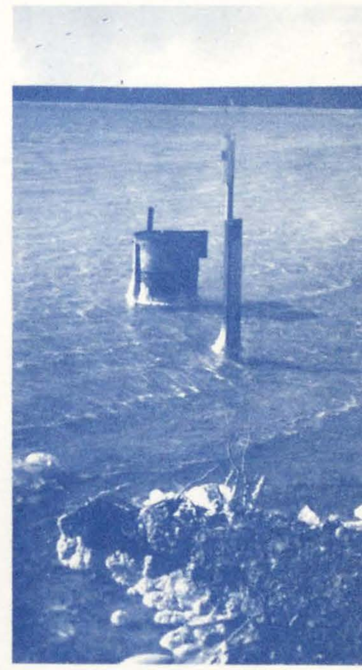
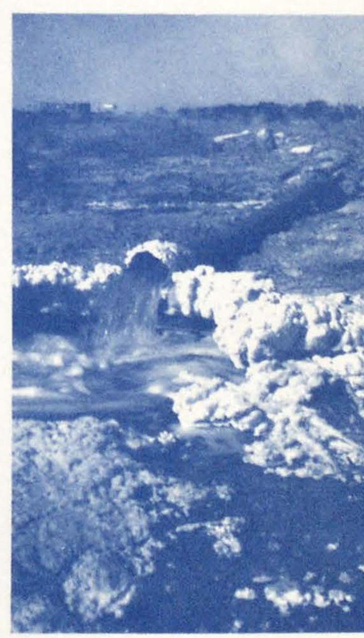
EVALUATION OF THE MALAGA BEND SALINITY ALLEVIATION PROJECT EDDY COUNTY, NEW MEXICO



PREPARED IN COOPERATION WITH THE PECOS RIVER COMMISSION

U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 80-1111



EVALUATION OF THE MALAGA BEND SALINITY ALLEVIATION PROJECT EDDY COUNTY, NEW MEXICO

BY J. L. KUNKLER

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PREPARED IN COOPERATION WITH
THE PECOS RIVER COMMISSION

SEPTEMBER 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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INCH-POUND UNIT TO METRIC UNIT CONVERSION FACTORS

In this report figures for many measurements are given in inch-pound units only. The following table contains factors for converting to metric units.

Multiply inch-pound units	By	To obtain metric units
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.004047	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
short (ton)	0.9072	metric ton
foot per minute (ft/min)	0.00508	meter per second
foot per day (ft/d)	0.3048	meter per day

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 "Mean Sea Level." NGVD of 1929 is referred to as sea level in this report.

EVALUATION OF THE MALAGA BEND SALINITY ALLEVIATION PROJECT EDDY COUNTY, NEW MEXICO

BY J. L. KUNKLER

ABSTRACT

In an effort to reduce the flow of brine springs in the Malaga Bend reach of the Pecos River in southeastern New Mexico, brine was pumped from an aquifer underlying the Malaga Bend reach to a local depression known as Anderson Lake. The attempt to improve the quality of river water with this experiment was not successful because brine leakage from Anderson Lake to the nearby Pecos River through permeable subsurface rocks was greater than the previous natural spring inflow.

Brine leakage from Anderson Lake from July 22, 1963, through September 30, 1968, was estimated by evaporation-pan, salt accumulation, and dissolved-constituent methods. The leakage values given by these three methods are in good agreement with each other and indicate that between the dates given, leakage from the lake was about 2,300 acre-feet, compared with a brine inflow to the lake of about 3,690 acre-feet. Other data indicate that pumping from the brine aquifer greatly reduced the natural inflow from brine springs to the Malaga Bend reach.

The rate of brine leakage from Anderson Lake is probably greater than might be expected from other brine lakes in the area because the cavities in the bottom of the lake apparently are in hydrologic connection with the Pecos River. This connection is shown by a relation between the salinity of the Pecos River and the reservoir stage of Anderson Lake.

INTRODUCTION

PURPOSE AND SCOPE OF THIS REPORT

This report has two purposes. The first is to evaluate the results of an experiment that attempted to reduce the inflow of brine springs to the Pecos River by pumping the brine aquifer supplying these springs and impounding the brine in a lake. The second is to describe and evaluate several methods used to estimate brine leakage from the lake.

ACKNOWLEDGMENTS

This project was conducted in cooperation with the Pecos River Commission, which gave valuable support to the effort. Special acknowledgment is given to C. J. Anderson, former manager of the Red Bluff Water Power Control District and Engineering Advisor to the Pecos River Commissioner for Texas. The pumping station and disposal area were named in memory of Mr. Anderson at their dedication, December 3, 1964.

THE MALAGA BEND AREA

DESCRIPTION AND HYDROLOGY OF THE AREA

During the Late Permian Epoch, about 245 million years ago, southeastern New Mexico was covered by a shallow sea. According to Kottlowski (1967, p. 46), this sea advanced and retreated over the area several times during the Permian. Toward the end of the period, several thousand feet of evaporite deposits accumulated in the Delaware Basin, southeast of Carlsbad, New Mexico.

During later geologic time, parts of the evaporite were dissolved by ground water and the overlying rocks collapsed. The resultant collapse sinkholes filled with various amounts of breccia and other material, mostly alluvium. In places, secondary collapse sinkholes have developed on the older sinkholes.

The debris filling the sinkholes generally is permeable. In many places the sinks are conduits which discharge water from otherwise confined aquifers. The permeability of near-surface breccia is enhanced in places by the tunnels of various burrowing animals.

The Pecos River, which flows south through a chain of these collapse sinkholes, collects a significant amount of saline water from some of them. In the Malaga Bend reach (fig. 1) the river flows across one of these ancient sinkholes that is hydrologically connected to a large aquifer containing brine saturated with sodium chloride. This aquifer is a permeable unit within the Rustler Formation. Brine flows from the aquifer into the brecciated debris in the sinkhole and then through the breccia to the surface.

Although the hydrologic properties of this brecciated aquifer are little known, it is apparent that the breccia discharges brine to the Pecos River in the Malaga Bend reach. The Malaga Bend reach is defined herein as the segment of the Pecos River between streamflow gaging station 08406500, southeast of Malaga, New Mexico, and streamflow gaging station 08407000, at Pierce Canyon Crossing, further southeast of Malaga (fig. 1). Hereafter, these stations are called the Malaga and Pierce Canyon streamflow gaging stations.

The rate of brine discharge to the Pecos River in the Malaga Bend reach has been reported previously as 0.44 ft^3/s (Theis and others, 1942, p. 38-75), but evidence given subsequently in this report indicates that the rates of brine inflow may have been underestimated. In any event, the amount of inflowing brine is small compared to the normal flow of the river; however, the large concentration of sodium chloride in the brine is sufficient to affect the utility of the river water, except during periods of flood flows.

The amount of water in storage in the brine aquifers probably exceeds several thousand acre-ft in the brecciated aquifer underlying Malaga Bend, and it may exceed 1 million acre-ft in the confined aquifer within the Rustler Formation. The recharge area of this aquifer is probably in Nash Draw to the northeast of Malaga Bend (fig. 1).

Overlying the brine aquifer in the Malaga Bend area is a system of water-bearing units known collectively as the shallow aquifer. This aquifer occurs partly in rocks of the Rustler Formation and partly in alluvium. The quality of the water contained in the aquifer varies with time and place. The shallow aquifer, hydrologically connected to the river, is sometimes recharged by river water. Data collected during August 1966 show that the top of the water table of this aquifer was at an average altitude of 2,896 feet (National Geodetic Vertical Datum of 1929). The altitude of the bottom of Anderson Lake (formerly called the Northeast Depression), a secondary sinkhole in the Malaga Bend area (fig. 2), is 2,928.7 feet. Hence, the top of the water table of the shallow aquifer was approximately 33 feet below the bottom of the lake during August 1966.

Average annual precipitation in the Malaga Bend area is about 12 inches. Summers are hot; daytime temperatures commonly are in excess of 100°F. Winters tend to be mild, although nighttime temperatures during much of the winter are less than 32°F.

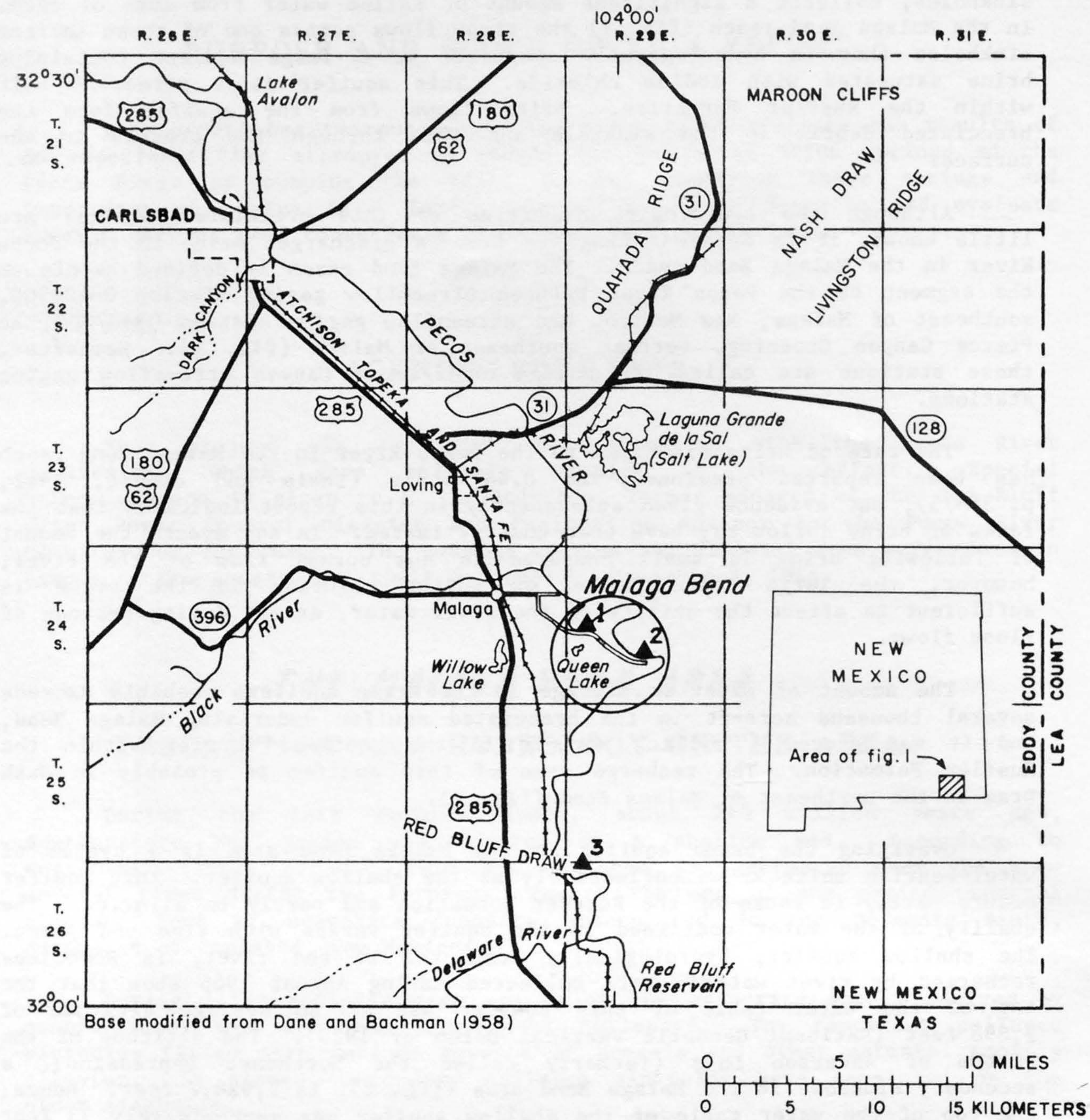


Figure 1. Location of Malaga Bend area and streamflow gaging stations (▲ 1) Pecos River near Malaga (08406500), (▲ 2) Pecos River at Pierce Canyon Crossing near Malaga (08407000), and (▲ 3) Pecos River at Red Bluff (08407500).

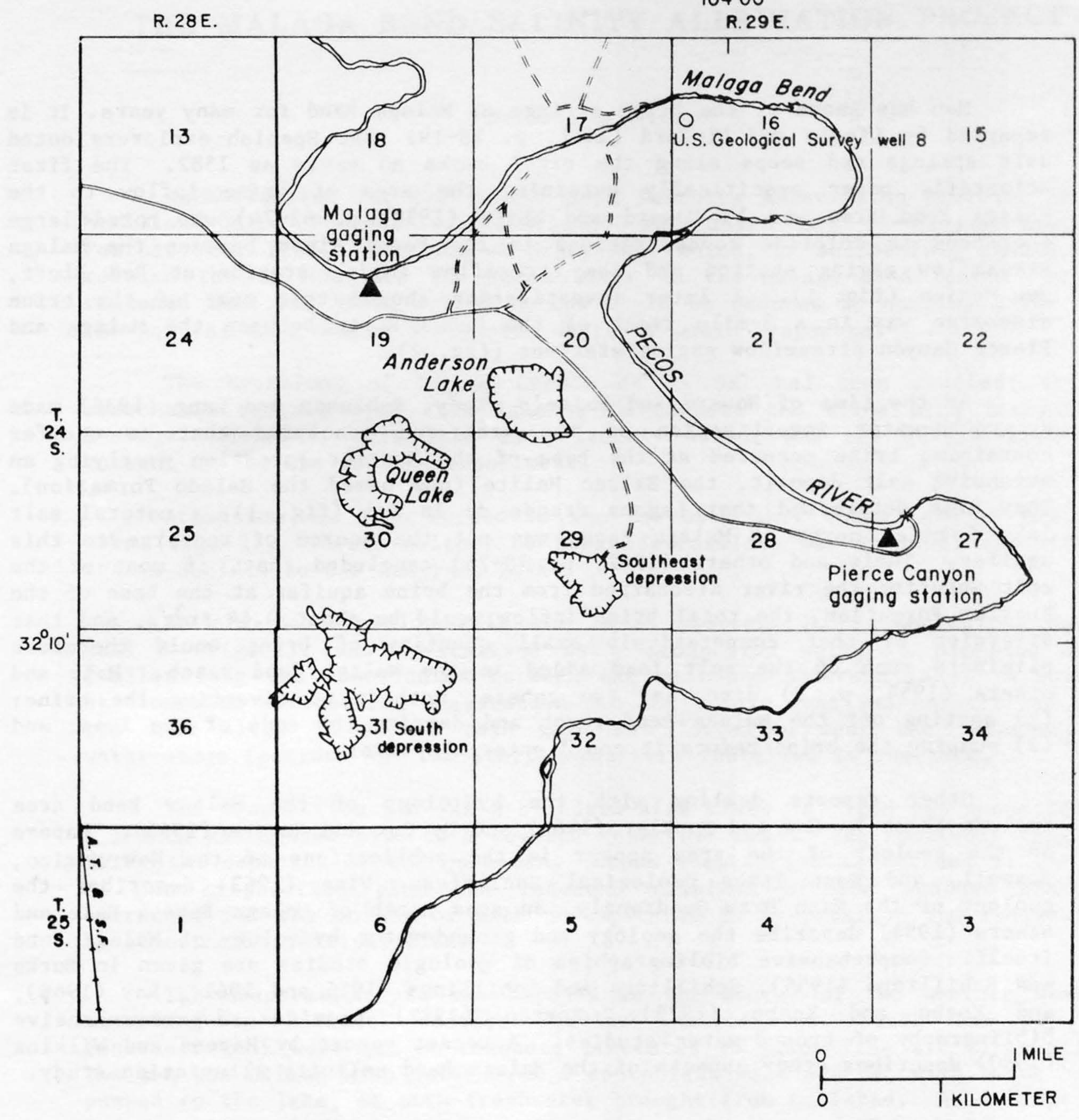


Figure 2. Malaga Bend area and location of U.S. Geological Survey well 8, Anderson Lake, and the streamflow gaging stations Pecos River near Malaga (08406500) and Pecos River at Pierce Canyon Crossing near Malaga (08407000).

PREVIOUS STUDIES

Man has known of the brine springs at Malaga Bend for many years. It is reported by Lingle and Linford (1961, p. 18-19) that Spanish explorers noted salt springs and seeps along the river banks as early as 1582. The first scientific paper specifically outlining the area of brine inflow to the Malaga Bend area was by Howard and White (1938, p. 62-74) who noted large increases in chloride concentrations in the Pecos River between the Malaga streamflow gaging station and the streamflow gaging station at Red Bluff, New Mexico (fig. 1). A later investigation showed that most of the brine discharge was in a 3-mile reach of the Pecos River between the Malaga and Pierce Canyon streamflow gaging stations (fig. 2).

At the time of Howard and White's study, Robinson and Lang (1938) made a ground-water investigation of the area and concluded that an aquifer containing brine occurred at the base of the Rustler Formation overlying an extensive salt deposit, the Salado Halite (now named the Salado Formation). They also determined that Laguna Grande de la Sal (fig. 1), a natural salt lake 5 miles north of Malaga Bend, was not the source of recharge to this aquifer. Theis and others (1942, p. 38-75) concluded that, if most of the salt entering the river discharged from the brine aquifer at the base of the Rustler Formation, the total brine inflow would be about 0.44 ft^3/s, and that diversion of that comparatively small quantity of brine would therefore eliminate much of the salt load added in the Malaga Bend reach. Hale and others (1954, p. 2) discussed two general methods of diverting the brine: (1) cutting off the Malaga Bend reach and damming the ends of the loop; and (2) pumping the brine before it could enter the river.

Other reports dealing with the hydrology of the Malaga Bend area include those by Cox and Kunkler (1962) and by Cox and Havens (1965). Papers on the geology of the area appear in the publications of the New Mexico, Roswell, and West Texas Geological Societies. Vine (1963) describes the geology of the Nash Draw Quadrangle, an area north of Malaga Bend. Hale and others (1954) describe the geology and ground-water hydrology of Malaga Bend itself. Comprehensive bibliographies of geologic studies are given in Burks and Schillings (1955), Schillings and Schillings (1956 and 1961), Ray (1966), and Koehn and Koehn (1973). Borton (1972) provides a comprehensive bibliography of ground-water studies. A recent report by Havens and Wilkins (1980) describes other aspects of the Malaga Bend salinity alleviation study.

THE MALAGA BEND SALINITY ALLEVIATION PROJECT

Methods of study

Authorization for the Malaga Bend Salinity Alleviation Division of the McMillan Delta Project was contained in Public Law 85-33 and approved February 20, 1958. This was an experiment which, if successful, should have reduced the salinity of the Pecos River in the Malaga Bend reach. It was reasoned that the brine spring inflow could be reduced by pumping brine from the aquifer to a nearby depression where it would evaporate.

The hydrology of Laguna Grande de la Sal had been studied; it was reasonably certain that this lake would contain the brine with insignicant leakage. However, this lake is privately owned, and the owners would not consent to its use for the experiment.

Attention was then turned to the use of either Queen Lake or Anderson Lake (fig. 2). Though neither of these depressions was an ideal repository, it was decided to use Anderson Lake.

An old well developed in the brine aquifer, U. S. Geological Survey well 8 (fig. 2), was revitalized as a production well. A pipeline about 2 miles long was constructed between the well and Anderson Lake. A weather station with a recording evaporation pan and a rain gage was constructed near the lake site. A second rain gage was installed near the lakeshore; a water-stage recorder and two staff gages were installed in the lake.

The evaporation pan was a standard-size class "A" land pan connected by a 1-inch galvanized pipe to a covered reservoir tank. The reservoir tank had twice the capacity of the open pan. Gross evaporation is defined as the sum of net evaporation plus the recorded rainfall at the weather station, corrected for the volume of salt precipitated by evaporation and redissolved by atmospheric precipitation.

The evaporation pan was exposed in the center of the weather station according to National Weather Service instructions. Both the pan and reservoir tank were set on unshaded platforms to allow free air circulation. The pan was filled with water from a convenient well nearby, with brine being pumped to the lake, or with freshwater brought from Carlsbad. An attempt was made to keep salt in the pan continuously so that evaporation would be from a saturated brine. During times of greatest evaporation considerable salt accumulated in the bottom of the open pan. A freshwater pan was operated in conjunction with the brine evaporation pan for more than a year to obtain comparative data.

A recorder set above the closed pan was intended to show changes in water level to the nearest 0.001 foot. However, the recorder was not as sensitive as desired. Water-level readings in the open pan seldom agreed closely with the recorder, so the error was proportioned throughout the week. Density differences between water in the open and closed pans may account for some of the error.

Several methods of treating the bottom of Anderson Lake to inhibit leakage were studied, but it was decided that only plowing and compacting were economically feasible. Funds were still insufficient to treat the entire bottom in this way, so only the lower 52 acres were plowed and compacted.

The U.S. Geological Survey maintained the weather station and collected and analyzed appropriate data for evaluating the project. Data collection was most intense from July 1963 to October 1968, but some data collection continued until May 1977.

On-site data were collected by various investigators during the course of the project, and in some instances it has been difficult to identify precisely the techniques used. Therefore, the author of this report has, in some instances, accepted data without being able to confirm its accuracy.

Hydrologic characteristics of Anderson Lake

Brine was pumped from U.S. Geological Survey well 8 into Anderson Lake from July 1963 to May 1976, except for a 7-month period in 1970-71. The combined volume of salt accumulation and brine in Anderson Lake was accurately known from the time pumping began until the gaging station at the lake was dismantled in 1976. The volumes of the solid and aqueous components were most accurately known at times when the volume of salt accumulation was measured. At other times the volume of deposited salt was estimated from evaporation data.

The volume of salt deposited on the bottom of Anderson Lake increased, although the rate of deposition varied with the season, with the pumping schedule of U.S. Geological Survey well 8, and with the composition of the inflowing brine. The volume of brine in storage varied with time, tending to be less in summer than winter due to greater summer evaporation rates, and was directly related to the pumping schedule of U.S. Geological Survey well 8.

On October 22, 1975, measurements showed that Anderson Lake contained 367 acre-ft of salt and 330 acre-ft of brine. During May 1977, most of the lake bottom was exposed as a hard, smooth salt surface slightly concave toward the center, where a small pool estimated to contain about 50 acre-ft of brine remained. The smooth surface contained several conspicuous cavities along the western side. Those examined were circular with an average diameter of 4 to 5 feet and a depth of about 1 foot; the sides were near vertical. The bottoms of these cavities were covered with mud. All contained brine although some were separated from the water in the lake by a horizontal distance of about 100 feet. The total surface of the cavities was less than 1 percent of the maximum surface area of the lake bottom. On February 2, 1978, the brine had entirely evaporated, and the lake contained 400 acre-ft of salt.

These cavities also had been observed during the spring of 1971 when the lake probably contained more brine than during May 1977; it was reported that brine movement was noticed in some of the cavities. Brine movement of less than 1 ft/min (1,440 ft/d) probably cannot be detected by the eye; therefore, this observation indicates that the velocity of brine movement in parts of the cavities may have exceeded 1,000 ft/d, although the mean velocity of brine movement through them would be much less. The cavities in the salt bottom of Anderson Lake indicate that virtually all leakage was through very permeable rocks or through cavities; these permeable conduits may be connected hydrologically with the Pecos River. The cavities may be partly or entirely of biological origin; it is possible that the lake floor contained numerous ancient animal burrows that may be extensive enough to provide a continuous hydrologic connection with the river.

During July 1974, a sample of the salt deposited in Anderson Lake was collected from below the brine surface and washed with a mixture of methyl and isopropyl alcohol. This sample was then ground to grain size about that of table salt in a mixture of these alcohols. After drying, the sample was redissolved in demineralized water and the resulting salt solution was analyzed. An assay computed from the analysis (table 1) shows that the deposited salt was 99.5 percent sodium chloride (NaCl).

Table 1. Assay of selected constituents in salt from Anderson Lake
[Analysis by U.S. Geological Survey]

Constituent	Percent by weight of total salt
Calcium	0.068
Magnesium	0.028
Sodium	39.9
Potassium	0.087
Bicarbonate	0.138
Carbonate	0
Chloride	59.6
Sulfate	0.178
Fluoride	0
Bromide	0.078

Salt deposited on the bottom of Anderson Lake appears to have a uniform porosity, measured at 15 percent. The density (D_m) of this salt was measured at 1,830 g/L (grams per liter). The theoretical density of a pure crystal of NaCl (D_s) is 2.16 g/mL (grams per milliliter) (Berry and Mason, 1959, p. 391) which is equivalent to 2,160 g/L.

Selected chemical analyses of brine from U.S. Geological Survey well 8 and Anderson Lake are given in table 2. Other chemical analyses of the brine from U.S. Geological Survey well 8 indicate that there was no significant change in the composition of this brine until April 1971 when the well began pumping brine undersaturated with respect to NaCl.

Table 2. Concentration of selected constituents in brine from U.S. Geological Survey well 8 and Anderson Lake

[Concentrations in milligrams per liter; analyses by U.S. Geological Survey]

Constituent	U. S. Geological Survey well 8			Anderson Lake		
	1-17-64	4-22-66	5-01-64	4-20-66a/	4-20-66b/	4-20-66c/
Calcium	550	504	436	480	556	428
Magnesium	2,750	2,710	3,540	3,790	3,740	3,820
Sodium	120,000	117,000	119,000	118,000	118,000	118,000
Potassium	4,500	4,880	6,300	6,920	6,920	6,930
Bicarbonate	102	121	146	158	161	164
Sulfate	13,100	12,700	15,300	17,100	16,900	16,900
Chloride	187,000	186,000	187,000	187,000	187,000	187,000
Boron	15	19	19	29	28	28
Dissolved solids	330,000	323,000	332,000	334,000	334,000	334,000
Density (at 20°C)	1.209	1.214	1.214	1.214	1.215	1.215

a/ At surface.
b/ Depth 2 feet.
c/ Depth 10 feet.

DETERMINATION OF RESERVOIR LEAKAGE

EQUATIONS RELATING TO RESERVOIR LEAKAGE

Because most data given in this report were collected years ago, there are several uncertainties on the details of some data collection. Most of these uncertainties are due to a later decision to recalculate reservoir leakage from data obtained from an evaporation pan by a method different than originally proposed.

The mathematical approach to calculating leakage with data from an evaporation pan is greatly simplified if brine evaporation is defined as illustrated by the following hypothetical experiment. Five liters of brine in a laboratory beaker are left to evaporate. After a time, the remaining brine and salt in the beaker are separated. The brine in the pores of the salt is calculated and added to the measured volume of the remaining brine. If the sum of the volume of the remaining brine plus the volume of calculated pore brine is equal to 4 liters, then, by definition, 1 liter of brine has evaporated. The virtue of this definition is that it permits some relatively simple and general mathematical relations between various hydrologic parameters necessary to calculate leakage from saline and brine lakes.

A more complex definition is not warranted because some measurements needed redefinition and mathematical corrections. In some instances the corrections are related to details on the method of measurement; where the method is uncertain, the corrections are sometimes ignored. It is shown in subsequent discussions that ignoring these corrections has no significant quantitative effect upon the calculation of leakage.

If pumping brine from the aquifer reduced the rate of brine inflow to the Pecos River, the quality of the river water would be expected to improve, provided there was no new source of brine inflow. Because one possible source of new inflow was leakage from Anderson Lake, it was planned to measure or estimate this leakage to determine its effect on the river water.

The volume of leakage from Anderson Lake (Q) can be evaluated if the volumes of brine inflow (I), freshwater inflow (F), evaporation (E), and the change in lake brine storage (R) are measured or estimated for a given test period t_1 to t_2. The leakage should be equal to the accumulative volume of inflow to the lake minus the evaporation and the change in brine storage. The equation for this relation is:

$$Q = I + F - E - R \qquad (1)$$

where R can have either a positive or negative value because it is the difference in brine storage from time t_1 to time t_2.

It is important to recognize that equation 1 is valid only if the volumes of all variables are measured or calculated as brine volumes. For example, values of F are not the volumes of freshwater flowing or falling into the lake but the equivalent volumes of brine formed by this freshwater. The value of E is not the volume of pure water lost by evaporation but the equivalent volume of brine. Furthermore, if the dissolved salt concentrations are significantly different, the volume of pure water in a unit volume of inflowing brine may be different from the volume of pure water in a unit volume of the reservoir brine.

Some of the variables in equation 1 cannot be measured directly. Rating curves giving the storage of Anderson Lake as a function of the brine stage (s) were available, but the difference in brine storage given by these values did not provide a value for R because of the decrease in reservoir capacity due to salt deposition. Moreover, a unit volume of freshwater contains more water than a unit volume of brine. Any freshwater inflow would dissolve salt previously precipitated by evaporation. Values of F were generally estimated from changes in the lake stage after a period of atmospheric precipitation, allowance being made for the amount of salt dissolved by the freshwater and for the water content of the resulting unit volume of brine.

Atmospheric precipitation refers to rain, sleet, snow, hail or any combination thereof that adds water to the lake. Precipitation refers to salt precipitation.

There is evidence that freshwater inflow dissolved previously precipitated salt to become a saturated NaCl brine within a few hours after entering the lake. This process was aided by wave motion and density currents that were observed soon after storms. Thus the assumption that virtually all evaporation was from brine appears justified.

Values of I were measured by a meter on the pump outlet of U.S. Geological Survey well 8 or estimated from power consumption. Both methods were checked by frequent calibrations using standard techniques of the U.S. Geological Survey. Although the meter was sometimes faulty, the measurements and estimates are believed to be accurate within ± 5 percent.

The equation for the salt balance in the reservoir is:

$$IC_x + FC_f = QC_Q + PD_m + (R_2 - P)\, C_z - R_1 C_y \qquad (2)$$

where the variables I, F, and Q have been explained, and:

C_x is the concentration of dissolved salt in the inflowing brine;

C_f is the concentration of dissolved salt in freshwater inflow;

C_Q is the concentration of dissolved salt in the leakage;

C_z is the concentration of dissolved salt in the reservoir brine at time t_2;

C_y is the concentration of dissolved salt in the reservoir brine at time t_1;

P is the volume of salt accumulation during the period t_2 to t_1;

D_m is the density of deposited salt;

R_2 is the reservoir capacity from a rating curve at time t_2;

R_1 is the reservoir capacity from a rating curve at time t_1.

When values of C_y and C_z are different, the value of C_Q is calculated as the average of C_y and C_z.

The assay of the precipitated salt given in table 1 shows that it was 99.5 percent NaCl; therefore, it will be sufficiently accurate to treat it as pure NaCl. The data in table 2 show that the concentrations of both sodium (Na^+) and chloride (Cl^-) ions in the inflowing brine (U.S. Geological Survey well 8) and in the reservoir brine were virtually equal. This indicates that the inflowing brine and reservoir brine were saturated with respect to NaCl, and the values of all brine concentrations given in equation 2 are equal.

From table 2, the average concentration of Na^+ for all chemical analyses is 118 g/L, and the average concentration of Cl^- is 187 g/L. Because the molar weights of Na^+ and Cl^- are 23.0 g/mole and 35.45 g/mole, these concentrations may be converted as follows:

$$\frac{118\ \text{g/L}}{23.0\ \text{g/mole}} = 5.13\ \text{moles of}\ Na^+/\text{L}$$

$$\frac{187\ \text{g/L}}{35.45\ \text{g/mole}} = 5.28\ \text{moles of}\ Cl^-/\text{L}$$

Therefore, when the salt in 1 liter of brine precipitates, 5.13 moles of Na^+ will combine with the same number of moles of Cl^- to form 5.13 moles of NaCl. This amount of salt is equal to:

$$5.13\ \text{moles} \times (23.0 + 35.45)\text{g/mole} = 300\text{g of NaCl}$$

All of the concentration values in equation 2, except C_f, are therefore equal to 300 g/L. Because the salt content of the freshwater inflow is negligible, C_f is taken as zero. With the introduction of these values equation 2 becomes:

$$300\ I = 300Q + 1830\ P + 300\ (R_2 - P) - 300\ R_1 \qquad (3)$$

Dividing both sides of equation 3 by 300 and substituting R for $(R_2-P)-R_1$ gives:

$$I = Q + 6.10\ P + R \qquad (4)$$

Rearranging terms, subtracting equation 1 from equation 4 and solving for P gives:

$$P = 0.16\ (E-F) \qquad (5)$$

The relation given by equation 5 was used to compute the depletion of reservoir storage due to salt deposition at times when P was not measured. Thus, the relation $R = R_2 - P - R_1$ becomes:

$$R = R_2 - 0.16\ (E-F) - R_1 \qquad (6)$$

This equation was valid until April 1971, when U.S. Geological Survey well 8 began to pump brine undersaturated with respect to NaCl.

From table 2 it can be shown that the average weight of a liter of reservoir brine is 1,214 g and that 334 g of the total weight is dissolved solids; hence, each liter of brine contains 1,214 - 334 = 880 g of water. Therefore, a liter of freshwater, which weighs 1,000 g/L, will dissolve enough salt to form 1,000/880 = 1.14 L of brine. Because a liter of brine contains 300 g of NaCl, a liter of freshwater entering the lake would dissolve 1.14 x 300 = 342 g of NaCl. This weight of reservoir salt is equivalent to 342/1830 = 0.19 L of salt precipitated on the lake bottom (15 percent porosity), so the net volumetric change in the lake from an inflow of 1 liter of freshwater is 1.14 - 0.19 = 0.95 L. This figure is slightly inaccurate because the redissolved salt would have contained some pore brine; also, some inaccuracy was inherent in the measurement of F. For these reasons, the coefficient 0.95 was rounded to 1 for calculations given in this report.

Values of Q can be computed by several methods. If values of E are from an evaporation pan, Q is computed from equation 1, R being determined using equation 6. Values of Q for a given test period also can be computed from equation 4 if the value of P has been measured for that test period, R then being computed as $R = R_2 - P - R_1$. Finally, values of Q for a given test period can be calculated from the concentrations of various ions, using equation 2. The following section describes the results of these three methods as they were applied to Anderson Lake.

ESTIMATES OF RESERVOIR LEAKAGE

Evaporation-pan method

The most concerted effort at estimating leakage from Anderson Lake was by the evaporation-pan method. Monthly brine evaporation was measured in the evaporation pan previously described, and the values obtained were multiplied by the monthly average area of the lake. The cumulative results for a given test period were multiplied by a pan coefficient of 0.70 to obtain reservoir evaporation for the test period. In theory, the pan coefficient should be applicable only to data collected for a full year; however, various manipulations of the evaporation data indicated little variation in the pan coefficient with the season of the year. This result was probably due to uninvestigated leakage-related factors that were large enough to obscure variations in the pan coefficient.

It is uncertain whether evaporation data were corrected for pan reservoir depletion. It is possible that such corrections might have increased the gross evaporation by 7 to 10 percent during periods of no atmospheric precipitation. The effect of the corrections would have been less on calculations of leakage; however, leakage values might be about 2 or 3 percent too large for some periods.

Because there was some concern about the accuracy of brine evaporation data, a freshwater pan was operated in conjunction with the brine evaporation pan for more than a year. A comparison of the data collected from October 23, 1970, to October 26, 1971, shows that evaporation from the brine evaporation pan was approximately 79 percent of that from the freshwater evaporation pan. According to Linsley and others (1949, p. 157), the annual evaporation rate for brine with a density of 1.214 g/mL should be about 82 percent of the rate for freshwater, so it appears that the data for brine evaporation are reasonably accurate.

The surface area (SA) of the lake in acres may be calculated from the lake stage (s) by a rating curve or, more conveniently, by a computer fitted equation:

$$SA = 3.729 + 7.373s - 0.290s^2 + 0.008s^3 - 1.5 \times 10^{-4}s^4 \qquad (7)$$

for stages between 7.0 and 16.0 feet. The apparent reservoir capacity in acre-feet (R_1 or R_2) may be calculated from the lake stage (s) by:

$$R_1 \text{ or } R_2 = -37.89 + 18.33s + 1.78s^2 - 1.16 \times 10^{-3}s^3 \qquad (8)$$

for stages between 7.0 and 16.0 feet. Evaporation and leakage values computed by this method (equation 1) for periods from July 1963 to September 1968 inclusive are given in table 3.

Table 3. Estimated leakage based on inflow, change in storage, and evaporation at Anderson Lake from July 1963 through September 1968

(Values given in acre-feet)

Period	$Q = I + F - R - E$				
	Brine inflow (I)	Freshwater inflow (F)	Change in reservoir storage (R)	Evaporation (E)	Leakage (Q)
July 1963 - Sept 1963	153	10	116	21	26
Oct 1963 - Sept 1964	680	28	178	267	263
Oct 1964 - Sept 1965	716	48	52	270	442
Oct 1965 - Sept 1966	668	117	67	239	479
Oct 1966 - Sept 1967	744	52	-24	294	526
Oct 1967 - Sept 1968	733	65	-24	262	560

Salt-accumulation method

On January 20, 1965, the accumulated salt deposition was measured by sounding the lake floor. From these measurements, P was calculated at 46 acre-ft. A later measurement on March 26, 1968, showed P equal to 191 acre-ft. Values of Q computed by equation 1 using data from the evaporation pan and by equation 4 using the above values for P are given in the following table:

Period	Leakage (acre-feet)	
	Evaporation-pan method	Salt-accumulation method
July 22, 1963 - January 20, 1965	390	430
July 22, 1963 - March 26, 1968	2,040	1,770

Dissolved-constituent method

Chemical analyses of the brine from U.S. Geological Survey well 8 and Anderson Lake (table 2) allow the calculation of leakage by use of equation 2. The potassium concentrations of the brine from U.S. Geological Survey well 8 and Anderson Lake were used for these calculations, the results of which are given in the following table. Leakage values computed by the evaporation-pan method and equation 1 are given for comparison.

Period	Leakage (acre-feet)	
	Evaporation-pan method	Dissolved-constituent method
July 22, 1963 - May 1, 1964	128	150
May 1, 1964 - April 22, 1966	815	818
July 22, 1963- April 22, 1966	928	982

The calculation of Q depends on data from the evaporation pan because the value of P in equation 2 is calculated using that data. The dependence, however, is not very great; for example, if P had been set equal to zero in the first calculation of the above table, a value of 125 acre-ft would have been obtained instead of 150 acre-ft. Therefore, errors in the data from the evaporation pan will not significantly affect the calculations. The use of the pan coefficient 0.70 (uncorrected for seasonal variation) results in some additional, slight error and accounts for the fact that leakage determinations for the entire period, July 22, 1963 to April 22, 1966, are not exactly equal to the sum of the values for the shorter periods.

The potassium ion normally is not used for such calculations because it is generally reactive in the hydrogeologic environment and becomes incorporated into precipitates; however, the composition of the deposits on the floor of Anderson Lake indicates that potassium is not significantly precipitated in that environment. Potassium was used in these calculations because its concentration was accurately determined while the concentrations of ions that might have served better were unknown, not accurately determined, or variable in the inflowing brine.

ANALYSIS OF LEAKAGE DATA

The following table shows the relation between brine inflow and leakage for various periods. The values of leakage are averages of the values obtained by the methods previously described. A progressively larger part of the inflowing brine leaked from the lake, indicating that leakage is probably a function of the lake stage.

Period	Q (Acre-feet)	I (Acre-feet)	Q/I x 100
July 22, 1963 - May 1, 1964	139	520	27
July 22, 1963 - January 20, 1965	410	1,060	39
July 22, 1963 - April 22, 1966	955	1,930	49
July 22, 1963 - March 26, 1968	1,900	3,330	57

From data in table 3, it was calculated that about 76 percent or 560 acre-ft of the brine inflow to Anderson Lake from October 1967 to September 1968 leaked from the lake. This is equivalent to an average of 47 acre-ft per month. The inflow of brine to the river from springs prior to pumping of U.S. Geological Survey well 8 was about 26 acre-ft per month. Therefore, if most of the brine leakage from the lake flowed back into the river in the Malaga Bend reach, the salinity of the river water would have increased even if pumping eliminated all natural brine spring inflow to the river.

RELATION BETWEEN RESERVOIR LEAKAGE AND THE QUALITY OF WATER IN THE MALAGA BEND REACH

Water-quality analyses and the recording of discharge for the Pecos River at streamflow gaging stations upstream and downstream from the Malaga Bend reach were continued during the period of this study. From these records, annual loads of dissolved chloride were computed at both streamflow gaging stations; the difference in these loads was divided by 365 to give the average gain in chloride in tons per day. Ideally, the daily gain in chloride would have been calculated directly, but this was not practical; instead, daily water samples were composited for chemical analysis.

Gains in chloride load for water years 1960 through 1975 are shown in figure 3. The decrease in chloride gains during the 1964 water year was even more dramatic than is apparent in the figure because of the effect of averaging monthly gains to obtain an annual average. The smallest monthly gain was about 50 tons per day during July 1964; this was due to the decrease in the flow of brine springs caused by pumping U.S. Geological Survey well 8. The average gains in chloride loads shown for the 1968 and 1974 water years were too small due to inadequate sampling during flood periods. The steady increase in gains in chloride during the 1965 through 1970 water years was related to an increase in reservoir leakage from Anderson Lake.

On or about September 6, 1970, lightning struck the power line supplying the pump at U.S. Geological Survey well 8. The pump was disabled, and the plastic casing of the well was damaged by the pump bowls, which became detached and fell into the well. The pump was repaired in April 1971, but the casing was not. Brine pumped after this date was undersaturated with respect to NaCl. During the period when the pump was inoperative, brine inflow in the Malaga Bend reach decreased due to the decreased stage of Anderson Lake; when pumping resumed, brine inflow in the Malaga Bend reach increased.

It has been speculated that some of the increased gain in chloride load shown in figure 3 might be due to an inflow of brine from potash refineries operating north of Malaga Bend. This speculation was prompted by the relatively recent (since about 1950) appearance of many brine lakes in the Nash Draw and Clayton Basin areas, likely recharge areas for the brine springs at Malaga Bend. While these new brine lakes may contain effluent brine from the potash refineries, their effect on the hydrology of the confined brine aquifer is obscure. Estimates of the surface areas of these lakes and of evaporation rates on the tailing piles at the refineries show that annual evaporation is sufficient to evaporate much of, in some instances more than, the brine effluent produced by the potash companies (U.S. Bureau of Land Management, 1975, p. II-197). Moreover, the ratio of potassium concentrations to sodium concentrations in the brine from Anderson Lake ranges from 0.05 to 0.06 (table 2), whereas the ratio of potassium

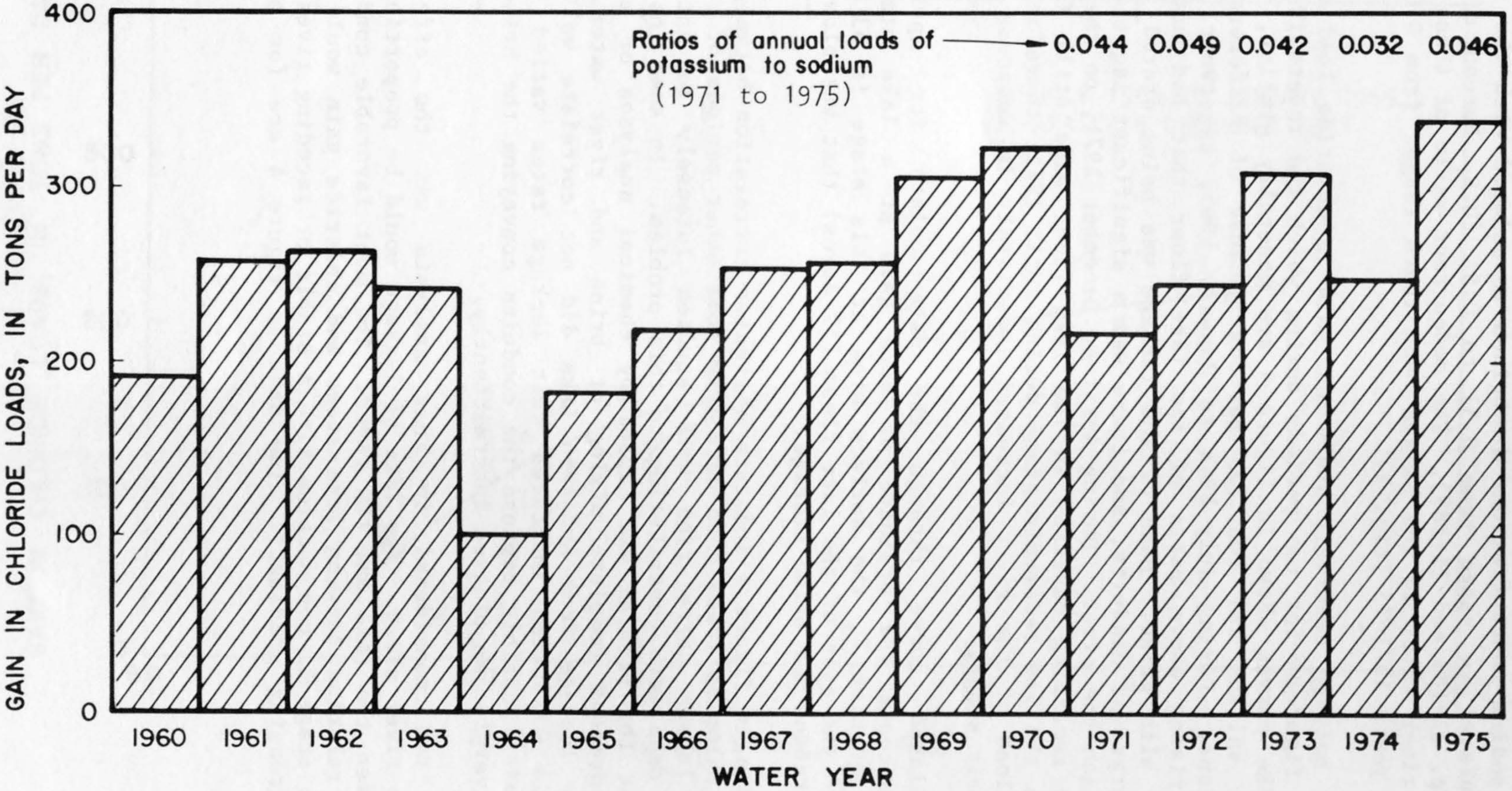


Figure 3. Gain in the loads of dissolved chloride in the Pecos River between the streamflow gaging stations Pecos River near Malaga (08406500) and Pecos River at Pierce Canyon Crossing near Malaga (08407000) for water years 1960 through 1975.

concentrations to sodium concentrations in brines associated with the potash effluent was calculated to range from 0.31 to 0.51 (U.S. Bureau of Land Management, 1975, p. II-188 and II-189). The concurrent ratio of these ionic concentrations in river water in the Malaga Bend reach ranged from 0.032 to 0.046 during water years 1971-75 (fig. 3).

The relation between reservoir stage and gain in chloride load in the river is shown in figure 4 for two periods during which the reservoir stage was increasing. The curves shown in figure 4 are generally similar, though they are somewhat shifted for the two periods because of differences in hydrologic conditions. During July 1964 to January 1965, reservoir levels were continually rising above parts of the lake floor that had not been previously covered with brine. Much of the leakage was being stored in the newly flooded underground conduits, and there was a significant lag time for this leakage to reach the river. During April to December 1971, on the other hand, most of the remaining cavities in the lake floor were still flooded with brine despite the low reservoir stage during April 1971; therefore, the gain in chloride load of the river increased immediately in response to an increase in reservoir stage.

The extrapolated curve through the data points for April to December 1971 intercepts the ordinate of zero gain at a lake stage of 9.55 feet. From equation 7, the surface area at this stage is 53 acres, which is similar to the area of the lake floor (52 acres) that was plowed and compacted in preparation for brine storage.

The data given in figure 4 indicate a greater correlation between lake stage and gain in chloride loads than data from some other periods of record. Some periods of lesser correlation were studied intensely to determine whether errors in data were contributing to this problem. In some instances it was likely that the problem was caused by chemical analyses of samples which did not represent complete mixing of brine and river water. The calculated monthly leakage from Anderson Lake did not correlate well with lake stages. This situation indicates that leakage rates varied widely within short periods, possibly because the conduits conveying the brine from the lake to the river became plugged intermittently.

One factor not considered in this analysis was the effect of fluctuation of the river stage. The rate of leakage would be proportional to the gradient between the lake and the river. The most favorable conditions for a consistent relation between lake stage and chloride gain would occur with a rising lake stage in conjunction with a stable or receding river stage (a constantly increasing gradient). The data in figure 4 are for similar circumstances.

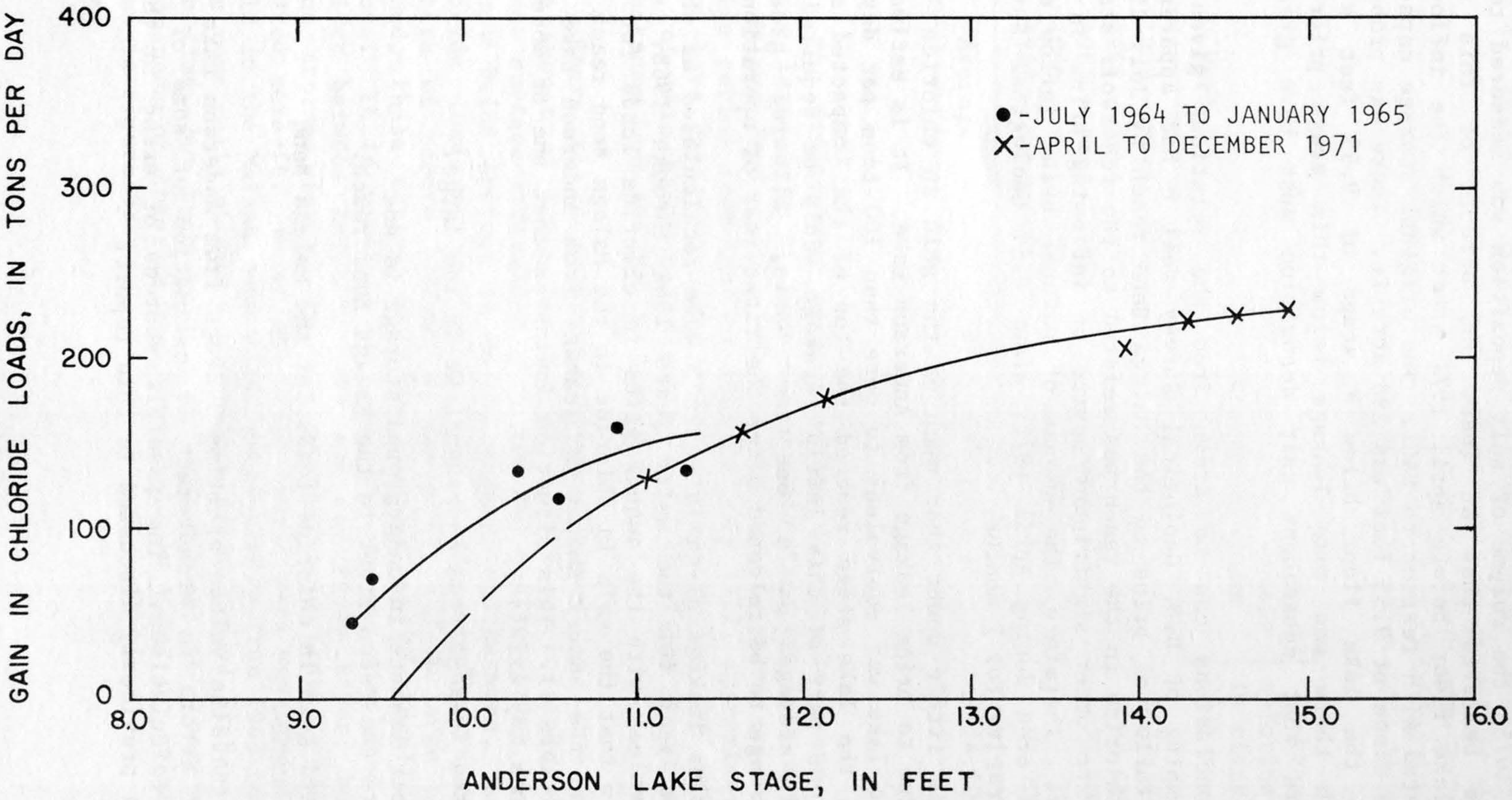


Figure 4. Relation between average monthly gain in chloride loads in river water between the streamflow gaging stations Pecos River near Malaga (08406500) and Pecos River at Pierce Canyon Crossing near Malaga (08407000) and the stage of Anderson Lake.

On October 22, 1975, the volume of salt deposition was measured to be 367 acre-ft. It is believed that at least 300 acre-ft of this salt accumulated on the lake floor before April 1971 after which the inflowing brine was undersaturated with respect to NaCl. The original storage capacity of the reservoir at a stage of 9.55 feet was 298 acre-ft. There was probably little leakage from the lake floor below a stage of 9.55 feet after April 1971. Although there was some leakage below this stage prior to July 1964, it appears that subsequent salt deposition must have greatly reduced the leakage.

Two general conclusions can be drawn from the relations given in figure 4. First, pumping of U.S. Geological Survey well 8 had apparently reduced the natural inflow of brine to the Malaga Bend reach by July 1964. Because the gain in chloride in the reach was related to the reservoir stage, there was apparently no other significant source of inflowing brine in the area after that date. Therefore, the amount of natural brine inflow must have been very small even during April 1971, after U.S. Geological Survey well 8 had been inoperative for 7 months.

Second, there is little doubt that much of the gain in chloride load after July 1964 was due to brine leakage from Anderson Lake. It is estimated that leakage from the lake was equivalent to more than 100 tons per day of chloride by the time the lake stage reached the top of the compacted area during July 1964. Some part of this initial leakage would be required to increase underground storage on a one-time basis, allowing greater percentages of the leakage to be released after the first year of operation.

Estimates of brine leakage given in table 3 were recalculated as short tons of chloride per year for the water years 1964 through 1968. The comparison of these values with the annual gains in chloride loads for the Malaga Bend reach show that the gain in chloride in the Malaga Bend reach was consistently less than the annual amount of leakage from Anderson Lake for each year of record (table 4). This situation indicates that one or more of the following conditions may exist:

1. The calculated leakage from Anderson Lake is too large.

2. Some reservoir leakage in underground storage is not discharging to the Pecos River in the Malaga Bend reach.

3. The calculated gain in chloride loads for the Malaga Bend reach is too small.

It is possible that the values of brine leakage from Anderson Lake are too large because of errors in measurement or estimation of some of the factors used in the calculations. The possible sources of error in these calculations have been previously discussed in this report.

Table 4. Estimated dissolved chloride loads of brine leakage from Anderson Lake compared to the increase in dissolved chloride loads in the river water between the Pecos River near Malaga (08406500) and the Pecos River at Pierce Canyon Crossing (08407000) streamflow gaging stations for the water years 1964 through 1968

Period	Chloride load leakage from Anderson Lake (short tons)	Increase in chloride loads in river water (short tons)	Ratio of column 3 to column 2
Oct. 1963 - Sept. 1964	68,800	37,200	0.56
Oct. 1964 - Sept. 1965	112,000	66,400	.59
Oct. 1965 - Sept. 1966	122,000	79,900	.65
Oct. 1966 - Sept. 1967	134,000	92,700	.69
Oct. 1967 - Sept. 1968	142,000	94,200	.66
Average	115,000	74,100	.64

The differences between values in columns 2 and 3 (table 4) indicate that a large part of the leakage from Anderson Lake may not have emerged in the Malaga Bend reach. If the differences shown are representative for the entire period from October 1963 to July 1977, approximately 2,000 acre-ft of brine have gone into underground storage during the period, or some, if not all, of this brine has discharged to the Pecos River at points upstream or downstream from the Malaga Bend reach.

There is no evidence that a new aquifer large enough to accommodate this amount of brine has formed. Aerial photographs show no evidence of a recent surface expression of a new and shallow brine aquifer or the presence of new brine springs in nearby sinks. Furthermore, the ratios of gains in chloride load to reservoir leakage are nearly constant after the first 2 years of record (column 4, table 4). If a large new brine aquifer had formed, these ratios would be expected to continually trend toward larger values. It is possible that the leakage has displaced water in the shallow aquifer between Anderson Lake and the Pecos River, but the amount of new brine storage formed by this displacement probably does not exceed a few hundred acre-ft. Water and brine levels were measured in several observation wells in the Malaga Bend area, particularly from 1963 to July 1968. The data from some wells showed a consistent trend toward higher water or brine levels with time, but such a trend was not evident at other wells. The net effect of changes of chloride concentrations in water or brine from these wells is given in figure 5.

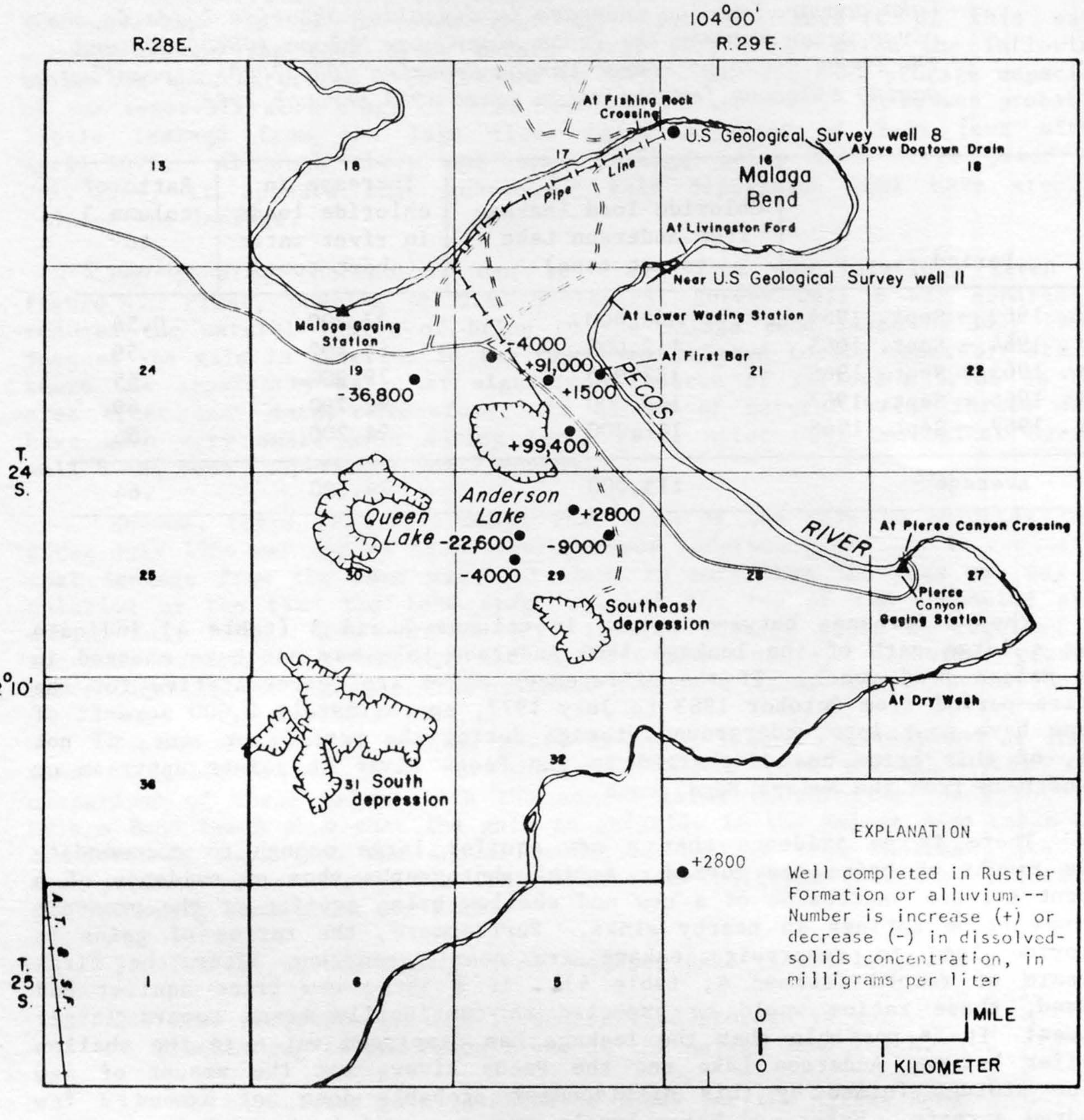
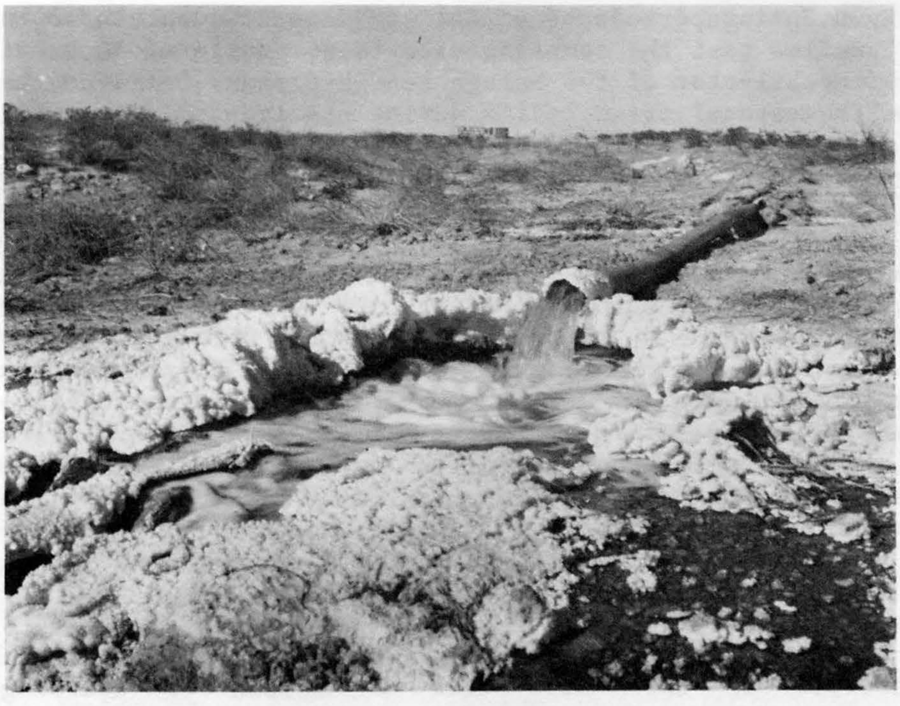


Figure 5. Changes in chloride concentrations of water from wells completed in the Rustler Formation or alluvium in the Malaga Bend area from June or July 1963 to July 1968.

There is some temporary storage of brine in the bed of the Pecos River. It is known, for example, that the small brine aquifer formed by leakage from Anderson Lake discharges into the Pecos River in a pool scoured by the flood of 1966. The upstream end of this pool is in section 20, T. 24 S., R. 29 E., at a point where the river bends to the southeast (fig. 2). The pool is approximately 3,000 feet long. Although its depth is more than 12 feet in places, the average depth is probably about 5 feet. Aerial photographs indicate an average river width of about 120 feet. Water-quality surveys show that the brine stored in the bottom of this pool is overlain by about 1 to 2 feet of saline water. Brine enters the pool through a spring or springs below the water surface. The amount normally in storage is probably 25 to 30 acre-ft. The upstream end of this pool is approximately at the downstream end of the previous reach of natural brine inflow. A river survey indicated no significant brine inflow upstream from the Malaga streamflow gaging station or downstream from the Pierce Canyon streamflow gaging station.



DATA UNCERTAINTIES

The methods for calculating the gain in chloride loads in the river are straightforward, but there were technical problems in obtaining the data needed for these calculations. It was noted previously that the average annual gain in chloride loads given in figure 3 is too small for the 1968 and 1974 water years. It is likely that the values are, in fact, too small for most of the years of record. The primary reason for this problem is that the Pierce Canyon streamflow gaging station is too close to the site of the brine inflow to obtain appropriate samples of water for chemical analyses.

The following problems are created by the proximity of the streamflow gaging station and sampling site to the sites of brine discharge:

1. Brine and river water were not thoroughly mixed during many sampling periods. The lower part of a river cross-section at the sampling site probably contains more saline water than does the near surface part.

2. During floods much of the brine in deep pools is flushed from the river bed by flood water. At times most of the daily load of dissolved solids was swept past the Pierce Canyon streamflow gaging station in less than an hour.

3. Even during periods of normal low flow, the rate of brine inflow past the sampling site is not uniform. A previous investigator of the Malaga Bend hydrology believes that the rate of brine inflow during his investigation of the problem in 1953-54 was inversely proportional to the barometric pressure (William E. Hale, U.S. Geological Survey, oral commun, 1954).

In addition, the site of the Pierce Canyon streamflow gaging station is too far upstream to measure and sample all irrigation return flow to the river. Irrigation water is periodically diverted from inside the Malaga Bend; chloride loads in the water returned to the river downstream from the Pierce Canyon streamflow gaging station were not included in the calculations of the annual loads. Data relating to the amount of water diverted for irrigation inside Malaga Bend were studied, but no satisfactory estimate was reached on the amount of this water that returned to the river downstream from the Pierce Canyon streamflow gaging station. Most observers believe that the amount was less than 5 percent of the annual river flow.

It was recognized at the outset of this study that the Pierce Canyon streamflow gaging station was too far upstream to obtain reliable data, but no alternatives to this site were accessible or hydrologically more desirable. Sporadic attempts were made to improve the quality-of-water record at the Pierce Canyon streamflow gaging station by installing continuous recording units to measure specific conductance, but these attempts were unsuccessful because the electrodes of the instruments became fouled with algal growth; moreover, it was never determined where the electrodes should be placed in a cross-section of the stream to obtain representative data. The possibility of placing automatic sampling devices at the Pierce Canyon streamflow sampling site was considered, but due to their expense and experimental nature at that point in time, they were not installed.

CONCLUSIONS

The following conclusions are made from this study:

1. The pumping of brine from the brine aquifer apparently reduced the flow of natural brine springs in the Malaga Bend reach to a small fraction of the natural inflow prior to July 1963.

2. Three methods developed for calculating brine leakage from Anderson Lake give reasonable and consistent results.

3. The gain in chloride loads in the Malaga Bend reach was a function of the reservoir stage of Anderson Lake. Most leakage from the lake reached the river through very permeable rocks or through cavities in the rocks.

4. The deposition of salt apparently was effective in reducing leakage through that part of the lake bottom that was plowed and compacted prior to storage of brine.

5. In general, surface depressions formed by the collapse of underlying rocks are not likely to be ideal storage receptacles. If similar features are to be used for the storage of brine in the future, they need to be carefully studied to determine if they have a history of reservoir storage after storms.

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