SUBSURFACE SALINE WATER RESOURCES
IN THE SAN ANTONIO AREA, TEXAS

By
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Texas Water Development Board
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SUBSURFACE SALINE WATER RESOURCES
IN THE SAN ANTONIO AREA, TEXAS

ABSTRACT

The study of Subsurface Saline Water Resources in the San Antonio Area was conducted from November 1973 to June 1974. The San Antonio area lies within the Nueces, San Antonio, and Guadalupe River basins. It consists of all or parts of Atascosa, Bexar, Comal, Frio, Guadalupe, Karnes, Medina, and Wilson Counties. The general scope of this investigation includes: (a) the occurrence, quantity, and quality of saline water available in the San Antonio area; (b) to discuss and identify aquifers containing saline water; and (c) studies of saline aquifers using digital computer model techniques and graphical yield rates.

The following are estimated quantities of saline groundwater in artesian storage by aquifer in the San Antonio area: (a) Wilcox Group - 387,000 acre-feet, of which 81,000 acre-feet are classed as moderately saline (containing 3,000 to 10,000 mg/1 of total dissolved solids); (b) Austin Group - 1,927,000 acre-feet; (c) Edwards and associated limestones - 2,131,000 acre-feet with 85,000 acre-feet being classed as moderately saline; (d) Glen Rose Formation - 2,447,000 acre-feet; and (e) Travis Peak Formation - 2,070,000 acre-feet.

Saline water in the Wilcox Group contains 3,000 to 50,000 mg/1 of total dissolved solids, in the Austin Group 3,000 to 29,000 mg/1 of total dissolved solids, and in the Edwards and associated limestones 3,000 to 220,000 mg/1 of total dissolved solids. Because of insufficient data, the exact water quality of the Glen Rose and Travis Peak Formations could not be determined.
INTRODUCTION

Purpose and Scope

The study of Subsurface Saline Water Resources in the San Antonio Area was initiated as part of the Texas Water Development Board's San Antonio Area Regional Environmental Project. The purpose of this open-file report is to present the results obtained from this investigation. It was conducted from November 1973 to June 1974.

The general scope of this investigation includes: (a) a discussion of the occurrence, quantity, and quality of saline water available in the San Antonio area; (b) discussion and identification of aquifers containing saline water; and (c) studies of saline aquifers using digital computer model techniques and graphical yield rates.

Location and Population

The area covered by this report will be referred to as the San Antonio area. This area occurs within the Nueces, San Antonio, and Guadalupe River basins. It includes all or parts of the following counties: Atascosa, Bexar, Comal, Frio, Guadalupe, Karnes, Medina, and Wilson. It differs somewhat from the San Antonio area as described in some other reports.

According to the figures obtained from the Texas Water Development Board's Economics, Water Requirements and Uses Division, the study area has an estimated 1970 population of 964,786. The largest population and trade center within the study area is San Antonio (1970 population estimate - 654,153). Population projections indicate Bexar County, in which San Antonio is located, will have a population of 1,260,900 by the year 2000. This compares with 830,500 in 1970.
Economy

The region derives its economy from military installations, governmental agencies, light industry, tourism, and the production of various agricultural products. Natural resources in the study area include oil, natural gas, clays, sands, and gravel. Clays used for ceramic purposes are produced in Bexar and Wilson Counties. Sand and gravel are produced throughout the area and are used as an aggregate in concrete and asphalt. Sand suitable for the manufacture of glass has been produced in Atascosa County.

Previous Investigations

Core Laboratories, Inc., as part of their "Survey of the Subsurface Saline Water of Texas" (1972), and Winslow and Kister's 1956 investigation of the "Saline-Water Resources of Texas" provided basic references and data on the occurrence, availability, and quality of saline ground-water resources.

Personnel

The study was carried out by the author under the direct supervision and guidance of Glenward R. Elder, District Chief, San Antonio District Office, and William B. Klemt, Chief of Groundwater Availability Branch, Water Availability Division. General direction of the study was provided by Robert L. Bluntzer, Division Director, Water Availability Division, and Lewis B. Seward, Principal Engineer-Project Development. Typing of the manuscript and various tables along with processing computer data was done by Mrs. Sue Reagan and Mrs. Peggy Behnken, secretaries.

Acknowledgments

The Texas Water Development Board is grateful to Dowell Chemical, Halliburton Division Laboratory, San Antonio City Public Service Board, and Schlumberger Well Surveying Corporation for chemical analyses of groundwater.
within the study area. Mr. Jim Ellis, Schlumberger Well Surveying Corporation, San Antonio Office, contributed advice and guidance in the field of electric log interpretation.

Acknowledgment is extended to the Texas Railroad Commission for the use of their reservoir characteristics records in the San Antonio area.

Special acknowledgment is extended to Mr. Dick Reeves, United States Geological Survey, and Mr. Porter Montgomery, Montgomery Stratigraphic Service. Mr. Montgomery generously permitted the use of his library and electric logs which greatly contributed to the successful completion of this investigation.

Definition of Terms

Acre-foot - The volume of water required to cover 1 acre to a depth of 1 foot (43,560 cubic feet) or 325,851 gallons.

Aquifer - A formation, group of formations, or a part of a formation that is water bearing; an underground stratum that will yield water in sufficient quantity to be of value as a source of supply. An artesian aquifer is overlain (confined) by an impermeable layer so that the water is under hydrostatic pressure. The water level in an artesian well will rise above the top of the aquifer. A water-table aquifer is an aquifer in which the water is unconfined - the upper surface of the zone of saturation is under atmospheric pressure only and the water is free to rise or fall in response to the changes in the volume of water in storage.

Aquifer yield rate - The maximum yield in gallons per minute produced from a single well pumping 100 years and with a drawdown of no greater than 500 feet.

Artesian storage - The volume of water which can be obtained when the
hydrostatic pressure of an artesian aquifer is lowered by pumping; water is derived from storage by the compaction of the aquifer and its associated beds and by expansion of the water itself. Units are in acre-feet.

**Coefficient of permeability** - The rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a unit hydraulic gradient.

**Coefficient of storage** - The volume of water an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface. The storage coefficient is a dimensionless term. In an unconfined water body it is virtually equal to the specific yield.

**Coefficient of transmissibility** - The number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide and having the height of the saturated aquifer when the hydraulic gradient is unity. It is the product of the field coefficient of permeability and the saturated thickness of the aquifer.

**Cone of depression** - The depression of the water table or piezometric surface surrounding a discharging well or group of wells which is more or less the shape of an inverted cone.

**Drawdown** - The lowering of the water table or piezometric surface caused by pumping (or artesian flow). It is the difference, in feet, between the static level and the pumping level.

**Lithology** - The description of rocks, usually from observation of hand specimen or outcrop with the aid of a low-power magnifier.

**Water-table storage** - The volume of water obtained when the water level is lowered by pumping. Groundwater is derived from storage by gravity drainage.
from the saturated pore space in the portion of the aquifer unwatered by the pumping. Units are in acre-feet.

**METHOD OF ANALYSIS**

A saline aquifer, as defined in this report, contains water having more than 3,000 milligrams per liter (mg/l) of total dissolved solids. The saline waters discussed are classified according to Winslow and Kister (1956) as follows:

- Fresh Water - 0 to 1,000 mg/l
- Slightly Saline Water - 1,000 to 3,000 mg/l
- Moderately Saline Water - 3,000 to 10,000 mg/l
- Very Saline Water - 10,000 to 35,000 mg/l
- Brine - More than 35,000 mg/l

All available literature pertaining to saline aquifers in the San Antonio area was researched to obtain the following: (a) water quality; (b) aquifer coefficients (permeability, transmissibility, and storage); (c) structure; (d) thickness; and (e) lithology.

Saline sand aquifer coefficients and water quality were estimated using methods devised by Archie (1942) and Gondouin and Scala (1958) where the literature did not contain sufficient information. Computer programs were written for these empirical relationships and the data was input into the Board's computer via the San Antonio remote terminal.

The nonleaky artesian solution (Walton 1962) was used to determine the aquifer yield rate, which for the purposes of this report is defined as the maximum yield produced from a single well pumping 100 years and with a drawdown of no greater than 500 feet. The following procedure was used to determine this rate: (a) a computer program utilizing the nonleaky artesian solution computed yields associated with drawdowns of 500 feet for a pumping
period of 100 years and varying transmissibilities; (b) the relationship between yield and transmissibility was graphed as illustrated in Figure 1; and (c) estimates of an aquifer's transmissibility at various locations were converted into aquifer yield rates which were then contoured or put into tabular form. The aquifer yield rate as determined from the above analysis is subject to the following assumptions: (a) a 100 percent efficient well completion; (b) aquifer recharge was negligible; and (c) the aquifer was assumed to have unlimited areal extent.

Other similar graphics were developed for a single production well within a well field (10 wells at ½ mile spacing) which relates yield and the maximum 500 foot drawdown to transmissibility. These graphics are also illustrated on Figure 1.

The total amount of water available from water-table and artesian storage was determined by calculating the volume in the area affected when static water levels are lowered to the base of the saline aquifer. These calculations assume an artesian storage coefficient of $1 \times 10^{-4}$ (0.0001) and a water-table storage coefficient ranging from 1 percent (0.01) to 5 percent (0.05) depending on the aquifer.

**STRATIGRAPHY**

The stratigraphic units in the San Antonio area which could possibly yield saline water to wells are of Paleozoic (oldest), Cretaceous, and Tertiary (youngest) age. Only saline aquifers Cretaceous and Tertiary in age were considered as this aquifer data was readily available. Table 1 gives the Cretaceous and Tertiary stratigraphic units in the study area.

The saline aquifers discussed in this report include the following: (a) Wilcox Group; (b) Austin Group; (c) Edwards and associated limestones; (d)
FIGURE 1
Graphs Showing the Relationship of Transmissibility to Drawdown and Yield as a Result of Pumping 100 Years in the San Antonio Area, Texas
Table 1 -- Cenozoic and Mesozoic Stratigraphic Units in the San Antonio Area, Texas

<table>
<thead>
<tr>
<th>Era</th>
<th>System</th>
<th>Series</th>
<th>Group</th>
<th>Geologic Unit</th>
<th>Approximate Thickness (ft.)</th>
<th>Character of Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Tertiary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eocene</td>
<td>Wilcox</td>
<td>Wilcox Formation</td>
<td>320 - 1,780</td>
<td>Interbedded sand, clay, and silt with discontinuous beds of lignite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Midway Formation</td>
<td>280 - 550</td>
<td>Shale</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Navarro Formation</td>
<td>300 - 1,300</td>
<td>Sand, shale, clay, marl, and sandstone</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Cretaceous</td>
<td></td>
<td></td>
<td>Taylor Marl</td>
<td>240 - 800</td>
<td>Shale and lime</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Austin Chalk</td>
<td>30 - 460</td>
<td>Chalk and marl</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eagle Ford Shale</td>
<td>0 - 90</td>
<td>Bituminous shale and limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Buda Limestone</td>
<td>13 - 170</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Washita</td>
<td>Del Rio Clay</td>
<td>12 - 140</td>
<td>Shale</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Georgetown Formation</td>
<td>5 - 275</td>
<td>Limestone</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Edwards Limestone</td>
<td>427 - 910</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fredericksburg</td>
<td>Comanche Peak Limestone</td>
<td>40±</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Walnut Clay</td>
<td>1 - 20</td>
<td>Clay, marl, and limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Glen Rose Formation</td>
<td>850 - 2,170</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Travis Peak Formation</td>
<td>1,010 - 4,000</td>
<td>Dolomite, clastics, sand, and limestone</td>
</tr>
</tbody>
</table>
Glen Rose Formation; and (e) Travis Peak Formation. All of the above saline aquifers are Cretaceous in age except the Wilcox Group which is Tertiary.

SALINE AQUIFERS

Wilcox Group

The Wilcox Group in the San Antonio area containing water greater than 3,000 mg/l of total dissolved solids consists of clays, cross-bedded river sands, thin lignite beds, and stratified silts. The approximate depth to the top of the aquifer ranges from 3,200 feet (Frio County) to 5,900 feet (Karnes County). The average net thickness is 890 feet. The altitude and depth to the top of the Wilcox Group is illustrated in Figure 2, the thickness is illustrated in Figure 3, and water quality is illustrated in Figure 5. The approximate total transmissibility of the Wilcox Group is illustrated in Figure 6 and the aquifer yield rate is illustrated in Figure 7. The following table summarizes the approximate range by county of total dissolved solids, transmissibility, and aquifer yield rates for the Wilcox Group:

<table>
<thead>
<tr>
<th>County</th>
<th>Total Dissolved Solids (mg/l)</th>
<th>Coefficient of Transmissibility (gpd/ft)</th>
<th>Aquifer Yield Rates Single Well Pumping 100 Yrs. With 500 Feet of Drawdown (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>3,000 - 20,000</td>
<td>200 - 8,700</td>
<td>40 - 1,500</td>
</tr>
<tr>
<td>Frio</td>
<td>3,000 - 9,000</td>
<td>200 - 1,000</td>
<td>40 - 200</td>
</tr>
<tr>
<td>Karnes</td>
<td>5,000 - 50,000</td>
<td>100 - 2,000</td>
<td>20 - 350</td>
</tr>
<tr>
<td>Wilson</td>
<td>3,000 - 6,000</td>
<td>700 - 1,000</td>
<td>100 - 120</td>
</tr>
</tbody>
</table>

The following table summarizes the approximate amount of saline water in storage by county for the Wilcox Group based on an artesian storage coefficient of $1 \times 10^{-4}$ (0.0001) and water-table storage of 5 percent (0.05):
FIGURE 2.
MAP SHOWING THE APPROXIMATE
DEPTH TO AND ALTITUDE OF THE
TOP OF MODERATELY SALINE TO BRINE WATER
(5,000 TO 50,000 m.g.l TOTAL
DISSOLVED SOLIDS) IN THE WILCOX GROUP
IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control
Depth to top of moderately saline to brine water
Elevation of top of moderately saline to brine water

Outcrop of Wilcox Group
Fault, dashed where approximate (Relative movement: 1/2 in./A.m.)

Water interface Surface
Shallowing approximate altitude of top of moderately saline to brine water
dashed where lacking control data

Contour interpretation
Approximate boundary indicating subsurface extent of fresh to
slightly saline water (less than 3,000 m.g.l Total Dissolved Solids)
MAP SHOWING THE APPROXIMATE TOTAL AND NET SAND THICKNESS CONTAINING MODERATELY SALINE TO BRINE WATER (3,000 TO 50,000 mg/l TOTAL DISSOLVED SOLIDS) IN THE WILCOX GROUP IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

- Well used for control
- Number indicates total thickness
- Outcrop of Wilcox Group
- Isopach
  - Shows approximate net thickness of sand containing moderately saline to brine water in the Wilcox Group, dashed where lacking control data
  - Contour interval 200 feet
  - Approximate boundary indicating admixture of fresh to slightly saline water (less than 2000 mg/l total dissolved solids)
FIGURE 4
MAP SHOWING THE APPROXIMATE TOTAL AND NET SAND THICKNESS CONTAINING MODERATELY SALINE WATER (2000 TO 10,000 mg/L TOTAL DISSOLVED SOLIDS) IN THE WILCOX GROUP IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control

Number indicates total thickness

Outcrop of Wilcox Group

Isopach

Number indicates net sand thickness

Contour interval 200 feet

Approximate boundary indicating thickness (less than 200/5 mg/L total dissolved solids)

Approximate boundary indicating extreme extent of moderately saline water
FIGURE 5

MAP SHOWING DISTRIBUTION OF TOTAL DISSOLVED SOLIDS OF WATER IN THE WILCOX GROUP IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for Control

Contour interval varies

Approximate boundaries including surface extent of fresh to slightly saline water (less than 3000 mg/l Total Dissolved Solids)

Total dissolved solids from reported data

Outcrop of Wilcox Group

Line showing approximate concentration of total dissolved solids, in milligrams per liter (mg/l), dashed where lacking control data

Number indicates concentration of approximate total dissolved solids, calculated from spontaneous potential logs, in milligrams per liter (mg/l)

Well used for Control @ 10,600
FIGURE 6

MAP SHOWING THE APPROXIMATE TOTAL TRANSMISSIBILITY OF THE NILCOX GROUP IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for test

0.004 Number indicates approximate total transmissibility in GPD/ft².

---

*--- Outcrop of Nilcox Group

Line shows approximate total transmissibility in GPD/ft², dashed where lacking sufficient data. Contour interval varies

--- Approximate boundary indicating subsurface extent of rock to slightly saline water. (less than 5000 mg/l Total Dissolved Solids.)
FIGURE 7
MAP SHOWING THE TOTAL CALCULATED AVERAGE YIELD RATE FOR THE WILLIAMS GROUP AS A RESULT OF PUMPING 100 YEARS WITH 500 FEET OF DRAWDOWN IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION
Well used for control
Outcrop of Williams Group
Line showing aquifer yield rate (gpm) for 1 well pumping 100 years with 500 ft drawdown,磔faith where lacking control data
Contour interval varies
Approximate boundary indicating subnormal content of fresh to slightly saline water (less than 3000 mg/l Total Dissolved Solids)
Water In Artesian Storage (acre-feet) | Water In Water-table Storage (acre-feet) | Total Water In Storage (acre-feet)
---|---|---
Atascosa | 102,000 | 9,152,000 | 9,254,000
Frio | 10,000 | 960,000 | 970,000
Karnes | 270,000 | 20,848,000 | 21,118,000
Wilson | 5,000 | 448,000 | 453,000

**Austin Group**

The Austin Group in the San Antonio area containing water greater than 3,000 mg/l of total dissolved solids consists chiefly of white to buff chalk, marl, and limestone. The approximate depth from the land surface to the top of the aquifer ranges from 700 feet (Guadalupe County) to 13,000 feet (Karnes County). The average thickness is 250 feet. The altitude and depth to the top of the Austin Group is illustrated in Figure 8 and the thickness is illustrated in Figure 9. The transmissibility of the Austin Group is low, averaging about 6 gallons per day per foot (gpd/ft); aquifer yield rates should range from 2 to 5 gallons per minute (gpm). Artesian storage approximates $1 \times 10^{-4}$ (0.0001) and water-table storage is in the neighborhood of 1 percent (0.01).

The following are estimated ranges of total dissolved solids for the Austin Group by county in the San Antonio area: (a) Bexar - 3,000 to 8,000 mg/l; (b) Guadalupe - 3,000 to 29,000 mg/l; and (c) Medina - 3,000 to 13,000 mg/l. Total dissolved solids in Frio County probably exceed 25,000 mg/l.

The following table summarizes the approximate amount of saline water in storage for the Austin Group:
FIGURE 1

MAP SHOWING THE APPROXIMATE DEPTH TO AND ALTITUDE OF THE TOP OF MODERATELY SALINE TO VERY SALINE WATER (3,000 to 29,000 mg/I TOTAL DISSOLVED SOLIDS) IN THE AUSTIN GROUP IN THE SAN ANTONIO AREA, TEXAS.
Figure 9
Map showing the approximate total thickness of strata containing moderately saline to very saline water (3,000 to 29,000 mg/l total dissolved solids) in the Austin Group in the San Antonio, Texas area.

Explanation:
- Well used for control
- Number indicates total thickness (ft)
- Outcrop of the Austin Group, dotted where approximate
- @ 200 shows approximate total thickness of strata containing moderately saline to very saline water in the Austin Group; dashed where lacking control data;
- Contour interval 50 ft
- Approximate boundary indicating subsurface extent of fresh to slightly saline water (less than 3,000 mg/l total dissolved solids)
County | Water In Artesian Storage (acre-feet) | Water In Water-table Storage (acre-feet) | Total Water In Storage (acre-feet)
---|---|---|---
Atascosa | 571,000 | 1,632,000 | 2,203,000
Bexar | 52,000 | 246,000 | 298,000
Frio | 366,000 | 2,270,000 | 2,636,000
Guadalupe | 73,000 | 680,000 | 753,000
Karnes | 536,000 | 803,000 | 1,339,000
Medina | 58,000 | 784,000 | 842,000
Wilson | 272,000 | 994,000 | 1,266,000

**Edwards and Associated Limestones**

The Edwards and associated limestones in the San Antonio area containing water greater than 3,000 mg/l of total dissolved solids is composed of hard, porous, and fossiliferous limestones and dolomites. The approximate depth to the top of the aquifer ranges from 1,200 feet (Guadalupe County) to 13,800 feet (Karnes County). The average thickness is 750 feet. The altitude and depth to the top of the Edwards and associated limestones is illustrated in Figure 10, the thickness is illustrated in Figure 11, and water quality is illustrated in Figure 13. The approximate total transmissibility of the Edwards and associated limestones is illustrated in Figure 14 and the aquifer yield rate is illustrated in Figure 15. The following table summarizes the approximate range by county of total dissolved solids, transmissibility, and aquifer yield rates for the Edwards and associated limestones:

<table>
<thead>
<tr>
<th>County</th>
<th>Total Dissolved Solids (mg/l)</th>
<th>Coefficient of Transmissibility (gpd/ft)</th>
<th>Aquifer Yield Rates Single Well Pumping 100 Yrs. With 500 Feet of Drawdown (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>3,000 - 168,000</td>
<td>100 - 10,000</td>
<td>20 - 1,740</td>
</tr>
<tr>
<td>Bexar</td>
<td>3,000 - 50,000</td>
<td>5,000 - 10,000</td>
<td>870 - 1,740</td>
</tr>
</tbody>
</table>
FIGURE 10

MAP SHOWING THE APPROXIMATE DEPTH TO AND ALTITUDE OF THE TOP OF MODERATELY SALINE TO BRINE WATER (3,000 TO 220,000 mg/l TOTAL DISSOLVED SOLIDS) IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control

- 3,000 ft. depth to top of moderately saline to brine water

- Elevations of top of moderately saline to brine water

- Outcrop of Edwards and Associated Limestones, dashed where approximate

- Fault, dashed where approximate (Relative amount: 44'-87'-100')

- Water-intersection contour

- Shading approximate altitude of top of moderately saline to brine water

- Dashed where lacking control data

- Contoured on top of Georgetown Formation

- Contour interval: 50 ft.

- Approximate boundary indicating subsurface return of fresh to slightly saline water (less than 355 mg/l Total Dissolved Solids)
FIGURE 11
MAP SHOWING THE APPROXIMATE TOTAL THICKNESS OF LIMESTONES CONTAINING MODERATELY SALINE TO BARTLETT 0.12 TO 3,000 mg/l TOTAL DISSOLVED SOLIDS IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control
Number indicates total thickness
Outlet of Edwards and associated limestones, dotted where approximate
Isopach
Shows approximate total thickness of limestones containing moderately saline to brine water in the Edwards and associated limestones, dashed where lacking control data
Contour interval 100 feet
Approximate boundary indicating subsurface effect of fresh to slightly saline water (less than 3000 mg/l Total Dissolved Solids)
FIGURE 12
MAP SHOWING THE APPROXIMATE TOTAL THICKNESS OF LIMESTONES CONTAINING MODERATELY SALINE WATER (5,000 TO 10,000 mg/l TOTAL DISSOLVED SOLIDS) IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control
0 500
Number indicates total thickness

Inch
Shade approximate total thickness of limestones containing moderately saline water in the Edwards and associated limestones

Approximate boundary indicating subsurface extent of moderately saline water
FIGURE 1.3
MAP SHOWING DISTRIBUTION OF TOTAL DISSOLVED SOLIDS OF WATER IN THE EDWARDS AND ASSOCIATED LIMESTONES IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control
0 ppm

Number indicates concentration of approximate total dissolved solids calculated from spontaneous potential logs, in milligrams per liter (mg/l)

2,000
Total dissolved solids from reported data

Outlet of Edwards and associated limestone.

10,000
Line showing approximate concentration of total dissolved solids, in milligrams per liter (mg/l). Exact location of outlet control unit.

10,000
Contact interval variables

Approximate boundary indicating subsurface extent of franc to slightly saline water (less than 3,000 mg/l total dissolved solids).
EXPLANATION

FIGURE 16.
MAP SHOWING THE APPROXIMATE TOTAL TRANS-MISSIBILITY OF THE EDWARDS AND ASSOCIATED LIME STONES IN THE SAN ANTONIO AREA, TEXAS.

Well used for Control

5,000 Number indicates approximate total transmissibility in 960 ft

Legend:

Contour lines on map
Approximate boundary of fault, etc., to strike of saline water (less than 3,000 m/ft Total Dissolved Solids)
FIGURE 15.
MAP SHOWING THE IDEAL CALCULATED AQUIFER YIELD RATE FOR THE EDWARDS AND ASSOCIATED LIMESTONES AS A RESULT OF PUMPING 100 YEARS WITH 500 FEET OF DRAWDOWN IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Weill used for control
10 wells pumping 10 years with 500 ft. drawdown
1 well pumping 20 years with 500 ft. drawdown

Ed.:
Line showing Edwards and associated limestone

Dashed line: Trend line showing aquifer yield

Contour interval varies

Approximate boundary indicating streams
area of fresh to slightly saline water
(less than 3000 mg/l TDS) in Edwards Group
### Aquifer Yield Rates

<table>
<thead>
<tr>
<th>County</th>
<th>Total Dissolved Solids (mg/l)</th>
<th>Coefficient of Transmissibility (gpd/ft)</th>
<th>Aquifer Yield Rates Single Well Pumping 100 Yrs. With 500 Feet of Drawdown (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comal</td>
<td>3,000 - 4,000</td>
<td>10,000 - 20,000</td>
<td>1,740 - 3,200</td>
</tr>
<tr>
<td>Frio</td>
<td>Greater than 10,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>3,000 - 50,000</td>
<td>5,000 - 10,000</td>
<td>870 - 1,740</td>
</tr>
<tr>
<td>Karnes</td>
<td>100,000 - 220,000</td>
<td>8 - 500</td>
<td>5 - 90</td>
</tr>
<tr>
<td>Medina</td>
<td>3,000 - 10,000</td>
<td>10,000 - 20,000</td>
<td>1,740 - 3,200</td>
</tr>
<tr>
<td>Wilson</td>
<td>20,000 - 164,000</td>
<td>200 - 9,000</td>
<td>40 - 1,560</td>
</tr>
</tbody>
</table>

The following table summarizes the approximate amount of saline water in storage for the Edwards and associated limestones based on an artesian storage coefficient of $1 \times 10^{-4}$ (0.0001) and water-table storage of 3 percent (0.03):

<table>
<thead>
<tr>
<th>County</th>
<th>Water In Artesian Storage (acre-feet)</th>
<th>Water In Water-table Storage (acre-feet)</th>
<th>Total Water In Storage (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>608,000</td>
<td>19,368,000</td>
<td>19,976,000</td>
</tr>
<tr>
<td>Bexar</td>
<td>65,000</td>
<td>5,000,000</td>
<td>5,065,000</td>
</tr>
<tr>
<td>Comal</td>
<td>1,000</td>
<td>92,000</td>
<td>93,000</td>
</tr>
<tr>
<td>Frio</td>
<td>427,000</td>
<td>18,643,000</td>
<td>19,070,000</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>95,000</td>
<td>7,029,000</td>
<td>7,124,000</td>
</tr>
<tr>
<td>Karnes</td>
<td>597,000</td>
<td>11,791,000</td>
<td>12,388,000</td>
</tr>
<tr>
<td>Medina</td>
<td>45,000</td>
<td>3,269,000</td>
<td>3,314,000</td>
</tr>
<tr>
<td>Wilson</td>
<td>294,000</td>
<td>9,055,000</td>
<td>9,349,000</td>
</tr>
</tbody>
</table>

**Glen Rose Formation**

The Glen Rose Formation in the San Antonio area containing water greater than 3,000 mg/l of total dissolved solids consists of beds of moderately resistant, massive, and chalky limestones alternating with beds of less resistant marly limestone. The approximate depth to the top of the aquifer
ranges from 500 feet (Bexar County) to 13,900 feet (Karnes County). The average thickness is 1,550 feet. The altitude and depth to the top of the Glen Rose Formation is illustrated in Figure 16 and the thickness is illustrated in Figure 17. Because of insufficient data, the water quality, transmissibility, and aquifer yield rates could not be determined for the Glen Rose Formation. The following table summarizes the approximate amount of saline water in storage for the Glen Rose Formation based on an artesian storage coefficient of \(1 \times 10^{-4}\) (0.0001) and water-table storage of 2 percent (0.02):

<table>
<thead>
<tr>
<th>County</th>
<th>Water In Artesian Storage (acre-feet)</th>
<th>Water In Water-table Storage (acre-feet)</th>
<th>Total Water In Storage (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>665,000</td>
<td>23,573,000</td>
<td>24,238,000</td>
</tr>
<tr>
<td>Bexar</td>
<td>119,000</td>
<td>12,090,000</td>
<td>12,209,000</td>
</tr>
<tr>
<td>Comal</td>
<td>3,000</td>
<td>545,000</td>
<td>548,000</td>
</tr>
<tr>
<td>Frio</td>
<td>480,000</td>
<td>23,244,000</td>
<td>23,724,000</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>112,000</td>
<td>9,506,000</td>
<td>9,618,000</td>
</tr>
<tr>
<td>Karnes</td>
<td>611,000</td>
<td>12,176,000</td>
<td>12,787,000</td>
</tr>
<tr>
<td>Medina</td>
<td>138,000</td>
<td>13,192,000</td>
<td>13,330,000</td>
</tr>
<tr>
<td>Wilson</td>
<td>320,000</td>
<td>12,226,000</td>
<td>12,546,000</td>
</tr>
</tbody>
</table>

**Travis Peak Formation**

The Travis Peak Formation in the San Antonio area containing water greater than 3,000 mg/l of total dissolved solids is composed of limestone, sand, and shale. The approximate depth ranges from 1,700 feet (Guadalupe County) to 15,000 feet (Karnes County). The average thickness is 2,400 feet. The altitude and depth to the top of the Travis Peak Formation is illustrated in Figure 18 and the thickness is illustrated in Figure 19. Because of
FIGURE 16

MAP SHOWING THE APPROXIMATE DEPTH TO AND ALTITUDE OF THE TOP OF MODERATELY SALINE TO BRINE WATER IN THE GLEN ROSE FORMATION IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for Control

Depth to top of moderately saline to brine water

Elevation of top of moderately saline to brine water

Outcrop of Glen Rose Formation

Fault, dashed where approximate (location uncertain)

Vertically Intermediate

Showing approximate altitude of top of moderately saline to brine water, dashed where lacking control data

Contour interval 500 ft.

Approximate boundary indicating Subsurface extent of trends to slightly saline water (less than 30 mg/l Total Dissolved Solids)
FIGURE 17

MAP SHOWING THE APPROXIMATE TOTAL THICKNESS OF LIMESTONES CONTAINING MODERATELY SALINE TO BRINE WATER IN THE GLEN ROSE FORMATION IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control
○ Number indicates total thickness

Cartop of the Glen Rose Formation

Isopach
Show approximate total thickness of limestone containing moderately saline to brine water in the Glen Rose Formation, dashed where lacking control data

Contour interval: 100 feet

Approximate boundary indicating subsurface extent of fresh to slightly saline water (less than 8000 mg/l Total Dissolved Solids)
FIGURE 18

MAP SHOWING THE APPROXIMATE DEPTH TO AND ALTITUDE OF THE TOP OF MODERATELY SALINE TO BRINE WATER IN THE TRANS-PEAK FORMATION IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for Conflict

Depth to top of moderately saline to brine water

Elevation of top of moderately saline to brine water

Fault, dashed where approximate (Relative movement: U, Up; D, Down)

Althow, dashed where approximate (Relative movement: U, Up; D, Down)

Contour interval 500 ft.

Approximate boundary indicating subsurface extent of fresh to slightly saline water (less than 500 ppm Total Dissolved Solids)
FIGURE 19

MAP SHOWING THE APPROXIMATE TOTAL THICKNESS OF STRATA CONTAINING MODERATELY SALINE TO BRINE WATER IN THE TRAVIS PEAK FORMATION IN THE SAN ANTONIO AREA, TEXAS

EXPLANATION

Well used for control
© 200
Number indicates total thickness

Isopack.
Shows approximate total thickness of strata containing moderately saline to brine water in the Travis Peak Formation, dashed where lacking control data.

Contour interval 100 feet
Approximate boundary indicating subsurface extent of fresh to slightly saline water (less than 3000/ft total dissolved solids)

- 32 -
insufficient data, the water quality, transmissibility, and aquifer yield rates could not be determined for the Travis Peak Formation. The following table summarizes the approximate amount of saline water in storage for the Travis Peak Formation based on an artesian storage coefficient of $1 \times 10^{-4}$ (0.0001) and water-table storage of 2 percent (0.02):

<table>
<thead>
<tr>
<th>County</th>
<th>Water In Artesian Storage (acre-feet)</th>
<th>Water In Water-table Storage (acre-feet)</th>
<th>Total Water In Storage (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>768,000</td>
<td>39,322,000</td>
<td>40,090,000</td>
</tr>
<tr>
<td>Bexar</td>
<td>120,000</td>
<td>7,133,000</td>
<td>7,253,000</td>
</tr>
<tr>
<td>Comal</td>
<td>1,000</td>
<td>26,000</td>
<td>27,000</td>
</tr>
<tr>
<td>Frio</td>
<td>593,000</td>
<td>39,520,000</td>
<td>40,113,000</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>161,000</td>
<td>7,416,000</td>
<td>7,577,000</td>
</tr>
<tr>
<td>Medina</td>
<td>46,000</td>
<td>589,000</td>
<td>635,000</td>
</tr>
<tr>
<td>Wilson</td>
<td>381,000</td>
<td>16,112,000</td>
<td>16,493,000</td>
</tr>
</tbody>
</table>

**AVAILABILITY OF MODERATELY SALINE WATER**

Moderately saline water (containing 3,000 to 10,000 mg/l of total dissolved solids) can be converted into fresh water by means of desalting. Desalting means demineralization to the extent that dissolved minerals are reduced well below 1,000 mg/l. The total cost of reducing dissolved solids from 2,500 mg/l to 500 mg/l in a plant that produces 100,000 gallons per day of fresh water is approximately $1.00 per 1,000 gallons (Johnson 1966).

The total amount of moderately saline water available from storage was determined for the Wilcox Group and Edwards and associated limestones; determinations were not made for the Austin Group, Glen Rose, and Travis Peak Formations due to insufficient data. The net sand thickness and downdip limits of moderately saline water in the Wilcox Group are illustrated in
Figures 4 and 5. The total thickness of limestones and downdip limits of moderately saline water in the Edwards and associated limestones are illustrated in Figures 12 and 13. The amount of water in storage was based on an artesian storage coefficient of $1 \times 10^{-4}$ (0.0001) and a water-table storage coefficient of 5 percent (0.05) in the Wilcox Group and 3 percent (0.03) in the Edwards and associated limestones. The following table summarizes the approximate amount of moderately saline water in storage for each aquifer:

**Wilcox Group**

<table>
<thead>
<tr>
<th>County</th>
<th>Water In Artesian Storage (acre-feet)</th>
<th>Water In Water-table Storage (acre-feet)</th>
<th>Total Water In Storage (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>39,000</td>
<td>3,258,000</td>
<td>3,297,000</td>
</tr>
<tr>
<td>Frio</td>
<td>9,000</td>
<td>864,000</td>
<td>873,000</td>
</tr>
<tr>
<td>Karnes</td>
<td>21,000</td>
<td>2,851,000</td>
<td>2,872,000</td>
</tr>
<tr>
<td>Wilson</td>
<td>12,000</td>
<td>1,142,000</td>
<td>1,154,000</td>
</tr>
</tbody>
</table>

**Edwards and Associated Limestones**

<table>
<thead>
<tr>
<th>County</th>
<th>Water In Artesian Storage (acre-feet)</th>
<th>Water In Water-table Storage (acre-feet)</th>
<th>Total Water In Storage (acre-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atascosa</td>
<td>16,000</td>
<td>171,000</td>
<td>187,000</td>
</tr>
<tr>
<td>Bexar</td>
<td>31,000</td>
<td>2,743,000</td>
<td>2,774,000</td>
</tr>
<tr>
<td>Comal</td>
<td>1,000</td>
<td>31,000</td>
<td>32,000</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>16,000</td>
<td>1,567,000</td>
<td>1,583,000</td>
</tr>
<tr>
<td>Medina</td>
<td>21,000</td>
<td>1,219,000</td>
<td>1,240,000</td>
</tr>
</tbody>
</table>

**WELL DESIGN**

Proper well design involves selecting the right materials to be used in its construction. Good design assures an optimum combination of performance, long service life, and reasonable cost. Sound engineering practice requires
that these objectives be considered together. Recommendations for proper
collection and completion of limestone and sandstone saline wells in the
San Antonio area are discussed in the following paragraphs.

A limestone saline aquifer requires the well to be drilled to the base
of the aquifer thereby utilizing its maximum thickness. The well should be
cased and cemented from ground level to the top of the aquifer. The casing
selected should resist corrosion, deterioration, and collapse.

Wells completed in a saline sand aquifer should be cased from land sur-
face to the top of the aquifer. To insure a long service life, the screen
length should be based on optimum screen entrance velocities of less than
two fpm (feet per minute). Other factors to be considered when determining
screen length are the aquifer thickness, available drawdown, and stratifica-
tion of the aquifer. Slot openings of the screen should be large enough to
retain only about 40 percent of the aquifer material in order that the well
may be developed naturally. The casing and screen should also be selected
on their ability to resist corrosion, deterioration, and collapse.

Well completions are seldom 100 percent efficient even when the best
construction methods are used. However, Figure 20 illustrates generalized
computer-simulated cones of depression associated with an idealized artesian
well field (10 wells at ½ mile spacing) pumping 100 years at a rate which
produces drawdowns of approximately 500 feet. The computer analysis assumes
all well completions are 100 percent efficient. Such an analysis can assist
in obtaining maximum efficiency of ground-water withdrawal from an aquifer.

SUMMARY

Large quantities of saline water are available in the San Antonio area
from aquifers which range in age from Cretaceous to Tertiary. These saline
Horizontal Scale
1 inch = 6000 ft.

Figure 20
Idealized Map Illustrating Computer-Simulated Cones of Depression Associated with an Artesian Well Field Pumping 100 Years at a Rate which Produces Drawdowns of Approximately 500 Feet in the San Antonio Area, Texas
aquifers contain the following amounts of water in artesian storage: (a) Wilcox Group - 387,000 acre-feet; (b) Austin Group - 1,927,000 acre-feet; (c) Edwards and associated limestones - 2,131,000 acre-feet; (d) Glen Rose Formation - 2,447,000 acre-feet; and (e) Travis Peak Formation - 2,066,000 acre-feet. At this time, saline water in water-table storage does not appear feasible to recover because of the great depths involved.

Moderately saline water (containing 3,000 to 10,000 mg/l of total dissolved solids) is available for demineralization from the above aquifers in order that it may be used for municipal, industrial, or agricultural applications. However, only the following aquifers were analyzed as to the amount of moderately saline water available from artesian storage: Wilcox Group - 81,000 acre-feet, and Edwards and associated limestones - 85,000 acre-feet.

Because the amount of water available for recovery from artesian storage would be small (10 to 50 percent), the extreme depths from which it must be recovered, the minimal yield rates, and the very high cost of development, it is doubtful the expenditure of large sums of money would be justified for the development of these aquifers.

SELECTED REFERENCES


Doyle, William M., Jr., 1955, Production and reservoir characteristics of the Austin Chalk in south Texas: Gulf Coast Geol. Soc. Trans., v. 5, p. 3-10.

Elmdahl, Ben A., 1955, The fundamental principles of core analysis and their application to Gulf Coast formations: Gulf Coast Geol. Soc. Trans., v. 5, p. 51-64.

Forgotson, James Morris, Jr., 1956, A correlation and regional stratigraphic analysis of the formations of the Trinity Group of the Comanchean Cretaceous of the Gulf Coastal plain: and the genesis and petrography of the Ferry Lake Anhydrite: Gulf Coast Geol. Soc. Trans., v. 6, p. 91-108.

George, W. O., and Petitt, B. M., Jr., 1956, Ground-water resources of the San Antonio area, Texas: Texas Board of Water Engineers Bull. 5608, v. 2, pt. 3.


Keahey, Robert, 1962, Fashing Field, Atascosa-Karnes Counties, Texas: Gulf Coast Geol. Soc. Trans., v. 12, p. 205-211.


Knebel, Robert M., and Jones, Franklin C., 1957, Edwards limestone fields of Atascosa County, Texas: Gulf Coast Geol. Soc. Trans., v. 7, p. 35-44.


Oliver, Fred L., 1958, Natural gas in the Wilcox trend of south Texas: Gulf Coast Geol. Soc. Trans., v. 8, p. 77-81.


Rose, P. R., 1972, Edwards Group, surface and subsurface, central Texas: Bur. Econ. Geology Rept. of Invs. No. 74, 198 p., Austin, Texas, Univ. of Texas.


Winter, Jan A., 1961, Stratigraphy of the lower Cretaceous (subsurface) of south Texas: Doctorate dissert., Univ. of Texas, (Published in G C A G S Trans.), v. 11, p. 15-24.

