UNITED STATES

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GEOLOGICAL SURVEY

EVALUATION OF HYDROGEOLOGIC ASPECTS OF PROPOSED SALINITY CONTROL PROGRAM IN PARADOX VALLEY, COLORADO

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PREFACE

This report, evaluation of the hydrogeological aspects of a plan to control salinity increases in the Dolores River where it crosses Paradox Valley in southwestern Colorado, was prepared at the request of the U.S. Bureau of Reclamation. The evaluations and recommendations presented in this report are based on data available to the authors in March 1975. The report has not been revised to reflect any additional information that has become available since then.

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EVALUATION OF HYDROGEOLOGIC ASPECTS OF PROPOSED SALINITY CONTROL PROGRAM IN PARADOX VALLEY, COLORADO

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ABSTRACT

The salt load in the Dolores River increases by about 200,000 tons per year where it crosses Paradox Valley, Colorado, because of the discharge of a sodium chloride brine from an underlying aquifer. A ground-water management program to nearly eliminate this major source of salt, which eventually enters the Colorado River, can be designed on the basis of an accurate description of the hydrogeologic framework of Paradox Valley.

INTRODUCTION

Statement of Problem

The high salinity of the Colorado River is a major water-quality problem affecting seven Colorado River basin states and Mexico. The Colorado River, draining an area of 242,000 square miles in the United States and 2,000 square miles in Mexico, is highly regulated. The river, historically characterized by a high concentration of dissolved solids, has been increasing in salinity as reservoir storage, diversions, and return flows have increased within the basin. The salinity will continue to increase as more states develop their allocated water supply.

The deteriorating water supply poses definite economic problems to 10 million water users in the lower reaches of the system. According to the Bureau of Reclamation, the average salinity at Imperial Dam at Yuma, Ariz., is 850 mg/L (milligrams per liter) and could reach from 1,160 to 1,340 mg/L by the year 2000.

Studies by the Bureau of Reclamation (1974) indicate average annual losses of $230,000 for each increase of 1 mg/L at Imperial Dam. The water-quality problem of the Colorado River affects not only the southwestern United States but the Republic of Mexico, which is guaranteed an annual supply of 1.5 million acre-feet of Colorado River water by a 1944 treaty.

The Bureau of Reclamation currently has a program to eliminate over 1.5 million tons of salt per year from the river--this would reduce the salinity at Imperial Dam by 150 mg/L. The measures devised by the Bureau will be ultimately aimed at maintaining salt concentrations below their present levels in the downstream reaches of the river. This will allow the continuation of beneficial uses and prevent serious economic damages that would otherwise occur.

The Paradox Valley of Colorado is in the Salt Anticline region of Utah and Colorado (fig. 1). A 4-mile reach of the Dolores River, a major tributary to the Colorado River, crosses Paradox Valley near the town of Bedrock. The valley is a breached anticline having a core of gypsum and salt beds. A very large increase in salt load of 200,000 tons per year is observed in the Dolores River where it crosses the Paradox Valley. The geology of the region has been described by Cater (1970).

The Bureau of Reclamation plans to reduce the salt contribution to Dolores River in Paradox Valley by an average of 180,000 tons per year and thereby lower the salinity of the Colorado River by about 16 mg/L at Imperial Dam (U.S. Bureau of Reclamation, 1974). The several plans of the Bureau to decrease salt inflow to Dolores River in the Paradox Valley can be categorized as control by (1) surface-water diversion, and (2) ground-water diversion. Briefly, the surface-water diversion plans call for damming the Dolores River upstream from the Paradox Valley and conveying the water through Paradox Valley by a channel or conduit. Another dam would be constructed on the river below the area of salt-water inflow to the river. This dam would capture the highly saline water and provide a pool where the water would be evaporated. The ground-water diversion plans include interception by wells of the saline water before it discharges to the river and conveyance of the saline water to a solar evaporation reservoir.

Purpose and Scope

The purpose of this study is to consider the proposed plans of the Bureau of Reclamation and to evaluate their feasibility in relation to the hydrologic system. The study thus encompasses:

(1) Evaluation of data collected.

(2) Formulation of a conceptual model describing the functional, chemical, and physical characteristics of the flow system.

(3) Consideration of the compatibility of the Bureau's plans with the natural operation of the system.

(4) Alternative plans and procedures that could be implemented consistent with the hydrologic characteristics of the system.

(5) Enumeration of data needs for definition of the system and understanding of the problem.

(6) Recommendations for approaches to analysis of the problem.

The scope of the study included a visit by the authors to Paradox Valley conducted by Errol Jensen of U.S. Bureau of Reclamation in Durango, a review of the literature on the geology and hydrology of the Paradox Valley, and study of the documents listed in the Appendix and provided to the authors by the U.S. Bureau of Reclamation.

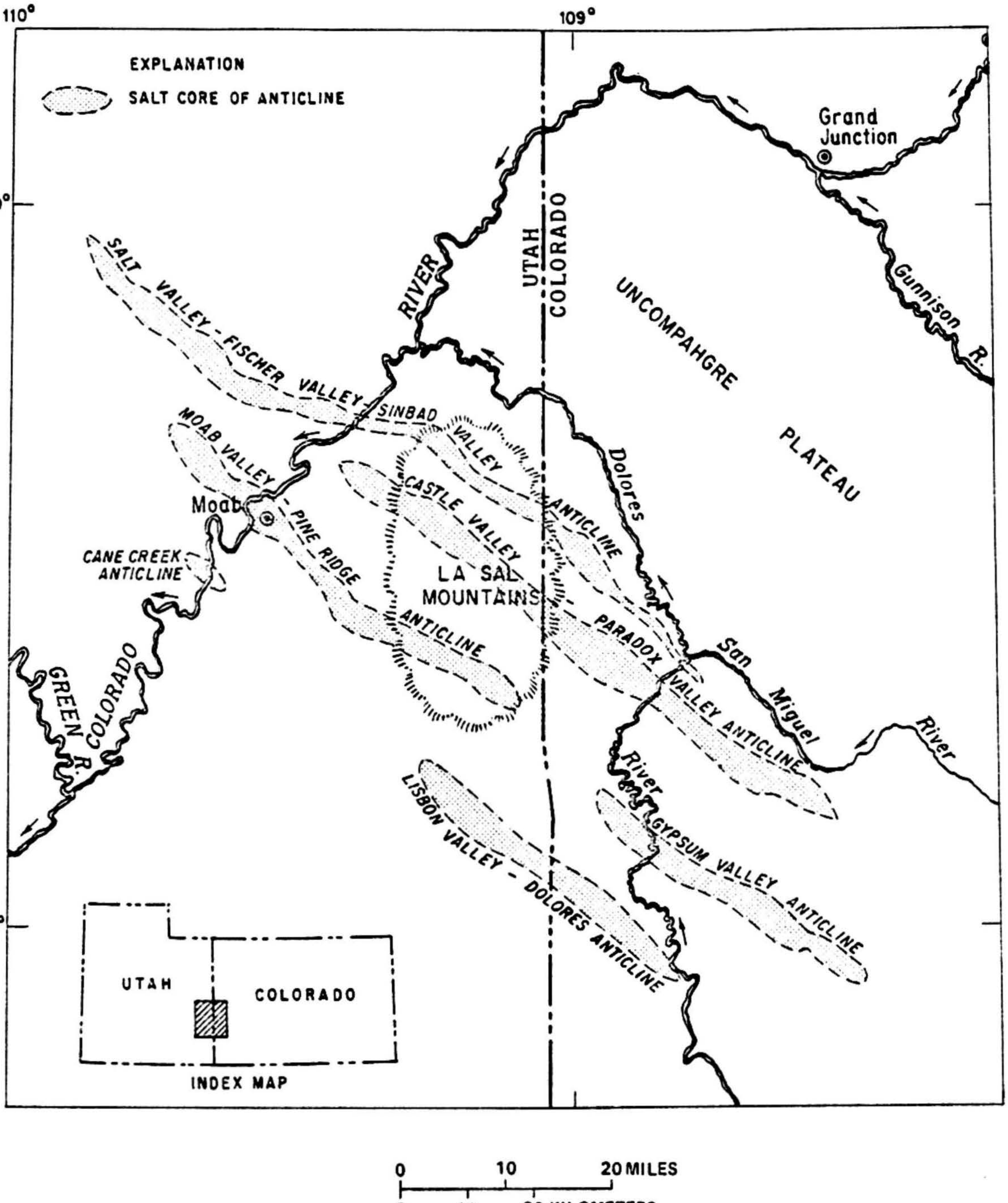

Figure 1.--Salt anticline region of Colorado and Utah
(from U.S. Bureau of Reclamation, 1974).

CONCEPTUAL MODEL

The salt-load pickup in the Dolores River where it crosses Paradox Valley represents the natural output of a complex hydrogeochemical system. The Water Quality Improvement Program of the Bureau of Reclamation will require altering, stressing, and managing this natural system. Any plan of action should be designed to:

(1) Minimize the salt-load pickup in the Dolores River.

(2) Minimize any concurrent reduction in water flow.

(3) Operate efficiently.

(4) Have a low risk of failure or of producing detrimental side effects.

We believe that these four criteria can only be evaluated and achieved if the physical and chemical processes controlling the discharge of the brine are understood well enough so that the response of the system to any set of imposed stresses, such as changes in river stage or pumpage from wells, may be accurately predicted.

An adequate understanding of the system requires detailed descriptions of the geologic, hydraulic, and chemical properties and boundaries of the system. These descriptions can then be integrated into a hypothesis or model of the system, which in turn can be used to evaluate alternative proposals. Sufficient data are presently available to formulate one preliminary conceptual model of the system, which is presented below. Other conceptual models also are possible. A conceptual model must be verified by using the model to make predictions and inferences about the system and testing these inferences by further experimentation and data collection. On the basis of these tests the model can be accepted, rejected, or modified. After the model is accepted, it can then be used to evaluate water-management plans, data requirements can be determined, and means suggested for testing the conceptual model.

On the basis of (1) our field visit, (2) data already collected by the Bureau of Reclamation, and (3) published geologic reports, we believe that the discharge of brine to the Dolores River is the result of the dissolution (or leaching) of salts in the Paradox Member of the Hermosa Formation, of Pennsylvanian age, by flowing ground water underlying Paradox Valley. Most of the ground water that discharges in Paradox Valley has probably moved within a relatively shallow (less than 500 ft (feet) deep) three-dimensional flow system, with the dissolution of salts primarily occurring near the contact between the gypsum-anhydrite caprock and the underlying salt deposits.

The alluvial deposits may be greater than 100 ft thick in places, and the gypsum-anhydrite caprock, which crops out in parts of the center of the valley, may be several hundred feet thick. Aquifer tests indicate that both are moderately to highly permeable. Because the underlying salt beds are subject to plastic deformation and are reported to contain high-pressure gas pockets, they probably have an extremely low hydraulic conductivity. The post-Hermosa Formation consolidated sedimentary rocks in the area consist primarily of sandstones and shales, and perhaps except for fracture zones, also have low hydraulic conductivity.

It is possible that some of the brine that discharges in Paradox Valley may be derived from deep sources below the Paradox Member. However, several factors suggest that this contribution would be negligible. First, the hydraulic conductivity of the salt beds is probably very low, and thus could not allow ground water to be transmitted through it at a significant rate. Second, Hite and Lohman (1973, p. 13) indicate that the only significant aquifer of all the pre-Paradox rocks is the Leadville Formation of Mississippian age. However, a potentiometric map of the Mississippian aquifer presented by Hanshaw and Hill (1969, p. 271) does not indicate the occurrence of ground-water discharge from this aquifer in Paradox Valley. Furthermore, Hite and Lohman (1973, p. 14) state that the Leadville Formation is overlain by the Molas Formation of Early Pennsylvanian age, which in turn is overlain by the "Pinkerton Trail" (lower member of local usage of the Hermosa Formation), and that these units form an effective seal between the Paradox Member of the Hermosa and the Leadville Formation.

A brine sample was collected from a seep adjacent to the Dolores River (approximate locate T. 47 N., R. 18 W., sec. 9) and was analyzed for chemical content by Blair F. Jones (U.S. Geological Survey, Reston, Va.). The results of the analysis are summarized in table 1. The water

Table 1.--Composition of Paradox Valley Brine Sample

[Blair F. Jones, written commun., 1975]

Constituent	Value[1]
Sodium	70,600
Chloride	110,000
Potassium	3,560
Calcium	1,100
Magnesium	1,190
Bicarbonate	196
Sulfate	4,360
Sulfide	1.3
Iron (total)	0.1
Fluoride	4.6
Boron	6.5
Phosphate	0.08
Silica	108
Manganese	1.9
Total dissolved solids	193,000
Specific conductance, field value, micromhos at 25°C	250,000
pH	7.2
Density	1.141

[1]Values are concentrations in milligrams per liter, except for specific conductance, pH, and density.

is predominantly a sodium chloride type of brine. Calcium, magnesium, and sulfate are present in concentrations indicative of gypsum-saturated waters. No other trace metals could be detected using the atomic adsorption method. Selenium could not be detected using a colorimetric method. An analysis of a hydrochloric acid extract of the sediment contained in the water sample indicated the presence of iron (0.1 percent), copper (0.01 percent), a trace of zinc (less than 0.01 percent), but no cadmium, nickel, or cobalt. The sediment was mainly medium- to fine-grained quartz, with coatings of iron sulfide. Although these analyses are consistent with a theory of modern dissolution of salts, isotopic analyses could help to determine the history and origin of the brine with more certainty. The economic potential for recovery of any marketable minerals from the brine appears low.

Our conceptual model of ground-water flow and salt transport in the valley can best be illustrated with a cross-sectional flow net and a water-table map. Figure 2 shows a flow net for a cross section parallel to the long axis of the valley and perpendicular to the Dolores River. This cross section indicates that ground-water flow along the line of the section, from East Paradox Valley towards the Dolores River, consists mostly of brine and that only the uppermost part of the saturated zone may contain freshwater. However, in West Paradox Valley there is a significant freshwater lens overlying the brine, and both the freshwater and the brine are flowing towards the Dolores River. In West Paradox Valley the cross section shows that a downward component of flow may exist near the higher water-table altitudes, indicating recharge to the aquifer in this area, and that an upward component of flow, which indicates ground-water discharge, exists near the Dolores River. Recharge of freshwater in Paradox Valley is probably derived from infiltration from irrigated fields, West Paradox Creek, unlined irrigation ditches, precipitation, and surface and subsurface runoff from adjacent valley walls and mountain flanks. There is no irrigation in East Paradox Valley, where the slightly lower hydraulic gradient indicates the occurrence of less recharge. The strongest vertical hydraulic gradients should occur near the Dolores River just upstream from the impermeable barriers formed by the sandstones and shales that comprise the valley walls. Upward flow in this area is sufficient to force the high-density brine to the surface. Piezometers located in the area of brine discharge do show that the hydraulic potential increases with depth. Note that figure 2 indicates that in West Paradox Valley the interface between the brine and the freshwater does not coincide with a flow line. This reflects our belief that the dissolution of salt and the formation of the sodium chloride brine probably occurs primarily near the contact between the caprock and the underlying salt (halite) beds. However, this contact itself may be gradational and occur at varying depths. Also, the actual interface probably is not as sharp as indicated in figure 2 because hydrodynamic dispersion tends to produce a zone of diffusion between the brine and the freshwater.

Although the hydraulic gradient is somewhat steeper in West Paradox Valley than in East Paradox Valley, it is possible that the total brine discharge from East Paradox Valley may be greater than from West Paradox Valley because a large percentage of the ground-water discharge from

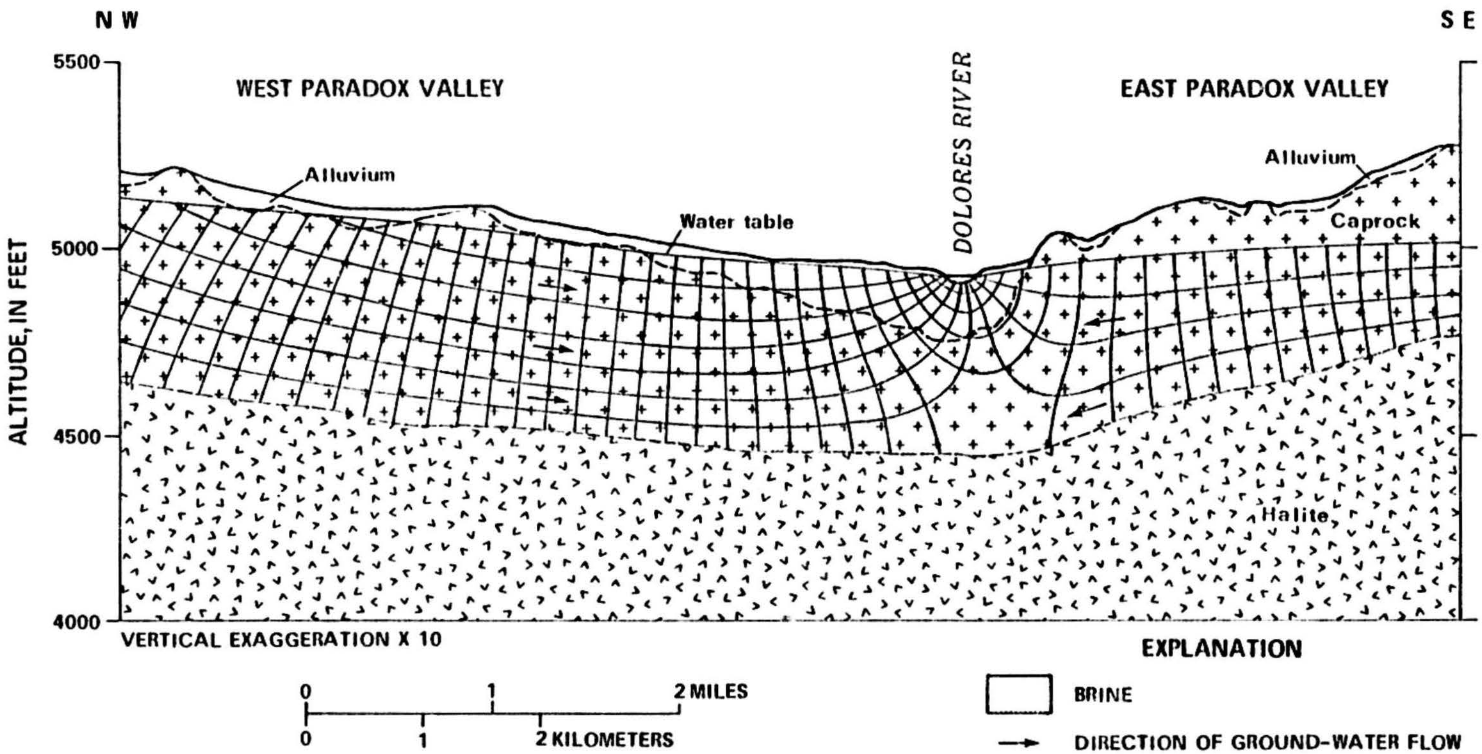

Figure 2.--Generalized northwest-trending cross section through Paradox Valley showing conceptual model of ground-water flow perpendicular to Dolores River (location of section shown on fig. 3). Flow net depicts hypothetical streamlines and equipotential lines.

West Paradox Valley consists of freshwater. The flow net indicates that in West Paradox Valley recharge in areas farthest from the Dolores River (that is, farthest to the northwest) would tend to follow flow lines to the deepest part of the aquifer. This water then would flow at depth through rocks containing increasing percentages of salt; the freshwater thus would dissolve both gypsum, thereby increasing its concentration of calcium, magnesium, and sulfate ions, and salt, greatly increasing its concentration of sodium, potassium, and chloride ions. Within short distances of the contact between the caprock and the salt beds the ground water would be transformed into a high-density brine. Freshwater that follows a relatively shallow flow path can still dissolve significant amounts of gypsum from the caprock, thereby increasing its concentration of calcium, magnesium, and sulfate ions.

The surface of the brine shown in figure 2 was largely inferred from the Bureau of Reclamation's map "Contours on top of salt brine based on resistivity survey." In West Paradox Valley the brine surface coincides with the interface between freshwater and the brine. In parts of East Paradox Valley the brine surface may nearly coincide with the water table, and be overlain by only a thin lens of freshwater, which may partly discharge by evapotranspiration in areas of shallow water table and partly mix with the brine due to dispersion and diffusion. Note that the thickness of alluvium is apparently much less in East Paradox Valley, as indicated by the outcrops of caprock. Because the caprock is at a higher elevation in East Paradox Valley, the contact with the underlying salt possibly may also be shallower. This possible occurrence of a greater thickness of caprock and greater depth to salt in West Paradox Valley than in East Paradox Valley might be the result of an influx and availability of greater volumes of freshwater to West Paradox Valley during the geologic history of the area, thereby removing a greater volume of salt and producing a greater depth of leaching. Again, note that the cross section is highly schematic and only intended to represent our conceptual model.

Figure 3 presents a map of part of Paradox Valley and shows the location of the cross section and also shows a possible water-table configuration. The control for these contours was land-surface altitude, spring altitudes, surface-water altitudes, and water-level data from the U.S. Bureau of Reclamation. The water-table map should be refined on the basis of additional water-level measurements in the wells. The water-table map indicates that in East Paradox Valley there is some recharge of freshwater along the valley walls. This is supported by the occurrence of freshwater springs and a shallow well producing freshwater south of the highway in East Paradox Valley.

The water-table map indicates that if the northwest-southeast cross section (fig. 2) were taken further to the southwest, it would probably indicate a greater thickness of freshwater in East Paradox Valley, and a greater depth to the brine surface. It is clear from figure 3 that the hydraulic heads present in either East or West Paradox Valleys are high enough to force the high-density brine to the surface in part of the discharge area. It is also possible that an additional driving force may be created by the release of gas (natural gas, methane, hydrogen

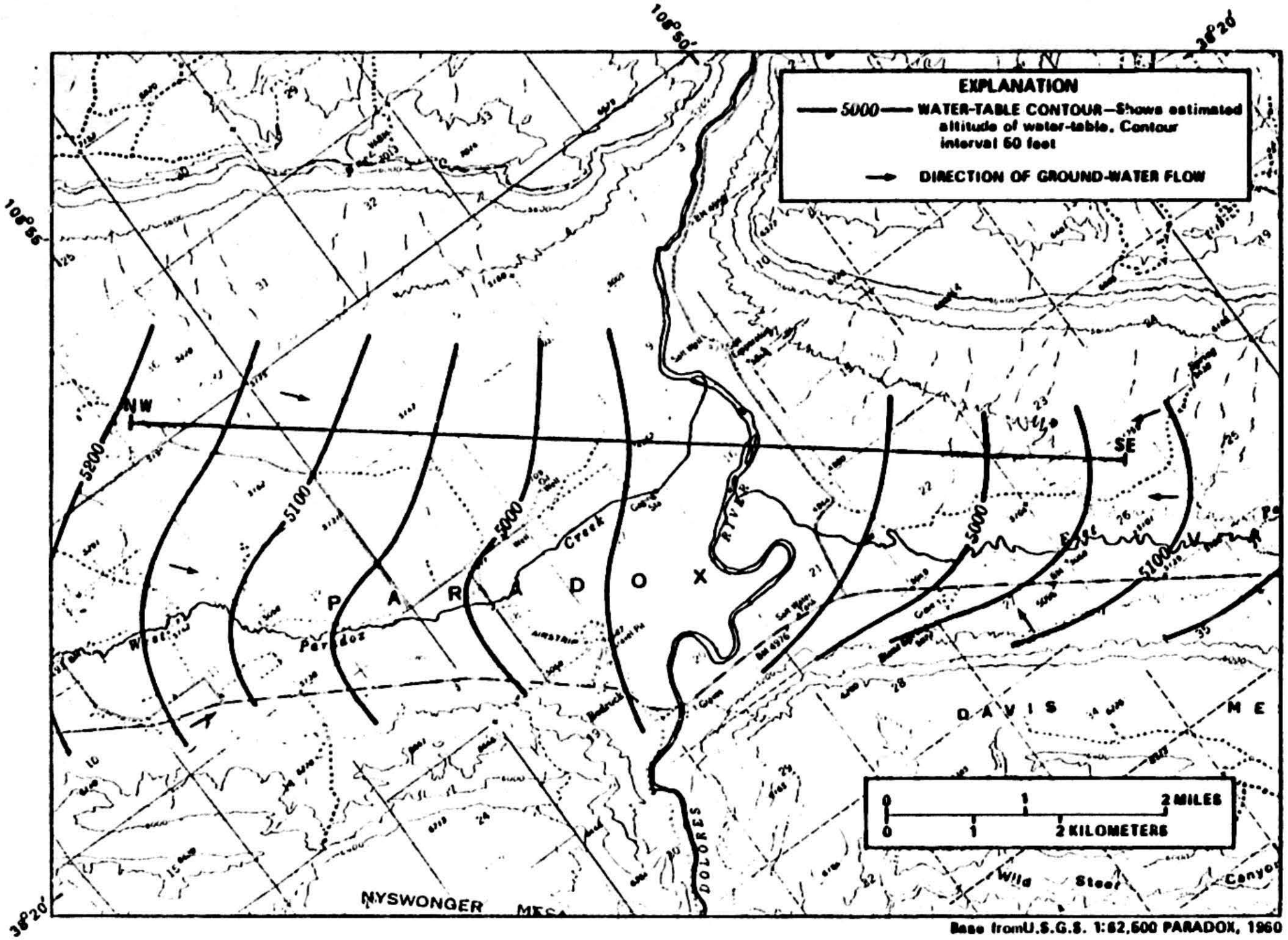

Figure 3.--Map of part of Paradox Valley showing location of section and estimated water-table configuration.

sulfide, or other gasses that may be associated with the Hermosa Formation), but presently the significance of this factor seems minimal. Note that the presence of flammable gases should be considered with appropriate caution in any plan for management of the system.

STRATEGY FOR DESIGNING A SALINITY-CONTROL PLAN

Any design for a salinity-control project should consider the entire physical system associated with the brine discharge. Our conceptual model defines the system of interest as consisting of an integrated stream-aquifer system in which the most important elements are the upper few hundred feet of rocks underlying Paradox Valley and the reach of the Dolores River that crosses Paradox Valley. Only by considering the entire system can one predict the effects of imposing stresses that are required for salinity control.

One major approach to salinity control is through management and regulation of the surface-water elements of the system. Examples of this approach include alternative plans 4 and 5 described in the U.S. Bureau of Reclamation report of August 1974 (Appendix, Item 1). These plans would include the construction of a bypass channel, dams, and an evaporation pond in Paradox Valley. The basis of this approach is to prevent the brine from entering the river by separating the river from the aquifer. Initially, this plan should produce the maximum possible reduction in salinity in the Dolores River. However, it was not mentioned in the report that the evaporation pond would have to hold not only the brine discharge, but also (1) any discharge of fresh ground water from West Paradox Valley, (2) seepage losses from the unlined bypass channel, (3) infiltration from flood flows that would inundate part of West Paradox Valley, and (4) any surface runoff from East Paradox Valley. In the long run these other sources of water (in addition to the anticipated brine discharge) may cause the evaporation pond to reach its designed capacity much sooner than predicted (perhaps within 25 years). Also, as the water level in the reservoir rises, so will the elevation of the ground-water potential throughout Paradox Valley. Eventually this may possibly cause some brine to discharge into the bypass channel.

A second major approach is through management and regulation of ground water. Examples of this approach include alternative plans 1, 2, 3, and 6 of the August 1974 report. These plans would include the construction of a well field in the area of brine discharge, an evaporation pond outside of Paradox Valley, and a pipeline from the well field to the reservoir. The basis of this approach is to prevent the brine from entering the river by intercepting and removing the brine from the aquifer before it discharges to the river. Theoretically, this plan can achieve the same benefits as the first approach of surface-water management, but can focus more specifically on just the brine alone.

An alternative ground-water mangement approach would be to prevent or intercept recharge to the aquifer, thereby minimizing flow through the aquifer, the dissolutioning of salt, and the consequent discharge of brine. However, a very detailed and accurate definition of the flow system throughout the whole valley is a prerequisite for planning this type of approach. But such data are not available now, and it would probably require several years of intensive field studies to gain the required data. Furthermore, because there are several different sources of ground-water recharge in the valley, and because it occurs over a large area, it is unlikely that a means to limit successfully or control recharge could be devised that is both sufficiently effective and economical to permit this to be the primary management approach.

If the problem in Paradox Valley is defined as the discharge of brine into the Dolores River, then the option of managing surface water may be considered as treating the symptoms or effects the problem. Similarly, managing the ground-water system by collecting the brine discharge in wells (and lowering the hydraulic potential in the brine) may be thought of as treating the cause of the problem. The third option of managing the system by reducing or eliminating ground-water recharge may be considered as preventive medicine. Because the continued long-term success of surface-water management is doubtful, this first option should be given a lower priority than ground-water management. Because ground-water recharge to the system is diffuse, whereas the brine discharge is concentrated in a relatively small area, the ground-water management option should involve collecting the brine with wells in the discharge area. Designing such a well field would require preparation of specifications for (1) number of wells, (2) their locations and spacing, (3) their depths, and (4) their pumping rates. We believe that these design criteria can only be computed accurately if the entire flow system is described and considered, primarily because the necessary quantitative hydraulic analyses require that both the properties and the boundary conditions of the system be specified.

The option of reducing recharge to the system should still be considered as a supplemental control measure. A variant of this option would involve intercepting fresh ground water upgradient from zones of leaching. Pumping fresh ground water where it occurs would (1) eventually reduce the rate of brine discharge, although not in a one-to-one ratio; (2) provide a source of water to augment the flow of the Dolores River during extreme low-flow periods, and replace the flow to the Dolores River that would be diverted by a well field in the area of brine discharge; and (3) provide a replacement source of irrigation water for farmers within the valley whose irrigation wells would experience lower yields due to interference from the brine wells.

TEST DRILLING AND TEST PUMPING

Test Drilling To Date

Approximately 23 test holes were drilled by the U.S. Bureau of Reclamation (shown in map, Appendix, item 6). Each test hole was completed as a well or wells. One was a large-diameter well that was equipped with a pump for evaluating aquifer pumping tests. Several test holes were completed as batteries of three observation wells. Each well taps a different horizon. Logs of 12 of these wells were supplied to us for this study (Appendix, item 18). These logs contain lithologic descriptions of material encountered, salinity of fluid from drill hole, casing log, and test hole diameter log.

Test Pumping and Analyses

Three pumping tests were made on well 23CX, about 200 ft from the Dolores River, from October 9, 1973, to December 19, 1973. For the first test, well DH23CX was perforated at depths of from 9 to 33 ft and 46 to 99 ft. The duration of the test was about 42 hours; the pumping rate was 250 gal/min (gallons per minute). For the second pumping test, well DH23CX was perforated from 229 to 279 ft. The duration of the test was 48 hours; the pumping rate was 300 gal/min. For the third pumping test, well DH23CX was perforated from 65 to 99 ft. The duration of the test was 48 hours; the pumping rate was 600 gal/min. Data on river stage (readings about every 2 hours) are included on one graph for the third test.

U.S. Bureau of Reclamation provided graphical plots of drawdown and recovery in selected wells, semilog plots used in calculating transmissivity and storage coefficient, and projections of drawdown to 1 year. Vertical cross sections showing pressure changes were supplied for the tests. These tests were considered preliminary and intended only to probe the general geologic, hydrologic, and quality-of-water conditions in the area.

Additional production and observation test wells are planned and more pumping tests will be made and analyzed. The additional well sites are not all shown on the maps provided, nor was a written narrative of plans for these tests provided. The following objectives, generally not obtained in the earlier pumping tests, should be achieved through design, operation, and interpretation of future pumping tests:

1. Degree of connection between the aquifer and the Dolores River.

2. Storage coefficient based on long-term pumping tests to provide a basis for predicting the effects of sustained pumping.

3. Drawdown measurements should be corrected for effects of barometric fluctuations and partial penetrations of wells.

4. Computations for transmissivity and storage should account for boundary conditions encountered (such as the Dolores River and impermeable boundaries).

5. Analyses of water-level recovery measurements should consider the effects of residual drawdowns.

Future pumping tests should undoubtedly be run for a longer period of time; perhaps more than 30 days would be required to observe all the effects listed previously. A recent article by Neuman (1975) discusses methods to analyze some of these effects.

REQUIREMENTS FOR PLANNING GROUND-WATER MANAGEMENT

Additional Data and Analyses

Additional data are needed to provide a more complete chemical and physical definition of the flow system so that accurate predictions can be made of the system's response to stresses. These data include areal and vertical variations of potentiometric levels, water quality, degree of connection between the Dolores River and the aquifer, lithologic and hydraulic properties of the aquifers, and aquifer boundaries.

Potentiometric control is needed for defining the water-table surface in the entire Paradox Valley within 5 miles of the Dolores River. More detailed areal and vertical definition of the potentiometric head is needed within 1 mile of the Dolores River. Definition of aquifer thickness, hydraulic conductivity, water quality, and storage coefficient are needed in approximately the same areal and vertical detail as hydraulic head. A quantitative flow net analysis could utilize the hydraulic head data to help define variations in hydraulic conductivity.

Combined, the data on hydraulic conductivity, aquifer thickness, ground-water quality, and potentiometric surface would be useful in computing the relative amounts of flow from East and West Paradox Valleys and relative amounts of fresh and salt water inflow from each side. Use of wells to intercept brine flow to the Dolores River would decrease evapotranspiration in the topographically low areas where water levels are shallow. This decrease in evapotranspiration would require a corresponding increase in withdrawal.

Data on stratification, lithology, and water-quality variations in three dimensions near the Dolores River are needed to evaluate pumping tests and design placement of interception wells in the system. These data would also be valuable for precisely defining where in the flow system the greatest dissolution of salt occurs. This would be needed to help determine (1) the optimal locations and depths of pumping wells, (2) whether modifications to the flow field will cause additional dissolution to occur, and (3) whether land subsidence due to dissolution of underlying salt is a serious hazard.

The degree of connection of the Dolores River and the aquifer must be determined to predict the potential rate of induced infiltration and the effects of bank storage. For pumping tests, piezometers should be installed and monitored at several sites and depths in the streambed itself. Analysis of these data could provide estimates of vertical hydraulic conductivity of the streambed and rates of infiltration. Natural fluctuations in river stage will affect water levels in adjacent wells, and careful observation of these effects could provide data to estimate the hydraulic properties of the aquifer. Bank-storage effects can modify the position of the interface between freshwater and brine, and thus changes in bank storage may impose a need to continually modify and adjust the operation of the salinity control program. The variation in monthly salt pickup shown in figure 5 of the August 1974 report may be largely related to bank-storage effects.

The additional data that are collected should first be used to either verify or modify the conceptual model of the system. Then these data should be incorporated into a mathematical model that can (1) further verify the conceptual model, (2) indicate where and which types of additional data are still needed, (3) describe the relative effectiveness for brine capture of various possible designs for a well field, (4) predict the effects of pumping on streamflow and water levels in other existing wells, and (5) help evaluate the design of an observation-well network. Standard analytical methods for aquifer evaluation, which are based on the assumption that the aquifer is homogeneous, isotropic, and infinite in areal extent, cannot provide an accurate predictive capability for this aquifer because of its complex geometry, recharge boundaries, barrier boundaries, and three-dimensional heterogeneity. Furthermore, standard analytical methods offer no means to predict salinity changes caused by the transport and dispersion of the brine. However, a physically based, digitally simulated, distributed parameter, system-response model that couples the ground-water flow equation with the transport-dispersion equation could account for and integrate the numerous effects that interact in this complex system. The effects of chemical reactions, such as salt dissolution, can be incorporated into this type of model. A three-dimensional model would be most desirable, but available two-dimensional models would also be quite valuable when applied to the five factors listed above.

Finally, consideration should be given to legal aspects of the proposed salinity control program, such as liability for reduced well yields in existing wells, water rights for streamflow depletion in the Dolores River, permits for drilling and pumping water wells, and permits for waste disposal.

Design and Operation of a Well Field

A well field must be designed to meet the main objective of the project, which is to prevent most brine from discharging into the Dolores River. This could be accomplished by sufficiently lowering the hydraulic potential within the brine-saturated part of the aquifer, so that the hydraulic head of the fresh ground water is higher than the head in the brine, everywhere near the Dolores River. This would require a more or less continuous withdrawal through wells of a volume of brine at least equivalent to or greater than the natural discharge to the river, or a minimum of about 1 ft^3/s (cubic foot per second) of brine at an average dissolved-solids concentration of 200,000 mg/L. Initially, withdrawal rates may have to be somewhat greater until the desired modifications to the flow field are attained.

Because a major part of the cost of the project using a ground-water management approach would be governed by the size of the pipeline required to transport the brine to a disposal area, the well field should be designed to require the maintenance of the smallest possible sustained withdrawal rate that can meet the main objective of the project. If the well field is properly designed and operated in conjunction with a continual monitoring program, then the total withdrawal rate should probably not have to exceed about 1.5 to 2.5 ft^3/s, rather than the 5 ft^3/s anticipated in the August 1974 report. Our discharge estimates assume that dilution would reduce the average dissolved-solids concentration of brine withdrawn from wells to a range of about 133,000 to 80,000 mg/L, respectively. The cost of a pipeline designed for 2.5 ft^3/s (or less) should be substantially lower than one designed for 5.0 ft^3/s.

The problem of designing the well field to achieve the objective with a minimum of pumping is not a simple one. The following factors must be considered: (1) location of well field, (2) total number of wells, (3) spacing between wells, (4) depth and interval of aquifer to be pumped, (5) pumping rates, and (6) well-construction details. These factors are interrelated and must be evaluated in light of detailed field data that accurately describe the properties and boundaries of the aquifer. Because these data are not yet fully available, only some advantages and disadvantages of several alternative specifications will be discussed for each of these factors.

The well field should obviously be located close to the Dolores River within the area of surfacing brine. If field data confirm the concept shown in figure 2 that brine is discharging towards the river from both East and West Paradox Valleys, then it would seem logical for maximum capture that wells should be located on both sides of the river. Wells on the west side should pump from within a relatively deep interval (perhaps 200 to 400 ft), while wells on the east side should pump from a relatively shallow interval (perhaps 10 to 50 ft). If all wells were located on only one side of the river, either east or west, then to achieve complete capture of brine inflow on the opposite side of the river, the influence of pumping would have to offset and extend past the potential recharge effects of the river, which can act as a recharge boundary (or a partially penetrating line source) if the hydraulic gradient is significantly lowered beneath it after a long period of pumping. This then would require higher total pumping rates, higher flow velocities in the aquifer, more dispersion of dissolved salts into fresher ground water, and consequently the need to pump and dispose of a greater volume of brine at a reduced concentration to achieve the goal of removing 180,000 or more tons of salt per year. Figure 4 illustrates the predicted pattern of the flow field after being modified by the effects of pumping from wells on both sides of the river. Pumping rates would have to be carefully monitored and adjusted to minimize induced infiltration from the river. Pumping rates from the deeper wells on the west side of the river might have to be larger than from the shallow wells on the east side to produce a flow field similar to that shown in figure 4.

The total number of wells required will be governed by the recommended spacing between wells, which in turn will be based on the hydraulic properties and boundaries of the aquifer. Although these detailed data are not yet available, some general guidelines and concepts can be presented for consideration. The diversion of brine due to pumping, as illustrated in figure 4, must be effective along the entire reach of the Dolores River within the area of salt pickup. Theoretically, two line

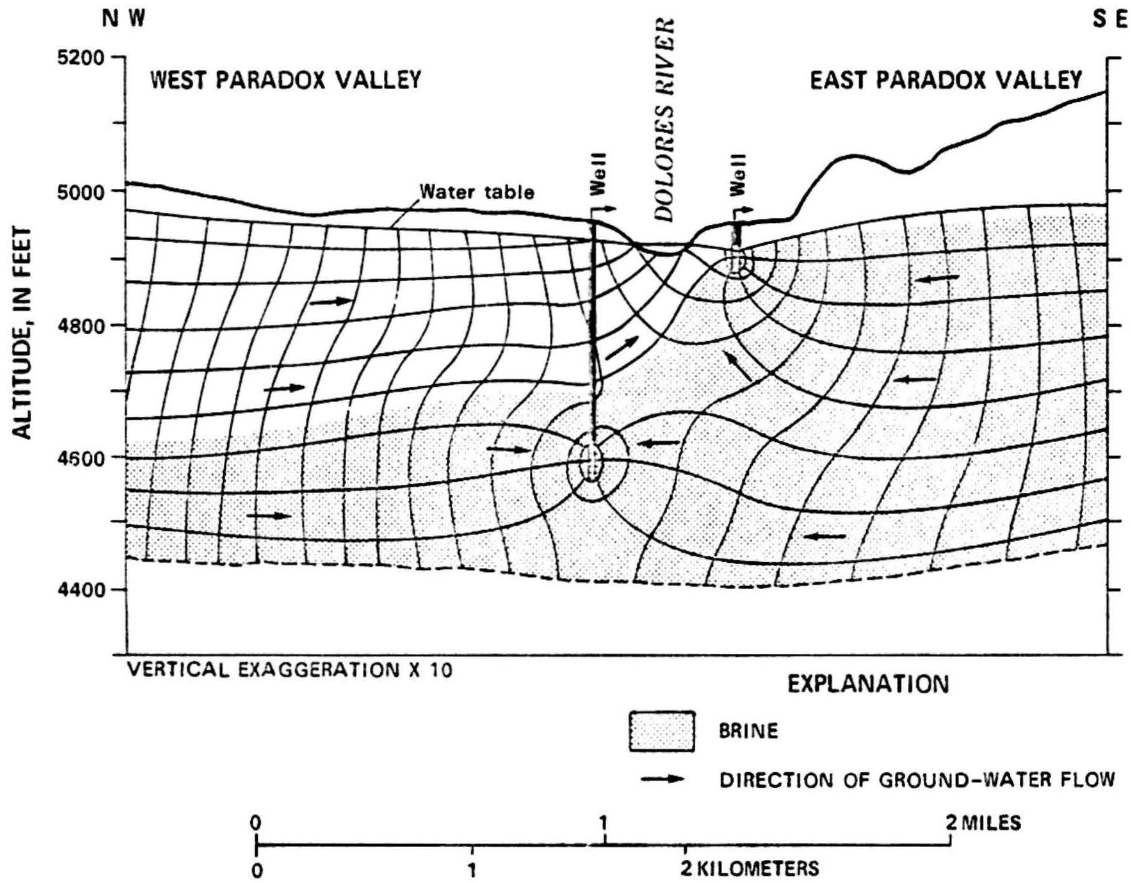

Figure 4.--Northwest-trending cross section through Paradox Valley showing possible configuration of flow field that has been affected by withdrawal of water from wells on both sides of the Dolores River. Note larger scale and shorter length of section in comparison with figure 2.

sinks passing through the two points of well diversion shown in figure 4 would offer an ideal solution to the real three-dimensional flow problem. In the field this can be approximated with two lines of closely spaced wells. Hydraulic interference between closely spaced pumping wells would minimize the risk that brine would surface in areas between wells. Having a large number of closely spaced wells would also (1) require a lower pumping rate in each well, thereby minimizing the percentage of fresh ground water that would be diverted; (2) allow greater flexibility to vary pumpage rates in individual wells in response to transient shifts in the position of the interface between freshwater and brine, thereby permitting more efficient operation and management of the system; and (3) allow individual wells to be temporarily shut down for routine maintenance or emergency repairs with a minimal reduction in the operational effectiveness of the salinity-control program.

The following example illustrates the relationship among several factors that must be considered. If the optimal spacing between wells is determined to be between 250 and 500 ft, then placing wells along both sides of the Dolores River within the area of brine discharge (in two reaches with a total length of about 7,500 ft) would require an approximate total of between 30 and 60 wells. But each well would only have to be designed and constructed to pump a maximum of about 0.04 ft^3/s (for 60 wells) to 0.08 ft^3/s (for 30 wells). The total cost of completing a large number of low-capacity wells should not be very much greater than the total cost of a few high-capacity wells.

Because of the very high chemical concentrations in the brine, care must be taken to select suitable materials for use in pumps, well casings, well screens, and pipelines to assure continued service over the life of the project. The use of screens is greatly recommended over the use of slotted or perforated casings. A gravel pack should be developed or placed adjacent only to the screened interval. The annulus around the well casing should be cemented or back-filled with low-permeability material to prevent downward seepage of fresh ground water from shallower depths.

An alternative to the shallow vertical wells on the east side of the river is the use of collector wells, which consist of a central cylindrical caisson from which horizontal perforated pipes are driven radially into the aquifer. Each collection gallery could pump more brine with less drawdown than an individual vertical well, and a line of several collector wells could probably intercept the brine discharge more completely and more efficiently. However, they would be more difficult and more expensive to construct than vertical wells.

The exact position of the interface between fresh ground water and the brine probably will shift over time, not only in response to the effects of pumpage in the well field, but also due to (1) the effects of seasonal variations in recharge to the aquifer, (2) changes in river stage and associated bank storage effects, and (3) pumpage from other wells in the area. Efficient operation of the well field would require that pumping rates be adjusted in response to changing conditions in the aquifer system. For example, if the salinity of the brine being pumped from a particular well decreases, it may indicate that too much freshwater is being diverted to that well, and the pumping rate should be reduced accordingly. On the other hand, if, in the future, the brine interface begins to rise after a long period of control, then the pumping rates should be increased accordingly.

After the salinity-control program has been implemented, the behavior of the stream-aquifer system must be monitored to provide continually updated operational guidelines. Thus, it is important that (1) the salinity or specific conductance, the discharge rate, and the water-level from each pumping well be measured frequently or continuously, both to monitor the efficiency of individual wells and to measure the total salt load being removed from the system; (2) an auxiliary network of observation wells be constructed and maintained for frequent water-quality sampling and water-level measurement, both to keep track of the position of the interface and to observe hydraulic potential; and (3) continuously recording discharge gages and water-quality monitors be maintained indefinitely at the present two gaging station sites on the Dolores River to monitor the overall effectiveness of the salinity-control program and to signal the occurrence of any unexpected discharge of brine. Observation wells should be constructed with an inside diameter of at least 4 in (inches), so that a small electric submersible pump could be utilized for proper sampling. Each well should also utilize a short (about 3 ft) section of well screen for an intake, and be located at several sites adjacent to and upgradient from the well field and at several different depths.

The possibility of intercepting and reducing recharge to the aquifer, as a means of reducing the volume of brine that is generated, should not be discounted and warrants further study. For example, the base flow of freshwater springs or tributary streams along the flanks or in the upper reaches of East and West Paradox Valleys might be diverted into lined drainage canals to prevent seepage losses into the underlying aquifer; or fresh ground water might be pumped from shallow wells. The latter could also provide a source of water to augment low flows in the Dolores River and replace the amount of streamflow depleted by the well field. It could also be used to supplement irrigation requirements in the valley and offset any reduced well yields in the valley due to interference from the brine well field. The potential long-term benefits are (1) reduced annual pumping requirements in the brine well field, (2) reduced annual costs for brine disposal through a pipeline, and (3) extended life of the project. However, it must be clearly and definitively shown that such measures would not themselves produce undesirable side effects or detrimental disturbances to the flow field.

ALTERNATIVES FOR BRINE DISPOSAL

A method for disposal or storage of the brine pumped from the well field must be an integral part of the salinity-control program in Paradox Valley. Because desalination of the brine would be extremely expensive, and there appears to be no market for sale of the brine or its dissolved salts, it would seem that the most economical plan would primarily involve storage in an evaporation pond. The reservoir site must be large enough to provide an adequate evaporative surface over the life of the project, and be located and constructed to prevent brine contamination of other ground or surface waters either by seepage losses from the reservoir or by flood overflows. The proposed Radium Reservoir, located approximately 10 mi east of the Dolores River and between Paradox Valley and Gypsum Valley, would apparently serve as a satisfactory site for an evaporation pond, although detailed geologic and hydrologic investigations should be conducted to confirm this.

Although total or permanent disposal of the brine within Paradox Valley appears impractical, several auxiliary steps might be undertaken in conjunction with the main plan to improve the overall efficiency of the project. The main option recommended for consideration involves the construction of one or more relatively small, preferably lined, preliminary evaporation ponds adjacent to the pipeline in East Paradox Valley. The main function of the preliminary evaporation ponds would be to preconcentrate the brine by evaporatively reducing its volume and increasing its salinity prior to pumping it through a pipeline to a distant reservoir site for permanent salt storage. This would help assure that the maximum capacity of the pipeline and associated pumping plants would not have to exceed 1.0 to 2.0 ft^3/s of brine that is at or near the limit of saturation for dissolved salts.

Including preliminary evaporation ponds in the design of the project could produce several benefits. First, by minimizing the required diameter of the pipeline and power of the pumping plants, the costs of construction should be reduced. Second, regardless of the pipeline capacity, the energy consumption required for pumping in the pipeline would be reduced, thereby also reducing the annual costs of operation. Finally, the preliminary evaporation ponds would provide a reservoir for temporary storage of the brine discharge from the well field, which may be necessary at times when the pipeline or relift pumping plants must undergo maintenance or repairs. Also, if the total discharge from the well field varies over time, the ability of the ponds to provide temporary storage would also smooth these variations and permit a nearly constant rate of input to the pipeline at lower rates than peak discharges from the well field.

There are many sites near the pipeline alignment in East Paradox Valley that appear to be topographically suitable for the construction of small evaporation ponds. If the net evaporation rate from a brine pond in East Paradox Valley would average approximately 4 ft/yr, then the evaporation rate would average 0.01 ft^3/s per acre of pond surface area. Thus, either one 50-acre pond or ten 5-acre ponds could provide the capacity to evaporate 0.5 ft^3/s before any significant lifting power is needed. The storage capacity of the ponds could also be utilized during periods of low evaporation to eliminate the effects of seasonal variations in the rate of evaporation. As an illustration of the value of preliminary evaporation ponds, assume that the well field must be pumped at an average rate of 2.0 ft^3/s of brine at an average concentration of 100,000 mg/L to achieve the desired removal of 540 tons of salt per day; then 50 acres of evaporative surface area in East Paradox Valley could reduce the pipeline input to 1.5 ft^3/s of brine at an average concentration of 133,000 mg/L. This alone would represent a 25 percent reduction in the energy consumption by the pumping plants, under the assumptions made above, and realistically could save up to several million kilowatt hours of electrical energy per year. There would not be any significant accumulation of precipitated salts in the ponds, so their function could continue for the life of the project, with little or no additional maintenance or operating costs. Furthermore, if the average depth of the ponds was 5 ft, then they would have a storage capacity of 250 acre-ft of brine, which is approximately equivalent to 1 ft^3/s for 4 months with no evaporation.

A major part of the cost of this system is related to lining the reservoir with an impermeable base, such as an asphalt or plastic type of membrane, to prevent seepage to the underlying aquifer. An alternative to lining that may be both economically and physically feasible in East Paradox Valley would be to have the evaporation ponds constructed on low permeability soils, and intercept or recapture the seepage losses with a small network of shallow drainage wells that recirculate the seepage losses back to the ponds.

Another option for handling the brine within Paradox Valley involves subsurface disposal through deep-well injection. An examination of the stratigraphic section for the area does not indicate a high probability of encountering a suitable reservoir rock that could sustain a long-term injection of a singificant percentage of the discharge from the brine well field. A significant expenditure would be required simply to evaluate and test the physical feasibility of this option. If it were physically feasible, its implementation would then require high initial design and construction costs, and possibly also high annual maintenance and operating costs. If high-pressure injection is required, considera-tion must also be given to possible geologic hazards, such as induced earthquake activity or upward migration of the injection brine along existing faults, fractures, or abandoned deep wells.

CONCLUSIONS AND RECOMMENDATIONS

1. The discharge of sodium chloride brine to the Dolores River in Paradox Valley, Colo., represents a major contribution of salt to the Colorado River. This source of salt could be prevented from entering the river through a properly designed and operated ground-water management program.

2. A successful solution to the problem requires an understanding of the source and movement of the brine. A conceptual model should consider that the ground water underlying Paradox Valley and the Dolores River and its tributaries within Paradox Valley together constitute one integrated stream-aquifer system.

3. Additional field data are needed to confirm the conceptual model and to make accurate predictions of the behavior of the system.

4. Data from previous aquifer tests are inadequate to predict the long-term response of the stream-aquifer system to continual pumping.

5. A digital simulation model would be valuable to help refine the conceptual model of the system, and in turn to evaluate the effectiveness and cost of the many alternative well field designs.

6. Wells should be located on both sides of the Dolores River. The operation of the well field should be continually updated and adjusted on the basis of frequent monitoring of the pumping wells and auxiliary observation wells.

7. There will undoubtedly continue to be some ground-water discharge to the Dolores River, but the remaining salt pickup should be largely limited to acceptable concentrations of calcium, magnesium, and sulfate ions.

8. After the salinity-control program has been implemented, the salinity, discharge rate, and water level from each pumping well should be measured frequently. An auxiliary network of observation wells should also be maintained for water-quality sampling and water-level measurements.

9. Discharge and water-quality monitoring should continue indefinitely at the two present gaging station sites on the Dolores River.

10. The use of preliminary evaporation ponds in East Paradox Valley should be considered as a means of reducing the required capacity of a pipeline to a disposal area.

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U.S. Bureau of Reclamation, 1974, Colorado River Water Quality Improvement Program, Paradox Valley Unit, Colorado: U.S. Bur. Reclamation, Western Colorado Project Office, Durango, Colo., August 1974, 25 p.

APPENDIX

Material Provided to the U.S. Geological Survey by the U.S. Bureau of Reclamation on Paradox Valley

1. Report: "Colorado River Water Quality Improvement Program, Paradox Valley, Unit, Colorado," prepared by the Upper Colorado Region, Western Colorado Projects Office, Durango, Colorado, August 1974, 25 pages.

2. Report: "Resistivity Survey for Paradox Valley Project, Montrose County, Colorado," by Applied Geophysics, Inc., Salt Lake City, Utah, May 1972, 4 pages, 1 map.

3. Report: "Report for Union Carbide Nuclear Company on Feasibility of Subsurface Disposal of Uravan Mill Waste Effluents in a Disposal Well," by Earlougher Engineering, Tulsa, Oklahoma.

4. Chemical analyses of water samples collected weekly from July 1971 to July 1974 at Dolores River at Bedrock, Colo. (sec. 20, T. 47 N., R. 18 W.), West Paradox Creek above Bedrock, Colo. (sec. 18, T. 47 N., R. 18 W.), and Dolores River near Bedrock (secs. 2 and 3, T. 47 N., R. 18 W.).

5. Chemical analyses of West Paradox Creek near Bedrock, Colo., collected monthly from October 1964 to April 1966.

6. Map of Paradox Valley in 2 sheets dated November 14, 1974, showing location of USBR core holes, rotary test holes, producing brine wells, and irrigation wells.

7. Map of Paradox Valley in 2 sheets showing water-table elevations and contours based on measurements made March 20-21, 1975.

8. Map of Paradox Valley in 2 sheets dated December 9, 1974 showing proposed exploratory holes and observation holes and existing observation holes.

9. USGS topographic map of Paradox, Colo., 7½' quadrangle, showing location of four irrigation wells in Paradox Valley.

10. Gamma ray, neutron log of USBR 23-CX.

11. Gamma ray and neutron logs by Schlumberger of SCORUP No. 1.

12. Gamma ray and neutron logs of Government No. 1, SW¼SW¼, sec. 10, T. 46 N., R. 17 W.

13. Lithologic log of Mullen No. 1, NE¼SW¼, sec. 4, T. 46 N., R. 17 W.

14. Log by American Stratigraphic Co. of well 1-0-30 Otho Ayers, SW¼SE¼, sec. 30, T. 47 N., R. 18 W.

Appendix (Continued)

15. Well Record from office of the State Engineer:
    Paradox Salt Co.
    SE¼, NE¼, sec. 17, T. 47 N., R. 18 W.

16. Drillers logs of Wilcox No. 1 (sec. 15, T. 47 N., R. 18 W.) and Wilcox No. 2 (sec. 6, T. 47 N., R. 18 W.).

17. Notes of Frank P. Jensen on SCORUP No. 1 well, 3/4 mi. NW of Paradox Salt project site, sec. 8, T. 47 N., R. 18 W.

18. Geologic logs of the following drill holes constructed by USBR:

    a. DH-23CX
    b. DH-1PX
    c. DH-2PX
    d. DH-3PX
    e. DH-4PX
    f. DH-5PX
    g. DH-6PX
    h. DH-7PX
    i. DH-8PX
    j. DH-9PX
    k. DH-10PX
    l. DH-11PX

19. Data and analyses on three pumping tests on hole DH-23CX. Data are principally in graphical form showing drawdown and recovery of selected observation wells for each test.