Tony

# PROCEEDINGS

# PERSPECTIVES ON
# THE
# EDWARDS AQUIFER
# (Balcones Fault Zone)

April 30, 1982

SWT

Edwards Aquifer Research and Data Center
Southwest Texas State University
San Marcos, Texas

# Briefing on the
# San Antonio - Guadalupe - Nueces River Basins Study

by
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I was asked to brief you on a study performed several years ago by the U.S. Bureau of Reclamation, on the San Antonio, Guadalupe, Nueces River Basins Study, an appraisal level investigation conducted by the Bureau of Reclamation.

The Bureau of Reclamation became involved in this particular study when the project sponsors, consisting of the City Manager of San Antonio; the General Manager of the City Water Board; and the General Managers of the Edwards Underground Water District, the Guadalupe-Blanco River Authority, and the San Antonio River Authority presented a formal request to congressional representatives that the Bureau undertake an investigation of the total water resources within the two combined river basins. Since the Upper Nueces Basin is an integral part of the study area through a common ground water supply, this area was included in our study and the Nueces River Authority joined our planning group. The principal objective was to formulate a comprehensive long-term plan for coordinated integrated use of all the basins' water resources that would recognize every conceivable beneficial use of those resources and extract therefrom the maximum benefits obtainable for the entire area.

Congress was satisfied the study was warranted and approved the budget request and the Bureau of Reclamation received funds to perform the study which began in 1973 and was completed in late 1978.

It goes without saying that planning for a water supply for the entire study area is time consuming; however, the data gathered was comprenhensive. There were some 17 federal, state, and local agencies or groups which coordinated and provided input to this study.

The study area encompasses 17 counties (Figure 1).

This total area consists of about 10,000 square miles and traverses some 350 miles from the headwaters of the Guadalupe River to San Antonio Bay and estuary system.

The total estuary system consists of San Antonio Bay and three minor bays. This combined area covers almost 200 square miles of marshland and bays. The environmental well-being of this complex system is a major issue fully addressed in the study report.

Let's identify at this time the major areas of concern or problems that have a direct impact on the water resources and potential development thereof. These are growth, estuary needs, and ground water conditions

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*Texas Representative, U.S. Bureau of Reclamation

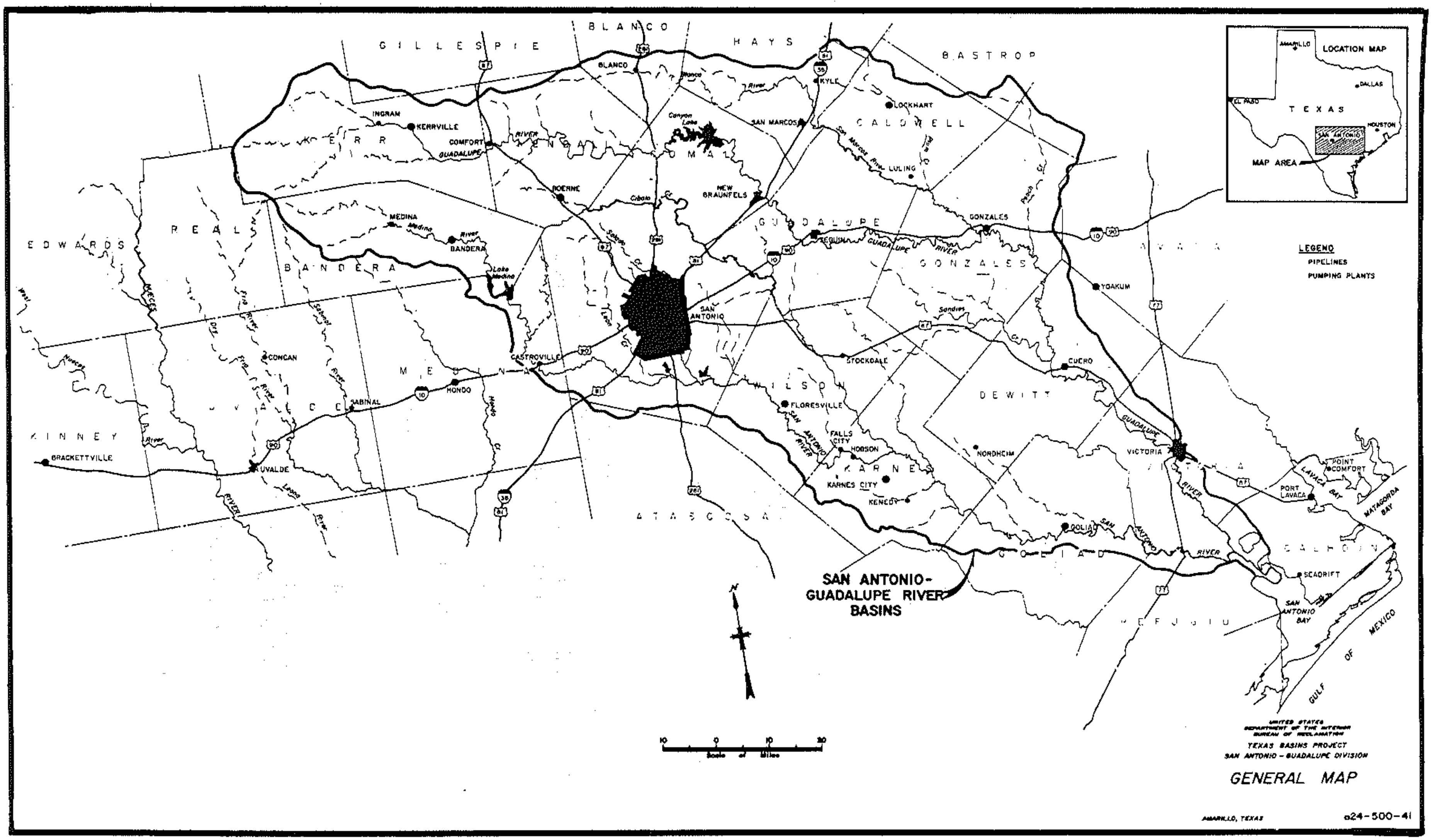


Figure 1. General Map of the San Antonio-Guadalupe River Basins Study Area

# CONCERNS

Growth. A condition synonymous with a flourishing economy, is certainly expected to occur.

The Texas Water Development Board's 1972 population projections were used for this study. You might be interested to know the projections used in this study are today considered about 15 percent too low.

We considered in addition to projecting water needs for population growth, expansion in industry, agriculture and energy.

Overall, the total water requirements for the San Antonio-Guadalupe River Basins under the high projections will almost triple from 1970 to 2020. In 1970 water use was slightly more than 50,000 acre-feet; by 2020 almost 1,500,000 acre-feet will be needed. In Bexar County, total water use will increase from 225,000 acre-feet in 1970 to almost 550,000 acre-feet in 2020 (Figure 2).

Our second major concern, as previously identified, is the San Antonio Bay and estuary.

The bay and estuary is controlled almost entirely by the discharge of its river system which contributes sediments, nutrients, dilution capacity, and some of the kinetic energy to move waters to the Gulf. Without the input of this river system, the bay could well become more saline in a relatively short time. During the prolonged droughts of the 1950's and 1960's, parts of the San Antonio Bay did become much more saline. Historically, Edwards Aquifer contributes about 21 percent of the runoff to the San Antonio Bay, whereas during the 1948-56 drought period the aquifer contribution was about 33 percent (Table 1). For the 1967-73 period, the Guadalupe River Basin received about 90 percent of its base flow from Comal Springs at New Braunfels and San Marcos Springs at San Marcos. One can readily see that a failure to properly manage both the Edwards Aquifer and surface water resources of the San Antonio-Guadalupe Basins could lead to the destruction of the estuary.

The final and perhaps most significant concern in the study area is the ground water situation. The role the major aquifers play in satisfying the current and future basin water needs is extremely important in determining what development, if any, should occur.

Ground water of acceptable quality for municipal, industrial, and irrigation use occurs at various depths in numerous water-bearing formations in most of the San Antonio and Guadalupe River Basins. The study area includes parts of four major Texas aquifers--the Edwards Plateau Aquifer, the Edwards Balcones Fault Zone Aquifer, the Carrizo-Wilcox Aquifer, and the Gulf Coast Aquifer.

In the interest of brevity this presentation will only include a discussion of this symposium's topic, the Edwards Balcones Fault Zone Aquifer, commonly called just the "Edwards Aquifer."

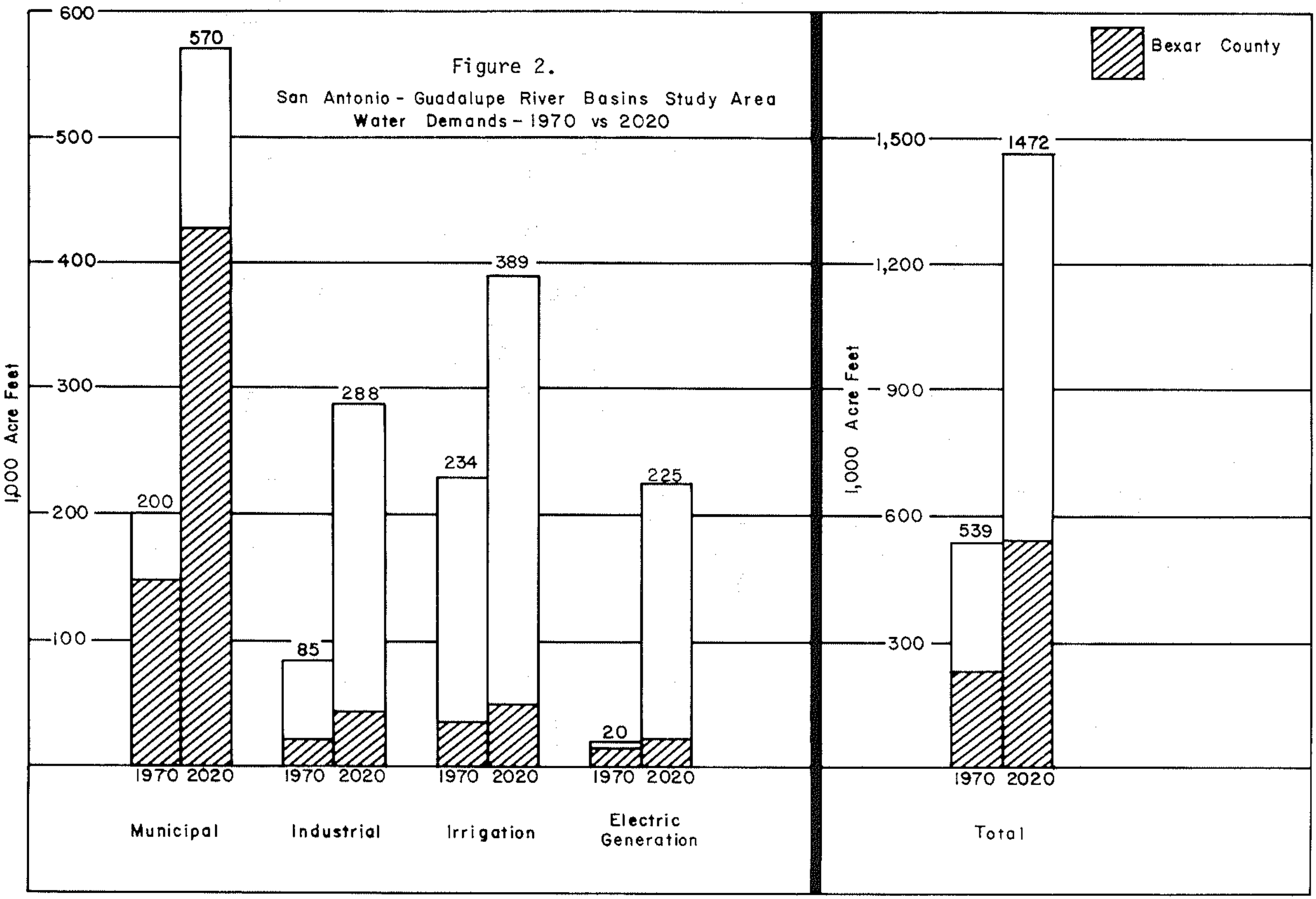


Figure 2.
San Antonio - Guadalupe River Basins Study Area
Water Demands - 1970 vs 2020

## Table 1.

## Historic Freshwater Discharge into San Antonio Bay

(1,000 acre-feet)

| Year | Runoff into San Antonio Bay from 10,321 $mi^2$ | Approximate contribution of Edwards underground reservoir to runoff |
|---|---|---|
| 1941 | 3,977 | 468 |
| 1942 | 3,114 | 454 |
| 1943 | 1,212 | 405 |
| 1944 | 2,313 | 442 |
| 1945 | 2,083 | 485 |
| 1946 | 3,519 | 462 |
| 1947 | 1,691 | 454 |
| 1948 | 928 | 318 |
| 1949 | 1,974 | 339 |
| 1950 | 773 | 311 |
| 1951 | 865 | 251 |
| 1952 | 1,415 | 241 |
| 1953 | 1,282 | 262 |
| 1954 | 350 | 207 |
| 1955 | 452 | 169 |
| 1956 | 264 | 106 |
| 1957 | 3,909 | 271 |
| 1958 | 3,585 | 465 |
| 1959 | 1,918 | 431 |
| 1960 | 3,811 | 464 |
| 1961 | 2,839 | 493 |
| 1962 | 922 | 367 |
| 1963 | 552 | 299 |
| 1964 | 819 | 279 |
| 1965 | 2,489 | 399 |
| 1966 | 1,743 | 393 |
| 1967 | 3,511 | 287 |
| 1968 | 3,647 | 503 |
| 1969 | 2,144 | 425 |
| 1970 | 2,048 | 471 |
| 1941-1970 | 60,149 | 10,921 |
| Average | 2,005 | 364 |
| 1948-1956 | 8,303 | 2,204 |
| Average | 922 | 245 |

Source: Texas Water Development Board - 1975
Bureau of Reclamation - 1975

(The Aquifer was described by Dr. Ogden, so I will go right into our study results.)

## Aquifer Description

The Edwards Aquifer is similar to a major surface reservoir from which water can be removed only by pumping or by overflow through spring spillways near the top. Except in the recharge area, all of the open spaces in the fault zone aquifer are full of water, which is forced by artesian pressure to rise above the confining roof in wells and natural openings. The aquifer is higher at its northern edge than at its southern boundary and higher at its western end than at its eastern end. As a result, the general direction of water movement in the aquifer is from north to south and from west to east.

The Edwards Aquifer provides an effective subsurface hydraulic interconnection between surface water supplies of the Nueces, San Antonio, and Guadalupe River Basins. When inflow to the reservoir exceeds outflow through wells and springs, the amount of stored water increases, water levels rise, and spring flows increase. Conversely, when outflow exceeds inflow, the amount of stored water decreases, water levels decline, and spring flows diminish.

## Study Results

Our studies show that, inflow to the Edwards Aquifer has varied widely from year to year, in response to rainfall and streamflow fluctuations, from a minimum of 44,000 acre-feet in 1956 to a maximum of 1,711,000 acre-feet in 1958. On the average, during 1934-73 Nueces River Basin streams and intervening areas provided about 55 percent of the total inflow with 45 percent originating in the other two basins. The proportion of the total inflow contributed by each stream and intervening area varied widely from year to year.

We estimate that the average recharge of the Edwards Aquifer for the period 1934-73 was 560,000 acre-feet per year (Table 2).

Well discharge has shown a steady increase during the period of record. During 1967-73 well discharge averaged 331,000 acre-feet per year. Of this amount, the San Antonio metropolitan area accounted for 53 percent of the average well discharge, or 175,000 acre-feet/year. Irrigation, almost entirely to the west of San Antonio and largely in the Nueces River Basin, accounted for 33 percent of total well discharge, or about 108,000 acre-feet. The remaining 14 percent was used for other purposes.

The area irrigated from the Edwards Aquifer has increased from about 30,000 acres in 1955 to 72,000 acres in 1974. The well discharge for irrigation varies widely from year to year because of variations in precipitation during and prior to the growing season.

During the 10-year period (1947-56), subnormal rainfall marking the most severe drought on record reduced average inflow to about 40 percent

## Table 2.

## Edwards Underground Reservoir Recharge, 1934-73

(1,000 acre-feet)

| Year | Recharge |
|---|---|
| 1934 | 179.6 |
| 1935 | 1,258.0 |
| 1936 | 909.6 |
| 1937 | 400.7 |
| 1938 | 432.7 |
| 1939 | 399.0 |
| 1940 | 308.8 |
| 1941 | 850.7 |
| 1942 | 557.8 |
| 1943 | 273.1 |
| 1944 | 560.9 |
| 1945 | 527.8 |
| 1946 | 556.1 |
| 1947 | 422.6 |
| 1948 | 178.3 |
| 1949 | 508.1 |
| 1950 | 200.2 |
| 1951 | 139.9 |
| 1952 | 275.5 |
| 1953 | 167.6 |
| 1954 | 160.9 |
| 1955 | 192.0 |
| 1956 | 43.7 |
| 1957 | 1,143.0 |
| 1958 | 1,711.0 |
| 1959 | 690.4 |
| 1960 | 824.8 |
| 1961 | 717.1 |
| 1962 | 249.4 |
| 1963 | 170.7 |
| 1964 | 411.2 |
| 1965 | 623.5 |
| 1966 | 597.7 |
| 1967 | 466.7 |
| 1968 | 884.7 |
| 1969 | 576.9 |
| 1970 | 661.6 |
| 1971 | 920.0 |
| 1972 | 754.5 |
| 1973 | 1,486.5 |
| Total | 22,393.3 |
| Average | 559.8 |

of the 40-year average. Outflow exceeded inflow, and water levels dropped as the amount of water stored in the reservoir was reduced by more than 2 million acre-feet. Year by year, with only minor exceptions, spring flows decreased as outflow through wells increased. Spring flows dropped from 426,000 acre-feet in 1947 to 70,000 acre-feet in 1956, while outflow through wells increased from 167,000 acre-feet in 1947 to 321,000 acre-feet in 1956 (Figure 3).

In the indicator well (well 26) at San Antonio, for which water-level records began in 1932, the water level dropped 73 feet from its high in 1935 to its lowest point (elevation 612.5 feet) in the summer of 1956. At this point, the water level was 10 feet below the outlet of Comal Springs and even farther below the outlets of San Antonio and San Pedro Springs. As a result of the 1947-56 water-level declines, Leona Springs did not flow from 1951-59, no flow was recorded from San Antonio and San Pedro Springs from 1949-58, and Comal Springs were dry from June through November 1956. San Marcos Springs, with their outlets 38 feet below the minimum water level at San Antonio, continued to flow throughout the record drought but at substantially reduced rates (Figure 4).

During 1957-61, inflow rose to record high rates, and nearly all the stored water lost during the 1947-56 drought period was replaced. The water level rose as reservoir content increased by about 2 million acre-feet, and spring flows returned to near-record highs.

During 1962-63, water levels declined sharply because of subnormal recharge. Above-average recharge during most subsequent years resulted in record high water levels in many wells in late 1973. The maximum recorded discharge for Comal Springs was 534 cubic feet per second ($ft^3/s$) on October 16, 1973; for San Marcos Springs, 300 $ft^3/s$ on November 5, 1973.

Remember our studies are now some 6 to 8 years old, and the discharge records of recent years are not included.

There is sufficient correlation between inflow and outflow estimates and water levels to support the conclusion that average annual inflow to the reservoir during 1934-73 was on the order of 560,000 acre-feet. Based on 1934-73 climatic conditions, this inflow is the maximum dependable yield then that could be obtained through wells from the Edwards Aquifer. Averages computed over this 39-year period do not reflect the severe conditions that could occur, such as an extended drought period. Pumping in this order of magnitude on a continuing basis would eventually eliminate virtually all spring flow. Pumping more than the recharge would cause a continuing decline of water level in the reservoir and, finally, dewatering of the aquifer. It is possible that lower water levels would draw highly mineralized water south of the reservoir into some of the wells along the southern reservoir boundary.

Recurrence of 1947-56 drought, coupled with annual pumping rates at present rates, obviously will reduce water levels, spring flow, and the amount of water stored in the reservoir considerably below 1956 drought conditions.

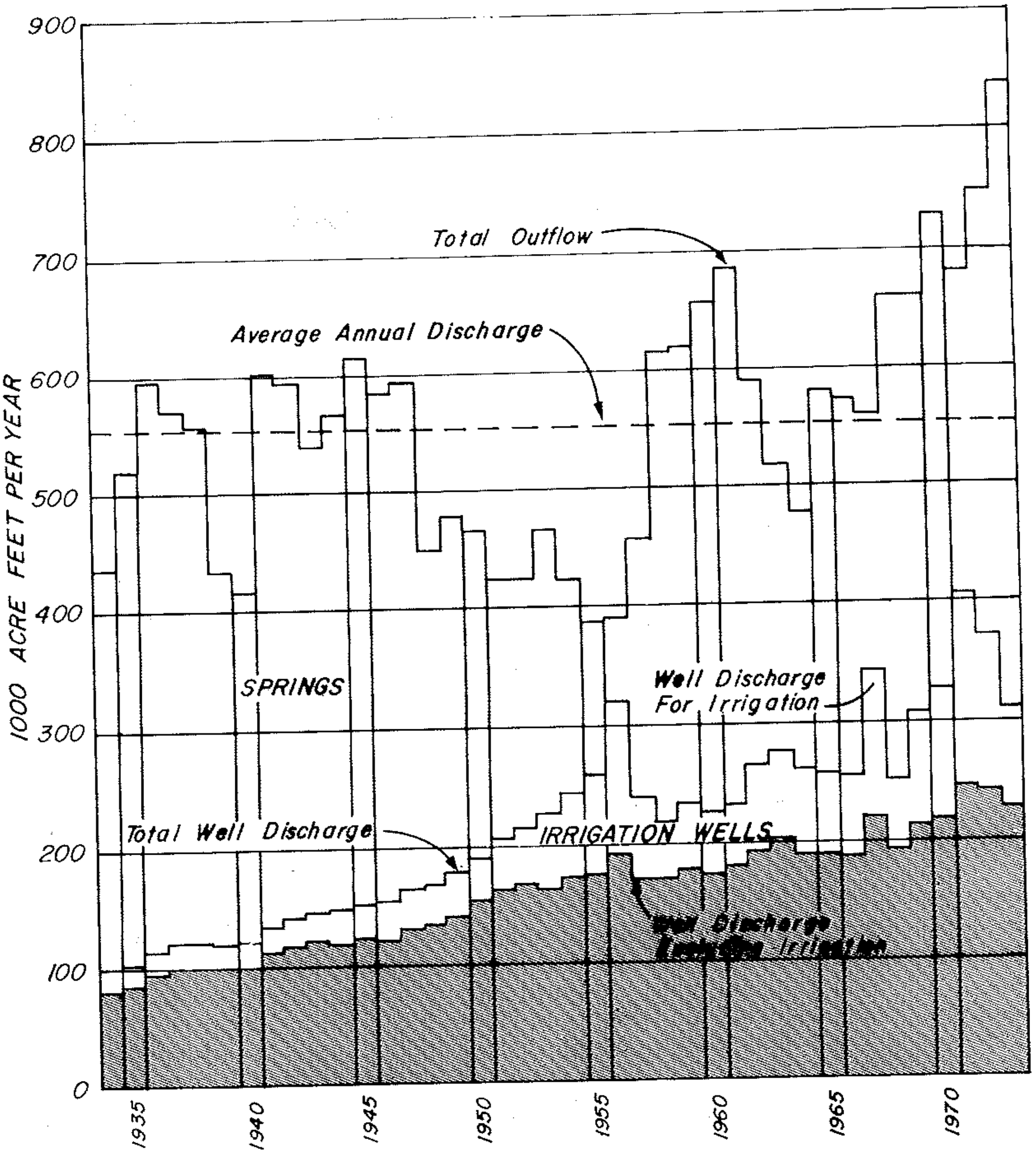


Figure 3.

ANNUAL OUTFLOW FROM EDWARDS UNDERGROUND RESERVO

(Historic-1934 thru 1973)

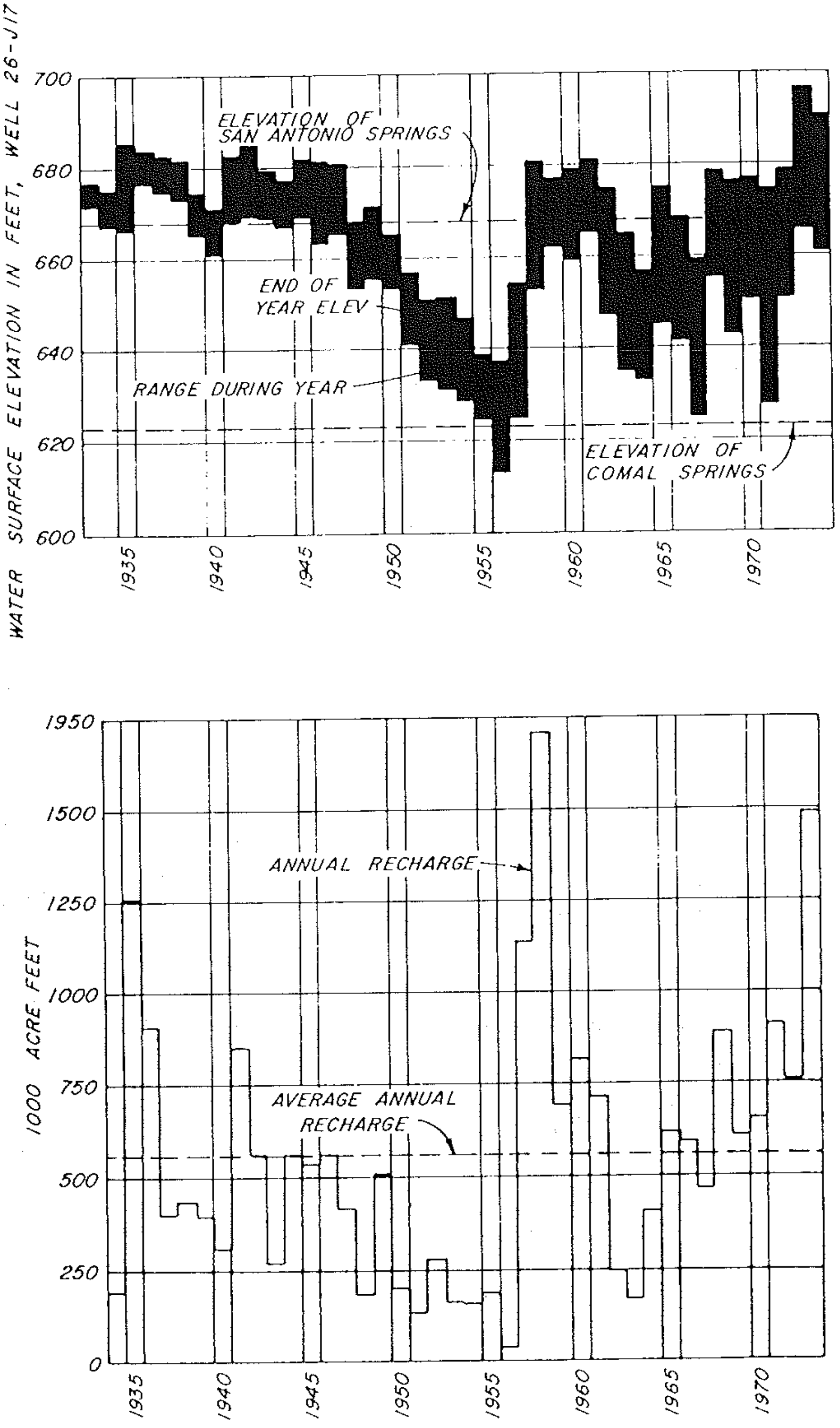


Figure 4.

RECHARGE TO EDWARDS UNDERGROUND RESERVOIR AND WATER SURFACE ELEVATION IN WELL 26 IN SAN ANTONIO

For simplicity, let's divide the Edwards into three pools by river basin (Figure 5). The westernmost pool is located west of the Frio River in the vicinity of the City of Uvalde. It receives recharge from the West Nueces and Nueces Rivers and possibly from the Dry Frio River. A partial barrier of relatively low transmissivity separates this Uvalde Pool from the Central Pool to the east. Water is discharged from the Uvalde Pool by Leona Springs, by wells (mostly for irrigation), and by underground flow over or through the barrier to the Central Pool to the east. If the underground flow to the Central Pool is at a sufficient elevation above the barrier, the Uvalde Pool will not be affected very much by what happens in the Central Pool. If the flow to the Central Pool is through the barrier at a low elevation or throughout the depth, then the Uvalde Pool will be affected by what happens in the Central Pool.

The Central Pool extends from the Frio River to New Braunfels. It receives surplus water from the Uvalde Pool and recharge from numerous streams that cross the recharge zone uphill from the Central Pool. San Antonio, San Pedro, Comal Springs, and numerous wells discharge water from the Central Pool. There is also underflow from the Central Pool to the San Marcos Pool. Most of the well discharge from the Central Pool is in the San Antonio metropolitan area.

The San Marcos Pool is located in Hays County in the vicinity of the City of San Marcos. The San Marcos Pool receives water by recharge from the Blanco River and possibly Dry Comal Creek and Cibolo Creek and by underflow from the central pool. Most of the discharge from the San Marcos Pool has been through San Marcos Springs. Well discharge has been relatively small.

Now that we have identified the problems of the study area, related these problems to future water needs, and established quantitative water demands based on reasonable assumptions, one more step must be taken. That is, where do we go from here? What course of action should be taken that will provide for the development, preservation, and well-being of the people and the water resources.

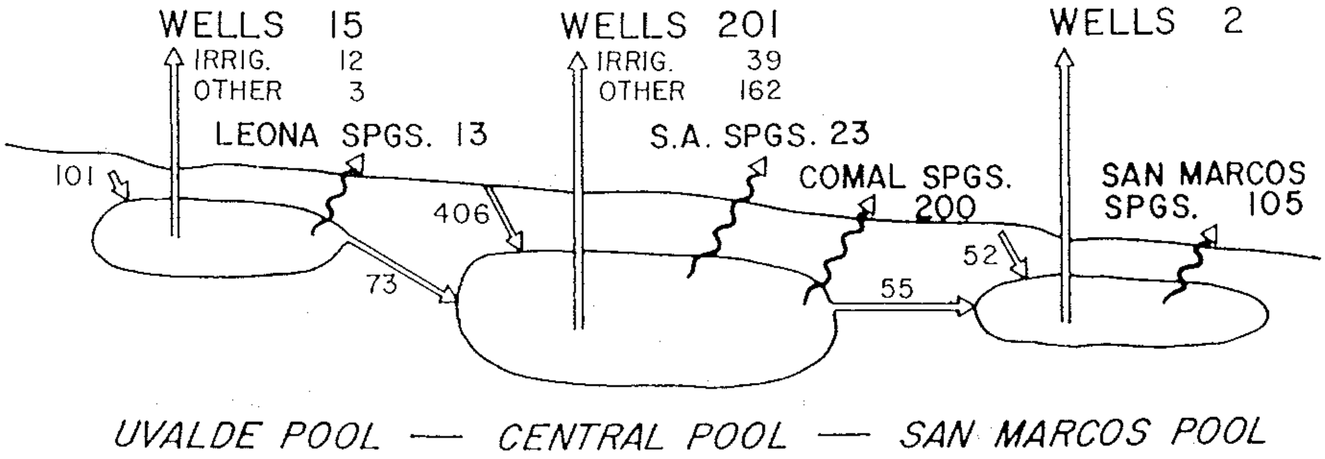
The Bureau of Reclamation's report shows four alternative plans for for substitution of surface water, along with their respective effects. They are:

A. No Management Scheme
B. Minimum Surface Water Development Plan
C. National Economic Development Plan
D. Environmental Quality Plan

I'll briefly cover only Plans A and C.

Before getting into the discussion on the alternative plans as presented in the report, one other aspect of planning needs to be pointed out. All known damsites in the two-basin area were evaluated using cost, yield and environmental criteria. Only those sites which have a favorable benefit-cost ratio, a low environmental cost or answered a need which could not be met in other ways were incorporated

HISTORIC
1934-1973 AVERAGES
1,000 A.F. Per Year



PRESENT CONDITIONS (1972)
1,000 A.F. Per Year

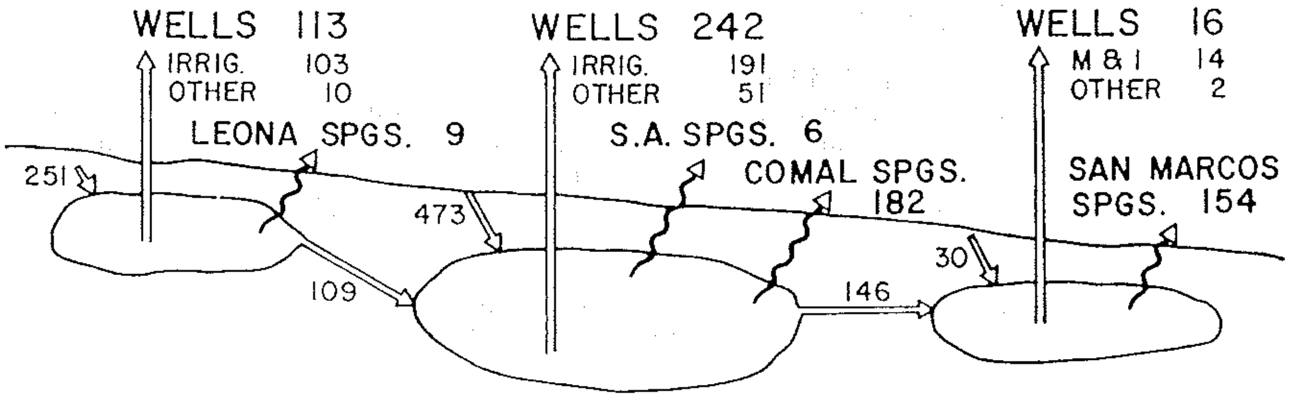


Figure 5. Water Balance in the Edwards Aquifer

into the plans. In the two basins, there are nine damsites which were evaluated but not included in the plans.

Plan A - No Management (No additional development)

Basically a no-management option assumes that there will be a projected future increase in water demands, but there will be no additional surface water development to help meet these demands. The Edwards Aquifer will be used to the maximum to meet future water demands.

The existing Medina and Canyon Reservoirs are the only major surface water supply reservoirs in the San Antonio-Guadalupe Basin. Some water could possibly be utilized from outside the basin; however, probably only on a temporary basis.

No-Management Effects

The anticipated effects of this option are many. Under the no-management option, the future well discharge from the Edwards Aquifer is projected to seriously exceed the maximum historic well discharge. Allowance was made for above-normal demands during dry years and below-normal demands during wet years. Under the assumption that if the 1948-56 drought conditions were to recur, combined with projected 2020 demands on the aquifer, the 2020 minimum water level in observation well 26, located in San Antonio, would be 212 feet below the historic minimum elevation of 612 feet recorded in 1956 (Figure 6). Comal Springs would not have any flow after some time about 2003. San Marcos Springs would become intermittent beyond 2011.

That anticipated reduction in spring flow will have a corresponding reduction in freshwater inflow to San Antonio Bay.

Based on the 2020 high projections, the freshwater inflow to the estuary is estimated to be in the neighborhood of 1,190,000 acre-feet per year. The gradual elimination of the flow of Comal Springs and San Marcos Springs would make future inflow to the bay more erratic than historic inflow.

We fear that decline in riverflow that will occur by the year 2020 will bring about a general lowering of primary estuarine productivity and decrease in commercial seafood catches.

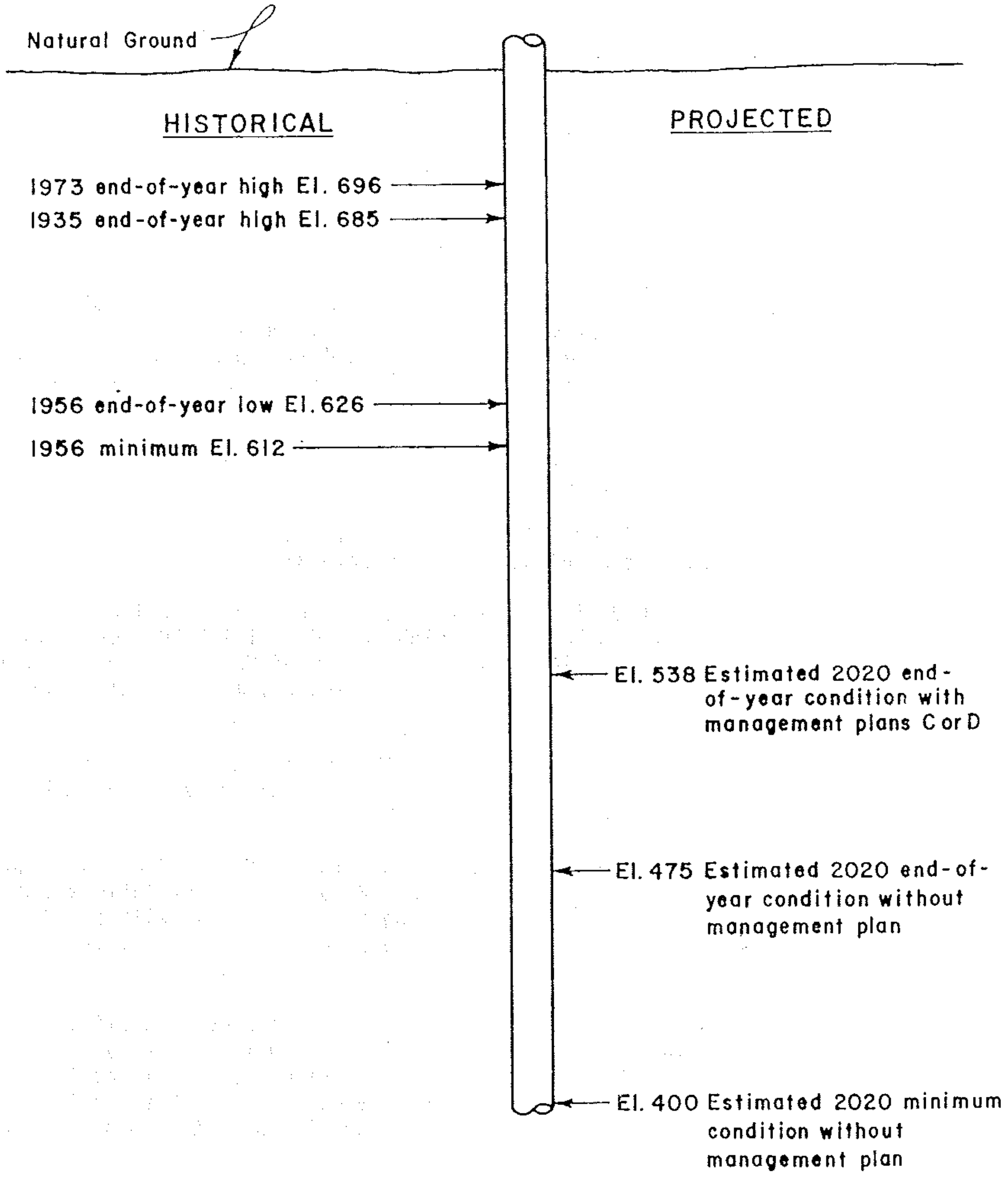
The effect of a declining water table in the Uvalde Pool would not be drastically felt until after the year 2000. The water table would drop rapidly beyond that point resulting in deeper wells with added drilling and pumping costs. The basin problem will be one of increasing competition for water at ever increasing pumping costs.

We have already suggested that the future high demands within the Edwards Aquifer will cause the springs in the aquifer to dry up. In two counties, Comal and Hays, recreation and tourism are almost totally dependent on the discharge of high quality waters from these springs. A significant part of the economic structure in these two counties would

Figure 6.

# SAN ANTONIO OBSERVATION WELL NO. 26

(CENTRAL POOL)
HISTORICAL AND PROJECTED ELEVATIONS



be affected, as well as the environmental destruction of the two major springs' ecosystems.

The two major effects that a declining Edwards Aquifer water table would have on the people of San Antonio would be increased water costs associated with higher pumping rates for deeper wells and the postponement of the inevitable -- the mining of the Edwards Aquifer to such a critical point that water could no longer be withdrawn. The aquifer levels have not yet dropped below elevation 612, and we do not know the extent of the water quantity and quality below that level.

An interesting side issue to the no-management plan, but serious none-the-less, is that a surface water shortage would occur in the Guadalupe Basin by 1994. Under the high projections, the demand on Canyon Reservoir will exceed the yield by 77,000 acre-feet by 2020. The surface water shortages would affect primarily the powerplant cooling water demands and other industrial water demands in Calhoun and Victoria Counties.

## Management Concept

An integrated ground and surface water management option appears to be the only logical way to meet the future increase in water needs in the basin. Under this option, withdrawals from the Edwards Aquifer would be limited to a level that would be related to the annual recharge. Surface water would be utilized when annual demands exceed available ground water supplies.

In order to control and protect the future of the Edwards Aquifer, we adopted a concept of limiting withdrawals from the aquifer to a safe level of 500,000 acre-feet per year. The concept has provisions for withdrawals greater than the safe limit during high recharge periods. The objective of limiting well discharge from the aquifer would be realized by substituting surface water for ground water use in San Antonio and later in New Braunfels, and San Marcos.

The future condition of the Edwards Aquifer under a management option would be better than with a no-management plan. The water levels in the aquifer will stabilize at levels only 50 to 100 feet below historic levels. We believe this would not seriously inhibit meeting any of the projected water demands on the Edwards including a continued increase in irrigated acreage.

This management plan limits the pumpage from the Edwards Aquifer to 500,000 acre-feet per year and this includes pumpage to artificially maintain the Comal Springs flow to protect the downstream ecosystem and local recreation and tourism base.

## Plan C - The Full Management Plan

Plan C was formulated to meet the objectives of National Economic Development. This plan (Figure 7) will meet the 2020 demand of 1,471,000 acre-feet per year (Table 3).

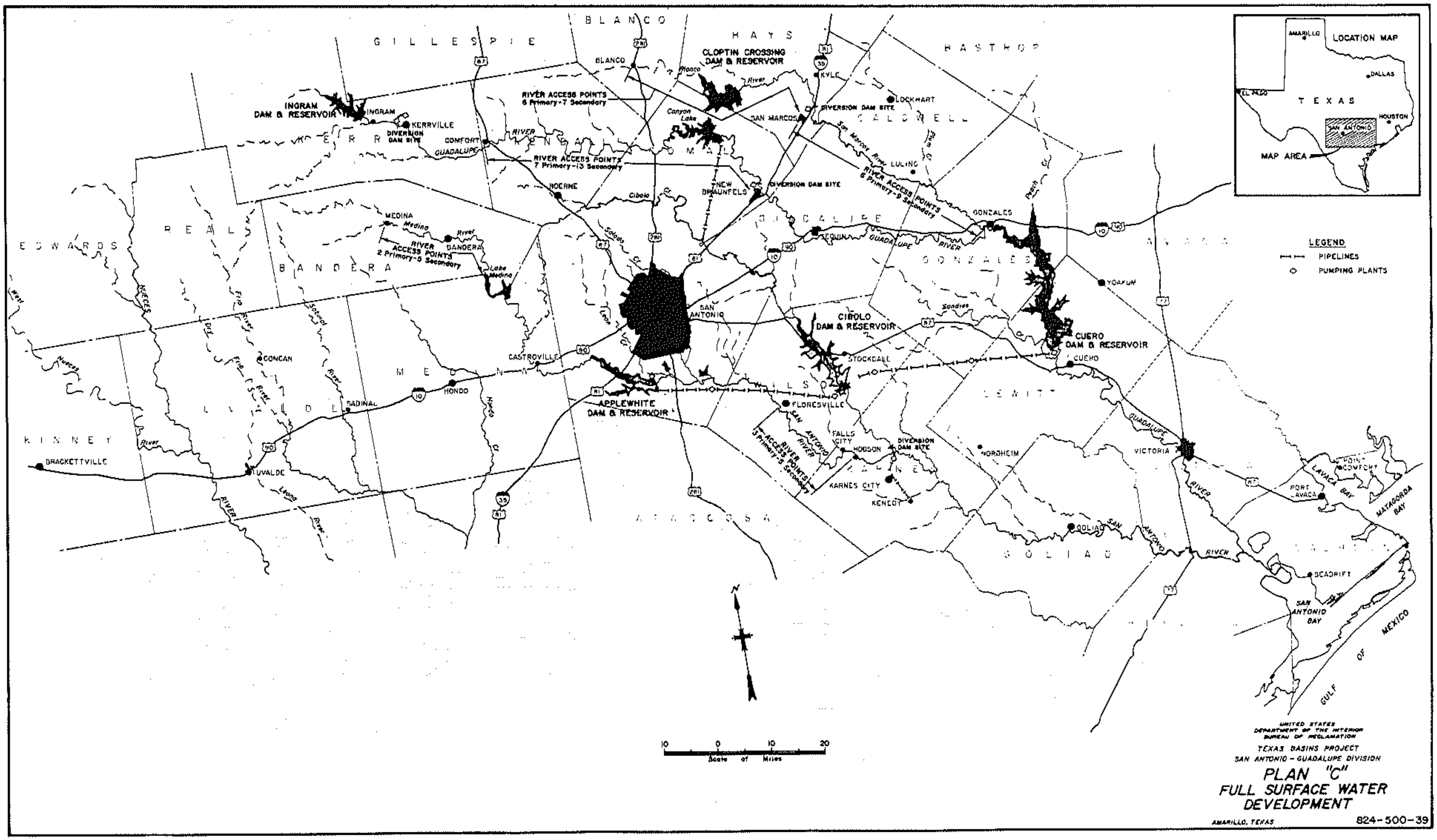


Figure 7. Plan "C" Full Surface Water Development Map

## Table 3. Plan "C" Sequence of Events

San Antonio-Guadalupe Study

| Year [1] | Event |
|---|---|
| 1985 | Ingram Dam and Reservoir completed and begins serving Kerrville - 9,000 acre-feet. |
| 1993 | Pipeline from Canyon Reservoir completed to San Antonio - 30,000 acre-feet. |
| 1994 | Cloptin Crossing Dam and Reservoir completed to provede downstream demands on the Guadalupe. An additional 20,000 acre-feet from Canyon available for San Antonio. |
| 1998 | Applewhite Dam and Reservoir completed - an average of 50,000 acre-feet available to San Antonio. |
| 2000 | Cuero Dam and Reservoir completed to meet downstream demands on Guadalupe. Comal Springs Well Field completed to maintain flows during low-flow periods - 12,000 acre-feet. |
| 2003 | Four additional wells will be required to satisfy San Antonio's need - 19,000 acre-feet. |
| 2003 | Cibolo Dam and Reservoir and pipeline to Applewhite completed - 19,000 acre-feet to San Antonio. Cibolo Creek diversion works and pipeline to Karnes City and Kenedy completed - 2,000 acre-feet. |
| 2003 | Pipeline completed from Cuero to Cibolo Reservoir. An additional 142,000 acre-feet to San Antonio via Cibolo. |
| 2005 | New Braunfels goes to surface water as primary source - 12,000 acre-feet. |
| 2006 | San Marcos goes to surface water as primary source - 17,000 acre-feet. |

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[1] Note that while the "year" column shows only a singular year, it should be understood that the "year" designated should actually represent an approximation of the center of a band or range. The year shown is mathematically computed by taking into account conditions forecast during a historic critical drought period together with many assumptions including population projections, future per-capita consumption, extent of industrial projections, etc.

## Management Effects

What are the anticipated effects of a management plan? As previously mentioned, the main objective is to protect the Edwards Aquifer. Even under high projections for 2020, the water levels in the aquifer becomes stable at only 50 to 100 feet below historic levels. Under assumed repetition of the 1950's drought period, the water elevation in well 26 at the end of 2020 would be only 88 feet below the 1956 elevation of 627; 134 feet below the minimum elevation of 612 (Figure 6). In the Uvalde Pool area, the water table in 2020 would drop to 106 feet below the historic 1956 low point.

Comal Springs would still go dry by 2011 and would require a supplemental pumping to maintain their environmental and economic viability. San Marcos Springs would flow most of the time but would go dry under moderate to severe drought conditions unless artificially maintained by pumping.

The addition of six reservoirs in the San Antonio-Guadalupe Basin will have an effect on the freshwater inflow to the San Antonio Bay. The combination of surface water diversions to meet future needs and increased evaporation from the reservoirs will reduce the annual inflow to the bay to an estimated 1,098,000 acre-feet by 2020. Compare this to the estimated 1,496,000 acre-feet per year under the no-management plan. We recognize that a basin-wide ground and surface management plan will significantly reduce the inflow to San Antonio Bay; however, surface water supplies may have a beneficial effect in that timed releases can be made into the estuary. Department of Water Resources studies in progress will be invaluable in assessing the requirements for timed releases.

Under a management option, a viable irrigation economy can be maintained in Uvalde and Medina Counties in the future through the protection of the Edwards Aquifer. The future high projections for irrigation in the two counties can still be realized under this option.

Kenedy and Karnes City would benefit from the better quality water provided by Cibolo Reservoir, and Kerrville would have a surface water supply to supplement its wells.

What are the effects on the City of San Antonio?

Under a basin management option, the City would have to choose one of two surface water plans.

One plan would require obtaining 30,000 acre-feet per year from Canyon Reservoir by 1993. Then in 1994, Cloptin Crossing would be constructed to allow expansion of the yield of Canyon Reservoir from 30,000 to 50,000 acre-feet per year.

The alternative to that plan is to build Cibolo Reservoir. The yield from Cibolo would be 25,000 acre-feet per year, of which about 6,000 acre-feet would be for downstream requirements, leaving about 19,000 acre-feet per year for delivery to San Antonio.

Under a management option, or proposal, the City would still have to deepen existing municipal wells and install future ones to meet that part of the demand supplied by the Edwards. Obviously, increased costs will be present; however, the City would at least be able to rely on the certainty of a specific future water table elevation.

The construction of a system of reservoirs to meet future projected demands will be economically more expensive to the basin, particularly San Antonio, than continued reliance on the Edwards Aquifer.

Summary of Our Conclusions (Table 4)

1. Without management of study area water resources, overdevelopment of the Edwards Aquifer during the study period would occur that would seriously damage the human and natural resources of the area.

2. This overdevelopment can and should be prevented. The development plan proposed is viable and would prevent this overdevelopment by limiting well discharges from the aquifer and substituting surface water supplies for some ground water supplies.

3. If overdevelopment is to be limited, we would recommend an annual pumping limitation from the aquifer of about 500,000 acre-feet/year.

4. Because any development is costly, the selected plan should be developed in stages.

5. Area citizens, through local governmental entities, must decide whether area water resources should be managed and if so, select a management plan (whether one as we propose or some similar combination), remove possible impediments to its development (political, water rights, etc.), possibly devise a method for limiting well discharge, and allocate the costs of the plan.

6. In order to implement the plan, perhaps a master conservancy district for the study area needs to be formed.

There are many considerations that will have to be taken into account under any plan or combination of plans. However, it should be clearly understood that our Bureau is included in this matter only from an investigative and planning standpoint. It will be the responsibility of the people of this basin to select and implement any plan directed toward integration of surface water and limiting ground water withdrawals.

What I have given you are facts and projections based on conservative logical assumptions. Those that are concerned with environmental responsibilities are going to demand the water necessary to maintaining a productive estuary, stream fisheries, etc. The farmer is going to demand his due amount, a healthy economy requires adequate water for industry, and John Q. Public has a multitude of water needs -- all rightfully so.

Those of us concerned with having ample supplies of water for our area feel the weight of this responsibility.

## Table 4. Full Management "C" Plan Cost Summary

| DAMS AND RESERVOIRS 1/ | | YEAR REQUIRED | CONSTRUCTION COST (DOLLARS) | YIELD OR SUPPLY (ACRE-FEET) |
|---|---|---|---|---|
| INGRAM -OR ALTERNATIVES | | 1985 | $31,865,000 | 9,000 |
| CLOPTIN CROSSING | | 1994 | 71,067,000 | 40,000 |
| APPLEWHITE | | 1998 | 38,327,000 | 50,000 |
| CUERO | | 2000 | 228,214,000 | 145,000 |
| CIBOLO | | 2003 | 76,524,000 | 25,000 |
| SUBTOTAL | | | $445,997,000 | 269,000 |
| CONVEYANCE FACILITIES | | | | |
| FROM | TO: | | | |
| GUADALUPE RIVER AT KERRVILLE | KERRVILLE FILTER PLANT | 1985 | 8,218,000 | |
| CANYON RES. | SAN ANTONIO NE FILTER PLANT | 1993 | 51,039,000 | |
| APPLEWHITE RES. | SAN ANTONIO SO. FILTER PLANT | 1998 | 50,245,000 | |
| CIBOLO CREEK DIV. DAM | KARNES CITY AND KENEDY | 2003 | 7,014,000 | |
| CIBOLO RES. | APPLEWHITE RES. | 2003 | 86,831,000 | |
| GUADALUPE RIVER ABOVE COMAL SPRINGS | NEW BRAUNFELS FILTER PLANT | 2005 | 9,437,000 | |
| BLANCO RIVER AT SAN MARCOS | SAN MARCOS FILTER PLANT | 2006 | 11,256,000 | |
| CUERO RES. | CIBOLO RES. | 2007 | 97,636,000 | |
| SUBTOTAL | | | $321,716,000 | |
| WELL FIELDS | | | | |
| COMAL SPRINGS WELL FIELD | | 2000 | 218,000 | 12,000 |
| ADDITIONAL WELLS IN THE SAN ANTONIO AREA | | 2003 | 1,280,000 | 19,000 |
| SUBTOTAL | | | $1,498,000 | 31,000 |
| TOTAL | | | $769,221,000 | 300,000 |

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1/ INCLUDES SPECIFIC COST FOR RECREATION, FISH AND WILDLIFE, ARCHEOLOGICAL HISTORY, RAINFALL NETWORK, AND HYDRAULIC INSTRUMENTATION. (APRIL 1976 DOLLARS)

# Current Status and Future Projections for the Edwards (Balcones Fault Zone) Aquifer in the San Antonio Region

by
Tommy R. Knowles, Ph.D.*

The Edwards (Balcones Fault Zone) aquifer is a very important resource in the San Antonio region. The aquifer consists of the Edwards and associated limestones of Cretaceous age which are in hydraulic continuity. These limestones include the Georgetown, Edwards, and Comanche Peak with the Edwards being the most important in that it yields large quantities of water due to its extensive honeycombed and cavernous nature. Water entering the aquifer moves generally southward across the reservoir and then eastward toward natural discharge points which include: the Leona River Springs near Uvalde, San Antonio and San Pedro Springs in San Antonio, Comal Springs in New Braunfels, and San Marcos Springs in San Marcos. In addition, water is artificially discharged from the aquifer by hundreds of wells in Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties. Municipalities which rely solely on the aquifer for their water supply include San Antonio, Uvalde, New Braunfels, San Marcos, and numerous smaller cities.

## Status of the aquifer

Many people refer to the Edwards aquifer as a reservoir and, in many ways, it acts very much like a surface-water lake. Water enters the aquifer through the recharge zone and moves generally in a south-southeast direction. Once in the deeper, artesian zone of the aquifer, the water begins to move eastward toward the large, natural discharge points of Comal and San Marcos Springs. Throughout most of the artesian zone, especially between eastern Uvalde County and northeastern Bexar County, the water surface in the aquifer is quite flat, similar to that of a lake. The two major spring systems are downstream from this large artesian zone, and they function the same way an uncontrolled spillway does on a lake. Once the water level is above the spring openings, water begins to flow and as the water level becomes higher, the rate of flow increases.

Using the spillway analogy, the Edwards is presently full and spilling. The aquifer contains a large volume of water, water levels are above the spring openings, and spring flow is occurring in spite of the large amounts of water being pumped from the aquifer. Such large quantities of water are entering the aquifer (recharge) that the water that is pumped out is replaced and the springs continue to flow.

The status of the aquifer may be quantifiably described by discussing water levels, recharge, discharge, and water quality. Presently, water levels are generally higher than long-term average values, but are about the same as they have been for the last 7 or 8 years. For example, in February, 1982, the water level in the Department's observation well

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*Engineer, Data Collection and Evaluation Section, Texas Department of Water Resources at San Antonio (Well no. 68-37-203) was about 677 feet above mean sea level. Each year since 1972, the water in the well has fluctuated above and below this level. For the period 1963 through 1972, however, the water reached this level only once, during February and March of 1968.

Recharge to the aquifer has been calculated since 1934. For the period 1934-1979, the average recharge has been 598,800 acre-feet (ac-ft) of water annually. The largest rate of recharge occurred in 1958 when 1,711,200 ac-ft entered the aquifer, and the smallest was in 1956 when only 43,700 ac-ft was recharged. For the period 1934 through 1972, the annual average recharge was 547,400 ac-ft, and for the years 1973 through 1979, the average was 940,600 ac-ft. The average recharge for the seven years 1973 through 1979 was more than 70 percent above the previous 39-year average.

Water is discharged from the aquifer through wells and by springs. For the period 1934-1979, the annual discharge averaged 596,500 ac-ft, almost identical to the average annual recharge. Over the long-term, the aquifer is in equilibrium. The amount of water entering the aquifer equals the amount of water leaving the aquifer. For the entire 1934-1979 period, 40 percent of the discharge from the aquifer was by wells. For the last 20 years of the period, about 45 percent of the discharge was by wells. During the 1950's, the average annual total well discharge was 236,800 ac-ft; in the 1960's, 267,200 ac-ft; and in the 1970's, 367,600 ac-ft. This represents a sizeable increase in pumpage. The total well discharge for 1979 (391,500 ac-ft) equals 65 percent of the long term recharge rate.

Flows from springs continue to be strong. During 1979, the springs flowed 523,000 ac-ft of water. In January, 1982, Comal Springs flowed at 340 cubic feet per second (cfs). The maximum flow from the springs occurred in 1977, when the rate was 550 cfs. The springs were dry in 1956.

The quality of water discharged from the aquifer continues to be good. Several entities monitor water quality, and there appears to be no evidence of its deterioration.

The status of the aquifer has changed with respect to its sensitivity to a drought. Severe droughts, of both short and long duration, have occurred and, no doubt, will continue to occur. As more and more water is withdrawn by wells, the effects of diminished recharge will become evident sooner and be more pronounced. For example, in the early summer of 1980, water levels in wells dropped 20 to 30 feet in one month, the most rapid drop known. This was a period when the aquifer experienced 2 months of low recharge coupled with a high pumpage caused by high temperatures. As compared to years earlier, a given drought occurring now will cause water levels to drop farther, more quickly, and spring-flow to diminish faster. Such droughts could even cause springs to stop flowing.

## Future Projections

In order to better be able to study the Edwards aquifer and to evaluate the impacts of steadily increasing withdrawals from the aquifer, the Texas Water Development Board (a predecessor agency of the Texas Department of Water Resources) began in 1971 to develop a computer model of the Edwards aquifer. The model is a finite-difference model which uses as input, recharge, well discharge, and aquifer parameters which yield an areal distribution of water levels and flows from the major spring system at any given point in time.

The model was constructed to represent the aquifer in the San Antonio region. The lateral boundaries of the modeled area are: (1) the edge of the Balcones Fault Zone on the north and northwest, (2) a ground-water divide near Brackettville in Kinney County, which separates underflow between the Nueces River and Rio Grande Basins, (3) a line on the south and southeast which represents the downdip extent of water containing less than 1,000 milligrams per liter of dissolved solids, and (4) a ground-water divide near Kyle in Hays County, which separates underflow between the Guadalupe and Colorado River Basins. Prior to its use as a planning tool, the model was calibrated to reproduce the aquifer's behavior. For the period 1947-1971, the model simulated each year of the aquifer's operation; and at the end of the 25-year period, the average difference between simulated and measured water levels equaled 0.68 foot. The difference between cumulative measured and simulated springflow was small, less than 4.3 percent of total flow.

This digital-computer model of the Edwards (Balcones Fault Zone) aquifer is therefore considered to be calibrated to a degree of accuracy sufficient to reproduce past events; consequently, the model can be used to predict future responses of the aquifer to prespecified conditions of recharge and pumpage.

The model has been used to simulate the Edwards aquifer's response to a wide range of pumpage rates and recharge sequences for the years 1975 through 2030 to provide water-supply data for this area of Texas. By comparing the aquifer's simulated response to various pumpage and recharge sequences, the effect of different management alternatives on the aquifer can be evaluated.

The period for which the aquifer was simulated begins on January 1, 1975, and ends on December 31, 2030. Measured water-level data for calendar year 1975 were utilized to reflect water levels in the aquifer at the start of the simulation period.

Following the standard practice in applied hydrology, a 45-year historical recharge sequence for the period 1925-1970, was "folded" and used for the future-condition simulation. The historical period was transposed 50 years in time so that historical recharge during the period 1925-1970 was used for the period 1975-2020. The average annual recharge for the period 1975-2030, by repetition of the folding, thus equaled 454,400 ac-ft. The sequence reflects the large fluctuations in precipitation and drought periods common to the area. The severe drought of the 1950's would occur in the 2000's.

Pumping rates were simulated to meet the water requirements projected in 1977 for the revision of the Texas Water Plan. Municipal, manufacturing, and steam-electric power generation water demands were assigned to the model on the basis of where the supplying wells were located. Irrigation water requirements were assigned to the model corresponding to areas presently under irrigation and areas where soils are suitable for future irrigation development. The rural-domestic and livestock water requirements were spread uniformly across each county underlain by the aquifer.

The projections for municipal, manufacturing, and stream-electric water requirements increase from 291,800 ac-ft for 1980 to 395,300 ac-ft for 2000 and to 630,900 ac-ft for 2030. The projection for irrigation water requirements assumes that irrigation would continue to increase, but at only one-fourth the historical development rate. Using this assumption, irrigation water requirements increase from 97,700 ac-ft for 1980 to 101,100 ac-ft for 2000 and to 114,700 ac-ft for 2030. Livestock water requirements increase from 4,800 ac-ft for 1980 to 5,800 ac-ft in 2000 and to 7,300 ac-ft for 2030. Total water requirements increase from 394,300 ac-ft for 1980 to 502,100 ac-ft for 2000, an increase of 27 percent or 1.4 percent per year. For 2030, the total requirements increase to 752,900 ac-ft, an increase of 91 percent or 1.8 percent per year.

The initial model simulation utilized the basic pumpage projections. Results show that both major spring systems cease to flow. Comal Springs ceases to flow during 1989 and fails to flow during 1990. The last year of flow is 1998. Comal Springs thus fails prior to the start of the severe drought period, 1997 through 2006. San Marcos Springs ceases to flow during the ninth year of the drought, 2005. The spring remains dry for 3 years until it begins to flow again in 2008. In 2013, flow is minimal and probably intermittent. The last year of any flow is 2022.

For the irrigation area 4 miles southeast of Sabinal in Uvalde County, the 2030 water level represents a 215-foot drop, which is 110 feet below the recorded minimum level. For the northeastern part of San Antonio, the 2030 water level decline is 240 feet, 170 feet below the previous minimum level for that area.

The principal conclusion which may be drawn from this simulation is that, under the projected recharge sequence, the aquifer is capable of meeting projected demands, with the exception of spring-flow demands, through the year 2030. However, it is important to note that water quality was not considered as a factor in these simulations. The drastic drawdown of water levels, particularly in the San Antonio area, could result in the encroachment of water of unacceptable quality for its intended use along the southern boundary of the aquifer. Although the volume of saline water which would encroach into the aquifer, or the direction it would move cannot be predicted at present, the conditions for significant saline-water encroachment would result from the above-described level of pumpage.

The model was also used to determine a safe annual yield of the aquifer; safe annual yield being defined as the level of pumpage from the aquifer which would allow San Marcos Springs to continue flowing during a recurrence of the 1925-1970 recharge sequence, and which would minimize conditions conducive to the encroachment of saline water into the aquifer. No attempt was made to maintain the flow of Comal Springs, because that is not considered feasible. Comal Springs is so closely associated hydrologically with water levels in the aquifer in the San Antonio area that a recurrence of the historical drought would cause the Springs to cease flowing even under current levels of pumpage. The water requirements for irrigation increase at the historical development rate. The requirements increase to 111,400 ac-ft for 1980 to 154,800 ac-ft for 2000 and to 206,500 ac-ft for 2030. Thus total water requirements increase from 408,000 ac-ft for 1980 to 555,800 ac-ft in 2000 and to 844,700 ac-ft in 2030. The maximum pumpage was determined by limiting the amount of water pumped for irrigation in the principal irrigation areas and for municipal and manufacturing uses in Bexar County. These uses account for the majority of the pumpage from the aquifer.

Model simulations were performed for several pumping limits; however, a maximum annual pumpage rate of 425,000 ac-ft allows acceptable spring flow. With pumpage limited to a maximum of 425,000 ac-ft annually, the minimum annual flow of San Marcos Springs equals 34,000 ac-ft which is slightly below its recorded minimum annual flow of 44,000 ac-ft, which occurred in 1956. The maximum pumping limit is not a limiting factor until the late 1980's. After that period, the constraint applies each year. The difference between projected requirements and maximum allowable pumpage is approximately 419,700 ac-ft in the year 2030, of which 288,000 ac-ft represents annual projected municipal and manufacturing water demands in Bexar County in the year 2030. San Marcos Springs would continue to flow, but Comal Springs would cease flowing for 7 years, beginning in 1999. The water levels generally show a decline during the drought period, but the impact of the drought is less severe than it would be if the management plan was not imposed. The relatively constant water levels are expected since ground-water withdrawals generally do not exceed recharge.

The principal conclusion which may be drawn is that if total pumpage from the aquifer is limited to 425,000 ac-ft annually by jointly limiting pumpage for irrigation and for municipal and manufacturing purposes in Bexar County, and the assumed recharge sequence occurs, San Marcos Springs can be expected to continue flowing during a recurrence of the severe drought period. Extreme water-level declines will not occur and the potential for saline-water intrusion will be greatly reduced.

Any management policy for the Edwards aquifer which imposes a maximum limit upon annual pumpage will necessitate, at some future time, the curtailment of additional development by some users of the aquifer. Such aquifer-wide limitation upon pumpage must involve Bexar County, as municipalities and industries in Bexar County are the largest users of water from the Edwards.

Assuming annual pumpage from the Edwards aquifer is limited to a maximum of 425,000 ac-ft, municipal and manufacturing requirements in Bexar County will exceed the supply from the aquifer by about 84,000 ac-ft annually in the year 2000 and 288,000 ac-ft annually in 2030.

The imposition of such a pumpage limit will result in some of the demands not being met or the demands will be satisfied with water from other sources. As part of the Department's 1977 planning effort, a means of supplying this demand was developed. The procedure represents only one of many possible methods of satisfying the demand and is presented here strictly for your information. The least-cost development schedule which would meet the projected 2000 water shortage in Bexar County requires the following developments in the indicated order: (1) 30,000 ac-ft from Canyon Reservoir, (2) 20,000 ac-ft from the authorized Cloptin Crossing Reservoir via Canyon reservoir, (3) 15,000 ac-ft from Applewhite Reservoir, and (4) the remaining 19,000 ac-ft from the authorized Cibolo Reservoir via Applewhite Reservoir. To meet the substantial shortages between 2000 and 2030, significant development would be necessary. The most feasible courses would be construction of Cuero I and II Reservoirs in the Guadalupe River Basin and interconnection of reservoirs in the San Antonio and Guadalupe River Basins.

# Research on the Hydrogeologic Characteristics of the Edwards Aquifer in the San Antonio Area, Texas

by
R.W. Maclay* and T.A. Small*

Regional differences in the porosity and permeability of the Edwards Aquifer (Figure 1) are related to three major depositional areas that existed during Lower Cretaceous time: the Maverick Basin, the Devils River Trend, and the San Marcos Platform (Figures 2 and 3). The rocks of the Maverick Basin are predominantly deep basinal deposits of dense, homogeneous mudstones of low primary porosity. Permeability is principally associated with cavernous voids in the upper part of the Salmon Peak Formation. The rocks of the Devils River Trend are a complex of marine and supratidal deposits in the lower part, and reefal or inter-reefal deposits in the upper part. Permeable zones, which occur in the upper part of the trend, are associated with collapsed breccias and rudist reefs. The rocks of the San Marcos Platform are predominantly micrites that locally contain collapsed breccias, honeycombed, burrowed mudstones, and rudist reefs that are highly leached and highly permeable. These rocks form the most transmissive part of the Edwards aquifer in the San Antonio area. Karstification of the rocks on the San Marcos Platform during Cretaceous time enhanced the permeability of the aquifer.

The intrinsic permeability of the Edwards Aquifer is directly related to particular strata (lithofacies) and to the leaching of these strata within the freshwater zone. Ground water moves along vertical or highly inclined fractures that act as passageways by which water can enter permeable strata. Water moves from the fractures into collapsed breccias, burrowed wackestones, and rudist grainstones that have high intrinsic permeability. Water has dissolved the pore walls within those rocks to create a highly permeable strata.

Recognition of the hydrostratigraphic subdivisions provides a basis for defining the nonhomogeneity of the aquifer and determining its storage characteristics. The aquifer is considered to have a fault-disrupted, multilayered framework in which lateral circulation is mainly through highly permeable, hydrostratigraphic subdivisions that are hydraulically connected at places by openings associated with high-angle, normal faults. The Edwards Aquifer is vertically displaced for its entire thickness at places along major northeastward trending faults. At these places, ground water circulation is diverted toward the northeast.

The drainable porosity, which is nearly equivalent to the specific yield, was defined by Maclay and Small (1976) as the porosity developed by pores that are interconnected by pore throats larger than 10 microns in diameter. Any pores connected by pore throats larger than 2.87 microns in diameter could slowly drain water by gravity; however, pore throats must be considerably greater than 2.87 microns in diameter for the water to drain quickly. Estimates of the drainable porosity of

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*U.S. Geological Survey

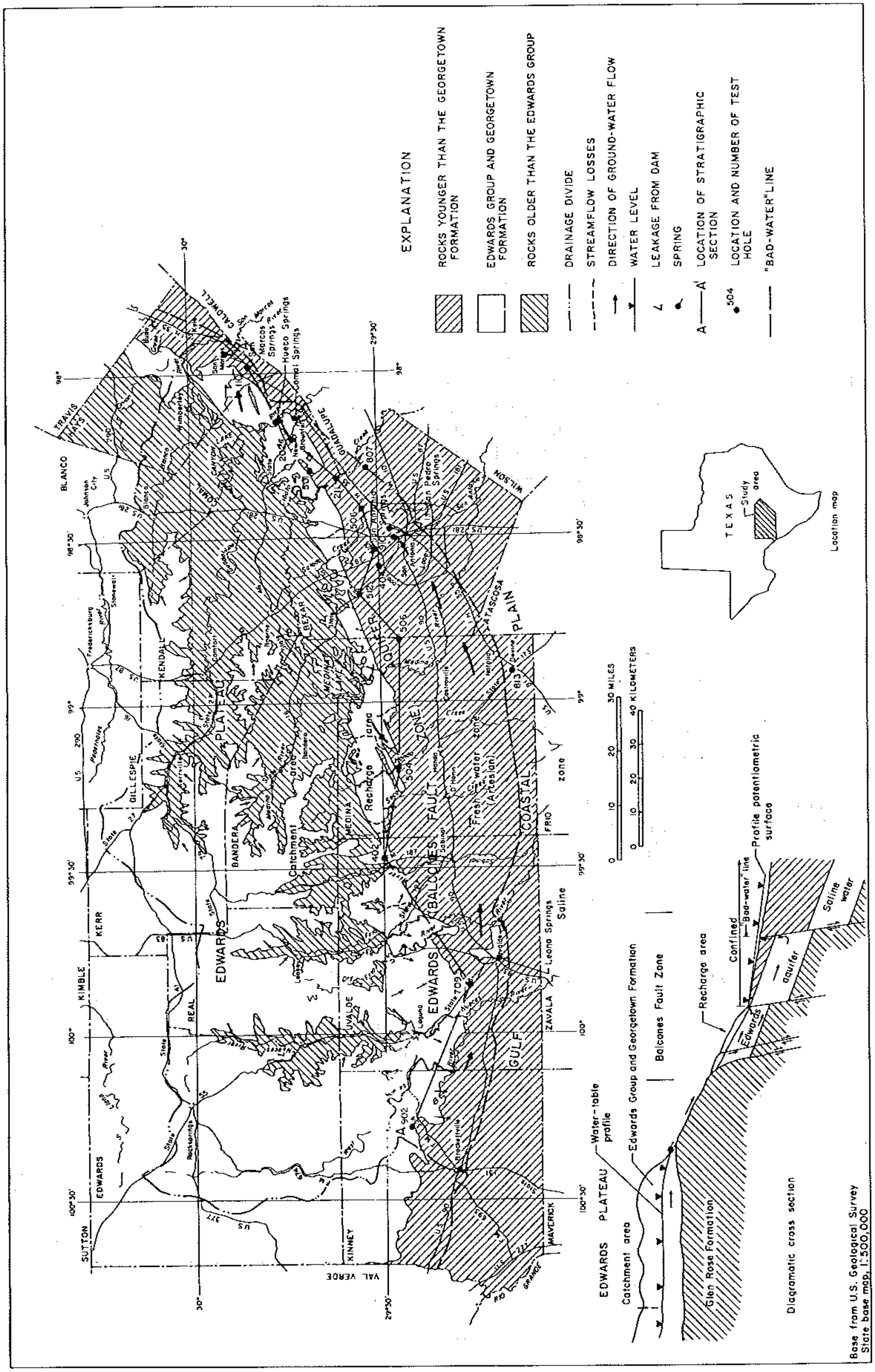
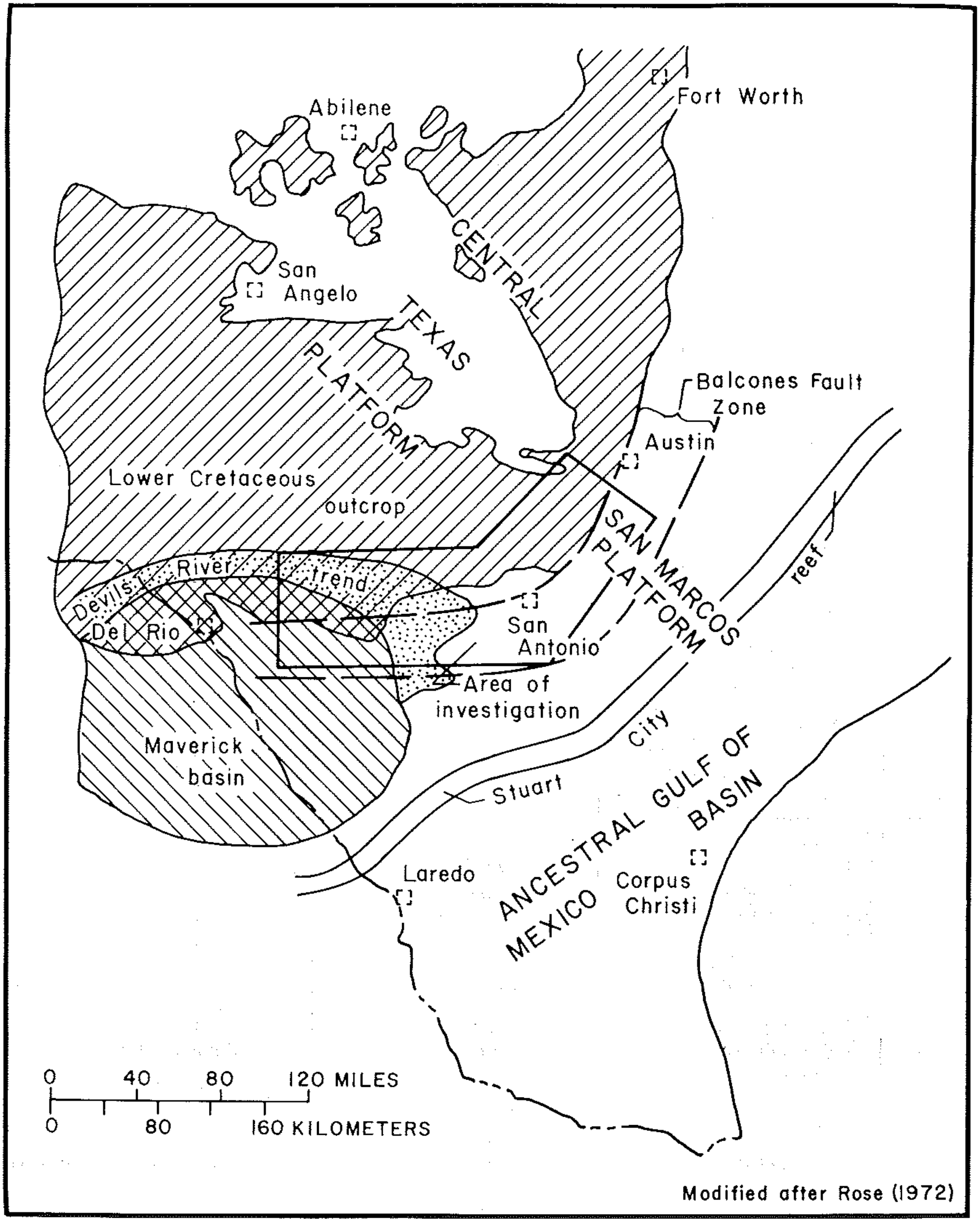


FIGURE 1.-Regional extent of the Edwards aquifer



Modified after Rose (1972)

FIGURE 2.-Depositional environment of the Edwards Group

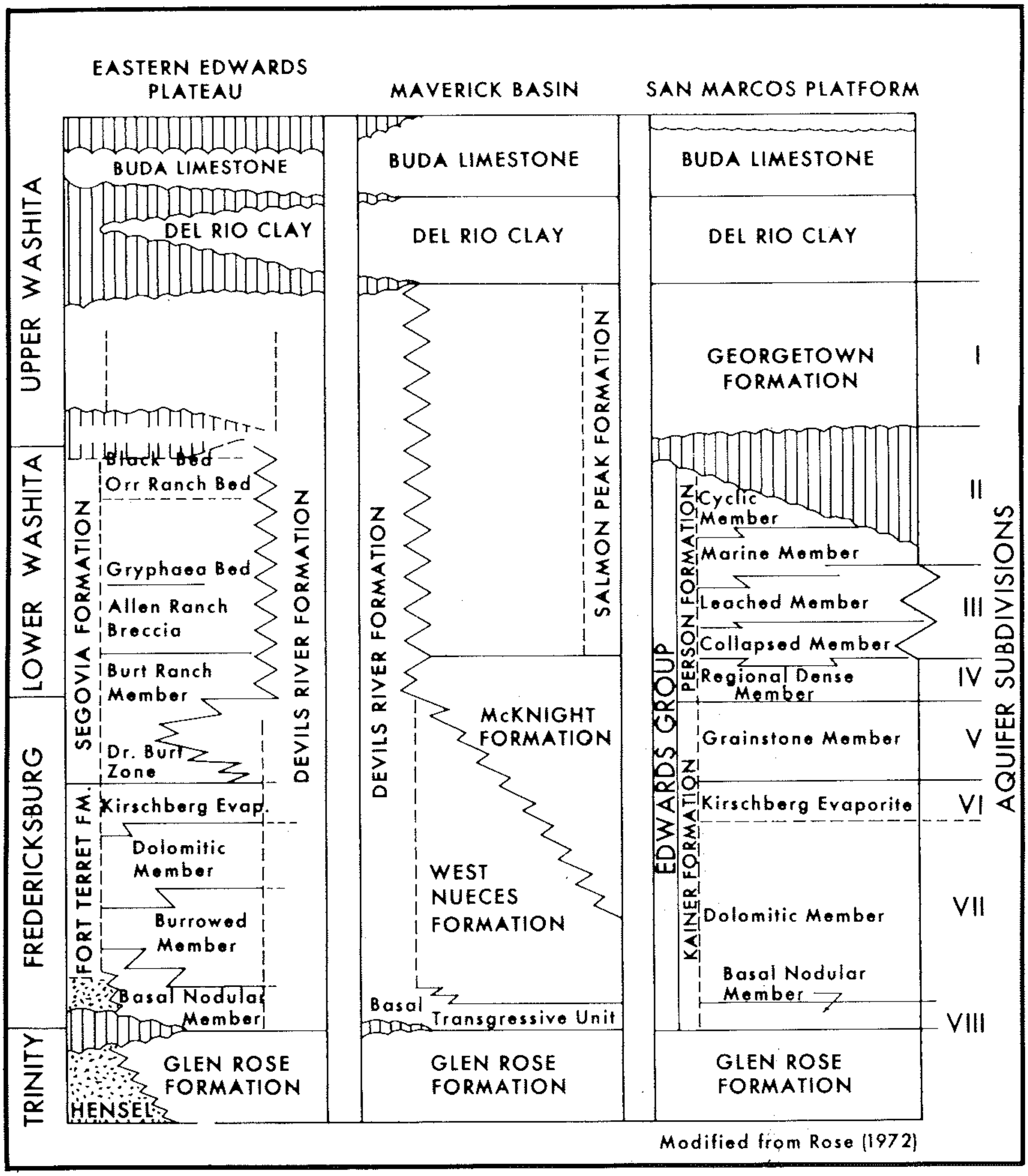


FIGURE 3.-Correlation of stratigraphic units of the Lower Cretaceous Series in South Texas

representative rocks that were obtained from the unconfined zone of the Edwards aquifer at the Lockhill test hole (AY-68-28-404) ranged from 0 to more than 17 percent.

The test procedures and the results of other rock-sample tests are given by Maclay and Small (1976).

The fractures and solution channels have a specific yield of about 1 percent while the micrites with texture-related porosity have a specific yield of several percent. Therefore, the capacity of the Edwards Aquifer to store water is determined largely by percentage of voids within the rock matrix, while the capacity to transmit water is determined by the number of fractures and solution channels.

An estimate of the regional specific yield in the unconfined zone of the Edwards Aquifer was made by Maclay and Rettman (1973) using records of annual recharge and discharge and observing water levels in 10 wells. The estimate of the regional specific yield was about 3 percent for the test range of water levels. This value may or may not be representative in the confined zone or for stages other than the test range. A summary of determined estimates of specific yield or drainable porosity is given in Table 1.

Estimates of specific yield for the confined zone cannot be determined directly because the aquifer is saturated. However, the rocks in the confined zone are stratigraphically and lithologically similar to those in the unconfined zone, for which the regional specific yield has been estimated. It should be noted that the complete geologic section forming the Edwards Aquifer was tested. Because of the dip of the aquifer, all the geologic strata occur at different places near the water table in the unconfined area.

The volume of water in storage in the confined freshwater zone of the aquifer, which has an area of 2,000 square miles (5,180 $km^2$), is estimated to be 26 million acre-feet (32,058 $km^3$). This estimated volume is based on an estimated average specific yield of 4 percent and an aquifer thickness of 500 feet (152 m). This is a very large amount of water, but only a small fraction of this volume can be recovered economically because of adverse conditions, such as many water-level declines, higher cost of pumping, and local invasion of saline water. Some of these adverse conditions could occur gradually and could be difficult to detect within a short period of time.

A plot of water levels in an index well in downtown San Antonio versus the accumulated difference between annual recharge and annual discharge is shown in Figure 4. The difference between the highest and lowest water level at the well from 1934 through 1976 is 69 feet (21 m). The curve indicates that about 41,000 acre-feet (50.6 $km^3$) of water is equivalent to a 1-foot (0.3-m) change in the annual water level at this index well. All estimates are based on water levels that represent approximate steady-state conditions within the aquifer at the time of measurement. Other estimates range from 39,000 to 55,000 acre-feet (48.1 to 67.8 $km^3$) per 1-foot (0.3 m) of change in the index well or 1-foot (0.3 m) of change in the average water level in 10 observation wells distributed throughout the aquifer.

Table 1. Summary of estimates of specific yield or drainable porosity of the Edwards Aquifer

| Method of estimate | Drainable porosity (percent) | Remarks |
|---|---|---|
| 1. Regional specific yield | 3 | Based on the annual water balance and the changes in stage in the aquifer. Annual estimates range from less than 1 percent to more than 4 percent. |
| 2. Estimates of drainable porosity for the entire thickness of the aquifer on the basis of visual examination of cores. | | Much of the observable porosity is poorly connected or not connected. Only a fraction will drain by gravity. Porosity consists of relatively small-size openings between the allochems or dolomite crystals. Visual openings in the rocks in the freshwater zone are, in general, of a large size. |
| A. Test holes in saline zone: | | |
| Randolph | 6 | |
| San Marcos | 6 | |
| Devine | 14 | |
| B. Test holes in freshwater zone: | | |
| Feathercrest | 10 | |
| Lockhill | 8 | |
| Castle Hills | 10 | |
| Rio Medina | 12 | |
| Sabinal | 8 | |
| 3. Estimates of drainable porosity on the basis of laboratory and geophysical data. | | Neutron porosity was multiplied by a porosity factor, which is a decimal fraction representing the amount of voids connected by pore throat diameters of more than 10 microns. |
| Test holes in freshwater zone: | | |
| Feathercrest | 2.0 | |
| Lockhill | 1.7 | |
| Castle Hills | 2.0 | |
| Rio Medina | 2.5 | |
| Sabinal | 2.1 | |

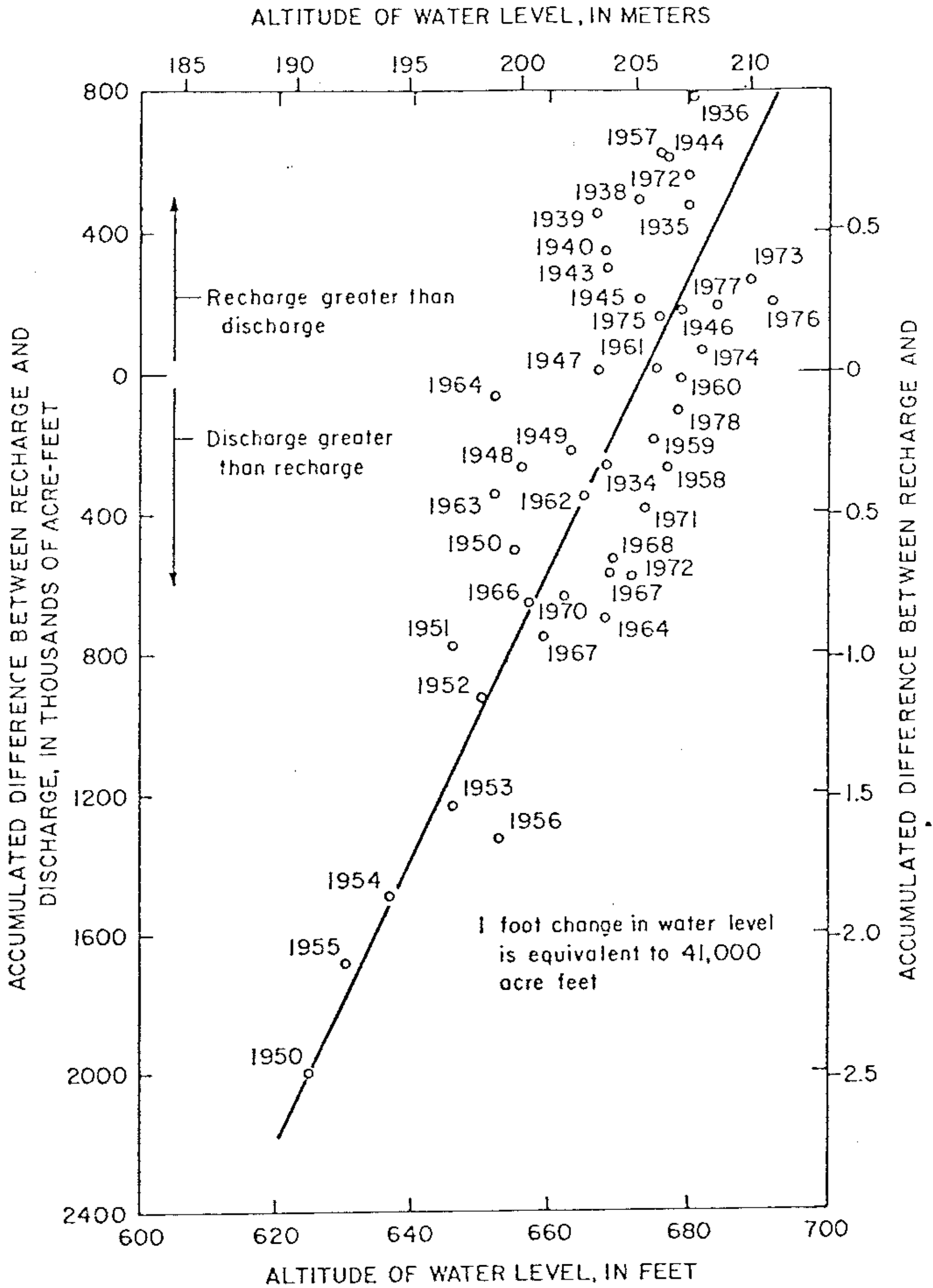


Figure 4. Accumulated difference between annual recharge and annual discharge in an index well in downtown San Antonio

These estimates of storage capacity apply to the range of historic water-level data, and any extrapolation beyond these limits will not assure the same amount of water in storage per 1-foot (0.3 m) of change in water levels. The storage capacity and drainage characteristics in the unconfined zone of the aquifer, where gravity drainage occurs, primarily determine the relationship between the water levels and the differences between recharge and discharge.

# The Edwards Aquifer and Its Future as a Source for Irrigation

by
John E. Hutchinson, Ph.D*.

I am indebted to Texas Department of Water Resources and Texas Crop and Livestock Reporting Service for much of the information included in my paper.

The Edwards Aquifer, together with the springs, artesian wells and the streams which feed from it, is the most important single factor in attracting the earliest settlers to this area and the continuously increasing concentration of people in the greater San Antonio area. When it comes right down to essentials, water is the most critical of all the elements of life when we consider the totality of all living things on the planet earth. So, it is appropriate indeed that this Edwards Aquife Research and Data Center has been established here at Southwest Texas State University to study ways of maintaining this critically important but fragile and finite resource. And, this seminar can be an important contributing force toward gaining the necessary level of understanding and sensitivity required for this effort.

The Edwards Aquifer extends approximately 175 miles from near Brackettville in Kinney County eastward to Kyle in Hays County and varies in width from about five to 40 miles. It underlies a part of Atascosa, Bexar, Comal, Guadalupe, Hays, Kinney, Medina and Uvalde Counties. Currently, it is the primary source of water for life sustaining purposes, sanitation, industry and irrigation.

From the earliest times as people settled in the area, even in Mission San Jose, supplemental irrigation was important in the production of food, feed and fiber.

The mean annual rainfall ranges from about 20 inches per year at Brackettville to about 33 inches per year at Kyle.

Most of the crops grown in the area require 24 to 36 inches of water per growing season. Supplemental irrigation is used to make up the difference between the amount of water available as rain after evaporation loss and the amount required by the crops.

Approximately 38 percent of the water pumped from the aquifer is used currently for irrigated agriculture.

To date, the Edwards Aquifer has been "holding its own" but we are approaching the point where the total discharge will begin to exceed th total recharge.

According to the Texas Department of Water resources, the total discharge during the period 1934 to 1977 was 25,721,300 acre-feet compared to a total recharge during the same period of 25,902,200 acre-feet. Thus, during the 43 year period total recharge exceeded total

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*Consultant, Texas Department of Agriculture (Former Director, Texas Agriculture Extension Service) discharge by 180,900 acre-feet. But, if we use the historic water-use trend as a guide, by the period 2010 to 2020 there will be a shortfall of 170,000 acre-feet per year. The shortfall could be much greater if the "full trend" projections for all types of usage is realized along with the projected increase in population.

The digital computer simulation for the period 1972 through 2040 of the Edwards Aquifer in the San Antonio region indicates the following:

Water entering the Edwards (Balcones Fault Zone) Aquifer moves generally southward across the reservoir and then eastward toward natural discharge points which include: (a) Leona Springs near Uvalde; (b) San Antonio and Pedro Springs in San Antonio; (c) Comal Springs at New Braunfels; and (d) San Marcos Springs at San Marcos. There are also hundreds of wells in the area.

Ignoring any water constraints, the aquifer is capable of meeting projected demands through the year 2049. The natural flow of Comal Springs will cease before the year 2020, if projected pumpage in the regions occur at the predicted rates. The addition of proposed artificial recharge does not result in appreciable increase in the aquifer's available water. Spring flows at Comal Springs can be maintained through groundwater management plans and there is sufficient storage in the aquifer to allow spring flow of Comal and San Marcos Springs to be replaced by augmentation pumpage through the year 2020.

Three counties, Bexar, Medina and Uvalde, have the largest acreage under irrigation of the counties underlain by the Edwards Aquifer. Irrigation trends are indicated by the following statistics: in 1958, the three counties had a total of 35,925 irrigated acres, in 1980 the total was 72,010 acres or more than doubled. Full-trend projections to the year 2000 call for 110,210 acres and by the year 2030, a total of 206,506 acres. If reduced to the one-half trend level, the total irrigated acreage for the three counties would be 150,987 acres; or, at the one-quarter trend level, the total irrigated acreage would be 114,689 acres.

Agriculture is important to the economy of the area in addition to being an essential industry to provide food, feed and fiber. In 1979, gross agricultural income for the eight counties involved was as follows: Atascosa - $47,663,000, Bexar - $50,018,000, Comal - $6,974,000, Guadalupe - $34,332,000, Hays - $13,051,000, Kinney - $17,288,000, Medina - $47,267,000 and Uvalde - $46,988,000 or a total of $273,581,000. This translates into a total economic impact of $930,175,400 on the greater San Antonio area. And, irrigation plays an important role in maintaining agricultural production and income.

The region derives its economy from military installations, government agencies, light industry and from the production of various agricultural products. Much of the light industry is concentrated near San Antonio and is related to the production of petroleum, natural gas, gravel, brick, tile and cement.

Agriculture is responsible for approximately 1/3 of the economic base. And, studies have shown that one of the most promising areas of industrial development is through an increase in the processing of agricultural products produced in the area.

Fortunately, there are many conservation measures that can be taken in applying irrigation practices and all other water uses. I will restrict my remarks to conservation and efficiency in applying irrigation practices.

For orchards and tree crops, drip irrigation reduces by a significant factor the amount of irrigation water required and is the most efficient method of application yet devised. For field crops, low pressure, low volume, and precision sprinkler irrigation systems currently being tested by the Texas Agricultural Experiment Station are increasing application efficiency by 20 to 25 percent and evaporation losses by as much as 50 percent under certain conditions. Energy requirements are also greatly reduced by the significant reduction in discharge pressure requirements. Current procedures for testing pump efficiency has resulted in reductions in energy requirements.

Moisture meters, some installed as a part of a computerized irrigation and fertilization system have taken much of the guess-work out of irrigation.

Furrow dikeing has greatly increased the efficient use of rainfall both during the pre-planting and the growing season.

If we become as concerned about the conservation of water as we have the conservation of gasoline and other petroleum products, we can find ways to conserve this even more vital resource. And, there are other developments which offer additional promise.

Perhaps the most promising technological development of all, from a production standpoint, is so-called bio or genetic-engineering. Less than two decades ago, two scientists at Stanford University, Arthur Kornberg and Paul Berg, began research relating to operations and manipulations with DNA - the chemical chain controlling the heredity of all organisms. Their work ultimately led to gene splicing. Expanding on the discoveries of Kornberg and Berg, Stanley Cohen of The Stanford School of Medicine and Herbert W. Boyer of the University of California School of Medicine have bred a living organism with characteristics and the ability to pass them on, fashioned by cementing together precise bits of gentic material gathered from two independent strains of bacteria. This development offers revolutionary possibilities across the spectrum of medical and industrial applications - such things as manipulating bacteria to produce everything from human hormones like insulin and virus battling interferon to vaccines and even fuels.

The gene splicing technique staggers the imagination. The apparent flexibility and possibilities are overwhelming.

In certain plants, soybeans for example, the genes that control senesence (or aging) have been manipulated to lengthen the production season. Such characteristics as quality, yields, resistance to insects and diseases, salt tolerance, drought tolerance, cold tolerance, and nitrogen fixation of plants other than legumes, are but a few of the potentials. There is much research to be done to identify precisely where in the genetic material the specific control mechanism for specific characteristics are located and develop improvements in the splicing technique.

Earlier in my remarks, I spoke of the fragile nature of the aquifer. This is because of the potential for direct flow of recharge water through cracks and crevices in the limestone into the aquifer. This requires the utmost in care by the total population of the area to prevent contamination of the aquifer. The stakes are high indeed. Success of the effort is critical to the future of this important resource.

# Public Health Aspects of the Edwards Aquifer

by
Tom Tiner, PE*

Due to the nature of the Edwards Aquifer, it is very important that drinking water supply wells be properly located and constructed. Wells should not be located in flood areas. If they are, certain precautions should be taken such as extending the well casing. Wells should not be located next to sinkholes, particularly in porous formations like the Edwards, which could result in potential contamination from immediate run-off. Septic tanks are not to be within 50 feet of wells or septic tank drainfields within 150 feet. Also, solid waste disposal sites should not be located within 500 feet of public water supply wells. This slide depicts the required distances from various sanitary hazards to public water supply wells (Figure 1).

Wells should be constructed so that well heads are not in pits where there is no drainage. Well head appurtenances should include a sampling tap, a six-foot sealing slab, and a screened breather vent. Of course, all public water supply wells are required to be pressure cemented and either housed or protected by an intruder-resistant fence.

Another very important public health aspect is properly plugging abandoned wells. The Texas Department of Water Resources has regulations in this regard. Abandoned wells which have been plugged have actually been used for sewage and chemical waste disposal purposes. You know the saying out-of-sight, out-of-mind.

I will now discuss a specific instance involving public health and the Edwards Aquifer, namely a waterborne disease outbreak which occurred in the summer of 1980 at Georgetown, Texas. Even though this outbreak resulted from Edwards wells located north of Austin and the Balcones Fault, it could have happened on the Edwards south of the fault or for that matter on any aquifer. This waterborne disease was a viral outbreak which afflicted 7,900 citizens. It was shown epidemiologically and bacteriologically that the City's four (4) wells at the main water plant were the cause of the outbreak. Bacterial samples collected directly from the wells showed fecal coliform counts ranging from 150 to 1,500 per 100 milliliters. I wish to emphasize that these were fecal coliform counts and not total. Fecal coliform limits the source of pollution to be from the intestinal tract of warm-blooded animals. To determine if it is human or animal, a fecal coliform to fecal strep ratio is made. Where did the viruses come from? As of today, we are still not certain. Speculatively, they came from one of the following:

1. From the filling of Lake Georgetown by heavy rains a month before the outbreak, this could have created a hydrostatic head on the Edwards formation which carried contaminants into the City's wells.

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*Director, Division of Water Hygiene, Texas Department of Health

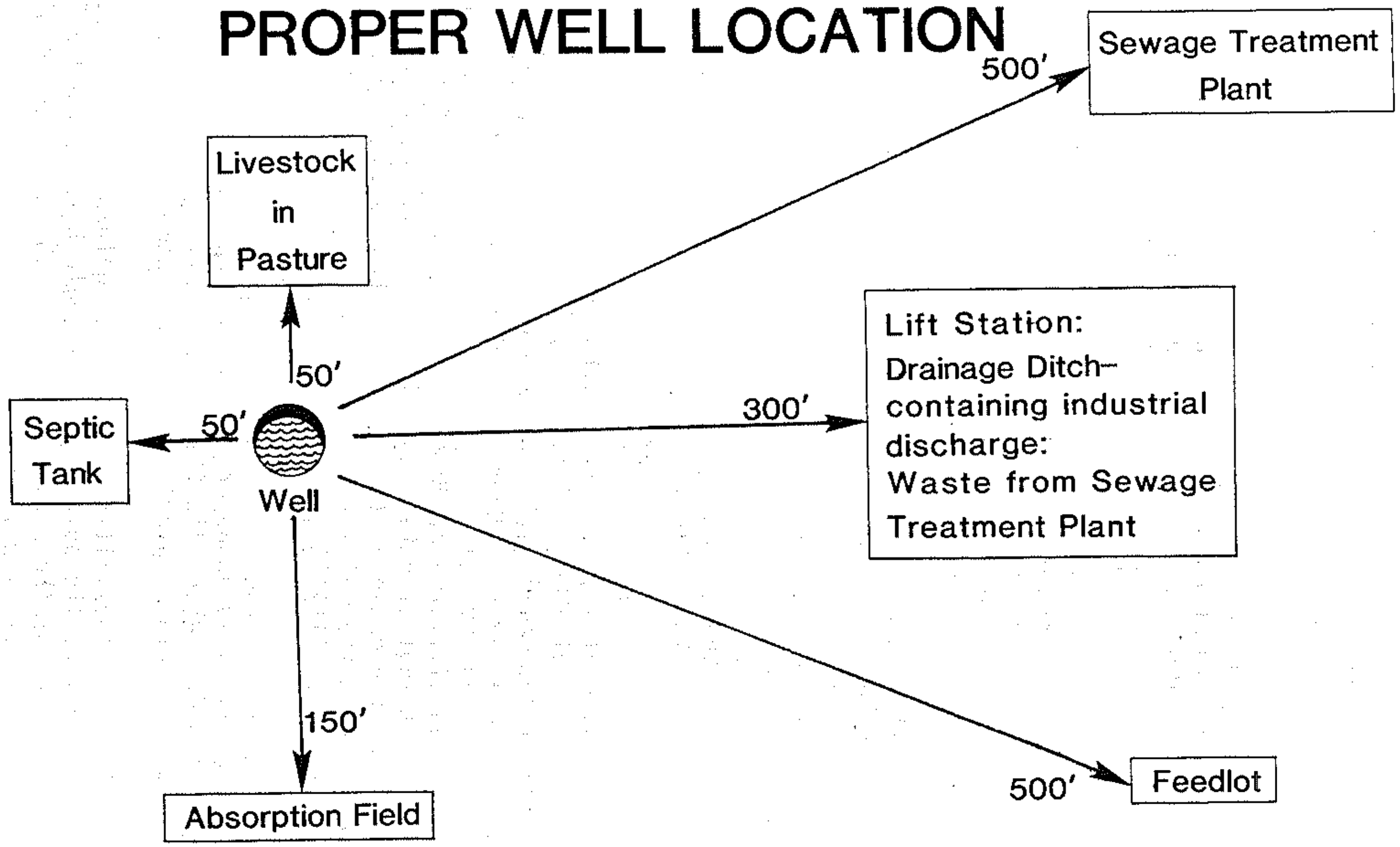


Figure 1. Proper Well Location

2. Another possibility which is based on the porous nature of the Edwards is from improperly installed septic tanks located outside the City limits in the recharge area.

3. Even though a thorough investigation was made of the sewer lines near the wells at the main water plant, the contamination could have resulted from line leakage. Extensive smoke and dye tests were conducted but no ruptured sewer lines were found.

4. Last but certainly not least, the problem may have been associated with an unplugged dug well adjacent to the City's wells.

This could have been the culprit since raw water samples now being collected for bacterial analysis are not showing anywhere near the degree of contamination since the dug well was properly plugged. Of course as previously mentioned, unplugged abandoned wells are a source of contamination not only to the Edwards Aquifer but to all aquifers in the State.

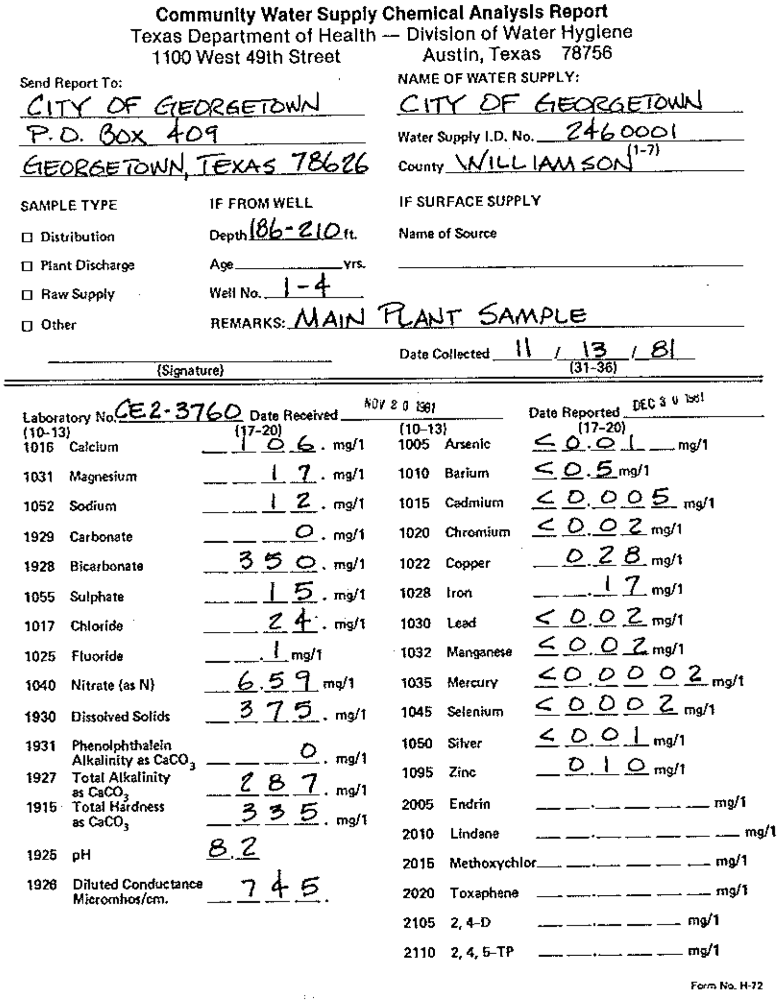
In the past it has been felt that when water wells were properly located and constructed, coliform organisms should not be present in the raw water. Today, however, we are finding more and more raw water positive samples from wells producing from various aquifers across the State. This is very alarming to all of us.

Regarding the chemical quality of the water from the Edwards, it is excellent. This slide shows a chemical analysis from the City of Georgetown's distribution system (Figure 2).

As you can see the water meets the primary standards of the Texas Department of Health and the U.S. Environmental Protection Agency (Figure 3). Primary standards are based on public health whereas secondary standards are based on aesthetics. As many of you may know, fluoride is currently listed as a primary standard. I strongly feel that fluoride in concentrations less than 6.0 mg/l is not a health problem but one of cosmetics. The fluoride level in the Edwards formation water is only about 0.3 mg/l which is well within the maximum concentration allowed of 1.6 mg/l. Actually, the fluoride concentration is so low that it is recommended that fluoride be added to increase the level to 0.8 mg/l to prevent dental caries. I know many people who do not understand that if you have a contaminant, why would you add it to a water supply. The reason of course is fluoride at optimum level of 0.8 mg/l prevents dental caries, but over twice the optimum level of 1.6 mg/l it may cause dental fluorosis (staining of teeth).

This slide shows the chemical quality of the water from San Antonio. As can be seen, it is generally the same as Georgetown's water and meets the standards in all aspects (Figures 4 and 5).

The radiological properties of the Edwards water as can be seen from this slide meets the recommended standards. The maximum limit is 5 pCi/l for combined radium 226 and 228 and 15 pCi/l for gross alpha (Figure 6).



**Community Water Supply Chemical Analysis Report**
Texas Department of Health — Division of Water Hygiene
1100 West 49th Street Austin, Texas 78756

Send Report To:
CITY OF GEORGETOWN
P.O. BOX 409
GEORGETOWN, TEXAS 78626

NAME OF WATER SUPPLY: CITY OF GEORGETOWN
Water Supply I.D. No. 2460001 (1-7)
County WILLIAMSON

| SAMPLE TYPE | IF FROM WELL | IF SURFACE SUPPLY |
|---|---|---|
| ☐ Distribution | Depth 186-210 ft. | Name of Source |
| ☐ Plant Discharge | Age ____ yrs. | |
| ☐ Raw Supply | Well No. 1-4 | |
| ☐ Other | REMARKS: MAIN PLANT SAMPLE | |

(Signature)

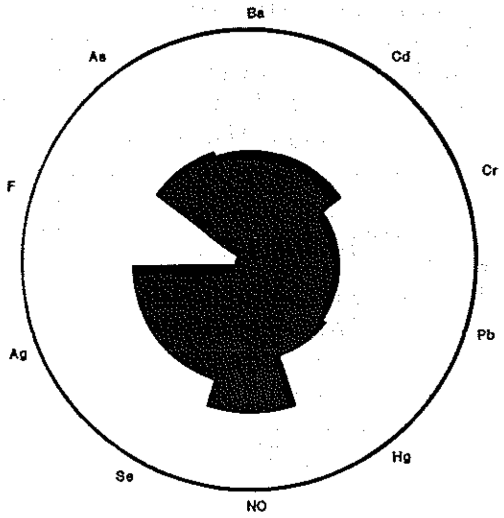
Date Collected 11 / 13 / 81 (31-36)

Laboratory No. CE2-3760 (10-13)
Date Received NOV 2 0 1981 (17-20)
Date Reported DEC 3 0 1981 (17-20)

| (10-13) | | (17-20) | (10-13) | | |
|---|---|---|---|---|---|
| 1016 | Calcium | 106. mg/1 | 1005 | Arsenic | ≤0.01 mg/1 |
| 1031 | Magnesium | 17. mg/1 | 1010 | Barium | ≤0.5 mg/1 |
| 1052 | Sodium | 12. mg/1 | 1015 | Cadmium | <0.005 mg/1 |
| 1929 | Carbonate | 0. mg/1 | 1020 | Chromium | <0.02 mg/1 |
| 1928 | Bicarbonate | 350. mg/1 | 1022 | Copper | 0.28 mg/1 |
| 1055 | Sulphate | 15. mg/1 | 1028 | Iron | .17 mg/1 |
| 1017 | Chloride | 24. mg/1 | 1030 | Lead | <0.02 mg/1 |
| 1025 | Fluoride | .1 mg/1 | 1032 | Manganese | ≤0.02 mg/1 |
| 1040 | Nitrate (as N) | 6.59 mg/1 | 1035 | Mercury | ≤0.0002 mg/1 |
| 1930 | Dissolved Solids | 375. mg/1 | 1045 | Selenium | ≤0.002 mg/1 |
| 1931 | Phenolphthalein Alkalinity as $CaCO_3$ | 0. mg/1 | 1050 | Silver | ≤0.01 mg/1 |
| 1927 | Total Alkalinity as $CaCO_3$ | 287. mg/1 | 1095 | Zinc | 0.10 mg/1 |
| 1915 | Total Hardness as $CaCO_3$ | 335. mg/1 | 2005 | Endrin | mg/1 |
| 1925 | pH | 8.2 | 2010 | Lindane | mg/1 |
| 1926 | Diluted Conductance Micromhos/cm. | 745. | 2015 | Methoxychlor | mg/1 |
| | | | 2020 | Toxaphene | mg/1 |
| | | | 2105 | 2, 4-D | mg/1 |
| | | | 2110 | 2, 4, 5-TP | mg/1 |

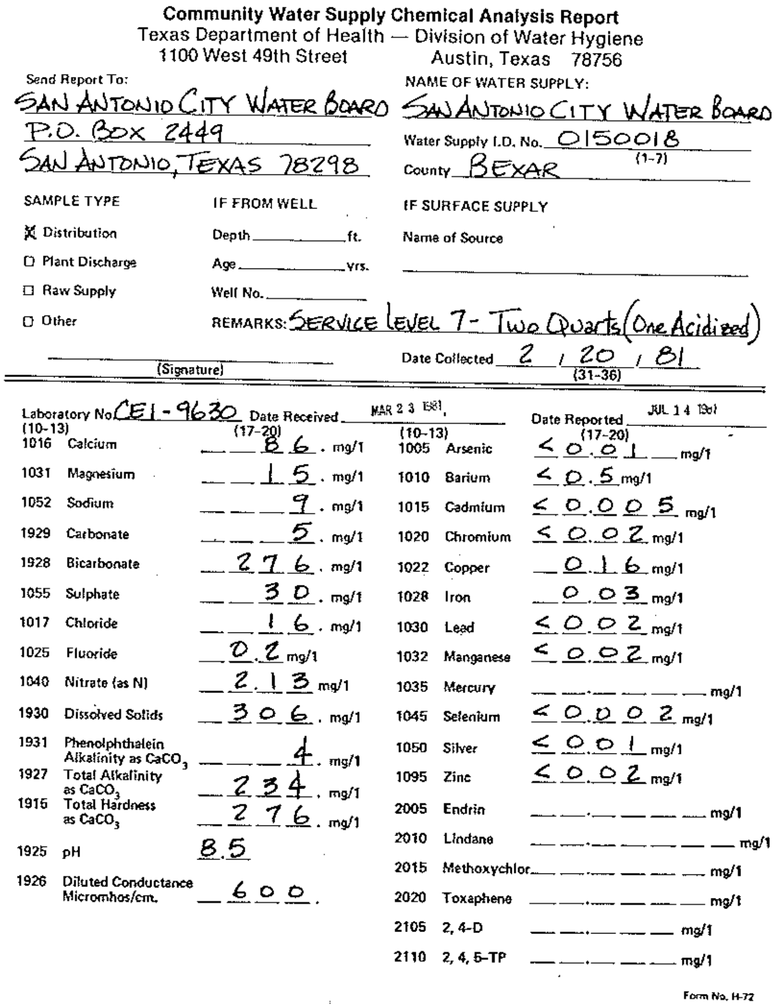
Form No. H-72

Figure 2. Chemical Analysis Report for Georgetown



| PRIMARY STANDARDS | | GEORGETOWN |
|---|---|---|
| ARSENIC | 0.05 | < 0.01 |
| BARIUM | 1.0 | < 0.5 |
| CADMIUM | 0.010 | < 0.005 |
| CHROMIUM | 0.05 | < 0.02 |
| LEAD | 0.05 | 0.02 |
| MERCURY | 0.002 | < 0.0002 |
| NITRATE | 10. | 6.59 |
| SELENIUM | 0.01 | < 0.002 |
| SILVER | 0.05 | < 0.01 |
| FLUORIDE | 1.6 | 0.10 |

Figure 3. Primary Standards and Georgetown Chemical Analysis



**Community Water Supply Chemical Analysis Report**
Texas Department of Health — Division of Water Hygiene
1100 West 49th Street Austin, Texas 78756

Send Report To:
SAN ANTONIO CITY WATER BOARD
P.O. BOX 2449
SAN ANTONIO, TEXAS 78298

NAME OF WATER SUPPLY: SAN ANTONIO CITY WATER BOARD
Water Supply I.D. No. 0150018 (1-7)
County BEXAR

SAMPLE TYPE
☒ Distribution
☐ Plant Discharge
☐ Raw Supply
☐ Other

IF FROM WELL
Depth ____ ft.
Age ____ yrs.
Well No. ____

IF SURFACE SUPPLY
Name of Source ____

REMARKS: SERVICE LEVEL 7 - TWO QUARTS (ONE ACIDIZED)

(Signature)

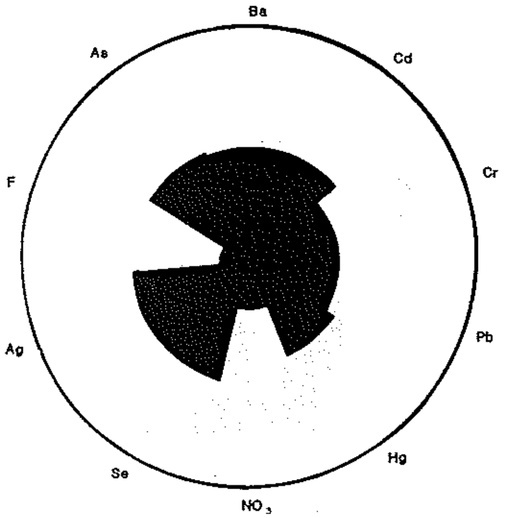
Date Collected 2 / 20 / 81 (31-36)

Laboratory No. CE1-9630 (10-13) Date Received MAR 2 3 1981 (17-20)
Date Reported JUL 1 4 1981

| | | | | | |
|---|---|---|---|---|---|
| (10-13) | | (17-20) | (10-13) | | (17-20) |
| 1016 | Calcium | 86. mg/1 | 1005 | Arsenic | < 0.01 mg/1 |
| 1031 | Magnesium | 15. mg/1 | 1010 | Barium | < 0.5 mg/1 |
| 1052 | Sodium | 9. mg/1 | 1015 | Cadmium | < 0.005 mg/1 |
| 1929 | Carbonate | 5. mg/1 | 1020 | Chromium | < 0.02 mg/1 |
| 1928 | Bicarbonate | 276. mg/1 | 1022 | Copper | 0.16 mg/1 |
| 1055 | Sulphate | 30. mg/1 | 1028 | Iron | 0.03 mg/1 |
| 1017 | Chloride | 16. mg/1 | 1030 | Lead | < 0.02 mg/1 |
| 1025 | Fluoride | 0.2 mg/1 | 1032 | Manganese | < 0.02 mg/1 |
| 1040 | Nitrate (as N) | 2.13 mg/1 | 1035 | Mercury | mg/1 |
| 1930 | Dissolved Solids | 306. mg/1 | 1045 | Selenium | < 0.002 mg/1 |
| 1931 | Phenolphthalein Alkalinity as $CaCO_3$ | 4. mg/1 | 1050 | Silver | < 0.01 mg/1 |
| 1927 | Total Alkalinity as $CaCO_3$ | 234. mg/1 | 1095 | Zinc | < 0.02 mg/1 |
| 1915 | Total Hardness as $CaCO_3$ | 276. mg/1 | 2005 | Endrin | mg/1 |
| 1925 | pH | 8.5 | 2010 | Lindane | mg/1 |
| 1926 | Diluted Conductance Micromhos/cm. | 600. | 2015 | Methoxychlor | mg/1 |
| | | | 2020 | Toxaphene | mg/1 |
| | | | 2105 | 2, 4-D | mg/1 |
| | | | 2110 | 2, 4, 5-TP | mg/1 |

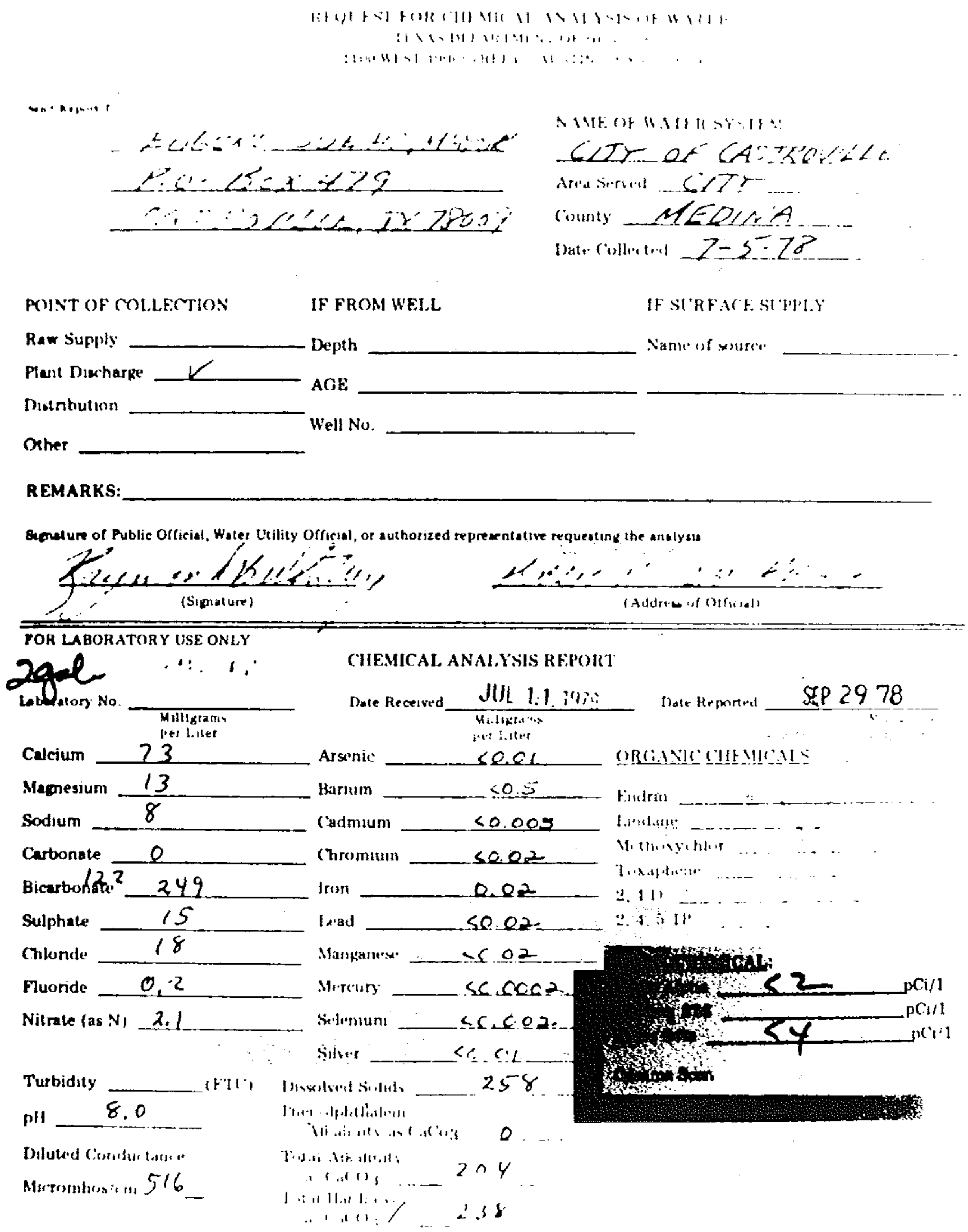
Form No. H-72

Figure 4. Chemical Analysis Report for San Antonio



| PRIMARY STANDARDS | | SACWB |
|---|---|---|
| ARSENIC | 0.05 | < 0.01 |
| BARIUM | 1.0 | < 0.5 |
| CADMIUM | 0.010 | < 0.005 |
| CHROMIUM | 0.05 | < 0.02 |
| LEAD | 0.05 | 0.02 |
| MERCURY | 0.002 | < 0.0002 |
| NITRATE | 10. | 2.13 |
| SELENIUM | 0.01 | < 0.002 |
| SILVER | 0.05 | < 0.01 |
| FLUORIDE | 1.6 | 0.2 |

Figure 5. Primary Standards and San Antonio Chemical Analysis



REQUEST FOR CHEMICAL ANALYSIS OF WATER
TEXAS DEPARTMENT OF [illegible]
1100 WEST 49th STREET AUSTIN [illegible]

Send Report To
[illegible]
P.O. Box 479
Castroville, TX 78009

NAME OF WATER SYSTEM: CITY OF CASTROVILLE
Area Served: CITY
County: MEDINA
Date Collected: 7-5-78

| POINT OF COLLECTION | | IF FROM WELL | | IF SURFACE SUPPLY | |
|---|---|---|---|---|---|
| Raw Supply | | Depth | | Name of source | |
| Plant Discharge | ✓ | AGE | | | |
| Distribution | | Well No. | | | |
| Other | | | | | |

**REMARKS:**

**Signature of Public Official, Water Utility Official, or authorized representative requesting the analysis**

(Signature)

(Address of Official)

**FOR LABORATORY USE ONLY**

2gal

Laboratory No.

CHEMICAL ANALYSIS REPORT

Date Received: JUL 11 1978
Date Reported: SEP 29 78

| | Milligrams per Liter | | Milligrams per Liter | ORGANIC CHEMICALS | |
|---|---|---|---|---|---|
| Calcium | 73 | Arsenic | <0.01 | | |
| Magnesium | 13 | Barium | <0.5 | Endrin | |
| Sodium | 8 | Cadmium | <0.005 | Lindane | |
| Carbonate | 0 | Chromium | <0.02 | Methoxychlor | |
| Bicarbonate | 122 249 | Iron | 0.02 | Toxaphene | |
| Sulphate | 15 | Lead | <0.02 | 2, 4 D | |
| Chloride | 18 | Manganese | <0.02 | 2, 4, 5 TP | |
| Fluoride | 0.2 | Mercury | <0.0002 | | |
| Nitrate (as N) | 2.1 | Selenium | <0.002 | | |
| | | Silver | <0.01 | | |

[illegible]ICAL:
[illegible] <2 pCi/l
[illegible] pCi/l
[illegible] <4 pCi/l
[illegible] Scan

Turbidity ____ (FTU)
pH 8.0
Diluted Conductance Micromhos/cm 516

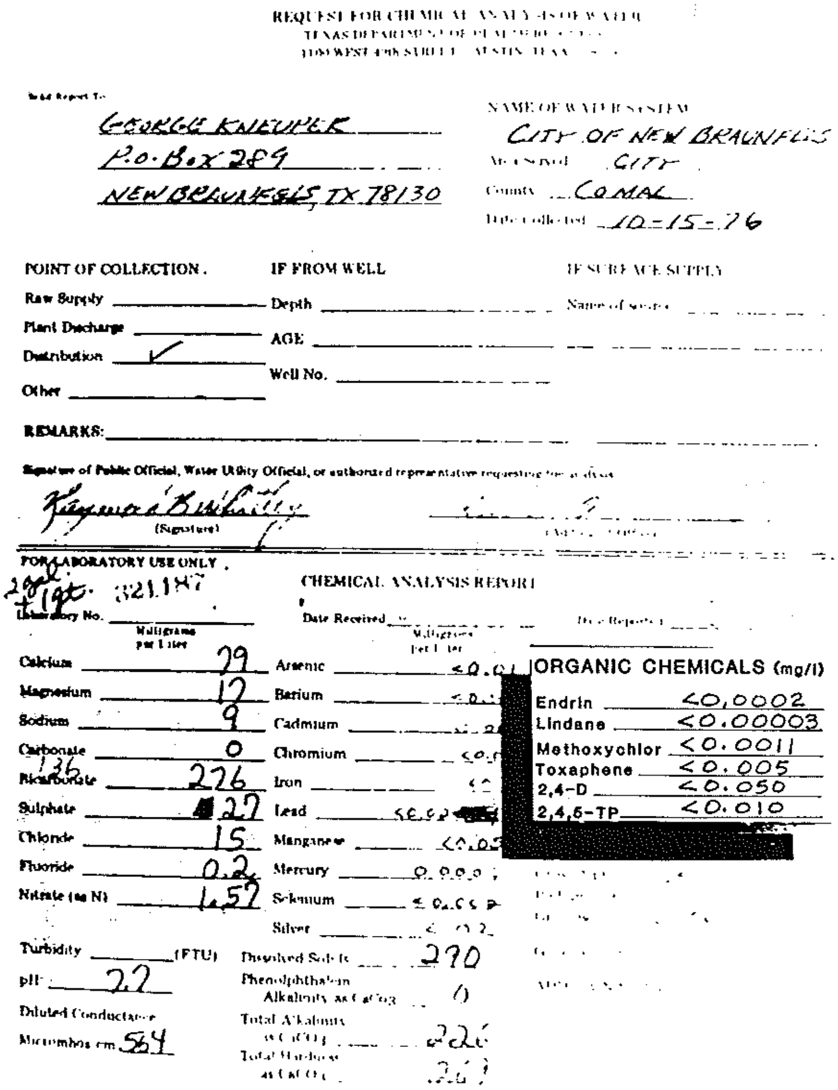
Dissolved Solids 258
Phenolphthalein Alkalinity as $CaCO_3$ 0
Total Alkalinity as $CaCO_3$ 204
Total Hardness as $CaCO_3$ 238

Figure 6. Chemical Analysis Report for Castroville with Radiochemical Data Highlighted (Best possible reproduction from original provided by author)

Concerning organics, this slide shows the analysis for various insecticides of a sample of water collected from the City of New Braunfels' distribution system. As you can see, the organic constituents analyzed for were not detectable (Figure 7).

Trihalomethanes (THM's) are a group of halogenated organics which you have been reading about and are now analyzed for since they are a suspected carcinogen. THM's have a permissible limit of 0.1 mg/l or 100 micrograms/l which I might mention relates to one second in 32 years. As you can see from this slide the water from the San Antonio City Water Board's distribution system is only 0.01 mg/l which is well within the permissible limit (Figure 8). Actually all groundwater in the State has very low THM's concentrations. THM's are generally associated with surface water reservoirs that have a lot of vegetation.

This concludes my presentation. Thank you.



REQUEST FOR CHEMICAL ANALYSIS OF WATER
TEXAS DEPARTMENT OF [illegible]
1100 WEST 49th STREET AUSTIN, TEXAS [illegible]

Send Report To
GEORGE KNEUPER
P.O. BOX 289
NEW BRAUNFELS, TX 78130

NAME OF WATER SYSTEM CITY OF NEW BRAUNFELS
Area Served CITY
County COMAL
Date Collected 10-15-76

| POINT OF COLLECTION. | | IF FROM WELL | | IF SURFACE SUPPLY | |
|---|---|---|---|---|---|
| Raw Supply | | Depth | | Name of source | |
| Plant Discharge | | AGE | | | |
| Distribution | ✓ | Well No. | | | |
| Other | | | | | |

REMARKS:

Signature of Public Official, Water Utility Official, or authorized representative requesting the analysis

(Signature)

FOR LABORATORY USE ONLY.

2 gal.
+ 1 qt. 321187
Laboratory No.

CHEMICAL ANALYSIS REPORT

Date Received
Date Reported

| | Milligrams per Liter | | Milligrams per Liter |
|---|---|---|---|
| Calcium | 79 | Arsenic | <0.01 |
| Magnesium | 17 | Barium | <0.[illegible] |
| Sodium | 9 | Cadmium | [illegible] |
| Carbonate | 0 | Chromium | <0.[illegible] |
| Bicarbonate | 136<br>276 | Iron | [illegible] |
| Sulphate | 27 | Lead | <0.0[illegible] |
| Chloride | 15 | Manganese | <0.05 |
| Fluoride | 0.2 | Mercury | 0.000[illegible] |
| Nitrate (as N) | 1.57 | Selenium | <0.00[illegible] |
| | | Silver | <0.02 |

| | |
|---|---|
| Turbidity | (FTU) |
| pH | 7.7 |
| Diluted Conductance Micromhos cm | 584 |
| Dissolved Solids | 290 |
| Phenolphthalein Alkalinity as CaCO3 | 0 |
| Total Alkalinity as CaCO3 | 226 |
| Total Hardness as CaCO3 | 267 |

ORGANIC CHEMICALS (mg/l)

| | |
|---|---|
| Endrin | <0.0002 |
| Lindane | <0.00003 |
| Methoxychlor | <0.0011 |
| Toxaphene | <0.005 |
| 2,4-D | <0.050 |
| 2,4,5-TP | <0.010 |

Figure 7. Chemical Analysis Report for New Braunfels with Organic Chemical Data Highlighted (Best possible reproduction from original provided by author)

**TOTAL TRIHALOMETHANES**
**AVERAGE FOR 1981**

MAXIMUM CONTAMINANT LEVEL 0.10 mg/l

| | |
|---|---|
| SAN ANTONIO CITY WATER BOARD | 0.01525 mg/l |
| BEXAR MUD | 0.01847 mg/l |
| SAN MARCOS | 0.05075 mg/l |
| UVALDE | 0.01815 mg/l |
| NEW BRAUNFELS | 0.02455 mg/l |
| GEORGETOWN | 0.07035 mg/l |

Figure 8. Total Trihalomethanes, Average for 1981