Water Supply Reliability As Influenced By Natural Salt Pollution

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INTRODUCTION

Natural salt pollution is the primary water quality problem constraining water resources management in several major river basins in the southwestern United States. The Arkansas, Brazos, Canadian, Colorado, Red, and Rio Grande Rivers supply agricultural, municipal, industrial, and environmental water needs in the states of Arkansas, Colorado, Kansas, Louisiana, New Mexico, Oklahoma, and Texas. Water management is governed largely by salinity in this region of increasing demands on limited water resources. Salinity severely limits the use of large quantities of water in major river/reservoir systems. The primary sources of salt loads in the rivers are geologic formations underlying portions of their upper watersheds. Federal, state, and local water agencies and university researchers have investigated various aspects of the salinity problem. The Corps of Engineers and other entities continue to perform feasibility studies and, in some cases, implement projects for controlling the runoff from primary salt source subwatersheds. The U.S. Geological Survey has conducted water quality sampling programs in support of the natural salt pollution control studies.

This paper provides a general overview of natural salt pollution in the Southwest, its impact on water management, and investigations addressing salinity problems conducted by water resources development agencies and university researchers. A general discussion pertaining to the entire region is combined with a focus on two representative river basins, the Brazos and Red.

SALT SOURCES, IMPACTS, AND CONTROL MEASURES

Salinity plays an important role in water resources development and management throughout the world, particularly in arid and semiarid areas with irrigated agriculture. Salinity is an important concern in river basin management in the western and southwestern United States. Dissolved solids or salts are impurities that occur in all natural waters because of weathering of rocks and soils. Total dissolved solids (TDS) or salinity increases as waters move over the land surface and through soils and aquifers. Evaporation and transpiration increase concentrations. Human activities such as irrigated agriculture and construction of storage reservoirs increase evaporation and the salinity of land and water resources. Ground water pumping, oil field operations, and wastewater disposal activities can also increase salinity.

Salinity is an important determinant of the suitability of water for drinking, irrigation, and industrial uses. The U.S. Environmental Protection Agency secondary drinking water standards suggest limits for TDS, chloride, and sulfate concentrations of 500 mg/l, 250 mg/l, and 250 mg/l, respectively. These recommended limits are set on the basis of health effects and taste preferences and because conventional treatment processes do not remove salinity. Salts damage pipelines, equipment, household appliances, and industrial facilities. Salinity tolerance for different types of industrial water use varies greatly. Salinity is a major consideration in irrigated agriculture. Although plants can tolerate and even require minerals for growth, excessive salts within the root zone reduces plant growth. Excess salinity increases the energy that the plant must expend to acquire water from the soil and undertake the biochemical adjustments necessary to survive. The deleterious effect of dissolved solids on plant growth escalates as the salt concentration increases to the point of being lethal to the plant. Acceptable salt concentrations for irrigation vary greatly depending on the type of crop, soil conditions, climate, and the relative amounts and timing of rainfall versus supplemental irrigation. Reasonable maximum TDS concentration limits for irrigation range from less than 1,000 mg/l to greater than 10,000 mg/l, depending on the circumstances.
Salinity is a major determinant of aquatic habitat. Many aquatic plants and animals are adapted to certain ranges of dissolved solids concentrations. Relatively small changes in salinity can have major impacts on ecosystems (Williams 1987). TDS affects saturation concentrations of dissolved oxygen and influences the ability of a water body to assimilate wastes. Eutrophication rates depend on TDS. Salts impact the mobility and transformation of metals and ionizable chemicals.

**Natural Salt Sources in the Southwest**

The river systems of the Southwest shown in Figure 1 are unusual in that extremely high concentrations in the upper reaches result from salt emissions from geologic formations occurring in relatively small isolated subwatersheds. Natural processes account for most of the salt loads of these major rivers. During the Permian age about 230 million years ago, this region was covered by a large inland sea (Rought 1984). Thick deposits of halite were formed as evaporating sea water precipitated salts. In the primary salt source areas of the upper watersheds, ground water percolates to the salt bearing strata through permeable rocks, rock fractures, and alluvium, where, through dissolution, salt brines are created. The brine moves laterally or vertically until it is discharged at a saline spring or along a stream bed. Evaporation of water at the land surface forms a crust of salt over what is commonly called salt flats or plains. Precipitation runoff transports the salt to streams and rivers. Springs and seeps and salt flats in upstream areas of the basins contribute large salt loads to the rivers. The mineral pollutants consist largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids.

![Figure 1. Major Rivers in the Southwest Affected by Natural Salt Pollution](image)

In the river systems of Figure 1, extremely high concentrations in the upper reaches result from natural sources in relatively small isolated subwatersheds. Salt concentrations in the downstream reaches of the rivers decrease with dilution from low-salinity tributary inflows. For example, mean TDS concentrations vary from 340 mg/l at a gage on the lower Brazos River 148 km above its mouth at the Gulf of Mexico, to 12,400 mg/l at a gage located 1,510
km from the Gulf on the Salt Fork just above its confluence with the main-stem Brazos River to over 40,000 mg/l on smaller tributaries of the Salt Fork of the Brazos River in the upper basin. Most lower basin tributaries have mean TDS concentrations ranging from 100 to 250 mg/l.

Lake Meredith on the Canadian River has TDS concentrations measuring as high as 1,880 mg/l and maximum chloride concentrations of 600 mg/l. About 70% of the sodium chloride flowing into Lake Meredith comes from New Mexico, primarily from natural groundwater brines entering the Canadian River near the city of Logan (Bureau of Reclamation 1985). In the Arkansas River below the confluence of the Canadian River, natural chloride loads average 3.6 million kg/day. Similarly, salinity in the Rio Grande at the Pecos River confluence ranges from 2,000 to 4,000 mg/l (Miyamoto and Fenn 1995). Much of the salt load in the Pecos River originates from groundwater emissions in Eddy County, New Mexico (Havens and Wilkens 1979). Likewise, subwatersheds of the Red River above Lake Texoma contribute mean salt loads of 3.3 million kg/day consisting largely of chlorides and sulfates. Salt concentrations in the river basins vary greatly both temporally and spatially.

**Impacts of Salinity on River Basin Management**

Population and economic growth combined with depleting ground water reserves are resulting in ever increasing demands being placed upon the surface water resources of these southwestern states. Salinity severely limits use of large amounts of streamflow and reservoir storage in areas where water demands are surpassing supplies. The water management activities of numerous cities, water districts, river authorities, irrigators, and industrial water users are significantly affected by the natural salt pollution. The impacts of salinity will be greatly magnified during future severe droughts comparable to the record droughts of the 1950's, 1930's, and 1910's.

Salinity in the river basins shown in Figure 1 and measures to reduce the salt loads in the rivers have both environmental and economic impacts. An array of adverse effects on municipal, industrial, and agricultural water users is caused by salts in water supplies. Various species and ecosystems have evolved in a saline environment and would be adversely affected by a reduction in salinity.

Natural salt pollution constrains water supply capabilities of reservoir/river systems and greatly influences the allocation of water resources among municipal, industrial, agricultural, environmental, and other water users and the allocation of reservoir storage among flood control, hydroelectric power, recreation, fish and wildlife, water supply, instream flow maintenance, and other purposes. Reallocation of storage and streamflow resources is required to fully utilize the improvements in water availability to result from natural salt pollution reduction measures.

Salinity limits capabilities of existing reservoir projects to meet growing water needs. Salinity constraints on the use of major reservoirs and water supply sources result in development of alternative water supply sources with accompanying environmental and economic costs. For example, to augment supplies for Houston, located in the San Jacinto River Basin, the Livingston Reservoir project on the Trinity River was constructed instead of purchasing water supplied by existing Brazos River Authority facilities. In the Trans-Texas Study currently being conducted jointly by the Texas Water Development Board and other state and local water agencies, other sources of supply for the Houston area are given preference over the Brazos River due to its salinity. Likewise, Dallas and Fort Worth have developed reservoir projects in the Trinity and Sabine River Basins instead of obtaining water from closer existing reservoirs on the Red and Brazos Rivers due largely to salinity considerations.

**Natural Salt Pollution Control Measures**

Federal, state, and local water management agencies, consulting firms working for the agencies, and university researchers have investigated measures for dealing with natural salt pollution in the river basins of Figure 1. The U.S. Geological Survey (USGS) and others have conducted data collection activities to identify the primary salt source areas and to support natural salt pollution control studies. A few of the many proposed salt control plans
have been implemented. Economic feasibility, institutional difficulties, environmental concerns, and lack of funding have prevented or delayed construction of most proposed projects. Additional salt control measures are expected to be implemented in the future in response to intensifying demands on limited water resources. Salt pollution control strategies typically involve subsurface or surface collection and disposal of the brine in the source areas to prevent runoff into the major rivers.

The Colorado River Municipal Water District owns and operates Thomas, Spence, and Stacy Reservoirs in west Texas for water supply. The Red Draw and Barber Reservoirs and recently constructed Mitchell County Reservoir are salt pollution control projects used to protect the quality of inflows to the water supply reservoirs. Water is diverted from the Colorado River and tributaries, whenever the chloride content is above desired levels, and transported via pipeline to the brine storage reservoirs. In the past, these salt control projects also supplied brackish water for oil field operations.

Havens and Wilkens (1979) describe an experimental project conducted by the USGS and Pecos River Commission in which brine was pumped from an aquifer and stored, in a primary salt source area in New Mexico, to reduce salts loads in the Pecos River. The Bureau of Reclamation (1985) documents a study that resulted in a proposed plan for protecting the salinity of inflows to Lake Meredith on the Canadian River in Texas by a salt control project in New Mexico consisting of interception of brine by well pumping and disposal by deep-well injection. However, recent more detailed investigations indicate that this plan is infeasible due to unfavorable geologic conditions.

The remainder of this paper focuses on natural salt control studies and projects for the Red River Basin and Brazos River Basin, respectively, conducted by the Tulsa and Fort Worth Districts of the Corps of Engineers in cooperation with other federal, state, and local agencies, consulting firms, and university researchers. University research studies addressing salinity in the Brazos River are also noted. Several brine interception projects have been proposed for the Red River Basin above Lake Texoma, two of the projects have been implemented, and preconstruction planning is underway for other projects. A desalination treatment plant allows water from Granbury Reservoir on the Brazos River to supplement other sources of municipal supply. Source area interception projects have been proposed but yet not implemented in the Brazos River Basin.

BRAZOS RIVER BASIN STUDIES AND PROJECTS

As indicated by Figure 2, the 118,000-km² Brazos River Basin extends from eastern New Mexico across Texas to the Gulf of Mexico. The main-stem Brazos River begins at the confluence of the Salt Fork and Double Mountain Fork, and flows in a meandering path about 1,480 km to the Gulf. In its upper reaches, the Brazos River is a salty, intermittent stream. Water quality is seriously degraded by natural contamination by salts consisting largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids. Much of the salt originates within a 3,900-km² area in the Salt Fork and adjacent subwatersheds of the upper basin. This semiarid region consists of gypsum and salt-encrusted rolling plains containing numerous salt springs and seeps. The quality of the river improves significantly in the lower basin due to dilution by tributaries. Mean discharges and TDS, chloride, and sulfate concentrations for the period 1964-1986, at selected locations shown in Figure 2, are tabulated in Table 1 (Wurbs et al. 1993). Flows, loads, and concentrations vary greatly temporally as well as spatially as illustrated by the plot of monthly TDS concentrations at the Seymour gage presented as Figure 3.

U.S. Geological Survey (USGS) water quality sampling activities in the Brazos River Basin date back to 1906. The USGS conducted an extensive water quality data collection program from 1964 through 1986, involving about 39 stations, in support of U.S. Army Corps of Engineers (USACE) natural salt pollution control studies. Wurbs et al. (1993) document a study performed for the USACE that consisted of compiling the USGS data into a readily usable format and performing various analyses. The primary focus was on evaluation of the impacts of proposed salt control impoundments on concentrations at downstream locations.
Natural salt pollution control studies conducted by the Corps of Engineers, in cooperation with other agencies, are documented by the Fort Worth District (1973, 1976, 1983) and summarized by McCrory (1984). The studies involved formulation and evaluation of a comprehensive array of strategies for dealing with the salt pollution problem. A number of the alternative plans consist of systems of salt control dams to contain the runoff from the primary salt source areas. The optimal plan recommended for implementation consists of three brine impoundments on small creeks in the primary salt source areas. In more recent studies, the previously recommended salt control plan and alternative plans were found not to be economically feasible based on current conditions. Federal participation in constructing the project was concluded to not be justified, and the plan for constructing the salt control dams is now essentially inactive.

![Figure 2. Brazos River Basin](image)

Table 1. Mean Flows and Salt Concentrations in the Brazos River

<table>
<thead>
<tr>
<th>Location</th>
<th>Drainage Area (km²)</th>
<th>Mean Flow (m³/s)</th>
<th>Mean TDS (mg/l)</th>
<th>Chloride (mg/l)</th>
<th>Sulfate (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt control dam sites</td>
<td>1,670</td>
<td>1.0</td>
<td>12,100</td>
<td>6,520</td>
<td>1,570</td>
</tr>
<tr>
<td>Aspermont Gage</td>
<td>10,700</td>
<td>1.4</td>
<td>10,000</td>
<td>6,590</td>
<td>1,320</td>
</tr>
<tr>
<td>Seymour Gage</td>
<td>40,200</td>
<td>7.6</td>
<td>3,590</td>
<td>1,480</td>
<td>696</td>
</tr>
<tr>
<td>Possum Kingdom Dam</td>
<td>61,100</td>
<td>19</td>
<td>1,510</td>
<td>601</td>
<td>309</td>
</tr>
<tr>
<td>Below Whitney Dam</td>
<td>70,400</td>
<td>35</td>
<td>928</td>
<td>342</td>
<td>178</td>
</tr>
<tr>
<td>Richmond Gage</td>
<td>117,000</td>
<td>194</td>
<td>339</td>
<td>79</td>
<td>56</td>
</tr>
</tbody>
</table>

120
Figure 3. Total Dissolved Solids Concentration at the Seymour Gage

The sites of the three proposed salt control impoundments are on Croton, Salt Croton, and North Croton Creeks, which are tributaries of the Salt Fork of the Brazos River and the Brazos River just below the Salt Fork confluence. The total drainage area and flow for the three sites are shown in Table 1 along with discharge-weighted mean concentrations. Flows and salt loads from these three salt source areas can be expressed as a percentage of the flows and loads at downstream locations. The mean flows, TDS loads, and chloride loads totaled for the three sites are 11%, 38%, and 49%, respectively, of the values at the Seymour gage and 0.36%, 14%, and 32%, respectively, of the mean flow, TDS, and chloride loads at the Richmond gage.

With the proposed salt control plan (Fort Worth District 1973, 1976, 1983), each of the three dams would consist of an earth-fill embankment and outlet structures for emergency releases only. The impounded watershed runoff would be lost to evaporation, with the remaining salts being permanently stored.

Spongberg and James (1995), James et al. (1996), and Spongberg and James (1996) describe a ground water modeling study performed at Texas A&M University, sponsored by the Texas Water Development Board and USACE Fort Worth District, to evaluate shallow well collection systems and deep well injection as a salt pollution control strategy. This approach was found to be much less expensive than construction of the previously proposed salt control impoundments.

The Brazos River Authority operates, since 1989, a 13,000 m³/day municipal water treatment plant at Lake Granbury that includes an electrodialysis reversal process to remove salt. However, the cost of constructing and operating other desalination plants has generally been prohibitive in the Brazos and the other river basins.

Forty-one reservoirs in the Brazos River Basin have storage capacities exceeding 6.17 million m³ (5,000 acre-feet). There are numerous smaller reservoirs. Thirteen reservoirs owned and operated by the Brazos River Authority and Corps of Engineers account for about 75% of the total conservation storage capacity of the 41 major reservoirs and all of the flood control capacity. The locations of these 13 reservoirs are shown in Figure 2. Possum Kingdom, Granbury, and Whitney are the only reservoirs on the main-stem Brazos River. The others are located on good-quality tributaries with TDS concentrations of less than 300 mg/l. Water in the three main-stem reservoirs is unsuitable for most municipal, agricultural, and industrial uses without significant dilution or costly desalination processes. Possum Kingdom and Whitney Reservoirs are the largest reservoirs in the Brazos River Basin and among the largest in Texas. The Brazos River Authority operates Possum Kingdom primarily for hydroelectric power, supply of thermal electric cooling water, and recreation. The Corps of Engineers operates Whitney primarily for flood control, hydroelectric power, and recreation. Granbury Reservoir is used primarily for thermal electric cooling water. As previously mentioned, the Brazos River Authority recently
constructed a desalination plant to treat Granbury Reservoir water for municipal use. The three main-stem reservoirs and other reservoirs located on good quality tributaries are operated as a system to supply municipal, industrial, and agricultural diversions from the lower reach of the Brazos River. Salt concentrations in the lower Brazos are drastically lower than in the upper reaches, but are still large enough much of the time to constrain water use. A majority of the water supplied from the Brazos River and its tributaries for municipal, industrial, and agricultural uses is diverted from the lower reach of the river. Much of the water is transported out of the basin for use in the adjoining area that includes the cities of Houston and Galveston. Subsidence in this coastal area, caused by decades of excessive groundwater pumpage, has forced a continuing shift from ground water to surface water supplies. Demands are increasing for supplying water from the Brazos River and tributaries for both use within the basin and transport to adjoining basins.

Wurbs et al. (1993 and 1994), Wurbs and Karama (1995), and Wurbs and Sanchez-Torres (1996) considered salinity constraints in evaluating water supply reliabilities of the reservoir system operated by the Brazos River Authority and Corps of Engineers. Simulation modeling studies combined specified water use scenarios with historical hydrology. Reliabilities were evaluated for meeting basinwide water demands represented alternatively by (1) actual water use in year 1984, (2) projected water use in year 2010, and (3) the storage and diversions legally allowed by water rights permits. The sensitivity of reliabilities to maximum allowable TDS, chloride, and sulfate concentrations was analyzed. Quality rather than quantity was concluded to be the limiting factor in controlling water availability. The studies evaluated the effects of two types of management strategies: multiple-reservoir system operating policies and impoundment of runoff from the primary salt source areas. Management strategies were evaluated from the perspectives of impacts on salt concentrations and water supply reliabilities. Potential for improving system reliability through refinements in multiple-reservoir release policies appears to be fairly limited. Controlling the runoff from the primary salt-source areas was demonstrated to significantly improve water supply reliabilities.

RED RIVER BASIN STUDIES AND PROJECTS

As indicated by Figure 4, the 243,000-km² Red River Basin extends from eastern New Mexico across portions of Texas, Oklahoma, Arkansas, and Louisiana to the Mississippi River. Natural salt pollution control studies and projects for the Red River Basin have been directed largely at reducing the loads of chlorides and other dissolved solids flowing into Lakes Texoma and Kemp. Lake Kemp on the Wichita River is the largest reservoir in the Red River watershed upstream of Lake Texoma. Lake Kemp is owned and operated by Wichita County Water Improvement District No. 2 and the City of Wichita Falls. Lake Texoma, impounded by Denison Dam, is located on the Red River between Oklahoma and Texas and is the largest reservoir in the two states and the only reservoir on the main-stem Red River. Construction was completed in 1944. The Corps of Engineers Tulsa District operates the project for flood control, hydroelectric power, recreation, water supply, and improvement of navigation in the lower reaches of the Red River. The project was constructed primarily for flood control and hydroelectric energy generation, while realizing that other purposes would become important in the future. Natural salt pollution in the Red River has severely limited the use of Lake Texoma for municipal, industrial, and agricultural water supply. Use of poor quality water for irrigation has lowered crop yields and damaged land and equipment. Many hectares of irrigable land along the Red River are not irrigated because of the salinity (Red River Chloride Control Project Evaluation Panel 1988). Large volumes of ground water in the shallow alluvium and terrace deposits along the Red River and its tributaries have been polluted through interactions with streamflow. Instead of diverting water from the Red River which flows through the city, Shreveport, Louisiana constructed a pipeline to transport water from Caddo Lake on Little Cypress Bayou, which is the only large natural lake in Texas and a very unique environmental resource. During the severe drought of the early 1950's, water was transported from Lake Texoma by pipeline to the Dallas metroplex in the adjoining Trinity River Basin where it was mixed with the limited supplies from the Trinity River and tributaries. For many years after that, pipes and facilities steadily deteriorated as a result of corrosion damage caused by the limited use of saline water (Rought 1984). In the early 1990's, the city of Dallas completed a pipeline project to facilitate use of Lake Texoma, during future drought periods, to supplement supplies from Trinity River Basin reservoirs. As demands
exceed supplies, other smaller cities have also turned to Lake Texoma as a water supply source. The Water Resources Development Act of 1986 (Public Law 99-662) authorized the Corps of Engineers to reallocate a portion of the hydroelectric power storage in Lake Texoma to water supply in increments as needed.

The USACE Tulsa District has conducted a series of chloride control studies dating back to the 1960's that built upon U.S. Public Health Service studies conducted during the late 1950's. Ten naturally occurring salt emission areas in the watershed above Lake Texoma were identified. About two-thirds of the 3.3 million kg/day salt inflow to Lake Texoma originates from these ten primary salt source areas, which are shown in Figure 4. The U.S. Congress authorized the Tulsa District to develop facilities to control the salt pollution at eight of the ten sites. Numerous planning and design documents have been prepared by the Tulsa District and consulting firms, universities, and other agencies working under contract with the Tulsa District since the 1960's. Recent feasibility studies are documented by the Tulsa District (1993, 1995, and 1995).

Construction of salt control projects at the eight sites was authorized by the Flood Control Acts of 1962, 1966, and 1970 as modified by the Water Resources Development Act of 1970 (Public Law 91-611). Facilities have been constructed at two of the sites. These two projects, the Estelline Springs ring dike and Truscott brine lake and associated collection facilities, are described later. The Water Resources Development Act of 1986 (Public Law 99-662) authorized development of chloride control projects for the other salt source areas pending transmittal of a report to the Secretary of the Army and the Congress of favorable findings of the effectiveness of the operation of the Truscott brine storage facility and associated brine collection system. A panel was established to assess the effectiveness of the project in improving downstream water quality. Their report (Red River Chloride Control Project Evaluation Panel 1988) recommended continued development of other chloride control projects.

![Figure 4. Red River Basin](image)

Congress has appropriated funds in each fiscal years since 1991 for the Corps of Engineers to continue the planning, design, and construction of the remaining projects. The Tulsa District recently completed studies
updating the previous feasibility reports and environmental impact statement for other salt collection and disposal facilities projects for subwatersheds above Lake Texoma (Tulsa District 1993, 1995, 1995). Officials of the Oklahoma Wildlife Department and U.S. Fish and Wildlife Service have expressed opposition to the salt control projects based on concerns that the reductions in salinity would damage ecosystems. The striped bass population of Lake Texoma, which is very popular with sport fishermen, could be severely affected. Proposed brine lakes are also considered to be a potential hazard to resident and migratory wildlife. Project proponents emphasize the benefits of the proposed salt control projects to municipal and agricultural water supply.

The facilities authorized for future construction and currently being studied consist of brine collection, transport, and disposal systems. Brine collection facilities include shallow wells and low-flow dams across streams to capture runoff from primary salt source areas. Pipelines, pumps, and channels are required to transport the brine to disposal facilities consisting of either surface storage reservoirs or deep injection wells. Facilities that have already been constructed include a ring dike at Estelline Spring and the Truscott Brine Lake and associated collection facilities.

Estelline Spring is in the floodplain of the Prairie Dog Town Fork of the Red River. Under natural conditions, the spring has a flow of about 0.1 m$^3$/s and contributes about 270,000 kg/day of chlorides to the river. In 1964, a project was completed that provides head to stop the spring flow. The chloride control project consists of encircling the spring by a 2.7-m high earthen dike with a diameter of 104-m with an impervious core to firm rock.

The Truscott Brine Lake on Bluff Creek became operational in 1987. Brine is pumped from the Bateman low-flow collection dam on the South Fork of the Wichita River above Lake Kemp and transported via pipeline for storage in Truscott Reservoir. Water evaporates from the Truscott impoundment leaving the salt permanently stored. The 143 million m$^3$ storage capacity of the Truscott project is designed to contain a 100-year accumulation of brine and sediment and a 100-year recurrence interval flood. Additional brine collection and transport facilities are planned for the future in the watershed above Lake Kemp. The Lowrance low-flow dam and pump station have been completed, but construction has not started on the pipeline, pumps, and controls necessary to transfer the brines to the Truscott Brine Lake for disposal.

CONCLUDING REMARKS

Effective water management is crucial to the environmental and socioeconomic vitality of the Southwest, which is a region of depleting groundwater reserves and limited surface water resources. Natural salt pollution is a governing factor controlling water resources development and management. The Corps of Engineers and other entities have investigated and, in some cases, implemented natural salt pollution control projects. The U.S. Geological Survey has conducted extensive water sampling programs to support these efforts. Primary salt source areas have been identified. Salinity control plans have focused on collection and disposal of the brine from these areas. The federal government has assumed a leadership role in natural salt pollution control efforts since salinity affects water management throughout the major river basins and the beneficiaries of control measures are diverse and widespread. Project implementation is complicated by institutional complexities in assigning responsibilities, funding limitations, economic feasibility, and environmental concerns. Additional research is required to better understand natural salt pollution, its impacts on water management, and strategies for dealing with the salinity.

REFERENCES


**Ralph A. Wurbs** worked in the water resources development program of the Corps of Engineers for nine years prior to joining the civil engineering faculty at Texas A&M University in 1980. He holds B.S., M.S. and Ph.D. degrees from Texas A&M University, University of Texas at Arlington, and Colorado State University, and is currently Associate Professor in the Environmental, Ocean and water Resources Division of the Civil Engineering Department.