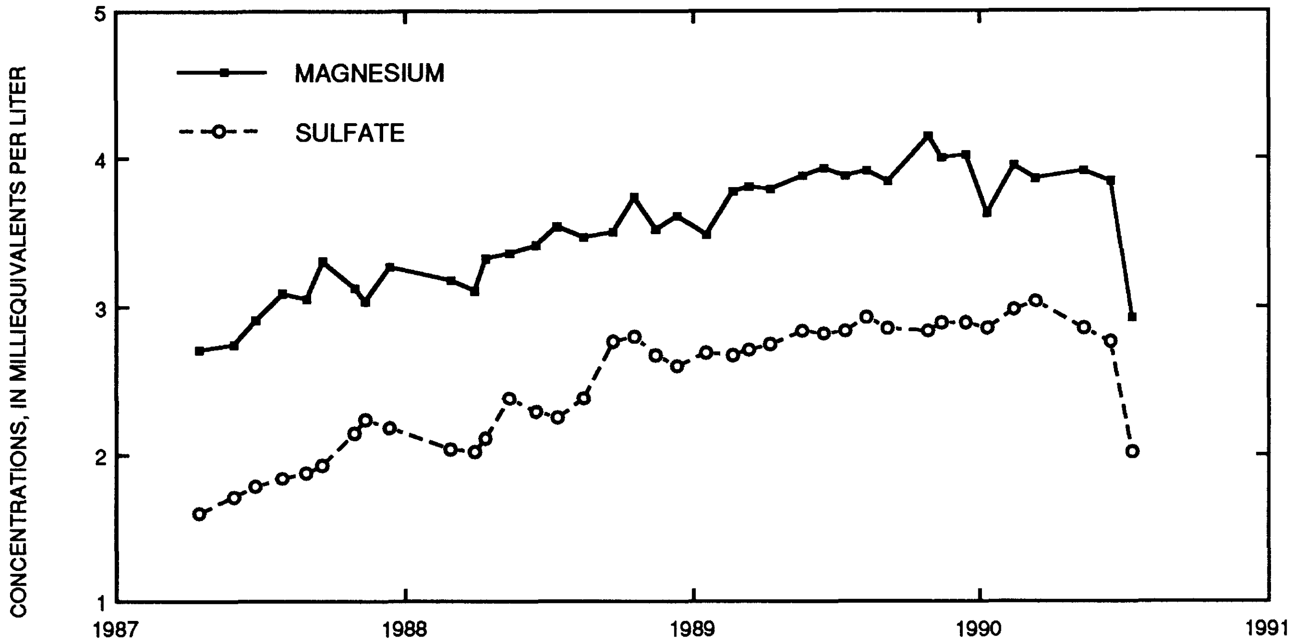


Figure 27.--Magnesium and sulfate concentration in samples from observation well 30-O (overburden-glacial sand), April 1987 - July 1990.

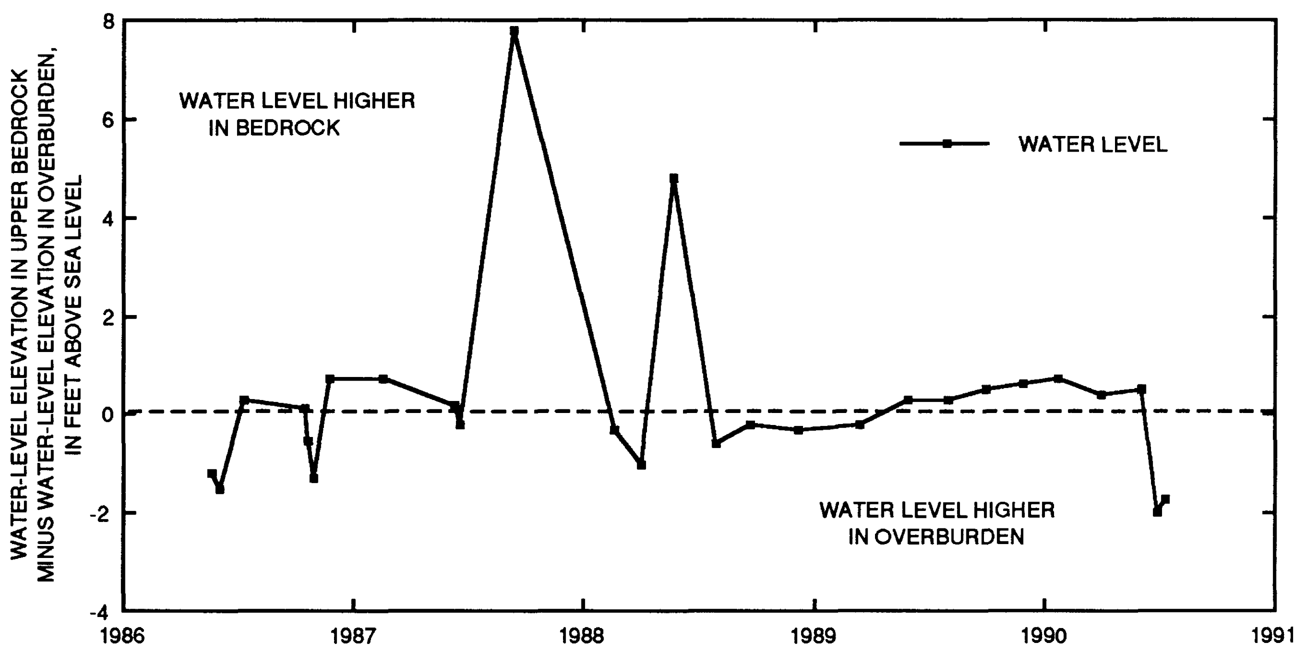


Figure 28.--Differences between water levels in the overburden and in the upper bedrock of the St. Louis Limestone at observation well 30-O (overburden-glacial sand), May 1986 - July 1990.

overburden in this area. In contrast, when the reservoir level increased to 766.3 ft during June 1990, the potentiometric surface in the overburden became higher than the potentiometric surface in the bedrock (fig. 28).

Some of the minor decreases in sulfate and magnesium concentrations in water-quality samples from well 30-O (fig. 27), evident during the general upward trend in concentrations of these ions since April 1987, correspond to changes in the relation between the potentiometric surface in the upper bedrock and the potentiometric surface in the overburden (fig. 28). It is apparent from decreases in sulfate concentration that less mineralized water entered the glacial sands of the overburden in February 1988, July 1988, November 1988, and June 1990. Out of these four periods, a corresponding increase in the elevation of the reservoir occurred in July 1988, November 1988, and June 1990. The elevation of the potentiometric surface in the overburden is increased by rising pool levels, and highly mineralized water that is being discharged to the overburden from the bedrock is temporarily flushed from the system and replaced by inflowing fresher water from Lake Red Rock. The similarity of the water composition in well 30-O to the reservoir water, as shown on the trilinear diagram in figure 26, supports the interpretation that the source of the fresh water is the reservoir. Geochemical data from water samples obtained from well 30-O imply that changing reservoir levels affect the water quality in the overburden of the northeast bluff.

A corresponding increase in reservoir level did not occur in February 1988, when a decrease in sulfate concentration was shown by analytical results from water-quality samples collected from well 30-O. Possibly complex ground-water flow paths in the upper bedrock in the northeast bluff cause anomalous distribution of ground water, drought conditions during this period altered ground-water discharge from the confined bedrock aquifer, or the estimated value for the potentiometric surface at the location of well 30-O was in error for this time period.

Chloride Tracer

The chloride ion is conservative in near-surface hydrologic systems and can be used as a natural tracer if there are no lithologic sources of chloride and mechanisms affecting concentration are known (Claassen and others, 1986). The most likely external source of chloride causing periodic increases and decreases in ground-water chloride concentration is Lake Red Rock. Assuming that reservoir water is the only varying source of the chloride ion in the immediate vicinity of the dam site, and that lithologic sources are not significant, the chloride ion can be used as a natural tracer in the ground-water system at Red Rock Dam.

Chloride minerals may be disseminated within the evaporite deposits in the St. Louis Limestone. During the initial months of the water-quality sampling program, chloride concentrations in the evaporite zone of the St. Louis Limestone at well 5-RA were as high as 100 mg/L (table 3). Chemical analyses from well 5-RA prior to June 1989 may be representative of formation water in the evaporite deposits. If the increase in chloride concentration in the ground water results from release of chloride ions through dissolution of the evaporite deposits, then changes in chloride concentration should be accompanied by changes in sulfate concentration. Sulfate concentration in well 23-R decreases while chloride concentration increases (fig. 29), so the chloride ions causing the large variations in concentration in the ground water are not derived from the evaporite deposits.

The concentration of chloride generally is greater in the reservoir water than in water samples obtained from observation wells 23-R (fig. 30), 5-RB (fig. 31), 30-O (fig. 32), 29-O (fig. 33), and R-87-4 (fig. 34) from April 1987 to July 1990 during the water-quality monitoring period. If the reservoir is the primary source of chloride ions for shallow ground water, it would be expected that the mean concentration of chloride in the ground water would be similar to the mean concentration in the surface water over an extended period of years. The apparent greater concentrations in surface water compared to ground water during the sampling period probably result from dry climatic conditions prior to the spring of 1990 and the lack of dilution of the chloride concentration in streamflow and,

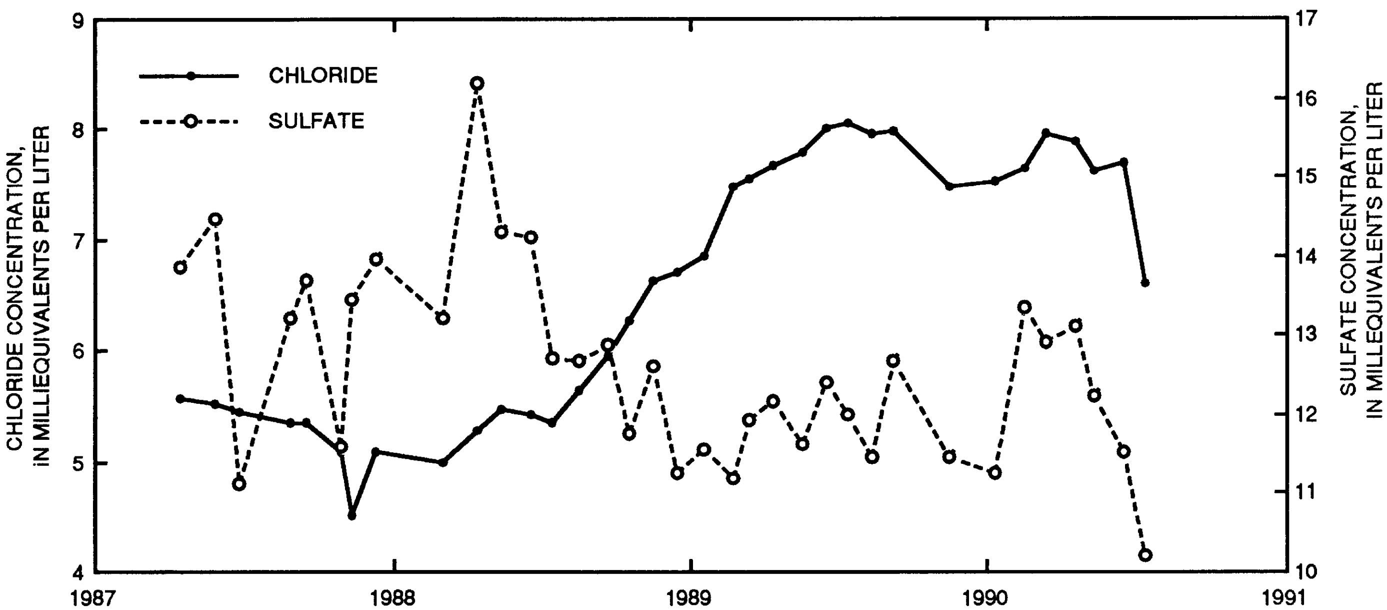


Figure 29.--Chloride and sulfate concentration in samples from observation well 23-R (evaporite zone), April 1987 - July 1990.

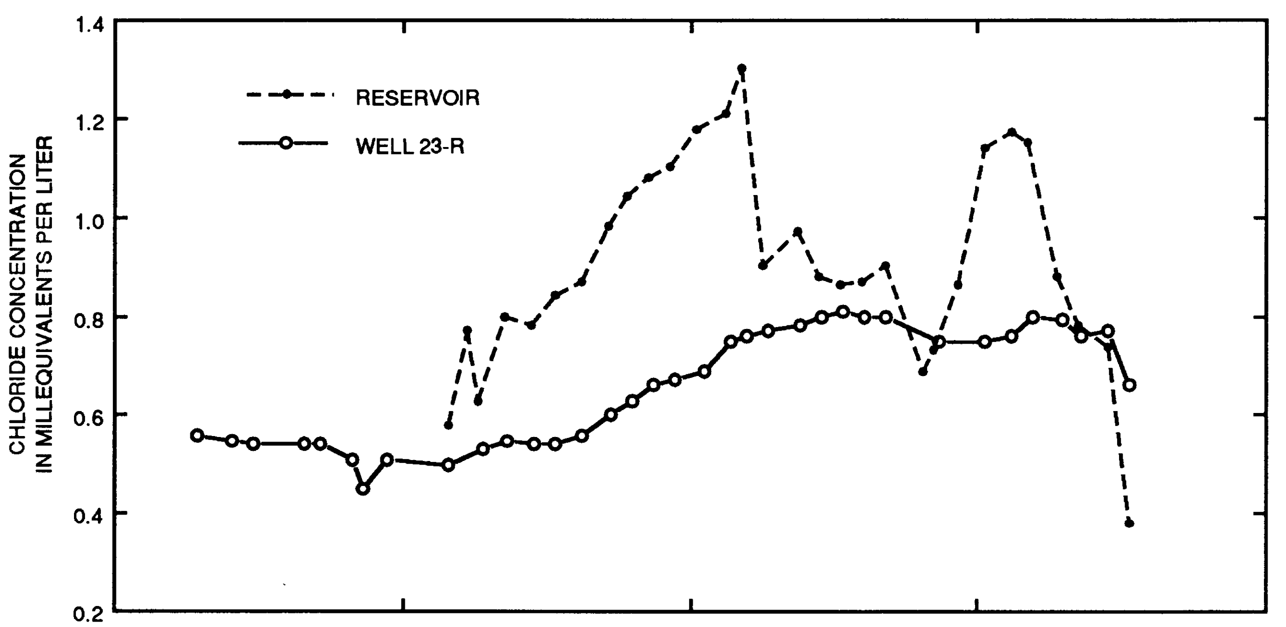


Figure 30.--Choride concentration in samples from reservoir and observation well 23-R (evaporite zone), April 1987 - July 1990.

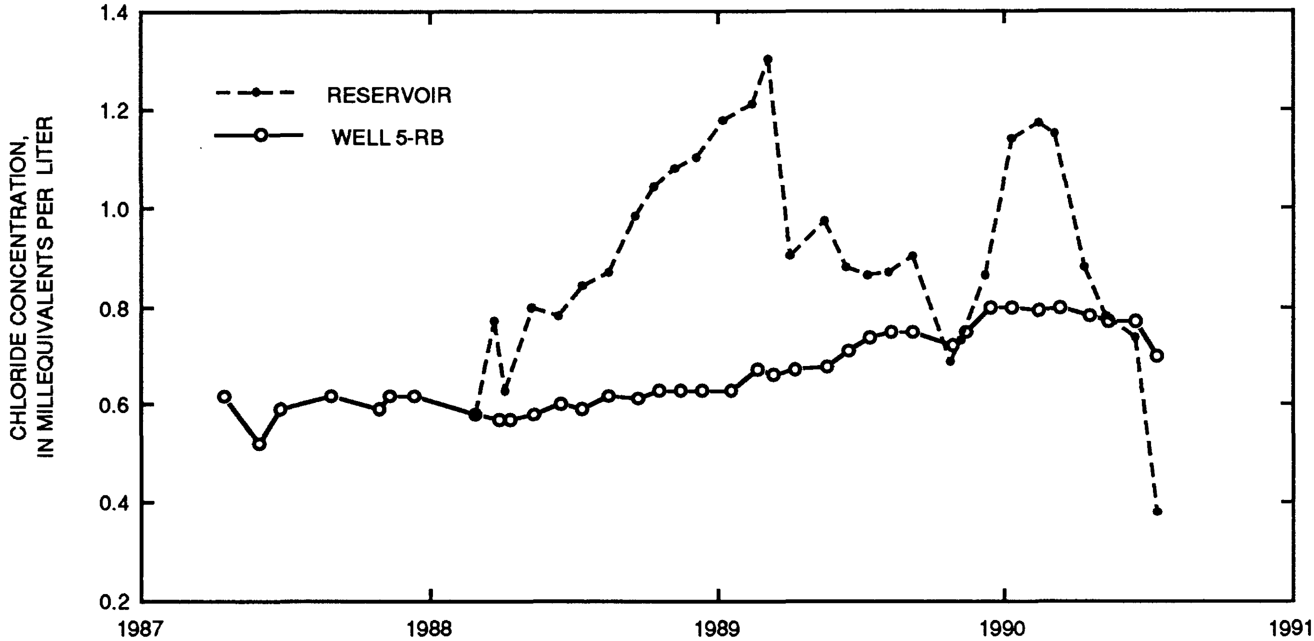


Figure 31.--Chloride concentration in samples from reservoir and observation well 5-RB (cavity zone), April 1987 - July 1990.

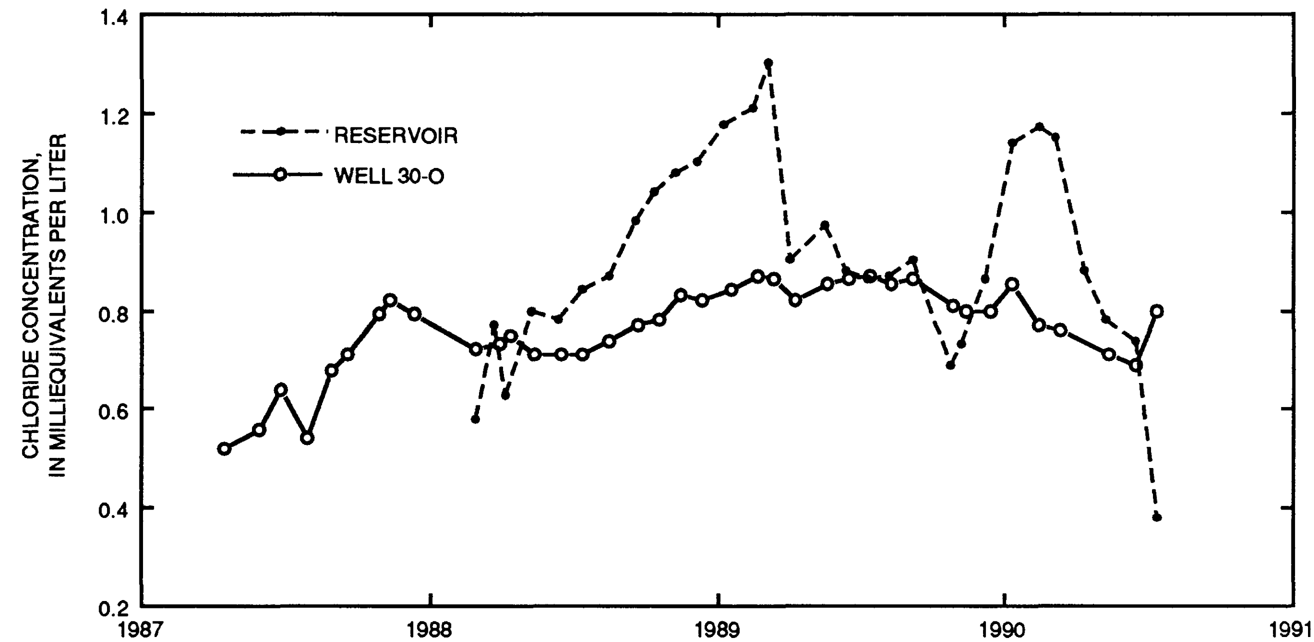


Figure 32.--Chloride concentration in samples from reservoir and observation well 30-O (overburden-glacial sand), April 1987 - July 1990.

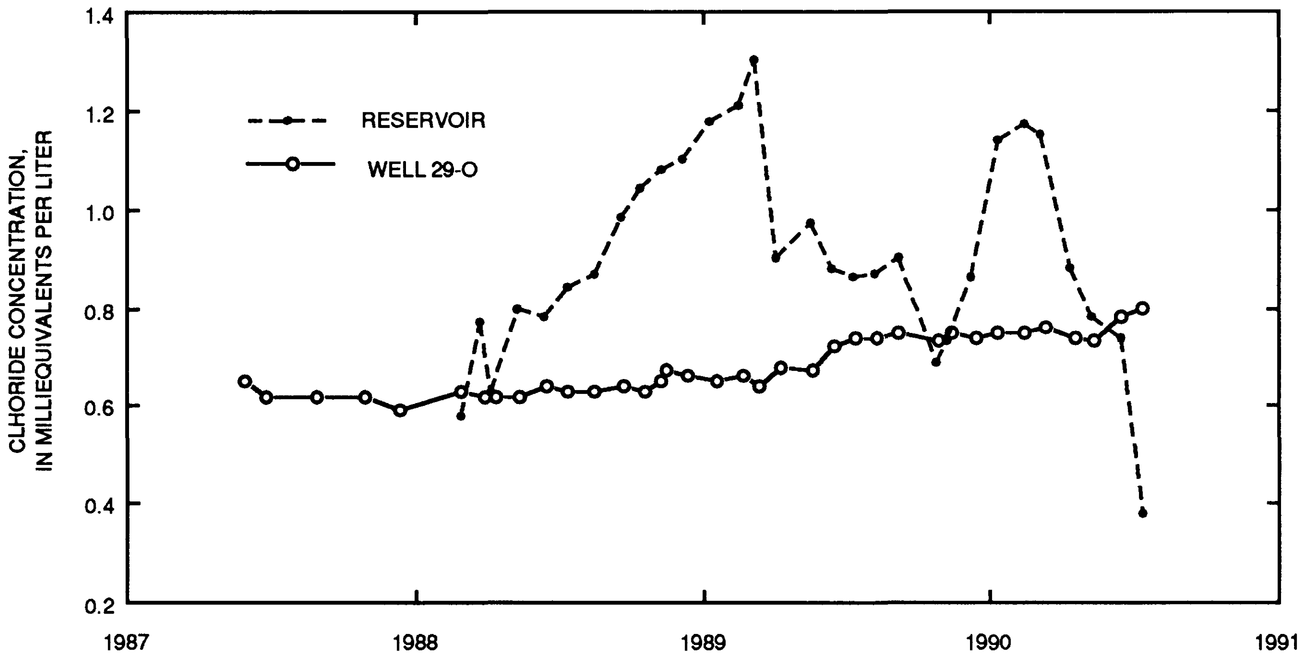


Figure 33.--Chloride concentration in samples from reservoir and observation well 29-O (overburden-alluvium), April 1987 - July 1990.

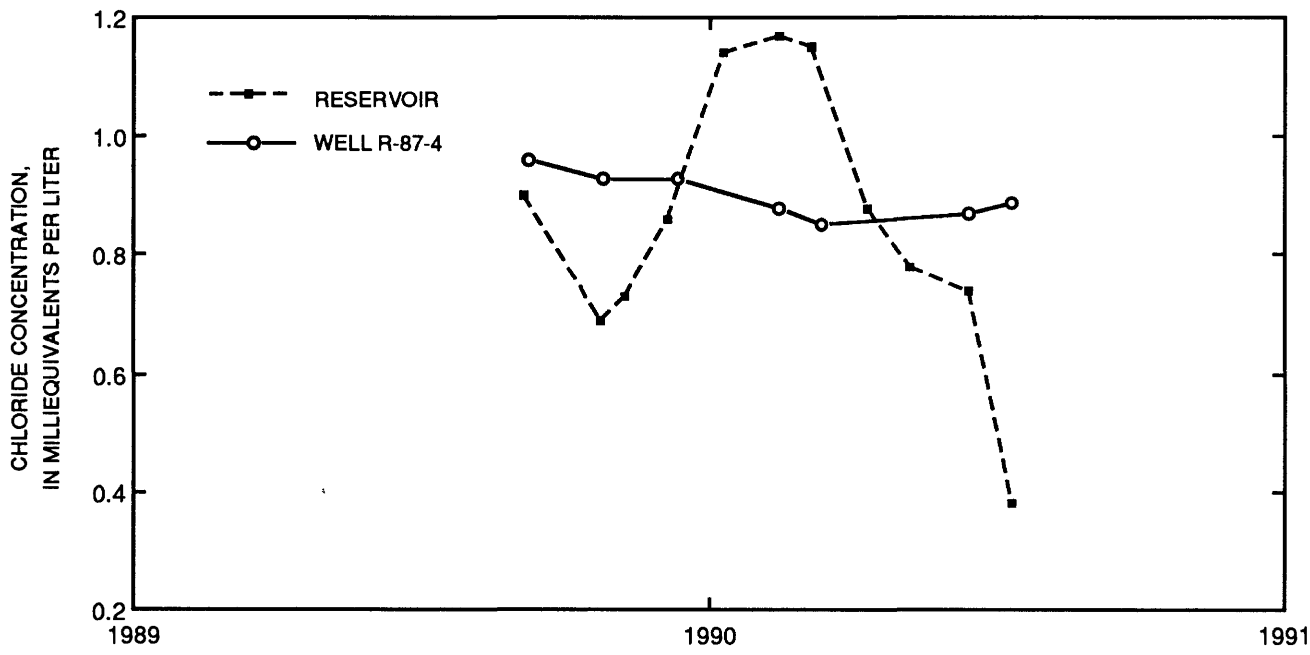


Figure 34.--Chloride concentration in samples from reservoir and observation well R-87-4 (evaporite zone), October 1989 - July 1990.

subsequently, Lake Red Rock. The chloride concentration in the reservoir drops well below that in the ground water in July 1990 after substantial precipitation and runoff increases the volume of Lake Red Rock, signifying a response to wetter climatic conditions. The 3-year period of relatively low pool levels following the high reservoir stand in late 1986 provided a unique opportunity to study the effects of the conservative chloride ion in the hydrogeologic system at Red Rock Dam without the complicating effects of widely fluctuating reservoir levels.

Peak concentrations of chloride occurred during the late winter and early spring months in the reservoir water; therefore, the primary source of the chloride is probably application of road salt upstream in the drainage basin of the Des Moines River, particularly in the Des Moines urban area. Another potential source of chloride in the hydrologic system is the application of potash fertilizer to the agricultural lands in the drainage basin.

The reservoir water could not always be sampled during the winter months (usually December, January, and February) because of ice cover or severe weather. Chloride concentration data from tailwater samples are used to represent reservoir water data, which allow monthly variations in chloride concentration to be presented throughout the year without data gaps. Tailwater samples were collected approximately 2,000 ft downstream from the control structure. There is little, if any, difference in the chloride concentration data between the reservoir and tailwater samples (table 3).

The variations in chloride concentration provide direct evidence for the existence of reservoir water moving through the ground-water system. Chloride concentration in water samples from observation wells 23-R (evaporite zone; fig. 30), 5-RB (cavity zone; fig. 31), 30-O (overburden-glacial sand; fig. 32), and 29-O (fig. 33; overburden-alluvium) vary throughout the sampling period and are similar to variations of chloride concentration in reservoir water samples for the same period. Limited chloride data are available for well R-87-4 since sampling began in October 1989 (fig. 34). Chloride cannot be entering the lower bedrock from the overburden in the river valley, because the potentiometric surface in the lower bedrock is greater than that in the overburden in this area. The increases of chloride concentration in water samples collected from wells 23-R and 5-RB in the lower bedrock in the river valley must be caused by downward movement of water from the reservoir.

During the spring months of 1989, a peak chloride concentration occurred in wells 5-RB and 29-O, approximately 4 months after the peak concentration occurred in the reservoir water, while there seems to be a time lag of 2-3 months at well 23-R and 1 month at well 30-O. The difference in lag times before the onset of the chloride peak indicates a shorter flow path for reservoir water entering the overburden in well 30-O than to the evaporite zone and cavity zone of the St. Louis Limestone or to the overburden in the river valley in the observation wells downstream of the dam. Of the five water-quality wells sampled from March 1988 to July 1990, the variation in chloride concentration at well 23-R most closely matched the variation in chloride concentration in the reservoir, implying that well 23-R has the best hydraulic connection to the reservoir.

Throughout 1989 chloride concentration steadily increased in wells 5-RB and 29-O. Although the distance from the hypothesized area of underseepage in the northeast bluff within the complex ground-water flow system dampens the effects of high chloride concentrations in the reservoir at these wells, the trend toward higher chloride concentration is indicative of underseepage. The chloride concentration in the ground water tends to increase from mixing with underseepage, because the chloride concentrations occurring in the reservoir during 1989 seldom are less than those in the ground water.

As in the spring months of 1989, chloride concentration increased in reservoir water sampled in January 1990, and a maximum chloride concentration followed 2 months later in well 23-R. As before, the plots of chloride concentration for water samples from wells 5-RB (fig. 31), 30-O (fig. 32), and 29-O (fig. 33) are more erratic than the plot of chloride concentration for well 23-R (fig. 30).

In the vicinity of well 30-O, the reversal of ground-water flow direction between the upper bedrock and the overburden (fig. 28) complicates the mixing analysis of ground water and reservoir water. Chloride ions from seepage of reservoir water enter the overburden (glacial sands) at well 30-O when the water level in the overburden is greater than the potentiometric surface in the bedrock allowing downward flow of ground water; otherwise, ground water is discharged upward from the bedrock into the overburden. The large increase in chloride concentration in water-quality samples collected from well 30-O prior to November 1987, which did not occur for the other water-quality monitoring wells, may result from the periodic reversals of ground-water flow direction within the northeast bluff. Ground water was being discharged upward from the bedrock into the overburden before November 1987 (fig. 28). As this flow direction was reversed, chloride concentration increased in the overburden.

Chloride concentrations varied more erratically at well 30-O than at well 23-R, indicating that underseepage follows different ground-water flow paths to these two well locations. The primary source of underseepage for reservoir water entering the evaporite zone at well 23-R is not intermittent downward flow from the glacial sands in the overburden of the northeast bluff in the vicinity of well 30-O. The more likely source is continual downward flow through overburden materials to the bedrock beneath the reservoir--either through alluvium in the northeast part of the river valley or through glacial materials near the base of the northeast bluff.

Chloride concentrations of approximately 0.9 meq/L in water samples from well R-87-4 are considerably larger than chloride concentrations analyzed in water from the other observation wells during the same period. The chloride ion may be providing evidence of underseepage in this area, because the well is completed in the evaporite zone near the grout curtain of the dam foundation. Either well R-87-4 is receiving underseepage of the larger chloride content reservoir water, or the higher chloride concentrations may result from dissolution of chloride salts associated with the evaporite deposits.

An estimate of the mixture of waters can be calculated using chloride concentrations in meq/L in the reservoir and an assumed background concentration of chloride in the ground water. A uniform background value of 0.6 meq/L for the concentration of chloride in the ground-water system is assumed. This value is based on averaging chloride values from wells 23-R (fig. 30), 5-RB (fig. 31), 30-O (fig. 32), and 29-O (fig. 33) from samples collected during the early part of the water-quality sampling program in 1987 when the reservoir remained at its conservation level. A peak chloride concentration of 1.3 meq/L in the reservoir water from March 1990 is used. For this analysis, the peak concentration value measured in the reservoir is assumed to cause the peak concentration value measured in the ground water.

The equation for the mixing percent calculation is:

$$Cm = [Crv \cdot (1 - x)] + [Cgw \cdot x] \quad (4)$$

where Cm = chloride concentration in the final mix;
Crv = chloride concentration in the reservoir water;
Cgw = chloride concentrations in the ground water;
x = percent ground water in the final mix; and
1 - x = percent reservoir water in the final mix.

For well 23-R the mixing calculation is:

$$0.8 = 1.3 \cdot (1 - x) + 0.6 \cdot x \quad (5)$$

Combining common terms gives:

$$-0.5 = -0.7 \cdot x \quad (6)$$

The final calculation gives "x" = 0.5/0.7 = 0.71 and "1 - x" = 0.29. The mix in the evaporite zone at the location of well 23-R, located about 370 ft downstream from the axis of the dam, is approximately 70 percent ground water and 30 percent reservoir water. Chloride concentration data from wells 5-RB and 29-O indicate that there is an approximate mixture of 80 percent ground water and 20 percent reservoir water.

The mixing analysis from the chloride data indicates a larger percentage of reservoir water in the vicinity of well 23-R (evaporite zone) than in either wells 5-RB (cavity zone) or 29-O (alluvium), so underseepage is more prevalent upgradient from well 23-R. Contours of the potentiometric surface (fig. 21) and changes in water levels during a 28-ft pool rise from March 30, 1990, to July 9, 1990, for wells completed in the evaporite zone of the St. Louis Limestone (fig. 22) provide supporting evidence that the primary source of underseepage is in the vicinity of wells R-87-1, R-87-2L, and 1-R in the northeast bluff.

Chloride concentrations at well 30-O steadily increased from August 1988 to March 1989 as the chloride concentration increased in the reservoir water, which is evidence for seepage of reservoir water through the glacial sands in the overburden of the northeast bluff. The water level in the overburden was greater than the water level in the upper bedrock throughout the period (fig. 28), causing sulfate concentrations to decrease in the ground water. Increases in chloride concentration (fig. 32) generally corresponded to decreases in sulfate concentration (fig. 27) in the ground water during rises in reservoir level (such as July 1990 and November 1988), demonstrating that the water chemistry in the overburden probably is being affected by fluctuations in reservoir level. Water-quality changes in the overburden at well 30-O also can be affected by short-term climatic conditions that allow changes in ground-water flow direction (upward or downward) that are unrelated to reservoir level changes. However, increases in chloride concentration data are inferred to be related solely to reservoir seepage, because the reservoir is considered to be the source of chloride.

Saturation Index

Of particular interest to the study of the geochemistry of the ground-water system in the vicinity of Red Rock Dam is whether or not undersaturated conditions exist with respect to the evaporite minerals in the St. Louis Limestone. Accelerated dissolution of these minerals because of changes in the ground-water system following construction of the dam could affect dam safety.

The USGS computer program WATEQ4F models chemical equilibrium of waters by determining the thermodynamic speciation of inorganic ions and complex species in solution and the relative saturation of the solution to given minerals. The degree of saturation is the saturation index (SI). The SI was calculated using WATEQ4F for calcite, dolomite, and gypsum for the monthly water-quality samples collected from April 1987 to July 1990 from the reservoir water (fig. 35) and from observation wells 23-R (evaporite zone; fig. 36), 5-RA (evaporite zone; fig. 37), R-87-4 (evaporite zone; fig. 38), 5-RB (cavity zone; fig. 39), 30-O (overburden-glacial sands; fig. 40), and 29-O (overburden-alluvium; fig. 41).

A positive SI implies that the mineral has the potential to precipitate, a negative SI implies the potential to dissolve, and an SI equal to zero implies equilibrium conditions (Freeze and Cherry, 1979). The SI is calculated:

$$SI = \log Q - \log K = \log [Q/K] \quad (7)$$

where Q is the activity quotient of the solution and K is the equilibrium constant for the mineral (Hem, 1985).

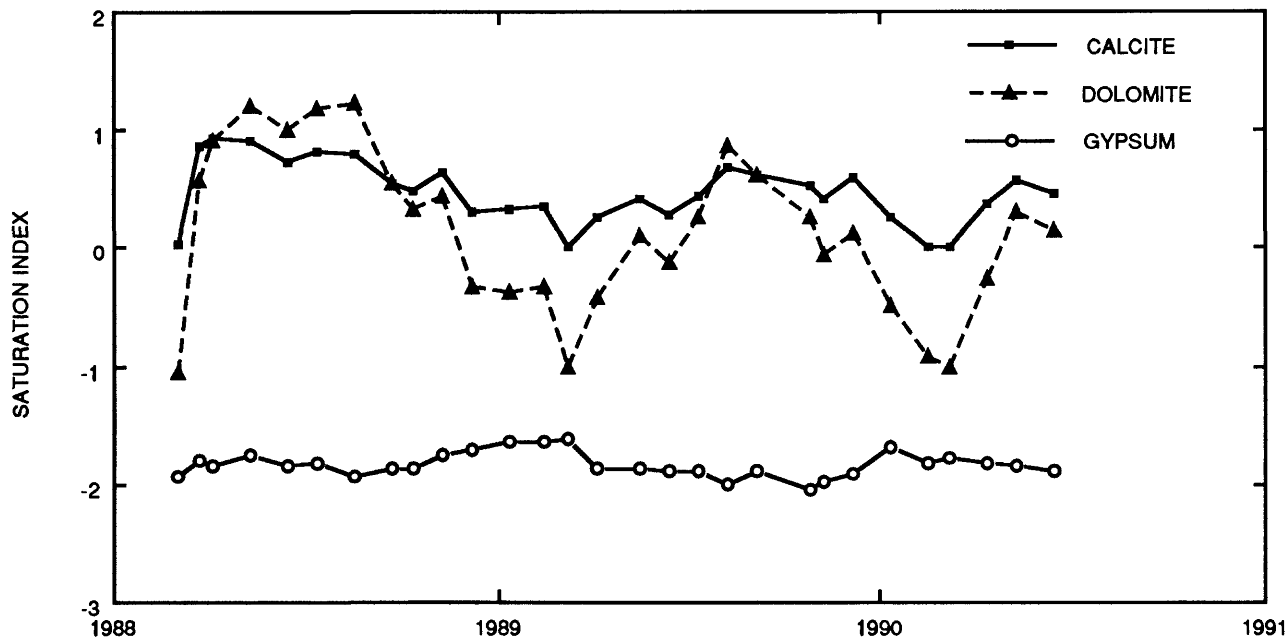


Figure 35.--Saturation indices for calcite, dolomite, and gypsum in samples from reservoir water, March 1988 - July 1990.

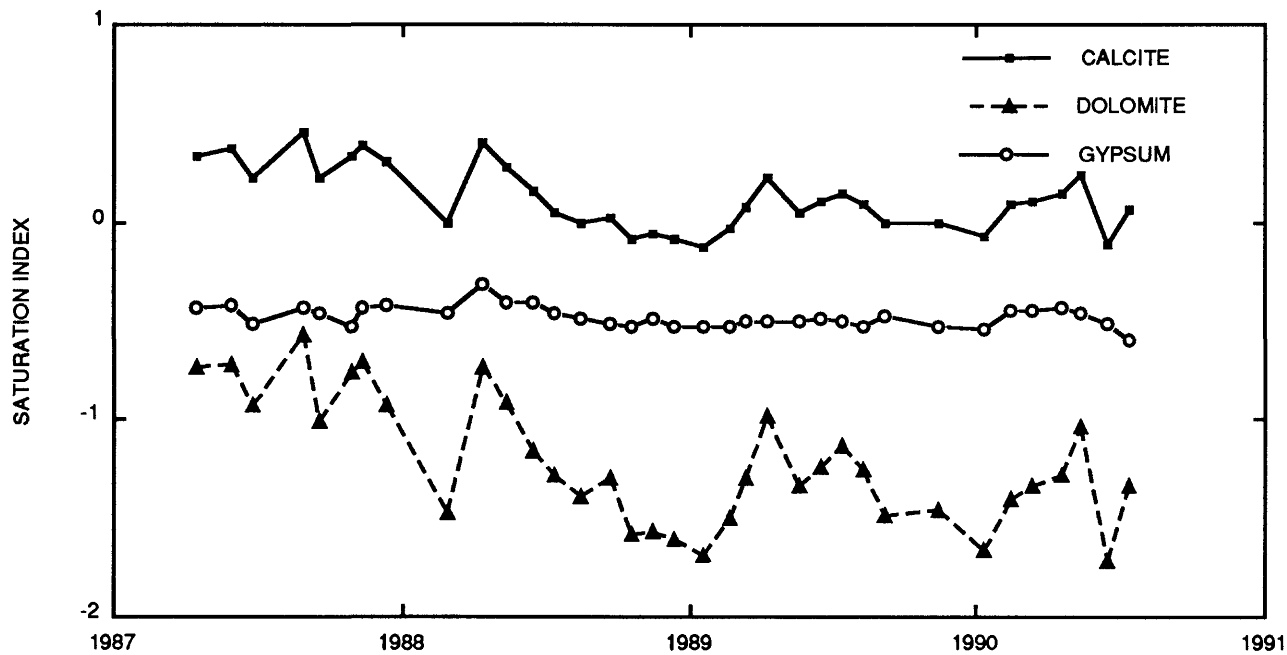


Figure 36.--Saturation indices for calcite, dolomite, and gypsum in samples from observation well 23-R (evaporite zone), April 1987 - July 1990.

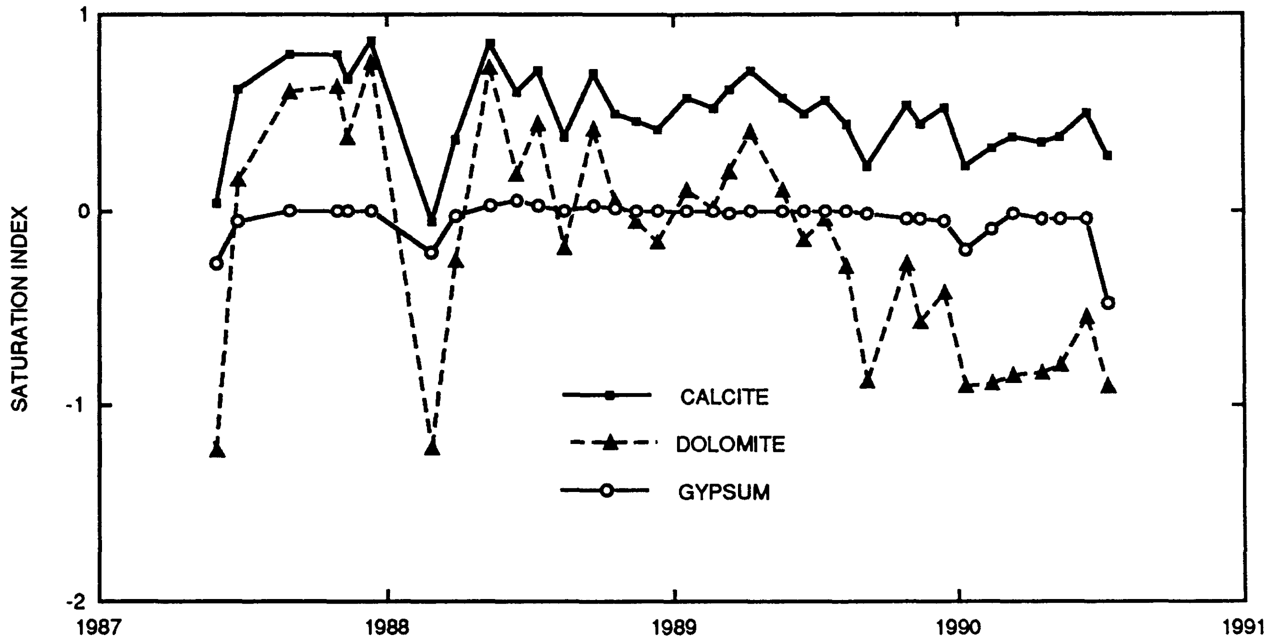


Figure 37.--Saturation indices for calcite, dolomite and gypsum in samples from observation well 5-RA (evaporite zone), April 1987 - July 1990.

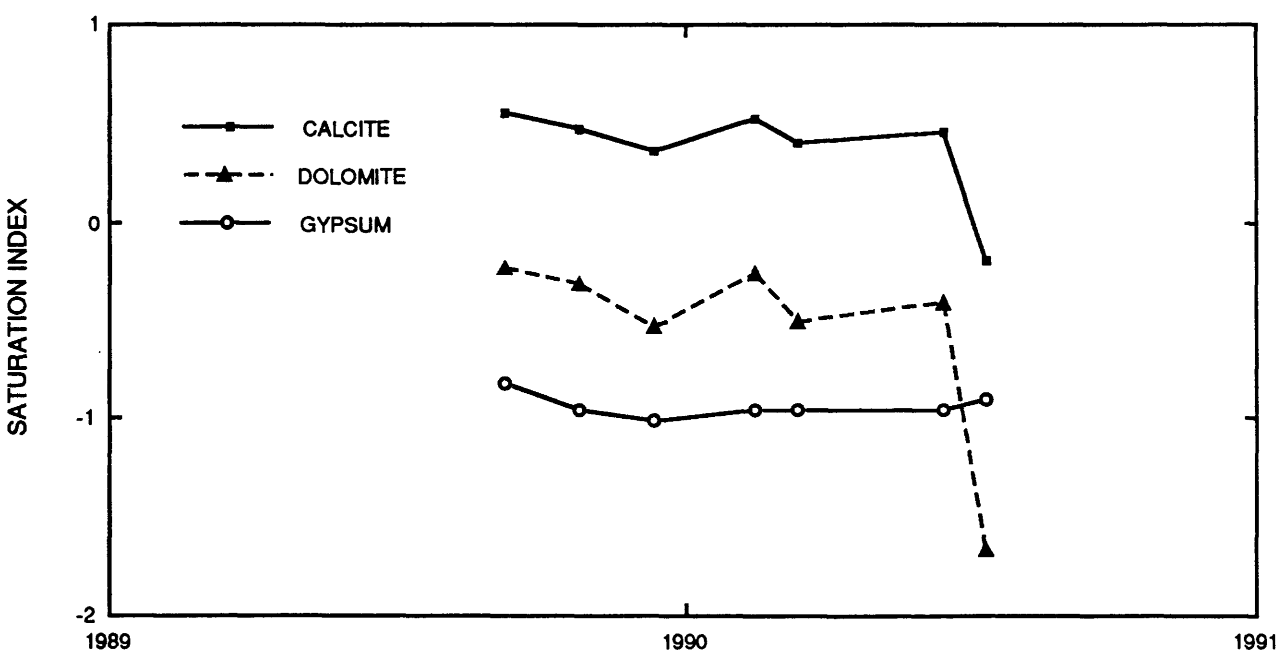


Figure 38.--Saturation indices for calcite, dolomite, and gypsum in samples from observation well R-87-4 (evaporite zone), October 1989 - July 1990.

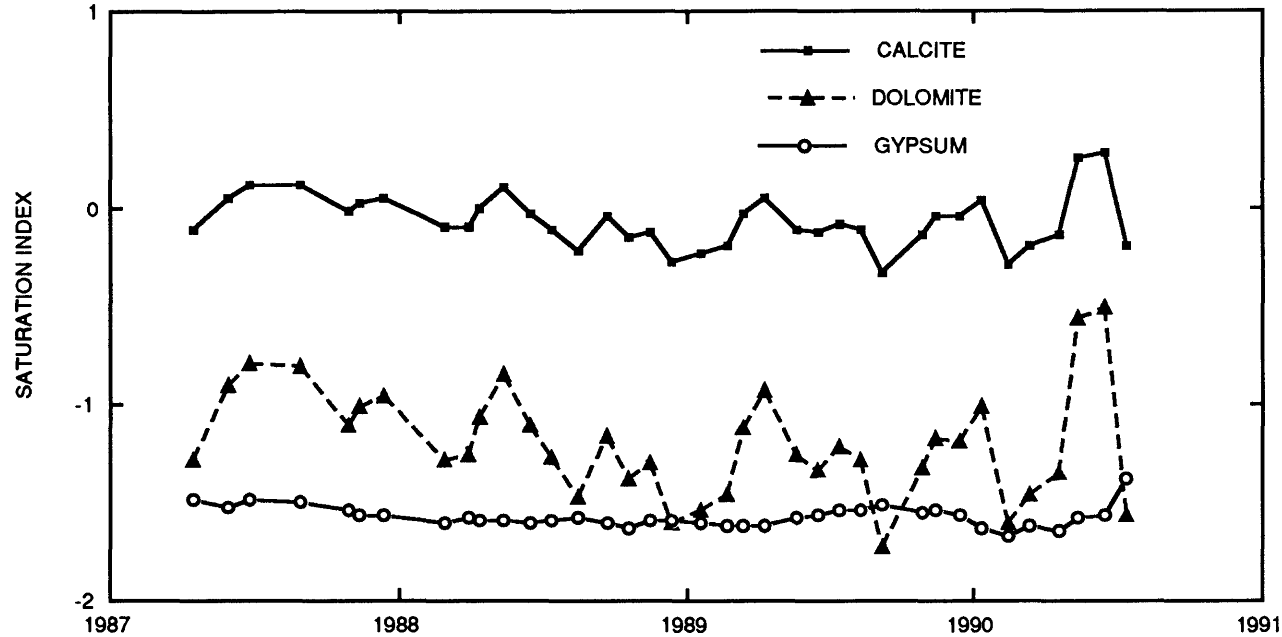


Figure 39.--Saturation indices for calcite, dolomite, and gypsum in samples from observation well 5-RB (cavity zone), April 1987 - July 1990.

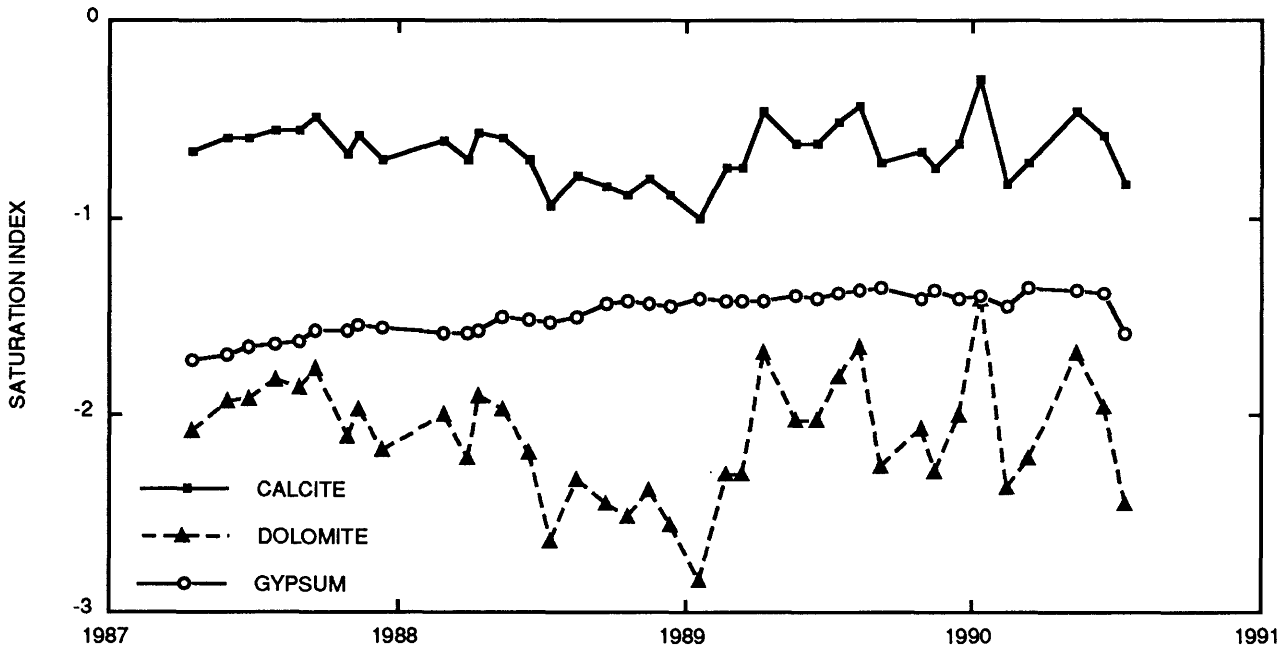


Figure 40.--Saturation indices for calcite, dolomite, and gypsum in samples from observation well 30-O (overburden-glacial sand), April 1987 - July 1990.

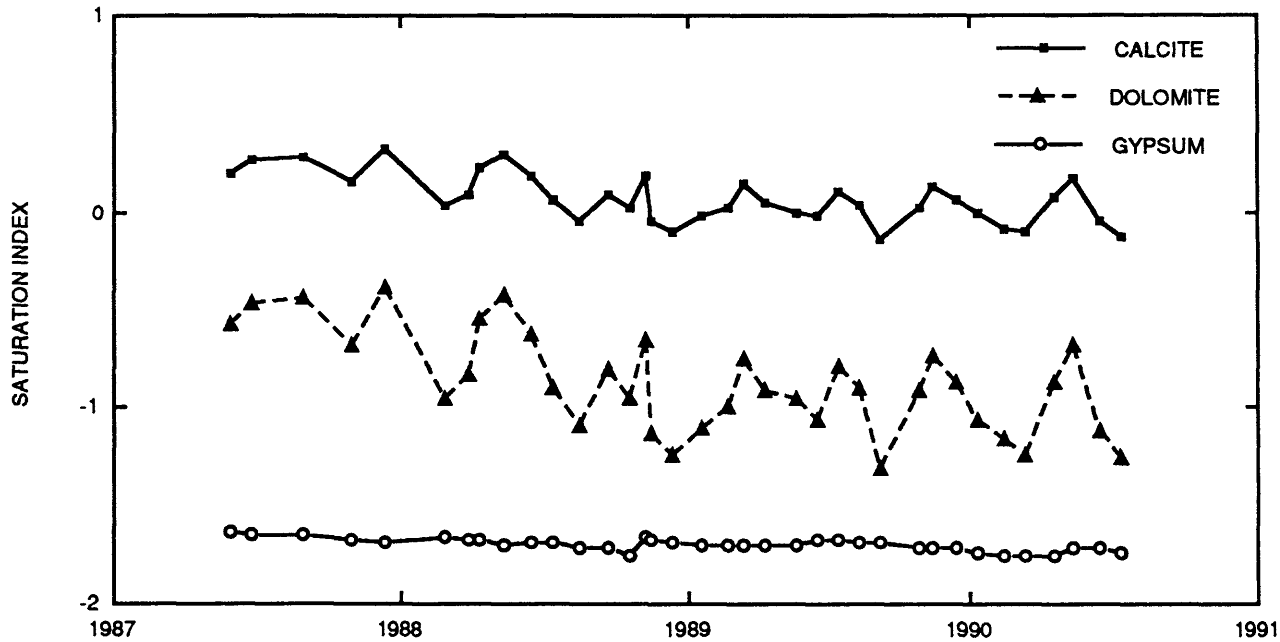


Figure 41.--Saturation indices for calcite, dolomite, and gypsum in samples from observation well 29-O (overburden-alluvium), April 1987 - July 1990.

The equilibrium constant (K) varies with temperature and pressure. The chemical formula and log K for anhydrite at standard conditions [25 °C (degrees Celsius), 1 atmosphere of pressure] are:

$$Ca^{+2} + SO_4^{-2} = CaSO_4; \text{Log } K = -4.38 \quad (8)$$

Gypsum is the hydrated form of anhydrite and its chemical formula and log K product at standard conditions are:

$$Ca^{+2} + SO_4^{-2} + 2 \cdot H_2O = CaSO_4 \cdot 2H_2O; \text{Log } K = -4.60 \quad (9)$$

Anhydrite is less stable than gypsum at standard conditions because the value of the log of the solubility product of anhydrite is less than that of gypsum (Stumm and Morgan, 1981). A calculated SI for gypsum provides information relative to the solubility of both evaporite minerals present in the St. Louis Limestone. Conditions in the shallow rock units of interest are essentially atmospheric pressure with temperatures ranging between 11 °C and 15 °C. Using 12.5 °C as a mean ground-water temperature during the water-quality monitoring period, the log K for anhydrite is -4.33 and the log K for gypsum is -4.59. On the graphs showing the SI (figs. 35-41), the SI of anhydrite would be approximately 0.25 unit less than that of gypsum at the near-surface temperatures and pressures pertinent to this study. Undersaturation with respect to anhydrite and gypsum near the evaporite beds implies quantities of ground-water flow large enough that equilibrium conditions are not reached, although dissolution of the evaporite minerals does occur.

Reservoir water samples are undersaturated with respect to gypsum and anhydrite (fig. 35). Reservoir waters are not sampled during the winter months, but water-quality data from tailwater samples collected downstream from the control structure of the dam are used to represent the reservoir water chemistry and provide a continuous plot of SI throughout the year. The SI for calcite and dolomite exhibit a seasonal variation related to temperature. Reservoir waters are oversaturated with respect to calcite and dolomite during the warmer seasons, while the water becomes undersaturated with respect to dolomite during the cooler months. Gypsum SI remain negative, varying between -1.6 and -2.0, and are not affected as dramatically by the seasonal processes affecting the SI of dolomite.

Ground water from the evaporite zone of the St. Louis Limestone in well 23-R is undersaturated with respect to gypsum and anhydrite. A SI for gypsum of -0.5 implies dissolution of gypsum and anhydrite within this 14-ft thick evaporite bed (fig. 36). The well location is 371 ft downstream from the dam axis, but the chemistry of the formation water in this area of the dam site is important because it demonstrates that dissolution of evaporite minerals can occur within the evaporite zone.

Water samples from well 5-RA usually have been saturated with respect to gypsum and slightly undersaturated with respect to anhydrite throughout the water-quality sampling period (fig. 37), as expected in formation waters occurring within a 9-ft thick anhydrite and gypsum evaporite bed. If dissolution of gypsum is occurring, ground-water flow rates are slow enough to allow equilibrium conditions to be attained. The ground water became undersaturated with respect to dolomite during mid-1989 when a solution channel may have developed, allowing adjacent formation water to mix with resident ground water within the evaporite beds. The ground-water flow system in the evaporite beds at this location generally is not conducive to significant additional dissolution of anhydrite and gypsum. However, a negative SI for gypsum in July 1990 may be indicative of mixing with fresher ground water from the overlying cavity zone caused by an increase in hydraulic head on the ground-water system as the reservoir level increased in June 1990. The elevation of the ground-water head in well 5-RB was 710.5 ft on July 9, 1990, which is slightly higher than the 710.4-ft elevation of the head in well 5-RA.

Water samples from well R-87-4 exhibit gypsum SI of -1.0 (fig. 38). Apparently there are adequate ground-water flow velocities that the formation waters do not equilibrate to gypsum, which is significant because the well is completed in a 9-ft thick evaporite bed near the grout curtain of the dam.

Ground-water samples from the cavity zone immediately above the evaporite beds in well 5-RB are undersaturated with respect to gypsum and anhydrite (fig. 39). Values of the gypsum SI generally are less than -1.5. These waters also are undersaturated with respect to dolomite and slightly undersaturated with respect to calcite and have the potential to dissolve the limestone and dolomite bedrock materials, as well as the evaporite materials. Water in the cavity zone has the potential to dissolve gypsum and anhydrite upon contact with the surface of the evaporite beds.

The ground water present in the overburden (glacial sands) of the northeast bluff sampled from well 30-O (fig. 40) is undersaturated with respect to calcite, dolomite, gypsum, and anhydrite. A trend of increasing SI for gypsum is apparent throughout the sampling period as ground-water movement has been predominantly upward from the bedrock into the overburden in this area, increasing the sulfate concentration. Water in the overburden (alluvial sands) sampled at well 29-O (fig. 41) indicates undersaturation with respect to dolomite, gypsum, and anhydrite and equilibrium or oversaturation with respect to calcite. The geochemical properties of the water in the alluvial sands are similar to those in the water in the cavity zone of the St. Louis Limestone because ground water is being continually discharged upward from the bedrock to the overburden in the river valley.

Ground-Water Movement

Hydraulic conductivity values for the lower bedrock calculated from water pressure test data are listed in table 4. The method used for these calculations is described by the Bureau of Reclamation (1985). Within the evaporite beds, hydraulic conductivities range from 0.002 ft/d (foot per day) in well R-88-6 to 1.6 ft/d in well R-87-1. In the cavity zone of the St. Louis Limestone, hydraulic conductivities range from 1.6 ft/d in R-87-2 to 5.8 ft/d in R-88-6. The hydraulic conductivity values in the cavity zone are within the range expected for fractured carbonate rock aquifers (Heath, 1987).

By assuming that the flow path is the shortest distance between the well and the reservoir, a minimum ground-water velocity can be estimated. The lag between the time a peak chloride concentration was measured in the reservoir and the time that peak was observed in a well during monthly water-quality sampling was used to estimate travel time. A value of 60 days was used for well

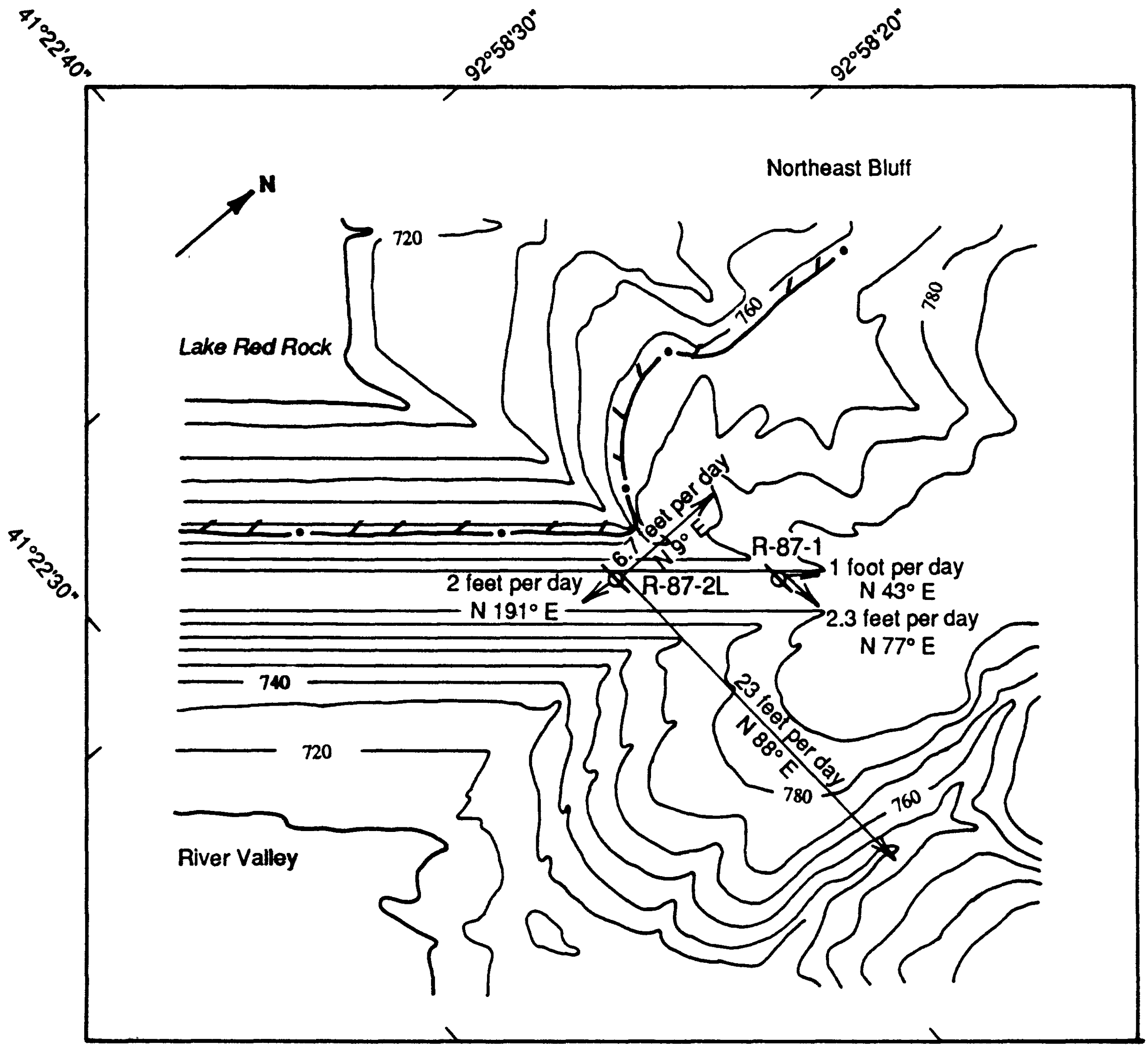
23-R, 120 days for well 5-RB, and 30 days for well 30-O. A minimum flow path distance of 480 ft was calculated for well 23-R and 350 ft for well 5-RB. The average ground-water velocity is 8.0 ft/d and 2.9 ft/d. These velocity values are minimums, because the tortuous flow paths through the solution cavities of the carbonate bedrock probably are much longer than the estimated straight-line distance. A flow path distance of 400 ft between the reservoir and the glacial sands in the overburden at well 30-O gives an estimated ground-water velocity of 13 ft/d.

Ground-water movement in the evaporite zone of the St. Louis Limestone was measured directly with a K-V Associates ground-water flowmeter system. Well R-87-1 is completed in an evaporite bed in the lower bedrock of the northeast bluff near the grout curtain of the dam foundation. Measurements at well depths of 157 and 158 ft below the surface in well R-87-1 gave flow velocities of 2.3 ft/d to N. 43° E. and 1.0 foot/day to N. 77° E. (fig. 42). Well R-87-2L is on the northeast side of the dam and also is completed near the grout curtain in an area of the evaporite zone where gypsum is scarce. Measurements at well depths ranging from 153 ft to 154.75 ft below the surface indicated flow velocities of 2 to 22 ft/d and the direction of flow varied from N. 9° E. to N. 191° E. (fig. 42). The scatter in flow direction and magnitude of velocity in well R-87-2L could be caused by fracture flow; however, the dominant vector for both wells is toward the east, which is expected when Lake Red Rock is considered a recharge area for the system.

Table 4.--*Hydraulic conductivities calculated from water pressure tests in bedrock observation wells at Red Rock Dam*

[Cavity zone, fractured carbonates containing cavities overlying or adjacent to basal evaporite beds of St. Louis Limestone; evaporite zone, basal evaporite beds of St. Louis Limestone; ft/d, feet per day; --, no data]

Well (plate 1)	Hydraulic Conductivity (unit gradient) Cavity zone (ft/d)	Hydraulic Conductivity (unit gradient) Evaporite zone (ft/d)
R-87-1	3.0	1.6
R-87-2	1.6	--
R-87-3	2.7	--
R-87-4	3.5	.8
R-88-4	5.1	--
R-88-5	3.1	.04
R-88-6	5.8	.002



Base modified from U.S. Army Corps of Engineers, 1984

0 250 500 FEET
0 50 100 METERS

EXPLANATION

LIMIT OF RESERVOIR--Hachures toward reservoir

GROUND-WATER FLOW VELOCITY AND DIRECTION--Arrow shows direction and is scaled to velocity magnitude (0.1 inch = 1 foot per day):

1 foot per day

10 feet per day

R-87-1 OBSERVATION WELL--Number explained on plate 1.

Figure 42.--Ground-water flow direction and velocity measured in the evaporite zone of the St. Louis Limestone, June 26, 1990.

SUMMARY AND CONCLUSIONS

The Red Rock Dam, located on the Des Moines River in Marion County, Iowa, consists of a concrete control structure between two earthen embankments. The St. Louis Limestone, which forms the bedrock foundation of the dam in the river valley, consists of interbedded sandstones and carbonates overlying a basal evaporite zone. Anhydrite and gypsum have been removed from the evaporite zone over geologic time, resulting in collapse features in the overlying strata. To decrease permeability and control underseepage, a grout curtain was installed through the St. Louis Limestone and terminated in the relatively impermeable dolomitic shales of the underlying Warsaw Limestone.

The primary evidence for the existence of underseepage along the northeast side of the dam through the basal evaporite zone of the St. Louis Limestone, the cavity zone above the evaporite beds, and unconsolidated materials in the northeast bluff includes:

1. Large variations in water levels in observation wells located on the northeast side of the dam correspond to reservoir level changes.

2. Chloride concentration data demonstrate the existence and movement of reservoir water that is undersaturated to gypsum and anhydrite within the evaporite zone of the St. Louis Limestone.

3. Water composition analysis indicates that a unique water type, unlike the major water types identified in the immediate area of the dam, occurs in the evaporite zone of the St. Louis Limestone near the grout curtain of the foundation of the dam.

4. Ground-water movement within the evaporite zone of the St. Louis Limestone occurs along the grout curtain of the dam.

Reservoir water and shallow ground water in the vicinity of the dam are undersaturated with respect to gypsum and anhydrite. Underseepage through the bedrock foundation of the dam is an engineering concern because of the potential for the evaporite beds to be removed in greater amounts with increasing ground-water flow velocities and volumes. As solution channels enlarge, overlying strata could collapse and threaten the integrity of the earthen dam.

Different hydrogeologic conditions exist on the two sides of the dam site. The potentiometric surface in the overburden has an extremely steep hydraulic gradient from the reservoir through the dam and southwest bluff to the downstream observation wells, which implies expected small permeability and minimal seepage through the dam and embankment materials. A lesser hydraulic gradient from the reservoir to the downstream observation wells exists on the northeast side of the dam, which could indicate excessive seepage through embankment material from larger than expected hydraulic conductivity or underseepage through bedrock. A contour map of the change in water levels from March 30 to July 9, 1990, for observation wells completed in the evaporite zone indicates areas of probable hydraulic connectivity to the reservoir. The change in the reservoir level during this period was more than 28 ft, and water levels in wells R-87-2L, R-87-1, and 1-R on the northeast side of the dam increased more than 26 ft. The largest water-level increase on the southwest side of the dam during this period was only 11 ft in well 11-R. In the overburden wells, the largest water-level increase during this period was more than 24.5 ft, which occurred on the northeast side of the dam near the base of the valley bluff.

The changes in water levels in bedrock and overburden observation wells on the northeast side of the dam seem to result from hydraulic connection to Lake Red Rock rather than to climatological effects. Wells R-88-2 and R-88-3, which are completed in the shale bedrock of Pennsylvanian age in the northeast bluff upgradient of the reservoir and the remainder of the observation well network, underwent water-level changes of -9.5 ft and 3.8 ft from March 30 to July 9, 1990. Precipitation could not have caused the more than 20-ft water-level change in wells R-87-2L, R-87-1, and 1-R.

Direct evidence of the existence of flow between the reservoir and the ground-water system downstream of the dam is provided by chloride concentration data. Peak chloride concentrations occurred in reservoir water during the early spring of 1989. Chloride concentrations peaked 2-3 months later in observation well 23-R, which is completed in the evaporite zone downstream of the dam; 4 months later in well 5-RB, which is completed in the cavity zone immediately above the evaporite zone downstream from the dam; and 1 month later in well 30-O, which is completed in the glacial sands of the overburden in the northeast bluff. Time of travel analysis based on chloride tracer results indicates the area of the northeast bluff as the primary source of underseepage from the reservoir. However, hydrogeologic mapping and statistical analysis of the water-level changes in the observation wells and the reservoir provide evidence that underseepage also occurs through the bedrock foundation of the dam in the extreme northeast part of the river valley.

Two dominant water types are present in the vicinity of the dam, including a calcium bicarbonate water in the reservoir, overburden, and shallow bedrock and a calcium sulfate water in the evaporite zone. Water composition analysis of samples collected from well R-87-4, which is completed in an evaporite bed near the grout curtain of the dam foundation in the northeast part of the river valley, indicates the presence of a water type unlike that found in the evaporite zone in other observation wells. The samples from well R-87-4 have a SI for gypsum of -1.0, implying that ground-water flow quantities are large enough that the system does not equilibrate to gypsum and that the evaporite material probably is being dissolved from this area.

Ground-water movement was measured with a flowmeter system in the evaporite horizon near the grout curtain of the dam, which corroborates the interpretation of ground-water movement from water composition analysis. Velocities ranging from 2 to 22 ft/d eastward away from the reservoir were calculated in well R-87-2L in an area of little evaporite material. Velocities of up to 2 ft/d eastward were obtained within the gypsum bed in well R-87-1. Greater ground-water velocities occurred in the fracture, cavity zone of the St. Louis Limestone than in the evaporite zone.

Dissolution of gypsum and anhydrite can occur when there is a connection and downward flow from the shallow ground-water system to the basal evaporite zone of the St. Louis Limestone. Although the evaporite material at the base of the St. Louis Limestone has been removed by weathering processes through geologic time, the construction of Red Rock Dam has altered the natural ground-water flow system and augmented its capabilities for gypsum and anhydrite dissolution. The increased hydraulic head imposed on the ground-water system by the impounded water of Lake Red Rock causes downward flow and recharge to the deeper bedrock rock units in the immediate vicinity of the dam.

Fracture or solution channels were not evident in cores recovered from the gypsum and anhydrite beds during exploratory borings drilled during 1987 and 1988 near the grout curtain of the dam. Hydraulic conductivity calculations from water pressure tests indicate that evaporite material is less permeable than the surrounding carbonate bedrock. Removal of evaporite material would be caused predominantly by the relatively larger quantities of water that is undersaturated with respect to gypsum and anhydrite flowing through the adjacent cavity zone. Flow velocities could be an order of magnitude greater in the cavity zone than in the evaporite beds, so dissolution of the evaporite beds would occur predominantly from the outermost surface inward rather than from enlargement of solution channels within the material.

Large variations in hydraulic conductivities characterize the lower zone of the St. Louis Limestone. The volumetric dissolution rate of anhydrite and gypsum varies with the distribution of solution cavities and fracture zones. A removal rate of evaporite material cannot be calculated with confidence, because the distribution of hydraulic conductivity within the bedrock foundation and grout curtain of the dam is uncertain. However, the interpretation of the hydrogeology in the vicinity of the Red Rock Dam presented in this study has indicated that reservoir water is flowing through the basal evaporite zone and the overlying cavity zone of the St. Louis Limestone with the potential to dissolve gypsum and anhydrite along its flow path. Where these flow paths are concentrated by enhanced permeability, dissolution and removal of evaporite material may be greatest. Hydrogeologic mapping indicates that the grout curtain in the bedrock under the northeast bluff is the zone of greatest underseepage. However, evidence for underseepage through the basal evaporite zone also exists along the axis of the dam from a point between wells R-87-4 and 7-R in the northeast part of the river valley to the vicinity of well R-87-1 in the northeast bluff.

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