TEXAS DEPARTMENT OF WATER RESOURCES

REPORT 234

GEOHYDROLOGY OF COMAL, SAN MARCOS, AND HUECO SPRINGS

By

William F. Guyton & Associates

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GEOHYDROLOGY OF COMAL, SAN MARCOS, AND HUECO SPRINGS

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Comal, San Marcos, and Hueco Springs are major natural discharge points for the Edwards (Balcones Fault Zone) aquifer, hereafter referred to in this section as the Edwards aquifer. Comal Springs are in the city of New Braunfels in Comal County and are the largest group of springs in Texas. San Marcos Springs occur in the city of San Marcos in Hays County and are the second largest group of springs in Texas. Hueco Springs are a smaller group of springs near the Guadalupe River about 3 miles north of New Braunfels in Comal County. All three groups of springs occur along major faults in the Balcones Fault Zone.

The formations comprising the Edwards aquifer in the area of the three groups of springs, from top to bottom, are the Georgetown Formation, the Person and Kainer Formations of the Edwards Group, and the Walnut Formation. The aquifer considered in this report occurs in an area about 5 to 30 miles (8.0 to 48.3 km) wide and 175 miles (282 km) long extending from a ground-water divide at Brackettville in Kinney County on the west through parts of Uvalde, Medina, Atascosa, Bexar, Guadalupe, and Comal Counties to a ground-water divide northeast of Kyle in Hays County. The formations range in total thickness in this area from about 400 to 1,000 feet (122 to 305 m).

The Edwards aquifer is recharged principally by seepage of water from streams crossing its outcrop, and by direct infiltration of precipitation falling on its outcrop areas. Average recharge for the period 1934-73 is estimated at slightly less than 600,000 acre-feet (740 million m^3) per year. Annual recharge during this period ranged between a minimum of less than 50,000 acre-feet (61.7 million m^3) to more than 1.7 million acre-feet (2,096 million m^3). Roughly one-fourth of the recharge occurs northeast of San Antonio and the remainder to the west.

Before there were any withdrawals from wells, essentially all the recharge that entered the Edwards aquifer was discharged through six major spring outlets: Leona Springs along the Leona River south of Uvalde in Uvalde County, San Pedro and San Antonio Springs at San Antonio in Bexar County, Comal Springs, Hueco Springs, and San Marcos Springs. The water moved generally from west to east, and the springs served as natural spillways for the aquifer. Since withdrawals from wells began, the spring flow has decreased, with the total reduction in volume of spring flow being roughly equal to the total volume of withdrawals from wells.

Estimates of storage of water in the aquifer range from about 15 million acre-feet (18.5 billion m^3) to about 45 million acre-feet (55.5 billion m^3).

The first substantial withdrawals of water from wells penetrating the aquifer were in the late 1800's. In 1934, the total withdrawal from wells was about 100,000 acre-feet (123 million m^3). Withdrawals reached their maximum in 1971, when they were 407,000 acre-feet (502 million m^3). In 1974, withdrawals were 364,000 acre-feet (449 million m^3). The primary effects of the withdrawals have been reductions in spring flows during periods of drought. Comal Springs were dry, for the first time on record, for about 5 months from July 1956 to November 1956. The lowest recorded flow for San Marcos Springs also occurred at that time.

The daily average flow reported for Comal Springs has ranged from a minimum of zero in 1956 to a maximum of 534 cubic feet per second (15.1 m^3/s) in 1973. Prior to 1948, the lowest daily average flow reported was 245 cubic feet per second (6.9 m^3/s) in 1939. The average annual discharge for Comal Springs during the period 1945-73 was 184,000 acre-feet (227 million m^3) per year.

The daily average flow of San Marcos Springs has ranged from a minimum of 46 cubic feet per second (1.3 m^3/s) in 1956 to a maximum of 316 cubic feet per second (8.9 m^3/s) in 1975. The average discharge of San Marcos Springs during the period 1945-73 was 105,000 acre-feet (129 million m^3) per year. Although Comal

Springs have shown progressively greater effects from withdrawals through wells, the flow of San Marcos Springs has not shown a very noticeable effect caused by the withdrawals except during 1956 when Comal Springs were dry.

Hueco Springs have ranged in flow from zero during a number of drought periods to a maximum of 131 cubic feet per second (3.7 m^3/s) in 1968. The average discharge of Hueco Springs during the period 1945-73 is estimated at 26,000 acre-feet (32.1 million m^3) per year.

The water from all three groups of springs is very good and is constant in mineral quality. Reported dissolved solids range from about 253 to 302 mg/l (milligrams per liter) for Comal Springs, 310 to 349 mg/l for San Marcos Springs, and 291 to 357 mg/l for Hueco Springs. The average temperature of Comal Springs is about 74.3°F (23.4°C), with a range from about 73.5 to 75°F (23.1 to 23.9°C). The average temperature of San Marcos Springs is about 71.6°F (22.0°C), with a range from about 71 to 72°F (21.7 to 22.2°C). The average temperature of Hueco Springs is about 70.4°F (21.3°C), with a range from about 68 to 73°F (20.0 to 22.8°C).

The tritium content of the water from Comal Springs in 1974 was 4.9 tritium units. In 1975 the tritium content of water from San Marcos Springs was 19 tritium units, and from Hueco Springs 24 tritium units. The analyses indicate that most of the water from Comal Springs is more than 20 years old. Much of the water from San Marcos Springs is considerably younger, and the water from Hueco Springs younger still.

Long-term total discharge from Comal, San Marcos, and Hueco Springs correlates well with long-term recharge and withdrawals from wells. The flow from Comal Springs correlates closely with water levels in wells to the southwest in San Antonio. The flow of San Marcos Springs correlates with water levels in wells in its vicinity. Major fluctuations in the flows of San Marcos and Hueco Springs correlate reasonably well with one another.

Available data indicate that the recharge area for Comal Springs includes (1) all the recharge area of the Edwards aquifer southwest of the Cibolo Creek basin, (2) probably a substantial part of the recharge area of the Cibolo Creek basin, and (3) probably a small amount of the recharge area of the Dry Comal Creek basin.

Roughly 55 to 60 percent of the average flow from San Marcos Springs is estimated to be water which flows past Comal Springs to San Marcos Springs from the southwest. The remaining water from San Marcos Springs is from local recharge derived primarily from (1) the Blanco River basin, (2) the Sink, Purgatory, York, and Alligator Creek basins, (3) the Guadalupe River basin recharge area east of the river, (4) probably part of the upper portion of the Dry Comal Creek basin recharge area, and (5) possibly part of the upper part of the Cibolo Creek basin recharge area.

The recharge area for Hueco Springs is considered to be relatively local for the most part and to be comprised primarily of the upper part of the Dry Comal Creek basin and the Guadalupe River basin recharge area west of the river, with perhaps some water from the upper part of the Cibolo Creek basin recharge area. Also there may be some water spilled from the main portion of the Edwards aquifer between San Antonio and Comal Springs into the area north of the Hueco Springs Fault which supplies Hueco Springs, when the water levels in the aquifer are especially high.

No evidence of major pollution has been found at any of the three groups of springs to date. Because of their sources and because of the present strict legal control over activities which might create pollution, it seems doubtful that any of the springs will be seriously polluted in the forseeable future.

Since 1956, when Comal Springs were dry, average withdrawals from wells have increased substantially. The next time a major drought of the size which occurred in the early 1950's occurs, Comal Springs may be expected to go dry again and to stay dry for a longer period that it did in 1956. Eventually, they may go dry even if a major drought does not occur, because average withdrawals from wells are slowly approaching average recharge to the aquifer, which in time will leave little or nothing to spill out through the springs.

In the future when Comal Springs are dry again, it is expected that the effects of well withdrawals will be felt again on San Marcos Springs, the intensity depending on the length of the period Comal Springs are dry and the depth to which water levels in the aquifer are lowered at that time. San Marcos Springs probably will go dry in one or more of these future periods if the withdrawals from wells are large enough and the drought is severe enough.

Hueco Springs may be affected to some extent by withdrawals from wells, but it is doubtful that such withdrawals will intercept much of the flow from Hueco Springs. There will be periods when the springs are dry, but they are likely to be caused mostly by droughts.

Because water that is pumped from wells in the Edwards aquifer diminishes spring flow by an equal amount, it is not possible to withdraw a major portion of the aquifer's recharge from wells and still keep Comal and San Marcos Springs flowing at high rates during droughts. It probably would be physically practical, however, to pump well water from the aquifer and convey it in the stream channels downstream from the springs during droughts to maintain moderate flows at times when the streams otherwise would be dry or have very low flow. In that case, dams probably would be required between those portions of the stream channels and the spring openings, to keep the pumped water from returning to the aquifer through the spring openings.

Future studies should include evaluation of all practical means of conjunctive use of ground water and surface water, to obtain the optimum development of both. Possibilities of artificial recharge should be investigated. The current U.S. Geological Survey's continuing observation and research studies of the Edwards aquifer should be continued indefinitely into the future.

It is recommended that special studies be made in (1) the area in which the artesian portion of the aquifer occurs from northeastern Bexar County to the northeastern limit of the aquifer near Kyle in Hays County, (2) the area within the Cibolo Creek basin where recharge enters the main portion of the aquifer, and (3) the area around Hueco Springs, between it and possible sources of recharge, and between it and San Marcos Springs.

In addition, further studies should be made of natural recharge to the Edwards aquifer in the Guadalupe River basin and the possibilities of artificial recharge through wells in this area. These studies should include detailed well inventories, water-level measurements, sampling of waters for chemical analyses and tritium determinations, and test drilling in selected localities. A continuous gaging station should be established to measure the flow of Hueco Springs, and waters from Comal, San Marcos, and Hueco Springs should be sampled approximately every 3 months for monitoring and evaluating possible pollution.

INTRODUCTION

Purpose

The purpose of this report is to document information now available on Comal, San Marcos, and Hueco Springs, and to define the geologic and hydrologic conditions under which the springs occur. The need for the report has been occasioned by the planning activities underway by the Texas Department of Water Resources with respect to water supplies for the Guadalupe, San Antonio, and Nueces River basins. In their upper reaches, these three basins are crossed and hydrologically connected by the Edwards (Balcones Fault Zone) aquifer, which is the principal source of water supplies for Uvalde, Sabinal, Hondo, San Antonio, New Braunfels, San Marcos, and other users in this area. The aquifer receives water principally by infiltration from the streams which cross it. The water in the aquifer moves generally from west to east, across the lines of surface drainage divides, and is discharged through wells and springs en route. Comal, San Marcos, and Hueco Springs are in the eastern part of the aquifer in Comal and Hays Counties, and their flow comprises most of the natural discharge of the aquifer.

Scope

This investigation has included a compilation of historical records of the flow of Comal, San Marcos, and Hueco Springs and the quality and temperature of the water. It also has included a compilation of measurements of tritium contents of the water and an evaluation of the hydrologic meaning of these measurements. Available published and unpublished reports on the geology in the vicinity of each group of springs have been studied, and maps and cross-sections have been prepared presenting the information for each locality. Existing knowledge of correlations of the spring flows with water levels in wells, pumpage, recharge, and streamflow has been compiled, and representative data are presented and discussed herein. Recharge areas for the three groups of springs have been investigated and described. The possibilities of contamination of the water issuing from the springs are discussed. Likewise, the possibilities of artifically regulating the discharge of the water from the springs are considered and discussed. Finally, because complete answers are not yet available, recommendations are made for additional research and observations in the future.

Area of Investigation

The locations of Comal, San Marcos, and Hueco Springs are shown on the various maps included in this report. The primary study area for this report has been that part of the Edwards (Balcones Fault Zone) aquifer lying east and northeast of San Antonio in parts of Bexar, Guadalupe, Comal, and Hays Counties. In studying the springs, however, it has been necessary to consider to some extent the remaining part of the aquifer in Bexar, Atascosa, Medina, Uvalde, and Kinney Counties. As shown on Figure 1, the Edwards (Balcones Fault Zone) aquifer in the San Antonio region, as defined by the Texas Department of Water Resources, extends from a ground-water divide at Brackettville on the west through San Antonio to the east, thence northeastward through New Braunfels and San Marcos, terminating at a ground-water divide north of Kyle about 12 miles (19.3 km) northeast of San Marcos. This portion of the entire Edwards (Balcones Fault Zone) aquifer has been called by others the "Edwards Underground Reservoir" or the "Edwards Limestone Reservoir." For convenience throughout the remaining discussions of this report, this portion of the entire aquifer will generally be called the Edwards aquifer or the aquifer.

Previous Investigations

Many investigations of the geology and water resources of this area have been made since the late 1800's. These investigations have been made by a large number of agencies and individuals, some of whom are named in the list of references at the end of this report. Additional references are given in the reports listed. Among the agencies involved are the U.S. Geological Survey; the Texas Department of Water Resources and its predecessors; the San Antonio City Water Board; the Edwards Underground Water District; the U.S. Army Corps of Engineers; the U.S. Bureau of Reclamation; and The University of Texas Bureau of Economic Geology. The geology of the area also has been studied extensively by students at The University of Texas at Austin in connection with masters theses and Ph.D. dissertations.

The most complete studies have been made since the late 1940's by the U.S. Geological Survey in cooperation with the Texas Water Development Board (a predecessor of the Department of Water Resources), the Edwards Underground Water District, and the San Antonio City Water Board. The U.S. Geological Survey has maintained an office continuously since that time in San Antonio for the purpose of studying the Edwards aquifer. During the past several years, the Texas Water Development Board also has maintained an office in San Antonio to study the Edwards aquifer, and it has conducted an extensive test drilling project and has developed a digital computer model of the aquifer.

Acknowledgements

The geologic maps and cross-sections and other information on the positions and thicknesses of the geologic formations given herein are based primarily on maps, reports, and records of the U.S. Geological Survey, The University of Texas Bureau of Economic Geology, and various other investigators from The University of Texas at Austin. Other factual information on the hydrology of the Edwards aquifer, such as spring flows, water levels in wells, quality of water, tritium content of water, etc., has nearly all been obtained from reports and records of the U.S. Geological Survey and its cooperators. Interpretations of data have been available from all the agencies named, as well as having been made by William F. Guyton and Associates in connection with this and previous studies.

Appreciation is expressed to the numerous persons who provided special information and assistance in the preparation of this report. Special thanks are due to Messrs. R. W. Maclay, R. D. Reeves, T. A. Small, and Celso Puente and Dr. F. J. Pearson, Jr., of the U.S. Geological Survey and Mr. W. B. Klemt and Dr. T. R. Knowles of the Texas Department of Water Resources, all of whom provided information from their recent studies of the Edwards aquifer. Grateful acknowledgement also is made of the cooperation provided by Mr. Don Simon, New Braunfels Parks and Recreation Director; Mr. C. R. Smith, New Braunfels City Sanitarian; Mr. Gene Phillips, President of Aquarena, Inc.; and Judge R. T. Pfeuffer, who provided access to and local information concerning Comal, San Marcos, and Hueco Springs, respectively.

Metric Conversions

For persons desiring to use the metric system, the metric equivalents of English units of measurements presented in this report are given in the text in parentheses following the English units. The English units may be converted to metric units by the following factors:

From	Multiply by	To obtain
acre-feet (ac-ft)	1,233	cubic meters (m^3)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
inches (in)	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
yards (yd)	0.9144	meters (m)
miles (mi)	1.609	kilometers (km)

To convert degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula:

$$^{\circ}C = 5/9\ (^{\circ}F - 32)$$

DESCRIPTION OF SPRINGS

Comal, San Marcos, and Hueco Springs each discharge water from the Edwards aquifer. Each of these groups of springs occurs in the Balcones Fault Zone along or near one or more major faults.

Comal Springs

Comal Springs are inside the city limits of New Braunfels in Comal County and are the largest group of springs in Texas. They issue crystal clear from a large number of openings in limestones of the Edwards aquifer along a distance of about 1,500 yards (1,372 m) at the base of the escarpment along the Comal Springs Fault. This escarpment runs approximately in a north-northeast direction. The largest spring discharges are near the southwestern end of the group, in Landa Park which belongs to the city of New Braunfels. The area to the northeast of the park, which surrounds about one-half of the 1,500-yard (1,372-m) stretch along which the springs occur, is privately owned.

The altitude of the spring openings is about 623 feet (189.9 m) above sea level. The water flows into a lake in the park and thence down the Comal River. The springs supply all the water that normally flows in the Comal River, which joins the Guadalupe River at a point about 1 mile east of the springs and at an elevation about 40 feet (12.2 m) below the level of the springs. The level of the lake in Landa Park is controlled by a small dam on the river at the southeastern edge of the park. The large amount of clear, pure water of nearly constant temperature which flows through Landa Park and then down the Comal River between the park and the Guadalupe River is responsible for a large amount of both public and private recreational development.

San Marcos Springs

San Marcos Springs are the second largest group of springs in Texas. They are located in the city of San Marcos in Hays County and are surrounded by land owned by Aquarena, Inc. Aquarena Springs is a privately-owned recreational development whose central feature is San Marcos Springs. The water discharges into a lake impounded by a dam on the San Marcos River about 1,000 feet (304.8 m) downstream from the principal spring outlets. At one time, the water from the lake was used by a small hydroelectric power plant, but this power plant has not been operated for many years. The level of the lake is controlled by boards on a spillway which are reported to be occasionally adjusted by Aquarena, Inc. in connection with its activities. The altitude of the lake surface is approximately 574 feet (175.0 m) above sea level. During dry periods when there is no surface runoff, the springs provide the entire flow of the San Marcos River in this locality.

The water from San Marcos Springs is very clear and pure and almost constant in temperature. The springs occur along or very near the San Marcos Springs Fault, which runs in a southwest-northeast direction. On the northwest side of the lake there is a steep fault-line escarpment, but on the southeast side the land is relatively flat. Water is reported to issue from five large openings in limestones of the Edwards aquifer in the rock bottom of the spring lake and from many smaller openings and sand boils. The water is at least 40 feet (12.2 m) deep in places, although the dam at the lower end of the lake is less than 10 feet (3.1 m) high.

As in the case of Comal Springs, a large amount of recreational development is associated with San Marcos Springs, including Aquarena Springs and public and private developments along the San Marcos River downstream.

Hueco Springs

Hueco Springs are on property belonging to Judge R. T. Pfeuffer. There is no apparent use of the water at this time other than a small amount of recreational and livestock use, although at one time the water was used to operate a very small hydroelectric power plant. The springs are on the west side of the Guadalupe River about 3 miles north of New Braunfels.

Water issues from stream gravels of the Guadalupe River floodplain in two places, one about 500 feet (152.4 m) and the other about 300 feet (91.4 m) west of the river at altitudes reported by the U.S. Geological Survey to be 652 and 658 feet (198.7 and 200.6 m) above sea level. The springs rise within the complexly faulted area related to the Hueco Springs Fault. The source of the water issuing from the springs is the Edwards aquifer. The spring openings are about 4 and 10 feet above the bed of the river, respectively, the one closer to the river being higher. The west spring flows down a small ravine into a diversion canal to a small lake, from which it spills into the river. The east spring rises from a deposit of stream gravels between the county road and the river and flows directly to the river.

Hueco Springs go dry periodically and are not considered to be one of the major spring groups of Texas. However, their average flow has been estimated by the U.S. Geological Survey to be 26,000 acre-feet (32.1 million m^3) per year for the period 1945-73, which makes the springs large enough to be seriously considered in any evaluation of water resources of the Edwards aquifer.

EDWARDS (BALCONES FAULT ZONE) AQUIFER

The Edwards (Balcones Fault Zone) aquifer in the San Antonio region is comprised of the Edwards Group and the associated limestones of the Georgetown and Walnut Formations. The entire Edwards (Balcones Fault Zone) aquifer extends along the Balcones Fault Zone in a relatively narrow belt from north of Georgetown through Austin, San Marcos, New Braunfels, San Antonio, Hondo, Sabinal, and Uvalde to Brackettville. That part of the entire aquifer generally considered in this report and simply called the Edwards aquifer, is the hydrologic system in the San Antonio region between the ground-water divide at Brackettville in Kinney County and the ground-water divide just north of Kyle in Hays County. Essentially it is that part of the entire Edwards aquifer which occurs in the Guadalupe, San Antonio, and Nueces River basins, and supplies water to several springs in these basins, including Comal, San Marcos, and Hueco Springs. The Edwards aquifer, so defined, is about 5 to 30 miles (8.0 to 48.3 km) wide and about 175 miles (281.6 km) long (Figure 1). Most of the discussions in this report emphasize and focus on that part of the aquifer northeast of San Antonio in parts of Bexar, Guadalupe, Comal, and Hays Counties, which is the area that includes Comal, San Marcos, and Hueco Springs.

Geology

The Edwards Group and the associated limestones comprising the Edwards aquifer formerly were named the Edwards, Comanche Peak, and Georgetown Formations. The name Comanche Peak is not now in common usage. Instead, in Hays, Comal, Guadalupe, Bexar, and eastern Medina Counties all of the rocks which formerly were called Edwards and Comanche Peak Formations are now included in the Edwards Group, which is divided into the Person and Kainer Formations. In the western part of the area, in western Medina, Uvalde, and Kinney Counties, the rocks formerly known as Georgetown, Edwards, and Comanche Peak Formations are now called the Devil's River Formation in a reef complex known as the Devil's River Trend, or the West Nueces, McKnight, and Salmon Peak Formations in the Maverick basin. They all, however, are still recognized as the rocks comprising the Edwards aquifer. In addition, the relatively thin Walnut Formation, formerly considered to be below the Edwards aquifer, is now included in the aquifer as its basal subdivision.

The Edwards aquifer ranges in thickness from about 400 to 1,000 feet (121.9 to 304.8 m). It is underlain by the Glen Rose Formation, which contains impermeable clays and relatively impermeable limestones and dolomites, and it is overlain by the Del Rio Clay, which forms a confining bed above the aquifer.

The Edwards aquifer lies within the physiographic province known as the Balcones Fault Zone. North of the fault zone, on the Edwards Plateau, the Edwards and associated limestones occur at the surface and dip gently to the south and southeast. At the north and northwest edge of the fault zone, where the topography slopes steeply, these formations have been almost completely removed by erosion. However, in the fault zone, the Edwards and associated limestones occur again, first at the surface and then passing beneath younger beds. A combination of increased dip and faulting exposes progressively younger beds at the surface in the downdip directions and places the Edwards aquifer at progressively greater depths beneath the surface.

Recharge

The Edwards aquifer is recharged principally by seepage of water from streams crossing the outcrops of the limestones comprising the aquifer, and by direct infiltration of precipitation falling on the outcrops of the limestones. The recharge area is shown on Figure 1. A large part of the recharge is contributed by perennial spring-fed streams, including the Nueces River, Frio River, Sabinal River, Hondo Creek, Medina River, Cibolo Creek, and Blanco River. The springs supplying the streams flow mostly from the Edwards and associated limestones at the edge of the Edwards Plateau where the streams have cut completely through these formations. Most of the perennial base flows of these streams are lost to the Edwards aquifer where the streams cross the recharge area of the aquifer to the south and southeast of the plateau.

Average recharge to the aquifer from all the streams except the Guadalupe River, and direct penetration of precipitation in the outcrop of the Edwards and associated limestones in their drainage basins, was estimated by the U.S. Geological Survey to have been about 561,000 acre-feet (692 million m^3) per year for the period 1934-73. Additional amounts, estimated to have been about 30,000 acre-feet (37 million m^3) per year and 6,000 acre-feet (7.4 million m^3) per year, have been contributed by inflow from the Glen Rose Formation and by direct penetration of precipitation in the outcrop of the Edwards and associated limestones in the Guadalupe River basin, respectively. There is no measurable recharge directly contributed to the Edwards aquifer by the Guadalupe River. Roughly one-fourth of the recharge to the aquifer occurs in the drainage areas of Cibolo Creek and other streams to the east and northeast. The remaining recharge occurs in the drainage areas west of Cibolo Creek.

Figure 2 shows the recharge computed by the U.S. Geological Survey for the period 1934 through 1973, with a maximum of about 1,711,000 acre-feet (2,110 million m^3) in 1958 and a minimum of about 44,000 acre-feet (54.3 million m^3) in 1956. This graph does not include any of the recharge from the Guadalupe River basin or the Glen Rose Formation. Until recently the U.S. Geological Survey has not considered these, or the discharge of Hueco Springs, in its water balance studies for the Edwards aquifer. Other studies, however, indicate that these quantities should be included.

Natural Discharge

Before there were any withdrawals from wells, all the recharge that entered the Edwards aquifer was eventually discharged by natural means. Essentially all of this discharge occurred through six major spring outlets: Leona Springs along the Leona River south of Uvalde, San Pedro and San Antonio Springs at San Antonio, Comal Springs at New Braunfels, Hueco Springs a short distance up the Guadalupe River from New Braunfels, and San Marcos Springs at San Marcos. The water moved generally from west to east, and the springs served as natural spillways for the aquifer. The largest springs were Comal Springs, San Marcos Springs, and San Antonio Springs. The total discharge of the springs varied from time to time depending on climate and the amount of water which entered the aquifer as recharge, but because of the dampening effect of the storage in the aquifer, the variation in discharge was not nearly as much on a year-to-year basis as the variation in the amount of recharge. Since the withdrawals from wells began, spring flows have decreased, with the total reduction in volume of spring flows being roughly equal to the total volume of withdrawals from wells.

The spring flows from 1934 through 1974 are shown on Figure 2. Hueco Springs discharge is shown separately from the discharges of the other springs because in the past it has not been included by the U.S. Geological Survey in its water balance studies for the Edwards aquifer.

Storage

The Edwards aquifer serves both as an underground conduit and an underground storage reservoir. As a conduit, it transmits water from recharge areas to points of discharge. En route, the water is held in storage in the intergranular porosity of the rocks and in the fractures and solution openings. In 1956, Petitt and George estimated that the specific yield of the aquifer might be about 2 percent and that in that case the total drainable storage of water in the reservoir would be about 15 million acre-feet (18.5 billion m^3). More recently, the Texas Water Development Board has estimated that the specific yield is about 6 percent (Klemt and others, 1975), and this is the number used in the digital model which the Water Development Board has developed for the Edwards aquifer. If this number is correct, the total storage in the aquifer is more nearly on the order of 45 million acre-feet (55.5 billion m^3) than the 15 million acre-feet (18.5 billion m^3) previously estimated by Petitt and George. Recent estimates by Maclay and Small (1976), based on studies of cores from test holes, are that the drainable intergranular porosity for the entire thickness of the aquifer ranges from 1.2 to 2.5 percent in the eastern part of the aquifer area and that it probably is smaller in the western part. This is water which is in addition to that held in the fractures and solution openings in the rocks. Other studies by Maclay and Rettman (1973), based on annual water balances and stage changes in the aquifer, indicate that the specific yield of the aquifer is about 3 percent. All of these studies indicate that the total drainage storage in the aquifer probably is somewhere in the order of 15 to 45 million acre-feet (18.5 to 55.5 billion m^3).

Studies by Lowry (1955), Petitt and George (1956), and Guyton & Associates (1963) indicate that the amount of storage in the Edwards aquifer in the zone of transient storage (that is, in that part of the reservoir through which the water level has fluctuated during historical time) amounts to roughly 2.5 million acre-feet (3.08 billion m^3). This is the amount of water which has been alternately stored and released when the water levels in wells have fluctuated about 70 to 75 feet (21.3 to 22.9 m) at San Antonio.

Bad Water Line

Chemical analyses of water from the Edwards aquifer show an abrupt change in the quality of the

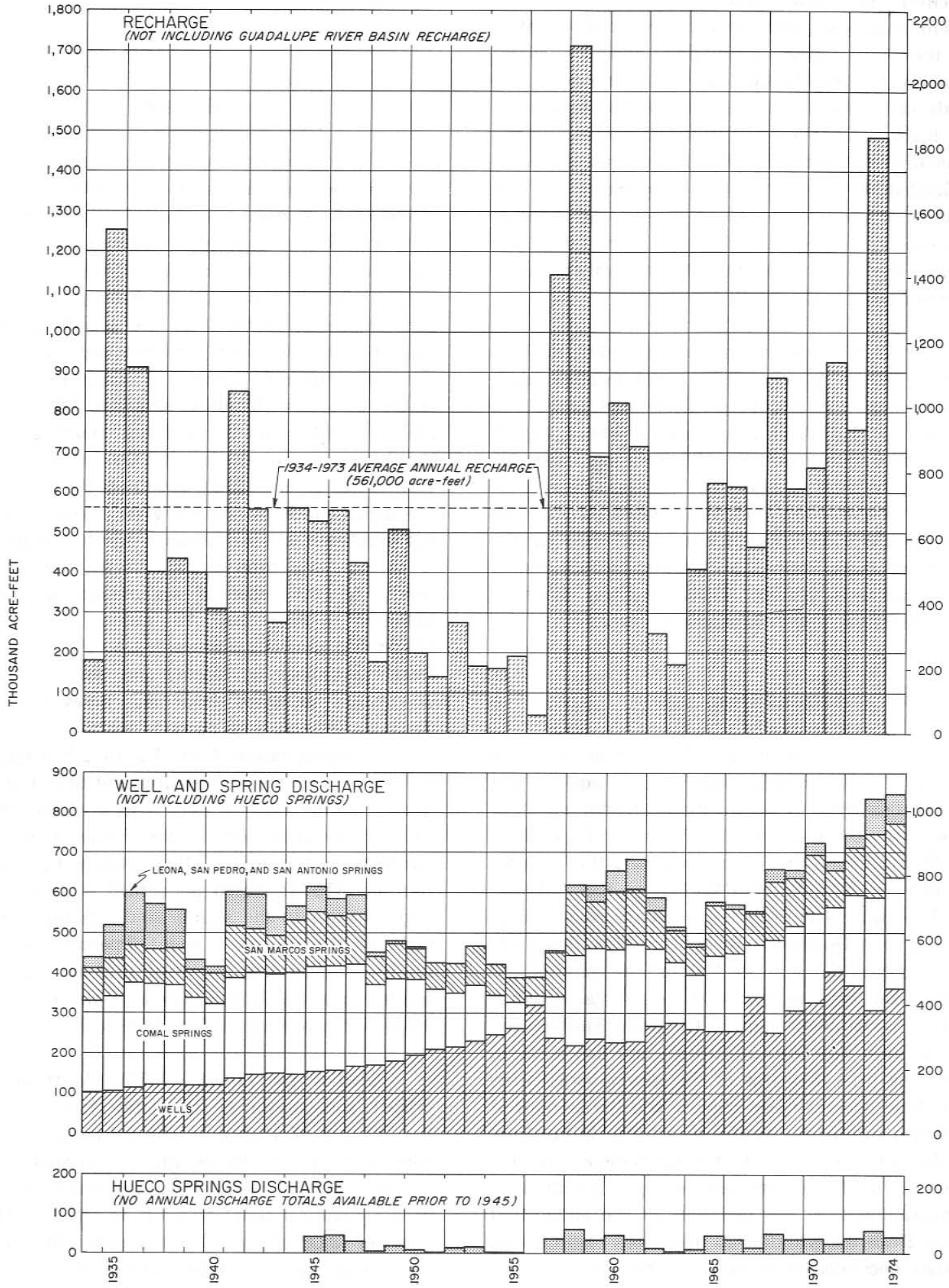

Figure 2

Recharge and Discharge of the Edwards Aquifer and Discharge From Wells and Major Springs

water along the south and southeast edge of the aquifer. This indicates that the openings in the limestones are not large or well connected in this direction and that the water in the aquifer does not circulate freely downdip from this line of quality transition. The zone of transition from fresh to mineralized water is relatively narrow and is commonly called the bad water line. In parts of the area, this bad water line coincides with faults. However, in other parts of the area, the line has no relationship to known structural features.

Recent studies by the U.S. Geological Survey have shown that the rock matrix in the fresh water zone is less porous than the rock matrix in the mineralized zone because recrystallization and cementation have obliterated or filled the interparticle spaces. However, fractures in the fresh water zone are relatively open, whereas they are generally closed or only slightly open within the mineralized zone (Maclay and Small, 1976).

The bad water line of the Edwards aquifer is shown on Figure 1, and in more detail on Figure 3 for that portion of the aquifer in parts of Bexar, Guadalupe, Comal, and Hays Counties northeast of San Antonio. The position of the line as shown is the most recent version by the U.S. Geological Survey, with a few modifications made as part of this study in the area northeast of San Antonio. This is the approximate position at which the water on the northwest side of the bad water line is believed to have less than 1,000 milligrams per liter dissolved solids and that on the southeast side of the line has more than 1,000 milligrams per liter dissolved solids. The control used to draw the bad water line is shown on Figure 3. It should be noted that the control is fairly good in places, but in other places it is severely lacking, especially on the southeast (bad water) side of the line. Also, it should be noted that the available control for positioning the line, as drawn by the U.S. Geological Survey in the vicinities of Comal Springs and San Marcos Springs, is especially limited.

In recent years, it has been found that the bad water line is not a vertical line through the entire Edwards aquifer along its entire length. In some places, the bad water line is farther downdip in the upper portion of the aquifer than it is in the lower portion. This has been shown by test holes on both sides of San Marcos.

Whether the bad water line will move in response to changes in recharge and withdrawals from wells has not been finally determined. The data which have been compiled to date indicate that there has not been much change so far, and that the chances do not appear great that there ever will be a change. However, research by the U.S. Geological Survey in cooperation with the Texas Department of Water Resources and the San Antonio City Water Board is still being conducted in order to predict with more certainty what will happen in the future if water levels in wells are drawn down to depths far below those which have prevailed in historical times.

Withdrawals of Water Through Wells

The first large wells penetrating the Edwards aquifer in the San Antonio area were drilled in the latter part of the 19th century. The first successful well for the San Antonio Water Company was completed in 1891. Other wells were soon constructed, and it is reported that in 1897 the discharge of wells in Bexar County was over 30,000 acre-feet (37 million m^3). In 1934 the withdrawals from wells in the entire Edwards aquifer in the San Antonio region was about 100,000 acre-feet (123 million m^3). Annual withdrawals from 1934 through 1974 are shown on Figure 2. The maximum annual withdrawal was in 1971, when the total was 407,000 acre-feet (502 million m^3). It will be noted from Figure 2 that withdrawals are greater during periods of low recharge, when the weather is dry and there is more need for water for public supply and irrigation. Total withdrawals from the reservoir through wells in each county in 1974 were as follows: Kinney County, 200 acre-feet (247,000 m^3); Uvalde County, 97,000 acre-feet (120 million m^3); Medina County, 29,000 acre-feet (35.8 million m^3); Bexar County, 220,000 acre-feet (271 million m^3); Comal County, 11,000 acre-feet (13.6 million m^3); and Hays County, 7,000 acre-feet (8.6 million m^3). These made a total of 364,000 acre-feet (449 million m^3).

Effects of Withdrawals

The primary effects to date of withdrawals of water through wells have been reductions in spring flows. The Edwards aquifer is still full to overflowing and water is still being discharged through the springs which are its natural spillways. So long as this is the case, any water withdrawn from a well is essentially offset by a subsequent reduction in discharge from a spring. Water levels in the aquifer fluctuate in response to changes in withdrawals, but the fluctuations are dampened by the changes in discharge from the springs, which offset the effects of the changes in withdrawals from the wells. So far in the history of withdrawals from the Edwards aquifer, the recharge and discharge relationships have been such that the aquifer has become completely refilled during wet periods after dry periods. In fact, the highest water levels on record and the highest spring flows have been reached during the period 1973-75.

The effects of withdrawals through wells are graphically shown on Figure 2. Note that the flows of Leona, San Pedro, and San Antonio Springs completely disappeared during the drought period from 1951 through 1956, when the pumping from wells was accelerating and reached a high of over 300,000 acre-feet (370 million m^3) in 1956. Comal Springs decreased in flow drastically during this period, and ceased to flow for a period of time from June 13 to November 4, 1956. The lowest recorded flow for San Marcos Springs also occurred in 1956, when the annual discharge was about 48,000 acre-feet (59.2 million m^3).

The effects of withdrawals through wells have been most evident at San Antonio Springs and San Pedro Springs, which are at altitudes of about 668 feet (203.6 m) and 661 feet (201.5 m), respectively, and which are in the area of heavy pumping in and near San Antonio. These springs have been dry or nearly dry in many years since withdrawals through wells became a large proportion of the total yield of the aquifer.

In recent years, Comal Springs have become more and more affected by pumping. This may be seen on Figure 2 and also on Figure 13, which gives monthly flows from the springs. Studies indicate that, for the most part, however, the flow from San Marcos Springs has been relatively unaffected by withdrawals from wells. The only very substantial effect recorded so far on San Marcos Springs occurred during 1956 when Comal Springs were dry.

Predictions by Guyton (1963), the U.S. Bureau of Reclamation (1972), and Klemt and others (1975), indicate that, if withdrawals from wells continue to increase to average amounts greater than the average recharge to the Edwards aquifer, both Comal and San Marcos Springs may be expected to cease to flow at some time in the future. When this happens, further increases in pumpage then will be solely at the expense of storage in the aquifer, and the water levels in the aquifer will decline more rapidly in response to unit increases in pumping.

GEOLOGY IN VICINITY OF SPRINGS

General

Stratigraphy

The rocks comprising the Edwards aquifer in the primary study area northeast of San Antonio in parts of Bexar, Guadalupe, Comal, and Hays Counties, and the formations overlying and underlying it in this area, are Cretaceous limestones, dolomites, shales, and clays, which are fractured and displaced by faulting in the Balcones Fault Zone (Figures 3, 4, and 14). These rocks are locally mantled by Quaternary alluvium. They are described, from oldest to youngest, in the following paragraphs.

Glen Rose Formation

The Glen Rose Formation, which underlies and serves as a confining base, or floor, of the Edwards aquifer, consists of limestone, dolomite, and clayey limestone as alternating resistant and recessive beds. The limestone is fine-grained, hard to soft, chalky and clayey, and has some silty, laminated, calcareous clay. The dolomite is fine-grained and porous. Fossils include molluscan steinkerns, rudistids, oysters, and echinoids. The upper part of the Glen Rose is relatively thinner bedded and more dolomitic than the lower part. The lower part is more massive, generally much more fossiliferous, and contains some rudistid reefs. The Glen Rose is about 900 feet (274 m) thick in northern Bexar, Comal, and Hays Counties (Bureau of Economic Geology, 1974b, 1974c; George, 1952; Stricklin and others, 1971).

Walnut Formation

The Walnut Formation is a relatively impermeable nodular limestone (Moore, 1959 and 1964; Abbott, 1973) at the base of the Edwards aquifer. The lower part of the Walnut is a hard, dense, clayey, burrowed, dolomitic limestone. The upper part is a soft to hard, nodular, clayey limestone containing common specimens of *Exogyra texana.* The upper part of the Walnut commonly contains minor quartz sand and glauconite. The Walnut is 30 to 50 feet (9.1 to 15.2 m) thick in the primary study area (Bureau of Economic Geology, 1974a; George, 1952; Newcomb, 1971).

Edwards Group

The Edwards Group is a thick section of white to gray, cherty limestones and dolomite, the most porous and permeable strata of the Edwards aquifer northeast of San Antonio. In the Balcones Fault Zone in northern Bexar, Guadalupe, Comal, and Hays Counties, the Edwards Group has been divided into the Kainer and Person Formations (Rose, 1972; Abbott, 1973). The Kainer Formation consists of a lower section of honeycombed and cavernous limestones, dolomitic limestones, and leached evaporitic rocks. The upper

section of the Kainer is mainly dense, chalky to hard, medium-grained, bioclastic limestone characterized by miliolid foraminifera (Maclay and Small, 1976). The Kainer is 230 to 285 feet (70.1 to 86.9 m) thick in the study area. The Person Formation is marked by the regional dense bed at its base, which is a dense, shaly, clayey limestone. The upper part of the Person is a sequence of hard, recrystallized limestones, variably dense to very porous. Locally rudistids are common both as small reefs and as individuals. Solution breccias and honeycombed beds are also common (Maclay and Small, 1976). The Person is 130 to 180 feet (39.6 to 54.9 m) thick in the primary study area.

Georgetown Formation

The Georgetown Formation consists mainly of nodular limestone with minor calcareous shale and is the uppermost subdivision of the Edwards aquifer in the primary study area. This limestone is fine grained and clayey and is usually soft and nodular. Some sections of the Georgetown may be hard, brittle, and thickly bedded. The most common fossils are marine oysters and brachiopods, including the small brachiopod *Kingena wacoensis.* The Georgetown is 15 to 50 feet (4.6 to 15.2 m) thick in the study area in Bexar, Guadalupe, Comal, and Hays Counties (Bureau of Economic Geology, 1974a and 1974c; George, 1952; Newcomb, 1971).

Del Rio Formation

The Del Rio Formation, which is the principal confining bed above the Edwards aquifer, consists of calcareous and gypsiferous clay containing common pyrite and becoming less calcareous and more gypsiferous upward. The Del Rio often contains some thin lenticular beds of very calcareous siltstone. Fossils include marine microfossils and pelecypods, in particular the oyster *Exogyra arietina.* A complete section of the Del Rio is 40 to 70 feet (12.2 to 21.3 m) thick in the primary study area (Bureau of Economic Geology, 1974a, 1974b, and 1974c; DeCook, 1956; George, 1952).

Buda Formation

The Buda Formation consists of an upper section of very fine-grained, porcelaneous, white to light gray limestone, and a lower section of harder, fine-grained, bioclastic, often burrowed, limestone that is a pinkish yellow brown or pale orange. The Buda is commonly glauconitic and pyritiferous and varies from massive, poorly bedded to nodular. The Buda is 35 to 70 feet (10.7 to 21.3 m) thick in the primary study area (Bureau of Economic Geology 1974a, 1974b, and 1974c; Bills, 1957; George, 1952; Newcomb, 1971).

Eagle Ford Group

The Eagle Ford Group consists of shale, siltstone, and limestone. The lower part is thinly bedded calcareous shale. The middle of the unit is a sequence of sandy, flaggy limestone which is overlain by an upper sequence of compact, silty shale. The Eagle Ford is about 30 feet (9.1 m) thick in the primary study area (Bureau of Economic Geology, 1974c; Bills, 1957; DeCook, 1956).

Austin Group

The Austin Group consists of chalky and clayey limestone. The chalky limestone and soft clayey limestone units alternate throughout the Austin and are locally broken by seams of bentonite. The Austin contains sparse glauconite and common pyrite nodules. Fossils are uncommon and consist mainly of foraminifera and *Inoceramus* prisms (Bureau of Economic Geology, 1974a, 1974b, and 1974c). The Austin is 140 to 200 feet (42.7 to 61.0 m) thick in the primary study area (DeCook, 1956).

Taylor Group

The Taylor Group consists of a lower and an upper section of calcareous, montmorillonitic clay separated by a usually thick section of chalk and chalky, clayey limestone. The clays contain variable silt-sized quartz and scattered calcite, glauconite, and pyrite. Both clays are blocky with conchoidal fracture and may develop poor fissility. The limestone is primarily a chalk grading upward to a chalky, clayey limestone (Bureau of Economic Geology, 1974a, 1974b, and 1974c). The Taylor Group is about 300 feet (91.4 m) thick in the primary study area (George, 1952; DeCook, 1960).

Navarro Group

The Navarro Group consists of calcareous clay that is locally silty or sandy, is thinly laminated and has conchoidal fracture. The Navarro is not mapped separately from the Taylor Group because of its similarity to the upper clay section of the Taylor (Bureau of Economic Geology, 1974a, 1974b, and 1974c). The Navarro is about 300 feet (91.4 m) thick in the primary study area (DeCook, 1960).

Quaternary Alluvium

Quaternary alluvium occurs discontinuously in the larger stream valleys in the hill country northwest of the Balcones escarpment and forms extensive deposits along major streams southeast of it. This alluvium is mainly floodplain and fluvial terrace deposits and consists of gravel, sand, silt, and clay in varying proportions. A few isolated outcrops of caliche-cemented gravel also occur in the area, occupying topographically high areas not associated with currently active streams (Bureau of Economic Geology, 1974b).

Structural Geology

The surface geology in the primary study area in Bexar, Guadalupe, Comal, and Hays Counties, and elevations of the top of the Glen Rose Formation (Figure 4), show this area to be very complex structurally. The rocks in the area are broken into numerous large tilted blocks by major faults and fault zones. In this area, the Edwards aquifer is comprised of a relatively shallow, water table subsystem on the northwest connected to an artesian subsystem on the southeast. In the primary study area, the artesian subsystem is continuous from Bexar County to Hays County and is characterized by surface outcrops of the Austin and Taylor Groups and extensive mantles of Quaternary alluvium. The area underlain by the shallow, water table subsystem is generally characterized by extensive outcrops of the Edwards Group and Walnut and Georgetown Formations.

Detailed Geology of Comal, San Marcos, and Hueco Springs Localities

The geology around Comal, San Marcos, and Hueco Springs (Figures 5 through 10) was taken from the best available existing geologic maps. These maps were briefly field checked in the immediate vicinity of each group of springs. The geologic units shown are those mapped by previous workers, except that the Edwards limestone has been treated as the Edwards Group and, where possible, the Kainer and Person Formations have been mapped separately. This usage follows the definitions of these units by Rose (1972) except where the Kainer Formation is emended to exclude the Walnut Formation, which is mapped after the usage of Abbott (1973) and Moore (1959 and 1964).

Comal Springs

Comal Springs issue from limestones of the Edwards Group at the base of the Balcones escarpment. In the vicinity of the springs, the Edwards Group crops out in a continuous escarpment with about 100 feet (30.5 m) of topographic relief that has been created along the Comal Springs Fault. Individual springs occur along the base of the escarpment for a distance of about 1,500 yards (1,372 m). Most springs issue directly from the limestone, but some spring water rises into and through the Quaternary alluvium that occurs southeast of the escarpment related to the Comal Springs Fault (Figure 5). All observed springs are less than 50 yards (45.7 m) from the base of the escarpment.

Northwest of Comal Springs, 300 to 350 feet (91.4 to 106.7 m) of the Edwards Group occurs above the Walnut and Glen Rose Formations. Outcrops of the Del Rio and Buda Formations overlie the Georgetown Formation northwest and northeast of the Comal Springs locality at Mission Hill and north of Gruene (George, 1952; Bureau of Economic Geology, 1974b; Whitney, 1956b; King, 1957). Assuming a linear dip between these outcrops places the base of the Edwards Group at about 460 feet (140.2 m) above mean sea level one mile (1.6 km) northwest of the springs along the line of the cross-section in Figure 6. The log of a U.S. Army Corps of Engineers core hole (George, 1952, Well G-49 or DX-68-23-302) places the elevation of the base of the Edwards Group at about 390 feet (118.9 m) above mean sea level just over 100 yards (91.4 m) northwest of the Comal Springs Fault near the largest spring outlet. Apparently the rocks immediately northwest of the Comal Springs Fault are folded or faulted about 70 feet (21.3 m) downward toward the southeast. The units are shown to be folded in Figure 6 because no direct evidence of faulting (displaced mappable horizons or units) was observed in the field. Dipping beds with a wide variety of strikes and dips were observed at many places in the area immediately northwest of the Comal Springs Fault. Faulting cannot be proven in this area with aerial photograph linears; however, linears traced from February 1951 photos show the limestones in the area immediately northwest of the Comal Springs Fault to be extremely fractured.

Along the main trace of the Comal Springs Fault, the rocks of the Edwards Group are faulted against the Taylor Group. Well data along the line of the cross-section show that the area southeast of the Comal Springs Fault is broken into at least three major blocks. The top of the Georgetown limestone is displaced in these three fault blocks to elevations of about 10 feet (3.1 m), 110 feet (33.5 m), and 170 feet (51.8 m) above mean sea level, respectively, toward the southeast. Drillers' logs of wells to the northeast along and southeast of the escarpment show the Edwards and Georgetown limestones at very shallow depths, suggesting that the Comal Springs Fault itself may consist of several closely spaced fractures.

The surface geology for the area surrounding Comal Springs (Figure 5) was taken almost entirely from George (1952). The San Antonio Sheet of the Geologic Atlas of Texas (Bureau of Economic Geology, 1974b) agrees completely in the vicinity of the springs with the map by George except where the atlas map shows two Quaternary alluvium units instead of one. A geologic map by Whitney (1956b) was also consulted, but it was not used because it did not agree at Comal Springs with the maps by George and the Bureau of Economic Geology. The geologic cross-section (Figure 6) was drawn from the surface geology (Figure 5) and available well data along the line of section. The thicknesses shown for geologic units northwest of the Comal Springs Fault were taken from Abbott (1973). Also consulted was the work of George (1952), King (1957), and Sieh.[1] Southeast of the Comal Springs Fault, the displacements and thicknesses shown were defined in successive fault blocks as follows: with a drillers' log from well DX-68-23-303 and an electric log from the Lower Colorado River Authority's (LCRA) Comal Plant No. 3 Well (DX-68-23-304) in the first fault block; with an electric log from the LCRA Comal Plant No. 2 Well or Test Hole in the second fault block; and with an electric log from the LCRA Comal Plant No. 1 Well or Test Hole in the third or southeasternmost fault block.

San Marcos Springs

San Marcos Springs issue from limestones of the Edwards Group at the head of the San Marcos River near the base of the Balcones escarpment. The springs are located along or very near the San Marcos Springs Fault. Near the springs, the Person (upper Edwards Group), Georgetown, Del Rio, and Buda Formations and the Eagle Ford Group crop out in a series of hills that comprise the escarpment. Quaternary alluvium mantles the flatland areas, and Quaternary colluvium locally mantles the hillsides (Figure 7).

Immediately to the northwest of San Marcos Springs, the Georgetown Formation and Edwards Group are exposed beneath a cap of the Del Rio and Buda Formations, and the Eagle Ford Group. The top of the Edwards Group varies from about 615 feet (187.5 m) to 595 feet (181.4 m) above mean sea level under most of the area northwest of the springs, with the rocks dipping slightly toward the southeast (Figure 8).

The top of the Edwards Group is at an elevation of about 575 feet (175.3 m) above mean sea level just northwest of the San Marcos Springs Fault near the springs and is at an elevation of about 230 feet (70.1 m) immediately to the southeast across the fault. The San Marcos Springs Fault displaces the Austin and Taylor Groups against the Person (upper Edwards Group), Georgetown and Del Rio Formations. This displacement is substantiated by outcrop and drillers' log data (DeCook, 1960, well H-58 and well H-82). Southeast of the San Marcos Springs Fault, the rocks are faulted into two major blocks by the northeastern extension of the Comal Springs Fault. The top of the Edwards southeast of the Comal Springs Fault is about 110 feet (33.5 m) below mean sea level, compared to about 230 feet (70.1 m) above mean sea level across the fault to the northwest. This displacement is also substantiated by drillers' log data (DeCook, 1960, well H-64 and well H-98).

The surface geology for the area surrounding San Marcos Springs (Figure 7) was taken almost entirely from DeCook (1956 and 1960). Maps by Whitney (1959) and the Bureau of Economic Geology (1974c) were also consulted, but the maps by DeCook appear to be the most accurate and most detailed geology available. The geologic cross-section through San Marcos Springs (Figure 8) was drawn from DeCook's surface geology (Figure 7) and available drillers' log and core hole data. Thicknesses shown on the geologic section were taken from DeCook (1960, Table 3), from DeCook's mapped thicknesses and drillers' logs (DeCook, 1960), and from U.S. Geological Survey log and core data from well LR-67-09-110 southwest of San Marcos. A U.S. Geological Survey gamma log from a well owned by Travis H. Tate was also consulted.

Hueco Springs

Hueco Springs issue from alluvium inside an incised meander bend of the Guadalupe River about three miles north of New Braunfels. The spring water rises from limestones of the Edwards Group, flows into the Quaternary alluvium along the west side of the Guadalupe River, and issues from two shallow depressions in the alluvial surface.

Hueco Springs are located just south of the trace of the Hueco Springs Fault, which has 380 to 400 feet (115.8 to 121.9 m) of displacement in the vicinity of the springs. The trace of the Hueco Springs Fault is exposed in the Guadalupe River bed just northeast of the springs as a small escarpment with a waterfall (George, 1952, Plate 1-A). Along the east bank of the river, the Person (upper Edwards Group) and Georgetown Formations are in contact with the Walnut Formation across the fault (George, 1952, and Guyton & Associates, 1975, field

[1] Sieh, T. W., 1975, Edwards (Balcones Fault Zone) aquifer test well drilling investigation: Texas Water Devel. Board unpublished file rept.

investigations). Northwest of the fault the Kainer (lower Edwards Group) and Walnut Formations are exposed. These rocks are apparently only slightly broken by faulting or other deformation. The Person, Georgetown, Del Rio, and Buda Formations, and the Eagle Ford Group are exposed in the complexly faulted and deformed area southeast of the Fault (Figure 9).

The exposed Kainer Formation northwest of the Hueco Springs Fault is deeply dissected by many small ephemeral drainages and is cut almost completely by the Guadalupe River. In most of this area near the springs the base of the Kainer is 650 to 660 feet (198.1 to 201.2 m) above mean sea level. Just northwest of the Hueco Springs Fault a small fault displaces the base of the Kainer to an elevation of 630 to 640 feet (192.0 to 195.1 m) (Figure 10).

Southeast of the Hueco Springs Fault the base of the Kainer is faulted down to between 210 and 370 feet (64.0 and 112.8 m) above mean sea level in a series of four fault blocks. Between the Hueco Springs Fault and the southeasternmost fault shown on the map (Figure 9) the rocks are in a complexly faulted and possibly folded graben characterized by surface exposures of the Del Rio and Buda Formations, and the Eagle Ford Group (Figure 10).

The surface geology for the area surrounding Hueco Springs (Figure 9) was taken mainly from Bills (1957). Maps by George (1952), Whitney (1956a and 1956b), Abbott (1973), and the Bureau of Economic Geology (1974b) also were consulted, but the map by Bills appears to be the most accurate and most detailed and complete geology available. The area northwest of the Hueco Springs Fault was modified after Abbott (1973). This modification involved using Abbott's mapping of the Walnut Formation rather than following the usage of Bills (1957) and George (1952). Mapping a thicker Walnut Formation places the top of the Glen Rose 30 to 40 feet (9.1 to 12.1 m) lower in this area than previously mapped by Bills and George.

The geologic cross-section (Figure 10) was drawn from the surface geology shown by the geologic map (Figure 9), except where the fault block containing Hueco Springs was reinterpreted based on field observations from this and previous studies (Guyton, 1958). Bills (1957, Plate 1) shows that the rocks in the fault block dip between 12 and 14 degrees away from the springs, with a dip direction of about S 60° to 70° W subparallel to the major faults. Bills also shows a Georgetown-Edwards Group contact about one-fourth mile southwest of the springs in the same fault block. If this fault block is not otherwise deformed, these data place the uppermost Glen Rose, the Walnut, or the lowermost Edwards Group beneath the alluvium at the springs, depending on whether the 14° or 12° dip is used. The occurrence of the lowermost Edwards Group, Walnut Formation, or uppermost Glen Rose Fromation beneath Hueco Springs is possible but not likely considering nearby exposures; thus, Bills' interpretation of the geology beneath Hueco Springs has been revised in this report. Immediately northeast of the springs and just southeast of the Hueco Springs Fault, the Person Formation (upper Edwards Group) and Georgetown Formation are exposed in the east bank of the Guadalupe River (George, 1952, and W. F. Guyton & Associates, 1975, field investigations). The Person Formation (upper Edwards Group) is exposed in a bluff immediately west of the springs (Guyton, 1958) and in a large depression or excavation 30 or 40 yards (27.4 or 36.6 m) north of the westernmost spring (W. F. Guyton & Associates, 1975, field investigations). The Georgetown occurs farther to the southwest in the same fault block (Bills, 1957, Plate 1). These exposures suggest that the uppermost parts of the Edwards Group (Person Formation) occur in the area immediately beneath the Quaternary alluvium at the springs. The southwesterly dips of 12° and 14° shown by Bills for these rocks may result from solution collapse structures or slope creep, because the areas shown as having dipping beds are limited "bedrock" exposures and thus cannot be explored completely. The interpretation of the geology beneath Hueco Springs has been changed in this report to show a nearly complete section of the Edwards Group (Person and Kainer Formations) below the alluvium at the springs.

Outcrop data from Bills (1957) and Whitney (1956a and 1956b) were used in the area south and east of the Hueco Springs map area (Figure 9) to show fault displacements in the two southeasternmost fault blocks shown on the cross-section (Figure 10). In addition, data from one well (George, 1952, well G-17) were used in the northwesternmost fault block.

Recent Geohydrologic Subdivision of Edwards Aquifer by the U.S. Geological Survey

The U.S. Geological Survey in cooperation with the Texas Water Development Board, the San Antonio City Water Board, and the Edwards Underground Water Districts has conducted a program of core drilling and detailed analysis of the rocks of the Edwards aquifer. A very important result of the Survey's work has been the vertical geohydrologic division of the aquifer into permeable and less permeable or non-permeable horizons (Figure 11) in the primary study area of this report. According to Maclay and Small (1976), the most porous and permeable sections are Subdivisions 3 (Leached and

Collapsed Member) and 6 (Kirschberg Member). The least porous and permeable sections are Subdivisions 1 (Georgetown Formation), 4 (Regional Dense Member), and 8 (Basal Nodular Member). Figure 11 compares these geohydrologic subdivisions to the terminology used on the geologic maps and cross-sections in this report.

SPRING FLOW

Figures 12 and 13 show average monthly flows of Comal and San Marcos Springs for periods when continuous gaging station records are available. For other periods miscellaneous individual measurements are shown on the graphs. Hueco Springs has never had a continuous gaging station and, accordingly, only individual measurements are available for those springs.

The references at the end of this report include a list of reports and records which provide a complete set of all measurements that have been made of the flows of these three groups of springs through September 1975.

Comal Springs

Records are available for Comal Springs since 1882. Only occasional measurements were made until 1927, at which time the continuous gaging station was installed. So far as can be ascertained, the measurements made prior to 1927 are reasonably representative, and all are included on Figure 12. During the period of record, the minimum monthly flow recorded was zero in 1956 and the maximum monthly average flow was 467 cubic feet per second (13.2 m^3/s) in 1973. The reported daily average flow ranged from a minimum of zero in 1956 to a maximum of 534 cubic feet per second (15.1 m^3/s) in 1973. Prior to 1948, the lowest reported daily average flow was 245 cubic feet per second (6.9 m^3/s) in 1939.

As shown by Figure 13, the seasonal fluctuation in flow from Comal Springs has become much greater during the period since 1927. This appears to be the result of seasonal changes in withdrawals from wells, which have been steadily increasing through the years. In early years, it appears that there was generally a base flow from the springs of about 250 to 300 cubic feet per second (7.1 to 8.5 m^3/s), with the fluctuations above this amount being caused by variations in recharge.

Annual discharges of Comal Springs are shown on Figure 2 for the period 1934-74, and are given for the period 1945-73 in Table 1. The average for the 1945-73 period is 184,000 acre-feet (227 million m^3) per year, with a minimum of 22,000 acre-feet (27.1 million m^3) in 1956 and a maximum of 279,000 acre-feet (344 million m^3) in 1973.

The gaging station for Comal Springs is on Comal River about 1 mile downstream from the springs. During periods of rainy weather, the flow in the river includes some surface runoff. This surface runoff must be substracted from the total flow recorded at the gaging station to estimate the spring flow. For the most part, this has been done by the U.S. Geological Survey in connection with its general studies of the Edwards aquifer. In some instances, however, it was done by this firm specifically for this report.

San Marcos Springs

Intermittent measurements are available for the flow from San Marcos Springs since 1894. However, data prior to 1916 are not included on the graph in Figure 12 because they are not believed to accurately reflect the flow of the springs. For example, a flow of 51 cubic feet per second (1.44 m^3/s) was reported for the springs in 1898. In searching to find out why such an anomalously low flow was reported at that time, it was found that the discharge of the springs was regulated by the stage of the lake at the springs, and the recorded measurements affected by other dams and diversion structures downstream from the spring lake and above the points of measurements. Analysis indicated that at least some of these early measurements were probably greatly affected by what had recently transpired with respect to the regulating structures upstream. Consequently, the first measurements considered reliable enough to include on Figure 12 are those beginning in 1916 when a continuous gaging station was installed on the river. This gaging station was discontinued in 1921 and periodic measurements were again made without a continuous gaging station until 1956. The intermittent measurements made during this 35-year intervening period are included on the graphs in Figures 12 and 13, but they should not be considered entirely reliable as indicators of the actual flows of the springs. Evidence was found to indicate that the U.S. Geological Survey personnel measuring the flow of the San Marcos River at those times usually attempted to make the measurements when the flows were apparently unaffected by regulation of the stream. However, this was not always the case, and it is not possible to distinguish the reliable measurements from those which are not representative. Consequently, while the records for the period 1916 to 1921 and for the period since 1956 are considered reliable as indicators of the actual spring flow, at least on a daily basis, the records for the

Table 1.--Ground-Water Recharge and Discharge, Edwards Aquifer Northeast of San Antonio

[All data from U.S. Geological Survey reports and records. Amounts rounded off to nearest thousand acre-foot.]

	Recharge				Discharge				
	Cibolo Creek Basin	Dry Comal Creek Basin	Sink, Purgatory, York, Alligator Creek Basins	Blanco River Basin	Comal Springs	Comal County Wells	Hueco Springs	San Marcos Springs	Hays County Wells
1945	93	37	25	11	261	2	42	136	2
1946	107	48	30	11	260	2	44	125	3
1947	67	22	21	11	255	2	30	124	3
1948	14	6	4	10	201	2	5	70	2
1949	37	19	13	11	207	2	18	87	3
1950	18	6	7	10	189	2	8	75	3
1951	10	3	4	7	149	2	1	68	2
1952	62	40	11	9	133	1	15	73	6
1953	22	20	14	11	139	3	16	98	4
1954	5	5	3	8	99	3	1	77	5
1955	3	0	3	7	66	4	1	61	3
1956	1	1	2	7	22	11	0	48	3
1957	253	145	31	45	103	10	37	110	3
1958	201	68	32	39	226	5	60	154	2
1959	50	28	15	18	227	5	34	116	2
1960	102	59	37	26	231	5	45	142	2
1961	70	41	32	18	242	8	34	138	2
1962	16	9	7	12	192	6	12	96	3
1963	12	10	5	12	151	5	3	79	3
1964	32	19	8	14	137	5	10	71	3
1965	63	52	33	34	189	6	44	123	3
1966	36	31	17	18	193	5	34	112	4
1967	31	27	5	14	131	8	15	78	5
1968	74	47	32	17	231	7	50	143	4
1969	58	42	27	20	211	8	37	118	4
1970	72	42	31	8	221	8	38	145	5
1971	58	25	9	13	159	9	25	92	7
1972	58	47	14	19	225	10	39	117	7
1973	147	65	46	36	279	10	58	158	6
Mean	61	33	18	16	184	5	26	105	4

period 1921 to 1956 are not considered entirely reliable for correlation studies, even though the U.S. Geological Survey has estimated total flows by months for part of this period and has used the estimates in correlation studies.

Although the gaging station is on the San Marcos River about 1.5 miles (2.4 km) downstream from the springs, the records reported by the U.S. Geological Survey are for spring flow only, as that agency, before publication, has subtracted any surface runoff which was recorded at the gaging station along with spring flow.

The maximum monthly average flow from San Marcos Springs during the period of record was 292 cubic feet per second (8.27 m^3/s) in 1975, and the minimum monthly average flow was 54 cubic feet per second (1.53 m^3/s) in 1956. The average flow during the period 1956-74 was 161 cubic feet per second (4.56 m^3/s). The maximum daily average flow reported was 316 cubic feet per second (8.95 m^3/s) in 1975 and the minimum daily average flow reported was 46 cubic feet per second (1.30 m^3/s) in 1956.

Except for the period during 1956 when Comal Springs were dry, the graph of the flow of San Marcos Springs does not indicate any very noticeable effect caused by withdrawals from wells. The springs seem to have a persistent base flow of slightly less than 100 cubic feet per second (2.83 m^3/s), with short-term fluctuations above this, lasting from a few months to a year or more and ranging in magnitude up to about 200 cubic feet per second (5.66 m^3/s). The graphs indicate that prior to the time withdrawals from wells greatly affected Comal Springs, Comal Springs had a much steadier flow, percentagewise, than San Marcos Springs. Now, however, Comal Springs have a more variable flow in terms of percentage, as they no longer have the sustained type of base flow they formerly had.

Figure 2 shows the annual discharges of San Marcos Springs for the period 1934-74, and Table 1 lists them for the period 1945-73. The average for the 1945-73 period was 105,000 acre-feet (129.5 million m^3), with a minimum of 48,000 acre-feet (59.2 million m^3) in 1956 and a maximum of 158,000 acre-feet (195 million m^3) in 1973.

Hueco Springs

Intermittent measurements are available for the flow from Hueco Springs since 1924, although only a few measurements were made prior to 1945. Beginning in 1945, measurements have been made on approximately a monthly schedule. All available measurements of the flow of Hueco Springs are shown on the graphs in Figures 12 and 13. It will be noted that the flow was zero during a number of drought periods, and that the maximum flow recorded was 131 cubic feet per second (3.71 m^3/s) in 1968.

The flows of the two spring outlets are measured separately. The east spring begins to flow when the flow of the west spring reaches about 25 cubic feet per second (0.71 m^3/s). The flows of the two spring outlets become nearly equal in the high range of their flows. The relative flows of the two outlets are undoubtedly related to the sizes of the openings leading to them.

Based on the monthly measurements, the U.S. Geological Survey has estimated the total volume of flow from the springs since 1945. The annual estimates are given in Table 1 and on Figure 2, and indicate discharges ranging from zero in 1956 to 60,000 acre-feet (74 million m^3) in 1958, with an average of 26,000 acre-feet (32.1 million m^3) per year for the period 1945 through 1973.

It may be noted from Figure 13 that the fluctuations of Hueco Springs are quite similar to those of San Marcos Springs, with Hueco Springs fluctuating above a base of zero and San Marcos Springs fluctuating above a base of slightly less than 100 cubic feet per second (2.83 m^3/s).

CHEMICAL QUALITY OF WATER

Table 2 shows all the standard chemical analyses available for water from Comal Springs, San Marcos Springs, and Hueco Springs. The water from each group of springs is relatively constant in quality. No progressive change with time is discernible from the records.

Comal Springs

The analyses for Comal Springs in Table 2 show that the silica ranges from 9.4 to 14 milligrams per liter (mg/l) and the iron from 0.00 to 0.05 mg/l. Only one analysis is available for manganese and it shows zero content. Calcium is shown to range from 43 to 102 mg/l, with most of the analyses being between 70 and 80 mg/l. Leaving out the one anomalous reading of 43 mg/l, the average for calcium is 76 mg/l. Magnesium is shown to range from 13 to 23 mg/l, with most of the analyses in the range of 15 to 20 mg/l, and the average being 17 mg/l. Sodium ranges from 6.2 to 8.5 mg/l and potassium from 0.4 to 3 mg/l. The range in bicarbonate reported is 236 to 300 mg/l, with most of the numbers being between 260 and 290 mg/l. Leaving out the one

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs

[Results in milligrams per liter (mg/l) except as otherwise noted and all analyses by U.S. Geological Survey except as noted.]

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) 1/	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temperature °F
Comal Springs																	
5-25-34	--	--	--	--	--	--	--	268	30	12	--	--	--	264	--	--	--
10-27-36	--	--	--	56	19	15*	--	244	26	17	--	--	253	219	--	--	--
4-10-38	--	--	--	75	17	3.3*	--	266	23	13	0.0	5.0	267	257	--	--	--
6-24-41	--	--	--	63	17	18*	--	272	23	12	--	3.7	271	227	--	--	--
8-13-41	--	--	--	--	--	--	--	272	23	11	--	--	--	--	--	--	--
9-16-41	12	--	--	73	17	4.8*	--	264	24	12	0.1	4.4	279	252	--	--	--
4- 2 -42	11	--	--	70	17	11*	--	274	22	12	0.1	4.0	282	244	--	--	--
12- 4 -43	--	--	--	73	17	6.7*	--	263	24	14	--	5.8	--	252	--	--	--
12- 4 -43	--	--	--	73	17	5.5*	--	261	24	13	--	5.5	--	252	--	--	--
1-10-44	--	--	--	78	17	5.5*	--	280	23	13	--	5.5	280	264	--	--	--
1-22-44	11	0.02	--	74	16	6.2	3.0	270	23	12	0.4	5.5	284	250	--	7.5	--
3-23-44	--	--	--	--	--	--	--	270	24	12	--	--	--	--	--	--	--
9-14-44	--	--	--	86	23	--	--	--	--	--	--	--	--	309	--	--	--
10-11-44	--	--	--	81	22	--	--	--	--	--	--	--	--	292	--	--	--
11-22-44	--	--	--	102	13	--	--	--	--	--	--	--	--	308	--	--	--
1-22-45	--	--	--	74	17	--	--	--	--	--	--	--	--	254	--	--	--
2-14-45	--	--	--	82	18	--	--	--	--	--	--	--	--	278	--	--	--
3- 5 -45	--	--	--	72	17	--	--	--	--	--	--	--	--	250	--	--	--
3-23-45	--	--	--	78	18	--	--	--	--	--	--	--	--	268	--	--	--
4-28-45	--	--	--	43	18	--	--	--	--	--	--	--	--	182	--	--	--
5-31-45	--	--	--	75	18	--	--	--	--	--	--	--	--	261	--	--	--
7- 6 -45	--	--	--	75	16	--	--	--	--	--	--	--	--	253	--	--	--
9-13-45	--	--	--	77	17	--	--	--	--	--	--	--	--	262	--	--	--
9-13-45	--	--	--	80	19	--	--	--	--	--	--	--	--	278	--	--	--

For footnotes see end of table.

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) 1/	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temperature °F
Comal Springs - continued																	
10- 9 -45	--	--	--	76	18	2.8*	--	274	20	14	--	5.6	271	264	--	--	--
10-18-45	--	--	--	76	19	--	--	--	--	--	--	--	--	268	--	--	--
11-23-45	--	--	--	50	16	--	--	--	1.5	--	--	--	--	191	--	--	--
2- 1 -47	--	--	--	80	20	2.1*	--	286	28	14	--	4.0	289	282	--	7.4	--
8- 7 -51	13	0.03	--	74	17	7.2	0.4	274	22	12	0.0	4.5	292	254	507	7.5	--
6-24-57	14	--	--	75	18	8.1	1.2	271	24	16	0.4	4.8	294	260	497	7.8	74
8- 8 -57	14	--	--	74	17	7.8	1.1	271	22	13	0.6	4.8	287	254	502	7.4	74
10- 4 -57	12	0.00	--	72	18	7.6	0.9	276	22	14	0.3	4.2	302	254	498	7.6	72
1-14-58	11	--	--	75	16	7.6	1.2	276	22	14	0.4	4.8	298	253	493	8.0	--
4- 9 -58	13	--	--	75	16	7.7	1.1	274	21	14	0.3	5.1	302	254	501	7.1	74
7-16-58	12	--	--	75	17	7.7	0.9	271	22	14	0.2	5.3	290	257	505	7.0	75
1-16-59	11	--	--	72	15	17*	--	280	22	13	0.3	6.8	296	241	508	7.4	74
6-18-59	9.4	0.03	--	76	15	7.5	1.0	276	23	12	0.2	6.1	286	251	502	6.9	--
11-23-59	--	--	--	--	--	--	--	277	27	14	--	--	--	253	517	6.8	74
9-29-60	--	--	--	--	--	--	--	--	22	9	--	--	--	--	--	--	75
3- 2 -61	--	--	--	--	--	--	--	282	22	16	--	--	--	252	518	7.5	74
8- 9 -61	--	--	--	--	--	--	--	280	22	14	--	--	--	254	508	7.1	72
3- 7 -62	--	--	--	--	--	--	--	276	22	14	--	--	--	248	502	7.4	75
9-27-62	--	--	--	--	--	--	--	284	21	14	--	--	--	256	509	7.3	75
3- 6 -63	--	--	--	--	--	--	--	280	23	15	--	--	--	258	509	7.5	74
9- 9 -63	--	--	--	--	--	--	--	276	24	15	--	--	--	254	501	7.5	74
3- 5 -64	--	--	--	--	--	--	--	279	23	13	--	--	--	258	512	7.5	74
8-18-64	--	--	--	--	--	--	--	278	24	12	--	--	--	252	503	7.3	74
2-25-65	--	--	--	--	--	--	--	--	24	14	--	--	--	--	--	--	--

For footnotes see end of table.

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manga-nese (Mn)	Cal-cium (Ca)	Magne-sium (Mg)	Sodium (Na) 1/	Potas-sium (K)	Bicar-bonate (HCO_3)	Sul-fate (SO_4)	Chlo-ride (Cl)	Fluo-ride (F)	Ni-trate (NO_3)	Dis-solved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temper-ature °F
Comal Springs - continued																	
5-18-65	--	--	--	--	--	--	--	286	--	13	--	--	--	--	508	7.3	75
8-26-65	--	--	--	--	--	--	--	284	23	11	--	--	--	256	518	6.7	75
2-18-66	--	--	--	--	--	--	--	284	22	12	--	--	--	260	520	7.2	74
8-24-66	--	--	--	--	--	--	--	288	21	13	--	--	--	270	524	7.4	75
2-27-67	--	--	--	--	--	--	--	282	22	12	--	--	--	260	512	7.2	75
8-18-67	--	--	--	--	--	--	--	260	22	11	--	--	--	240	471	7.3	74
3-13-68	--	--	--	--	--	--	--	286	23	12	--	--	--	278	510	7.2	75
8-29-68	--	--	--	--	--	--	--	276	22	12	--	--	--	264	499	7.5	75
3- 7 -69	--	--	--	80	16	--	--	286	23	12	--	--	--	266	517	7.2	73.5
8-19-69	--	--	--	--	--	--	--	284	22	12	--	--	--	284	516	7.6	73.5
3- 3 -70	--	--	--	--	--	--	--	286	23	12	--	--	--	288	522	7.1	74.5
8-14-70	--	--	--	--	--	--	--	258	23	13	--	--	--	254	485	7.2	73.5
2-17-71	13	--	--	79	16	8.7*	--	284	24	13	0.2	7.1	301	260	519	7.2	--
3-12-71	--	--	--	82	16	--	--	284	23	13	--	--	--	270	521	7.5	73.5
7-20-71	11	0	0	75	16	8.1	1.3	276	23	12	0.3	5.5	302	250	481	7.4	--
8-12-71	--	--	--	--	--	--	--	--	--	--	--	--	--	--	516	--	75
3-27-72	--	--	--	--	--	--	--	286	24	15	--	--	--	270	522	7.4	73.5
5-12-72	12	--	--	80	16	7.8	1.4	286	24	15	0.3	7.1	298	270	522	7.6	--
7-18-72	--	--	--	--	--	--	--	236	23	12	--	--	--	230	455	7.5	74.5
2- 6 -73	13	--	--	78	16	8.7*	--	280	25	12	0.2	8.0	299	260	515	7.1	74
5-15-73	12	--	--	80	16	7.6	1.2	283	25	14	0.3	3.4	296	270	479	7.6	74.5
11-23-73	12	--	--	79	17	8.1	1.4	300	22	13	0.2	8.4	301	270	528	7.1	75
4- 2 -74	12	--	--	77	16	8.4	1.3	280	22	15	0.2	7.1	290	260	522	7.3	74.5
6- 6 -74 2/	--	--	--	78	16	--	--	279	24	15	--	7.1	298	260	494	--	--

For footnotes see end of table.

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) 1/	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temperature °F
Comal Springs - continued																	
12-16-74	12	--	--	77	16	8.5	1.6	283	23	14	0.2	7.1	300	260	520	6.5	74.5
San Marcos Springs																	
10- 4 -37 3/	--	--	--	90	15	17*	--	268	22	51	--	4/	335	284	--	--	--
5-16-47	11	0.05	--	90	20	7.1	5.4	334	19	22	0.8	3.0	349	306	602	7.2	--
3-23-55	13	--	--	82	21	5.2	0.5	309	17	16	1.0	4.6	334	291	556	7.4	--
7-12-55	--	--	--	--	--	--	--	307	--	16	--	--	--	278	563	7.6	--
6-18-59	9.2	0.03	--	84	18	10	1.3	307	25	20	0.2	8.5	327	284	567	7.1	71.5
11-25-59	--	--	--	--	--	--	--	307	24	20	--	--	--	282	579	7.3	71.5
9-30-60	--	--	--	--	--	--	--	298	20	18	--	--	--	268	545	7.6	71.5
3- 2 -61	--	--	--	--	--	--	--	310	23	22	--	--	--	280	585	7.8	72
8- 3 -61	--	--	--	--	--	--	--	250	22	22	--	--	--	234	503	7.3	72
3-12-62	--	--	--	--	--	--	--	304	22	21	--	--	--	276	570	7.0	71
2-28-63	--	--	--	--	--	--	--	308	22	20	--	--	--	288	571	7.4	71
9-13-63	--	--	--	--	--	--	--	300	26	20	--	--	--	284	571	7.0	72
3- 6 -64	--	--	--	--	--	--	--	316	22	16	--	--	--	290	574	7.6	71
8-17-64	--	--	--	--	--	--	--	312	23	16	--	--	--	284	558	7.6	--
5-18-65	--	--	--	--	--	--	--	314	24	20	--	--	--	284	569	7.3	72
8-26-65	--	--	--	--	--	--	--	308	24	17	--	--	--	290	578	6.9	72
2-18-66	--	--	--	--	--	--	--	304	24	20	--	--	--	288	585	7.3	71
8-24-66	--	--	--	--	--	--	--	310	22	19	--	--	--	286	575	7.2	72
3- 6 -67	--	--	--	--	--	--	--	308	24	19	--	--	--	284	564	7.3	72
8-18-67	--	--	--	--	--	--	--	312	23	17	--	--	--	292	570	7.2	72
3-13-68	--	--	--	--	--	--	--	314	25	20	--	--	--	306	578	7.1	71.5

For footnotes see end of table.

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) 1/	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temperature °F
San Marcos Springs - continued																	
8-29-68	--	--	--	--	--	--	--	300	21	17	--	--	--	300	545	7.4	73.5
10-31-68	11	--	--	82	19	7.4*	--	300	23	19	0.3	0.6	310	282	574	7.0	--
3- 7 -69	--	--	--	84	18	--	--	304	25	21	--	--	--	284	565	7.4	71.5
8-19-69	--	--	--	--	--	--	--	308	23	18	--	--	--	300	568	7.3	71.5
3- 3 -70	--	--	--	--	--	--	--	302	25	20	--	--	--	298	582	7.1	71.5
10-19-71 5/	--	--	--	--	--	--	--	--	24	19	--	4.4	--	--	588	7.5	74
7-31-72	11	0.01	--	81	17	10	1.4	308	22	17	0.3	5.8	316	270	569	7.1	71.5
3- 7 -73	--	--	--	84	18	10	1.6	308	26	19	0.3	5.8	--	280	567	--	--
5-15-73	11	--	--	86	17	9.6	1.4	306	25	20	0.2	4.8	322	290	507	7.6	71.5
4- 4 -74	--	--	--	84	19	9.9	1.5	324	21	19	--	5.8	--	290	560	7.1	71.5
6- 6 -74 2/	10	--	--	88	17	10*	--	314	22	19	0.2	--	--	290	--	--	--
12-16-74	11	--	--	86	17	13	2.0	313	25	22	0.2	--	337	290	549	6.6	71.5
Hueco Springs																	
6-24-41	--	--	--	97	11	13*	--	334	11	16	--	9.8	322	287	--	--	7/
8-13-41	--	--	--	--	--	--	--	334	11 6/	12	--	--	--	--	--	--	--
9-16-41	--	--	--	102	14	1.6*	--	334	13	13	--	12	320	312	--	--	--
1-22-44	--	--	--	109	13	2.5*	--	358	9 6/	13	--	12	335	326	--	--	--
9-14-44	--	--	--	88	9.8	0.7*	--	282	6.7	12	--	8.0	291	260	--	--	--
10- 9 -44	--	--	--	107	16	--	--	--	--	--	--	--	--	333	--	--	--
11-22-44	--	--	--	98	12	--	--	--	--	--	--	--	--	294	--	--	--
12- 5 -44	--	--	--	76	18	--	--	--	--	--	--	--	--	264	--	--	--
12- 7 -44	--	--	--	100	16	--	--	--	--	--	--	--	--	316	--	--	--
1-22-45	--	--	--	96	9.6	--	--	--	--	--	--	--	--	279	--	--	--

For footnotes see end of table.

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) 1/	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temperature °F
Hueco Springs - continued																	
2-14-45	--	--	--	109	12	--	--	--	--	11	--	--	--	322	--	--	--
3- 5 -45	--	--	--	99	10	--	--	--	--	--	--	--	--	288	--	--	--
3-23-45	--	--	--	107	10	--	--	--	2 6/	--	--	--	--	308	--	--	--
4- 1 -45	--	--	--	98	10	--	--	--	--	--	--	--	--	286	--	--	--
4-27-45	--	--	--	112	14	--	--	--	--	--	--	--	--	337	--	--	--
5-31-45	--	--	--	79	14	--	--	--	--	--	--	--	--	254	--	--	--
7- 5 -45	--	--	--	86	14	--	--	--	--	--	--	--	--	272	--	--	--
7- 9 -45	--	--	--	64	15	--	--	--	--	--	--	--	--	221	--	--	--
9-13-45	--	--	--	102	20	--	--	--	--	--	--	1.5	--	336	--	--	--
10-19-45	--	--	--	93	12	--	--	--	11 6/	--	--	--	--	282	--	--	--
10-19-45	--	--	--	89	11	2.8*	--	294	8 6/	10	--	12	317	267	--	--	--
11-23-45	--	--	--	104	16	--	--	--	3 6/	--	--	--	--	326	--	--	--
6-24-57	12	--	--	93	11	13*	--	295	16	18	0.4	23	336	276	571	7.2	--
8- 8 -57	12	--	--	99	13	7.3	1.5	319	13	16	0.8	19	340	300	583	7.2	--
10- 4 -57	10	0.00	--	92	9.6	6.2	1.4	289	13	12	0.3	19	318	269	535	7.9	--
1-14-58	8.2	--	--	98	9.0	7.2	1.2	296	14	18	0.2	21	336	282	553	7.3	--
3- 9 -58	11	--	--	100	10	9.1	1.3	304	17	22	0.2	20	357	290	587	7.2	--
7-21-58	11	--	--	102	11	7.7	1.2	318	14	17	0.2	14	350	300	592	7.0	--
1-14-59	11	--	--	97	11	14*	--	324	14	16	0.2	18	340	287	586	7.2	--
9-10-59	11	--	--	90	14	6.9	1.4	313	15	10	0.3	12	318	282	542	6.9	--
2-24-61	--	--	--	--	--	--	--	316	15	16	--	--	--	278	565	7.2	--
10-31-68	11	0.03	0.00	98	15	7.4*	--	340	15	14	0.3	9.2	337	306	596	6.9	--
11- 4 -69	--	--	--	101	--	--	1.4	--	--	--	--	--	--	--	571	--	--
10- 4 -72	11	0.00	0.00	97	15	7.5	1.4	346	14	11	0.2	8.5	336	300	592	7.0	--

For footnotes see end of table.

Table 2.--Chemical Analyses of Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Silica (SiO_2)	Iron (Fe)	Manga- nese (Mn)	Cal- cium (Ca)	Magne- sium (Mg)	Sodium (Na) 1/	Potas- sium (K)	Bicar- bonate (HCO_3)	Sul- fate (SO_4)	Chlo- ride (Cl)	Fluo- ride (F)	Ni- trate (NO_3)	Dis- solved Solids	Total Hardness as $CaCO_3$	Specific Conductance (micromhos)	pH	Temper- ature °F
Hueco Springs - continued																	
5-15-73	10	0.00	0.00	110	10	7.2	1.1	330	16	14	0.2	2.5	--	306	439	7.4	--
11-23-73	11	0.00	0.00	100	11	8.1	1.4	348	14	13	0.2	8.0	342	300	594	7.3	--
12-16-74	10	--	--	97	13	7.4	1.5	342	14	11	0.2	--	330	300	539	6.6	--

1/ Asterisk (*) indicates sodium and potassium calculated as sodium.

2/ Espey, Huston & Associates, Inc., 1975, analysis by Texas State Department of Health Laboratory.

3/ Analysis by WPA under direction of USGS.

4/ Nitrate less than 20 mgl.

5/ Texas Water Quality Board analysis.

6/ Turbidity.

7/ Temperature of water from Hueco Springs given in Table 2.

low analysis of 236 makes the average bicarbonate 277 mg/l. Sulfate is shown to range from 20 to 30 mg/l, except for one odd analysis which shows 1.5 mg/l. If this low number is excluded, the average for sulfate is 23 mg/l. Chloride ranges from 9 to 17 mg/l and the average is 13 mg/l. The fluoride content of the water ranges from 0.0 to 0.6 mg/l. The range in nitrate is from 3.4 to 8 mg/l and the average is 6 mg/l. Dissolved solids are shown to range from 253 to 302 mg/l, with most of the analyses showing a range of about 280 to 300 mg/l and the average being 289 mg/l. Total hardness is shown to range from 182 to 309 mg/l as $CaCO_3$, with most of the analyses showing a range of 250 to 280 mg/l. If four low numbers are left out, the hardness averages 261 mg/l. Specific conductance ranges from 455 to 528 micromhos at 25°C. Leaving out the 455 value, the average is 508 micromhos.

San Marcos Springs

The silica in the analyses which are available for San Marcos Springs ranges from 9.2 to 13 mg/l. The iron ranges from 0.01 to 0.05. Calcium is shown to range from 81 to 90 mg/l and to average 85 mg/l. Magnesium ranges from 15 to 21 mg/l and averages 18 mg/l. The range in sodium is from 5.2 to 13 mg/l, and in potassium from 0.5 to 5.4 mg/l. The range in bicarbonate shown by the analyses is from 250 to 334 mg/l, with most of the analyses being from 300 to 320 mg/l and the average 306 mg/l. Sulfate ranges from 17 to 26 mg/l and averages 23 mg/l. Chloride is 16 to 22 mg/l except for one odd analysis which shows 51 mg/l. If the 51 is excluded, the average is 19 mg/l. The range in fluoride is from 0.2 to 1.0 mg/l. Nitrate ranges from 0.6 to 8.5 mg/l and averages 5 mg/l. The range shown for dissolved solids is 310 to 349 mg/l and the average is 329 mg/l. Hardness is shown to vary from 234 to 306 mg/l, with most of the analyses showing a range of 280 to 300 mg/l and the average being 285 mg/l. The range shown for specific conductance is 503 to 602 micromhos at 25°C, with most of the analyses showing 550 to 580 micromhos and the average being 566 micromhos.

The water from San Marcos Springs appears to have a little more calcium bicarbonate and a little more chloride than the water from Comal Springs; and the dissolved solids, hardness, and specific conductance are also slightly higher for San Marcos Springs.

Hueco Springs

The quality of water from Hueco Springs varies slightly more than that from the other two groups of springs. The range of the Hueco Springs water in silica in the analyses for which this constituent is available is from 8.2 to 12 mg/l. Most of the available analyses show no iron, but one analysis shows 0.03 mg/l. Four analyses show no manganese. The range in calcium shown by the analyses is from 64 to 112 mg/l, with most of the analyses showing a range of 90 to 110 mg/l and the average (excluding the one 64 value) being 98 mg/l. The range in magnesium is from 9 to 20 mg/l and the average is 13 mg/l. Values for sodium range from 6.2 to 9.1 mg/l, and potassium is shown as about 1 to 1.5 mg/l in all the analyses for which this constituent was analyzed. The range shown for bicarbonate in the analyses is from 282 to 358 mg/l and the average is 321 mg/l. Sulfate is shown to range from 2 to 17 mg/l, with most of the analyses showing a range of 8 to 16 mg/l and the average (excluding two low values) being 13 mg/l. Chloride has a range of 10 to 22 mg/l and an average of 14 mg/l. The analyses of fluoride show a range of 0.2 to 0.8 mg/l. For nitrate the range is 1.5 to 23 mg/l and the average is 13 mg/l. Dissolved solids are shown to range from 291 to 357 mg/l, with most of the analyses showing a range of 320 to 350 mg/l and the average being 331 mg/l. Total hardness ranges from 221 to 337 mg/l. Most of the hardness values range from 270 to 310 mg/l, and the average (excluding the 221 value) is 295 mg/l. Specific conductance varies from 535 to 596 micromhos at 25°C, except for one analysis which shows 439 micromhos. Leaving out the 439 value, the average is 572 micromhos.

The water from Hueco Springs is indicated to have about the same degree of total mineralization as that from San Marcos Springs and to be slightly more mineralized than the water from Comal Springs. The magnesium, sulfate, and chloride appear to be a little less and the calcium, bicarbonate, and hardness a little greater in the water from Hueco Springs than in the water from San Marcos Springs. The nitrate varies over a considerably wider range for Hueco Springs than for the other two groups of springs, and is generally higher.

TEMPERATURE OF WATER

Measurements of temperature of water from Comal, San Marcos, and Hueco Springs are listed in Tables 2 and 3. These include all available measurements except a few which were omitted because they were believed to be incorrect. Some of those that were left in the tables, however, also probably should be omitted for this reason.

Shallow ground water which does not have rapid movement normally has about the same average temperature as the average air temperature of that locality. The average annual air temperature in the vicinity of New Braunfels and San Marcos is about 69 degrees Fahrenheit (20.6 degrees Celsius). The temperature of ground water in most places where the rate of ground-water movement is slow will increase about 1 to 2°F (0.5 to 1.1°C) per 100 feet (30.5 m) of depth. If ground-water movement is relatively rapid, this condition will not necessarily hold.

The fluctuation in temperature of water from springs will depend on the size of the aquifer and the source and magnitude of the recharge. If the aquifer is large, with a relatively uniform recharge, the temperature of the spring flow will be relatively uniform. If the aquifer is small, and especially if the recharge is quite variable, the temperature of the water may vary considerably. The temperature of the spring flow will also depend in part on the timing of the recharge. When used in conjunction with other evidence, such as geology and chemical character of the water, temperature can be helpful in tracing the sources of water to springs.

Comal Springs

George (1952) reported that the average temperature of water from Comal Springs was about 74°F (23.3°C) and that the maximum observed variation in temperature was not more than 1°F (0.5°C). The data shown in Table 2 would indicate that this is not a correct statement inasmuch as the temperatures shown range from 72 to 75°F (22.2 to 23.9°C). However, it is believed that the two temperature readings of 72°F (22.2°C) shown in Table 2 are probably not correct and that George's statement is probably true. If these two readings are omitted, the temperature is shown to range from 73.5°F (23.1°C) to 75°F (23.9°C) with an average of about 74.3°F (23.4°C).

Based on data presented by Petitt and George (1956) the temperature of the water from Comal Springs correlates with temperatures of water from wells in the Edwards aquifer in San Antonio which have depths of about 700 to 1,000 feet (213.4 to 304.8 m). The relatively high and constant temperature of water from Comal Springs (74.3°F or 23.4°C) as compared to the mean annual air temperature at New Braunfels (69°F or 20.6°C) indicates that the water from the springs comes from a large aquifer of considerable depth.

San Marcos Springs

The temperature of San Marcos Springs is reported by Aquarena, Inc. to remain a constant 71°F (21.7°C), with a variance of 0.6°F (0.3°C) year round. The data in Table 2 indicate that the temperature ranges from 71 to 74°F (21.7 to 23.3°C), although only two of the measurements were greater than 72°F (22.2°C). If these two measurements are omitted, the average temperature reported is 71.6°F (22.0°C).

The fact that the temperature of the water from San Marcos Springs is so constant indicates that the aquifer from which it comes is quite large, but the fact that the water is about 3 degrees cooler than the water from Comal Springs indicates that the water from San Marcos Springs must, in considerable part, come from different sources than the water from Comal Springs.

Hueco Springs

Table 3 shows the temperature of water from Hueco Springs to range from a low of 68°F (20.0°C) to a high of 77°F (25.0°C). However, only two readings are above 73°F (22.8°C), and it is believed that these two should be omitted from consideration because of probable error. If this is the case, the range in temperature for the springs is shown to be about 5°F (2.8°C) and the average temperature to be about 70.4°F (21.3°C).

The lower temperature and the greater fluctuation for Hueco Springs than for San Marcos Springs indicates that a greater percentage of the flow from Hueco Springs comes from a smaller and possibly shallower portion of the aquifer.

TRITIUM CONTENT OF WATER

Analyses of the tritium content of water are a means of helping to determine how long the ground water has been underground since it originated as precipitation. Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years. Cosmic radiation produces tritium in the upper atmosphere. For the years prior to 1953, the tritium concentration in precipitation in the San Antonio area has been estimated at 6 to 8 tritium units. Beginning in 1953, the tritium concentration in precipitation increased as a result of thermonuclear testing. From 1953 to 1963, the tritium content in the precipitation increased greatly, with various peaks and lows depending on the thermonuclear tests, up to nearly 2,000 tritium units at Waco, Texas in 1963 (Pearson and others, 1975). After 1963, the tritium in precipitation has been generally declining as a result of the Test Ban Treaty. In 1971, the tritium in precipitation at Waco ranged from about 25 to more than 100 tritium units.

Table 3.--Temperature of Water From Hueco Springs

Date	Temperature of Spring Water °F	Date	Temperature of Spring Water °F	Date	Temperature of Spring Water °F
1-22-44	70	7-23-49	71	7-31-53	71
9-14-44	71.5	8-26-49	71	8-13-53	72
10- 9 -44	71	9-28-49	71	9-10-53	71
12- 5 -44	71	11- 4 -49	70	2-24-57	70
12- 7 -44	71	12- 8 -49	71	4- 4 -57	70
12-11-44	69	1-12-50	71	5-20-57	70
12-12-44	69	2-10-50	69.5	6-24-57	71
12-13-44	69	3-22-50	70	7- 2 -57	72
12-20-44	69	4-21-50	70.5	8- 8 -57	72
1- 8 -45	69	5-24-50	70	10- 4 -57	72
1-22-45	69	6-28-50	71	1-14-58	68
1-27-45	68	8- 2 -50	72	3- 9 -58	69
2-14-45	68	9- 9 -50	72	7-21-58	76
3- 5 -45	68.5	11-15-50	71	1-14-59	70
3-23-45	69	6-14-51	71	9-10-59	77
4-27-45	69	4-11-52	71	2-24-61	68
5-31-45	69.5	6-18-52	71	11- 4 -69	71.5
7- 5 -45	70	7-24-52	71	10- 4 -72	71.5
8- 9 -45	70	9-18-52	72	5-15-73	70
9-13-45	70	9-23-52	71	11-23-73	71.5
10-19-45	69.5	10-30-52	71	12-16-74	70.5
11-23-45	70	12-10-52	70		
12-20-45	70	1-14-53	71		
4- 1 -49	69	2-26-53	70		
5-16-49	70	4- 8 -53	71		
6-16-49	70	5-20-53	73		

Figure 14 shows tritium analyses made by the U.S. Geological Survey for water from Comal, San Marcos, and Hueco Springs and selected wells drawing on the Edwards aquifer northeast of San Antonio. Based on the information supplied by Pearson and others, it appears that if all of the water produced from a well or discharged from a spring had been underground since before 1953, its tritium content in 1975 should be about 2 tritium units or less. If all of the water had originated as precipitation exactly 12 or 13 years ago, its tritium content in 1975 should be in the hundreds of tritium units. For ages between 13 and 22 years since the water originated as precipitation, the tritium content probably would be in the range of somewhat less than 10 to more than 50 and perhaps up to 100 tritium units, and for ages less than 12 years since the water originated as precipitation, it probably would be in the range of 40 to perhaps 200 or more tritium units. Mixtures of waters of different ages should show tritium units for the total somewhere in between these numbers.

One of the problems in determining how long water has been in the Edwards aquifer is that much of the recharge to the reservoir comes from the low flows of streams which themselves originated from springs upstream. Therefore, this recharge is comprised of water which has already had varying periods of storage in the ground before entering the Edwards aquifer. It is not at all a simple matter, consequently, to calculate the age of the Edwards aquifer recharge from the tritium content of the water found in the discharge of a well or spring. However, the relative amounts do serve as one means of helping to trace the source of the water.

Comal Springs

The first analysis of tritium in the water from Comal Springs was made in August 1963 and was 2.0 tritium units. After that, the tritium content increased up to 6.7 tritium units in 1971. Then it was 4.9 tritium units in 1974. The tritium analyses for this spring flow indicate that only a very small part of the water occurred as precipitation less than 10 years ago and that not much of the water was precipitated less than 20 years ago. The tritium analyses indicate that at least most and perhaps nearly all of the water discharging from Comal Springs has come through the Edwards aquifer from the direction of San Antonio along a fairly narrow path, relatively close to the bad water line, where the Edwards aquifer is fully saturated and the water is under artesian pressure.

San Marcos Springs

The water from San Marcos Springs has a much higher tritium content than the water from Comal Springs. The first analysis was for 1964 and showed 30 tritium units. The highest analysis was 34 tritium units in 1964, and the lowest has been the latest analysis in 1975, which shows 19 tritium units. These analyses indicate that at least a large part of the water from San Marcos Springs did not come from the same source area as Comal Springs and that, on the average, the water from San Marcos Springs is much younger than the water from Comal Springs. The fairly uniformly trending tritium content, without large fluctuations, of the water from San Marcos Springs, however, indicates that the water from San Marcos Springs originates from a reasonably large portion of the aquifer.

Hueco Springs

The highest tritium count measured for any well or spring in this area was from Hueco Springs in 1968, when 60 tritium units were recorded for the water from those springs. Also, a significant fluctuation in tritium count is shown by the analyses for Hueco Springs. The first analysis was in 1967 and showed 39 tritium units; the second, in 1968, showed 60; and the last, in 1975, showed 24 tritium units. These analyses indicate that the water from Hueco Springs is younger on the average than the water from San Marcos Springs and much younger than the water from Comal Springs. They also indicate that the portion of the aquifer supplying Hueco Springs is substantially smaller than that which supplies San Marcos Springs and very much smaller than that supplying Comal Springs.

Wells

Tritium counts for water taken from wells downdip from the bad water line show very little to no measurable tritium, indicating that this water is very old. Moving north or northwestward toward the recharge area from the bad water line, the tritium contents from well water become generally higher, indicating younger and younger water as the recharge area is approached. However, there is a variation from time to time, such as that shown by well DX-68-16-502 between Comal Springs and San Marcos Springs, which showed a moderately young water with a tritium content of 11.5 tritium units in 1968 and a substantially older water with a tritium content of 6.0 tritium units in 1975. This

and other analyses indicate that the water at a given place is not necessarily always a uniform mixture of waters from the same sources. Inasmuch as recharge occurs in different amounts at different times and moves along different paths, and inasmuch as wells are sampled after various periods of shutdown and under varying conditions of pumping, a substantial variation should be expected in the tritium analyses from at least some of the wells, and this is what the analyses show. Even in the recharge areas there undoubtedly are pockets or zones of old water which have not been flushed out yet by water which was precipitated since the thermonuclear testing began in 1953.

SPRING FLOW CORRELATION STUDIES

Numerous studies have been made of the correlation of the flows of Comal Springs and San Marcos Springs with other factors, and some have been made for Hueco Springs. The most successful correlations have been between spring flow and water levels in wells. Precipitation and streamflow correlate with spring flow only in a general way, in that they reflect changes in recharge conditions. No correlation has been found between the flows of any of these three groups of springs and the stage of Canyon Lake.

On an overall basis, there is a good correlation between the spring flows and recharge to and pumpage from the Edwards aquifer, because the total recharge and total discharge from the aquifer over a long period of time are in approximate balance, and these three groups of springs comprise most of the natural discharge from the aquifer.

Long-Term Recharge and Discharge

The highest water levels in the artesian portion of the Edwards aquifer are in the vicinity of Brackettville on the western end of the aquifer. The lowest water levels are at San Marcos Springs. Water slopes toward San Marcos Springs all the way from Brackettville, and also from Kyle, which is a few miles northeast of San Marcos Springs. The long-term recharge and long-term discharge of the aquifer are still in approximate balance, and any water which enters the aquifer as recharge is eventually discharged. Any water which is taken from wells is water which is offset by a reduction in spring discharge. The stage of the water in the aquifer rises and falls in response to imbalance between short-term recharge and discharge.

Comal and San Marcos Springs are the two largest groups of springs discharging from the Edwards aquifer, and historically have comprised more than one-half of the total discharge from the aquifer. Inasmuch as the long-term recharge and long-term discharge of the aquifer have been correlated with one another, it necessarily follows that the flows of Comal and San Marcos Springs have been correlated with withdrawals from wells and recharge on a long-term basis. Of the three groups of springs under consideration, the effect of well withdrawals on Comal Springs is by far the most pronounced and noticeable. As pointed out earlier in this report, the effect of withdrawals on Comal Springs is clearly shown by Figures 2 and 13.

Recent Correlations by U.S. Geological Survey

In recent months, the U.S. Geological Survey has been making a study of correlations of water levels, spring flow, and streamflow for the Edwards aquifer in the eastern San Antonio area (Puente, 1976). From its studies the U.S. Geological Survey has concluded that changes in water levels and spring flow can be estimated accurately by a set of empirical equations. It has concluded that (1) the flow of Comal Springs is mostly regional underflow that has moved through the deeper artesian part of the Edwards aquifer adjacent to the Comal Springs Fault as it enters Comal County from the southwest; (2) Hueco Springs are supplied mainly from local recharge in the drainage area of Dry Comal Creek north of the Hueco Springs Fault and west of the Guadalupe River in Comal County; and (3) San Marcos Springs are supplied by regional underflow past the Comal Springs area and from local recharge in northern Comal and Hays Counties.

Figure 15 shows a relationship developed between the flow of Comal Springs and the water levels in well DX-68-23-302 in Landa Park in New Braunfels. Figure 16 shows a similar correlation between the flow of Comal Springs and the water level in well AY-68-37-203. This is a key observation well in northeastern Bexar County. It is well J-17 according to the former numbering system of the U.S. Geological Survey and is very near well 26, which is the old Beverly Lodges well and which was the key observation well for the San Antonio area for many years. Well J-17 shows almost exactly the same water-level elevations and fluctuations as well 26, and the records of the two wells usually are shown as a composite graph.

The very good correlation between water levels in these two wells and the flow of Comal Springs indicates that the water levels in the two wells themselves correlate closely. Together with similar correlations developed for other wells in this part of the Edwards aquifer, they indicate that the flow of Comal Springs is

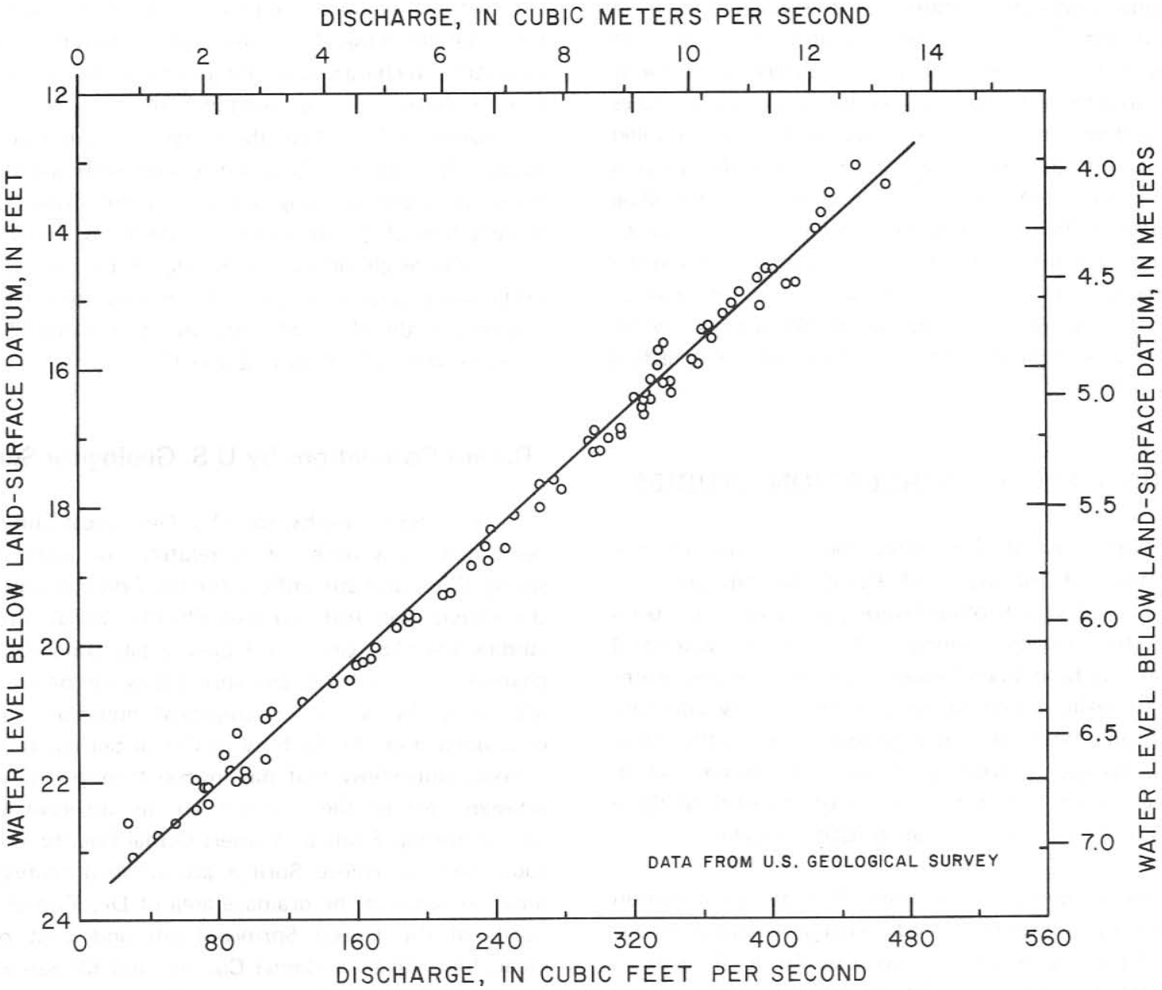

Figure 15.—Relationship Between the Flow of Comal Springs and the Water Level in Well DX-68-23-302

controlled primarily by the piezometric surface of the aquifer between Comal Springs and San Antonio.

Based on the annual mean discharge of Comal Springs and the annual mean water level in well AY-68-37-203, the U.S. Geological Survey developed an equation of correlation and then used this equation to compute the spring flow for the period 1934 through 1973 for comparison with the observed spring flow during that period. The observed and computed spring flows are given herein in Figure 17. The equation of correlation is:

$$Y = 655.4 - 5.5X,$$

where Y is the annual mean Comal Springs flow in cubic feet per second and X is the annual mean water level at well AY-68-37-203 in feet below land surface.

The U.S. Geological Survey also developed a relationship between the flow of San Marcos Springs and the water level in well LR-67-09-102, a local well in the vicinity of San Marcos Springs. This relationship is shown on Figure 18.

From its studies, the U.S. Geological Survey determined that there is an underflow of water through the Edwards aquifer past Comal Springs to San Marcos Springs. Based on the discharge of San Marcos Springs when the local recharge was at a minimum, and partly during the period when Comal Springs were dry, a relationship was established between the water level in well DX-68-23-302 and the regional underflow to San Marcos Springs. This relationship is shown in Figure 19. Two correlation equations were developed and the correlation lines are shown on Figure 19. Equation 20 was accepted as the more valid equation and is stated as:

$$SMQ^1 = 223.25_e - 0.05\ LP(W/L),$$

where SMQ^1 is the monthly average underflow component in cubic feet per second; e is the natural logarithm base, 2.71828; and LP(W/L) is the monthly

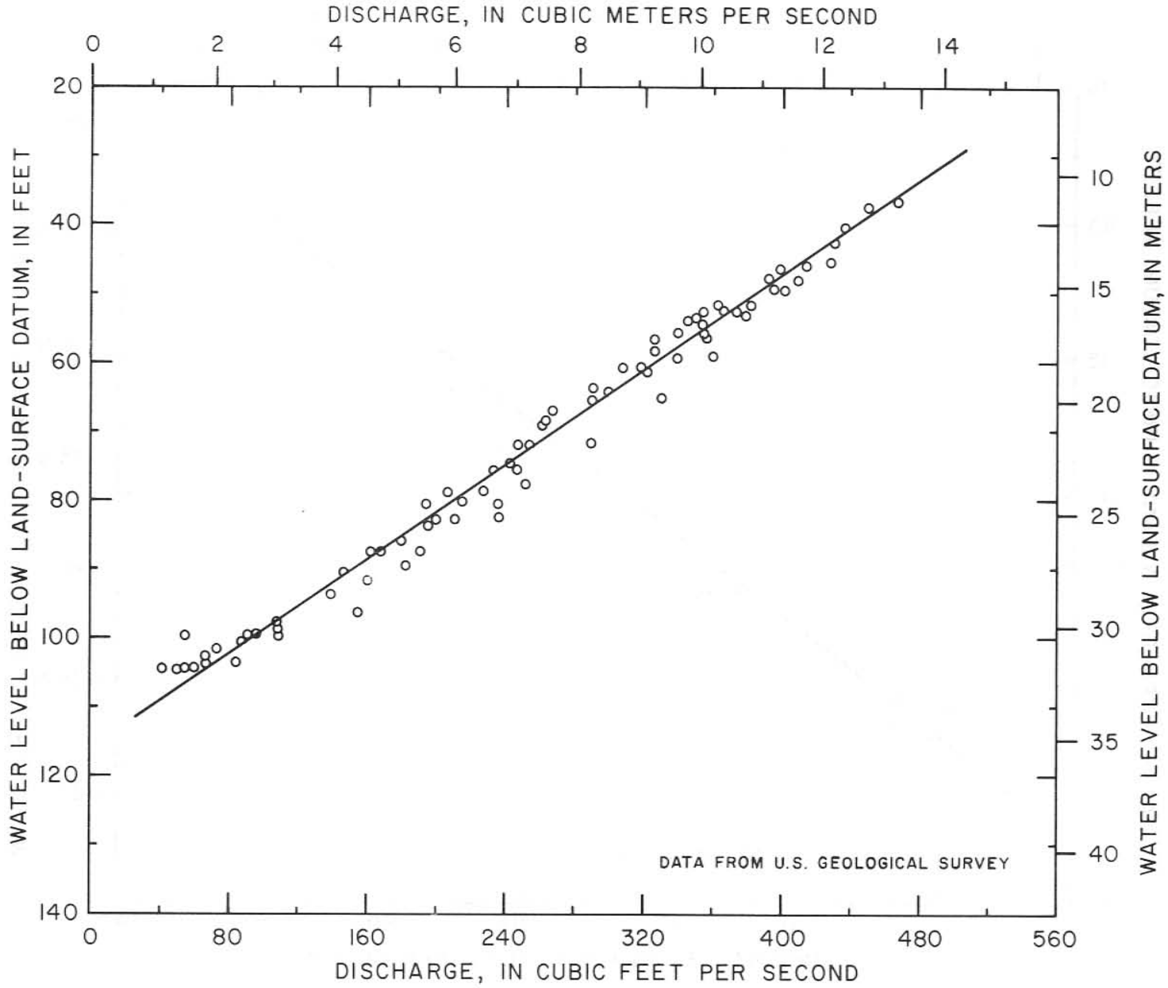

Figure 16.—Relationship Between the Flow of Comal Springs and the Water Level in Well AY-68-37-203

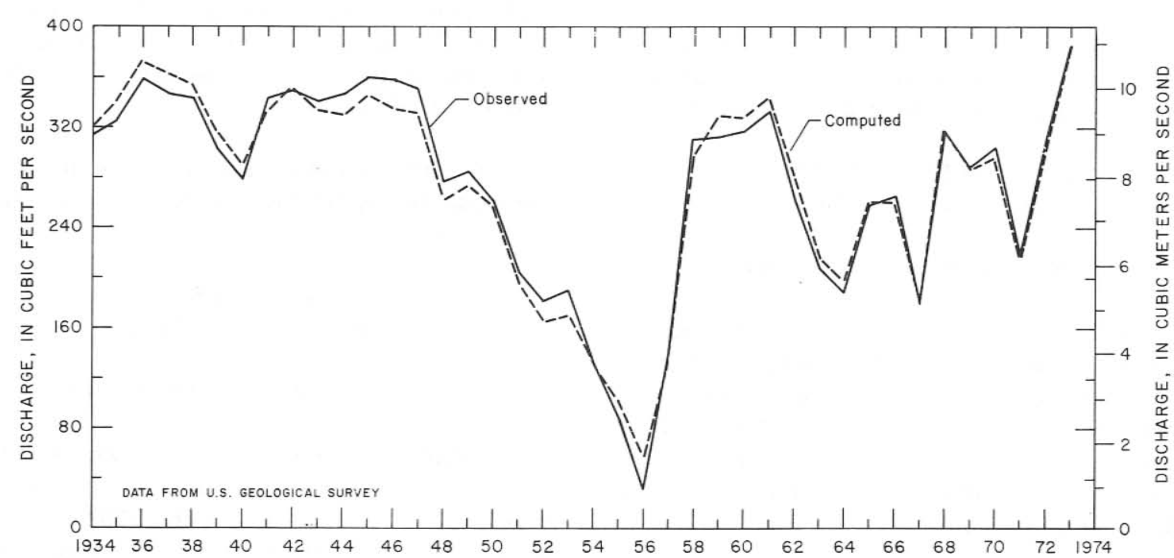

Figure 17.—Comparison of Observed and Computed Annual Average Discharge of Comal Springs

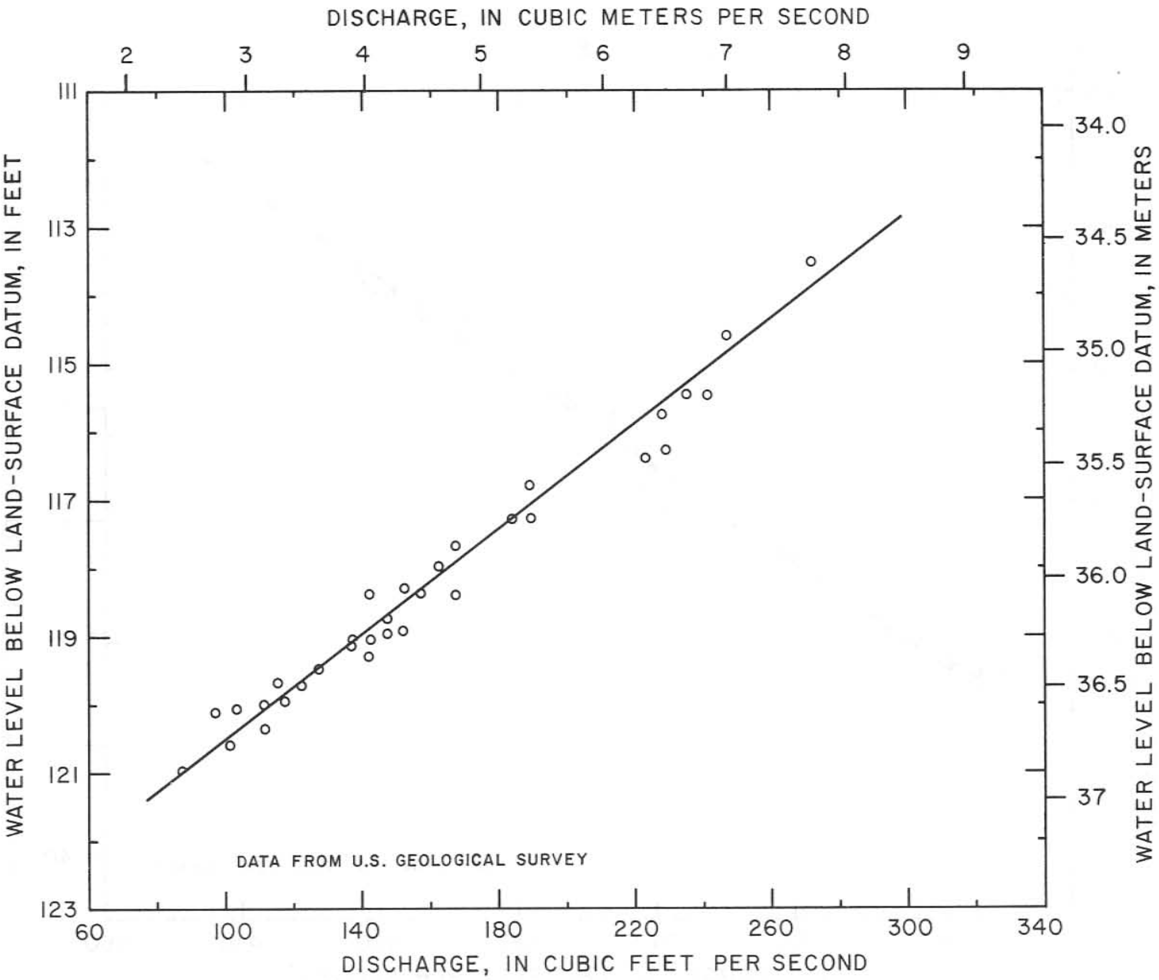

Figure 18.—Relationship Between the Flow of San Marcos Springs and the Water Level in Well LR-67-09-102

average water level at well DX-68-23-302 in feet below land surface.

Additional studies by the U.S. Geological Survey yielded an equation for the local recharge component of the discharge of San Marcos Springs. The equation is:

$$SMQ^2 = 114.12 - 8.05\ LP(W/L) + 54.74\ \mathrm{Log}_{10}\ [BLAN(Q)]\ ;$$

$$\text{if } SMQ^2 \leqslant 0, \text{ then set } SMQ^2 = 0.0,$$

where SMQ^2 is the monthly average local recharge component of the total monthly average discharge of San Marcos Springs in cubic feet per second, LP(W/L) is the monthly average water level in well DX-68-23-302 in feet below land surface, and BLAN(Q) is the previous monthly average discharge of the Blanco River at Wimberly, Texas, in cubic feet per second.

The total monthly average flow of San Marcos Springs (SMQT) is the sum of the regional underflow component (SMQ^1) plus the local recharge component (SMQ^2). Based on these equations, the annual average discharge of San Marcos Springs has been computed by the U.S. Geological Survey for the period 1950 through 1974 and is shown in comparison to the observed discharge on Figure 20.

A similar equation was developed by the U.S. Geological Survey for the flow of Hueco Springs. This equation is:

$$HS(Q) = 41.54 - 4.60\ LP(W/L) + 46.77\ \mathrm{Log}_{10}\ [BLAN(Q)]\ ;$$

$$\text{if } HS(Q) \leqslant 0 \text{ then set } HS(Q) = 0.0,$$

where HS(Q) is the average monthly discharge of Hueco Springs in cubic feet per second, LP(W/L) is the average monthly water level in well DX-68-23-302 in feet below land surface, and BLAN(Q) is the average monthly discharge of the Blanco River at Wimberly in cubic feet per second. Figure 21 gives a comparison of observed

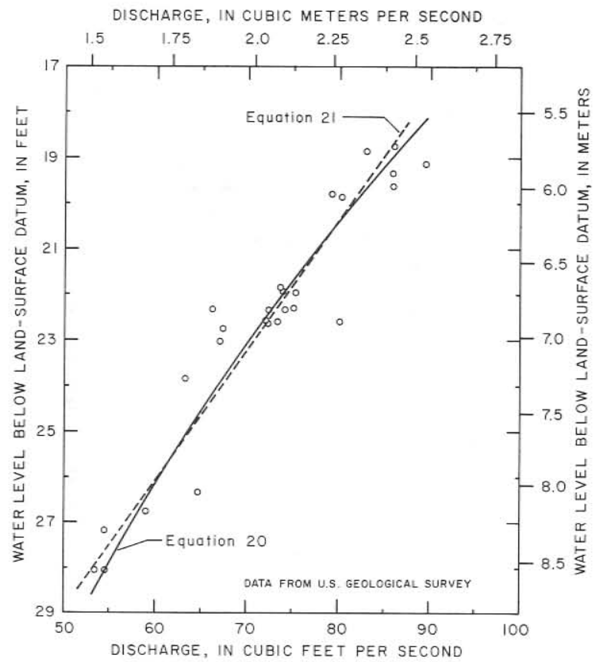

Figure 19.—Relationship Between the Water Level in Well DX-68-23-302 and the Discharge of Regional Underflow at San Marcos Springs

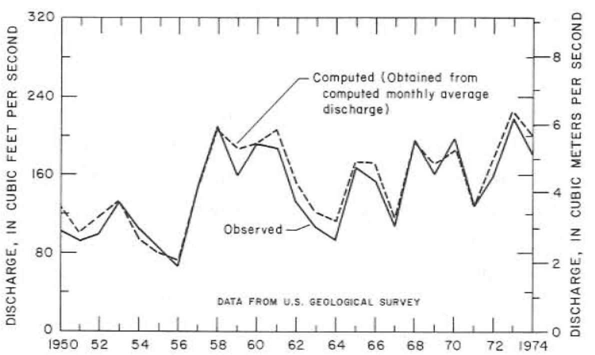

Figure 20.—Comparison of Observed and Computed Annual Average Discharge of San Marcos Springs

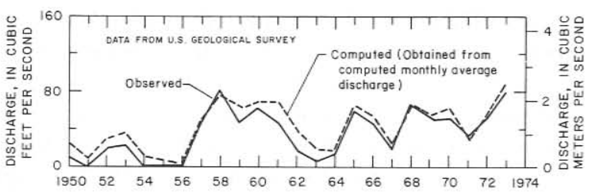

Figure 21.—Comparison of Observed and Computed Annual Average Discharge of Hueco Springs

and computed annual average discharge at Hueco Springs, with the computed values being obtained by this equation. It is recognized by the U.S. Geological Survey that neither the water level in this well at Landa Park nor the flow of Blanco River is directly related to the flow of Hueco Springs. However, it is considered that these factors are indicative of others that are related. The correlation was made with these particular factors because complete data are not available on recharge and water levels in the source area for Hueco Springs.

Study by William F. Guyton & Associates

In 1963, a method was devised by Guyton (1963) for predicting water levels in the Edwards aquifer in the San Antonio area under varying future conditions of recharge and well withdrawals. By its nature, this method requires the prediction of spring flows. A relationship was established between the change in storage in the Edwards aquifer, the change in water levels, and spring flow.

The relationship between storage in the Edwards aquifer and the water level in the aquifer was based on a correlation between the annual water levels in the Beverly Lodges well and the accumulated annual change in storage (based on differences between the annual recharge to and discharge from the aquifer) from 1934 through 1961. Figure 22 shows a correlation of year-end water levels in the Beverly Lodges well with changes in storage in the Edwards aquifer. Figure 23 shows a correlation that was developed between the average yearly water levels in the Beverly Lodges well and Comal Springs flow, and Figure 24 shows a correlation with water levels in the same well with the San Antonio and San Pedro Springs flow. If the future recharge and well withdrawals are assumed, the three remaining unknowns for a water budget then are the flow of San Marcos Springs, the flow of Hueco Springs, and the flow of Leona Springs.

It was assumed that, for like periods of recharge, the flow of San Marcos Springs would be the same for future years as in the past, so long as Comal Springs continued to flow. It was assumed, however, that when Comal Springs dried up, the flow of San Marcos Springs would be reduced by 1.55 cubic feet per second (0.0439 m^3/s) for each additional foot of depth to water in the Beverly Lodges well below the depth at which Comal Springs stopped flowing.

Flow from Hueco Springs was estimated to be comprised of two parts, a flow from local recharge and a flow from the main part of the Edwards aquifer. The average yearly water level at the Beverly Lodges well was used to estimate the flow from the main part of the Edwards aquifer on the assumption that the flow from the main aquifer would be zero with a water level of

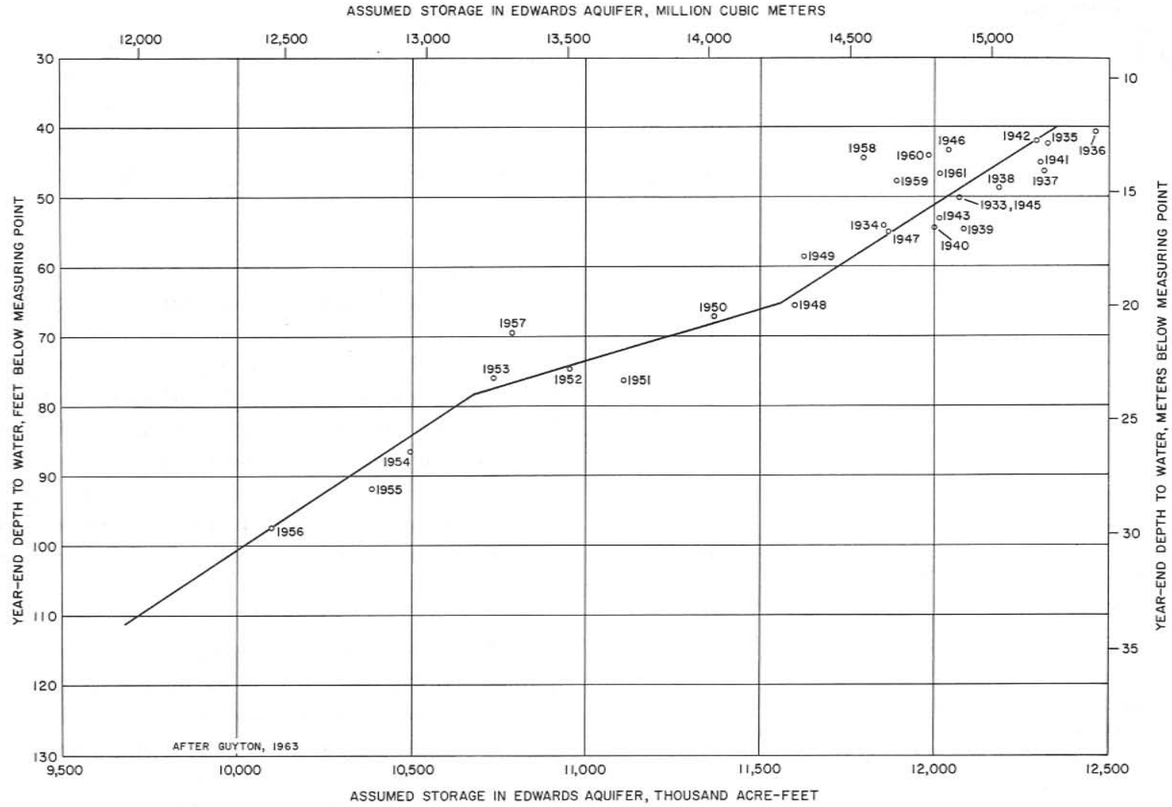

Figure 22.—Correlation of Year-End Water Levels in Beverly Lodges Well With Change in Storage in the Edwards Aquifer

61 feet (18.6 m) in the Beverly Lodges well and would vary linearly from there through the point of 17,000 acre-feet (21 million m^3) per year at a water level of 50 feet (15.2 m). The future local flow was assumed to be the total historical spring flow, for like periods of recharge, less the computed historical flow from the main part of the Edwards aquifer.

In predicting the flow of Leona Springs, the historical spring flow for like periods of recharge was used for predicted depths to water in the Beverly Lodges well of less than 70 feet (21.3 m). For depths to water greater than 70 feet (21.3 m) the predicted flow of Leona Springs was zero.

Based on the above assumptions and correlations, the future spring flows and Beverly Lodges water levels were then calculated in 1-year steps by computing a water balance for each year. To check the procedure, the water levels in the Beverly Lodges well were calculated for the period 1934-61. A comparison of the calculated and actual water levels is shown on Figure 25. It indicates that the method is reasonably accurate for computing water levels in the Beverly Lodges well for the historical range of recharge and water-level conditions. In turn this indicates that the computed discharges of Comal and San Antonio and San Pedro Springs are also reasonably accurate. Whether the computations of flows from San Marcos, Hueco, and Leona Springs are accurate under assumed future conditions of pumpage and recharge, when water levels in the Edwards aquifer will be greatly depressed, cannot be ascertained from this comparison, because the assumed changes in these spring flows at such low water levels of the aquifer go beyond the range of the previously measured data.

Studies by U.S. Bureau of Reclamation

In 1972 and subsequently, the U.S. Bureau of Reclamation has made estimates of future water levels in wells and spring flows for the Edwards aquifer in connection with its water-planning activities. These estimates were made in a similar manner to those described above for the Guyton studies of 1963, except that the Bureau of Reclamation divided the Edwards aquifer into three segments called the Uvalde Pool, the Central Pool, and the San Marcos Pool. The Bureau of Reclamation made an annual water balance study for each year for each pool, with the spill from the Uvalde Pool going into the Central Pool and the spill from the Central Pool going into the San Marcos Pool, and with the spring flows in each pool being controlled by the

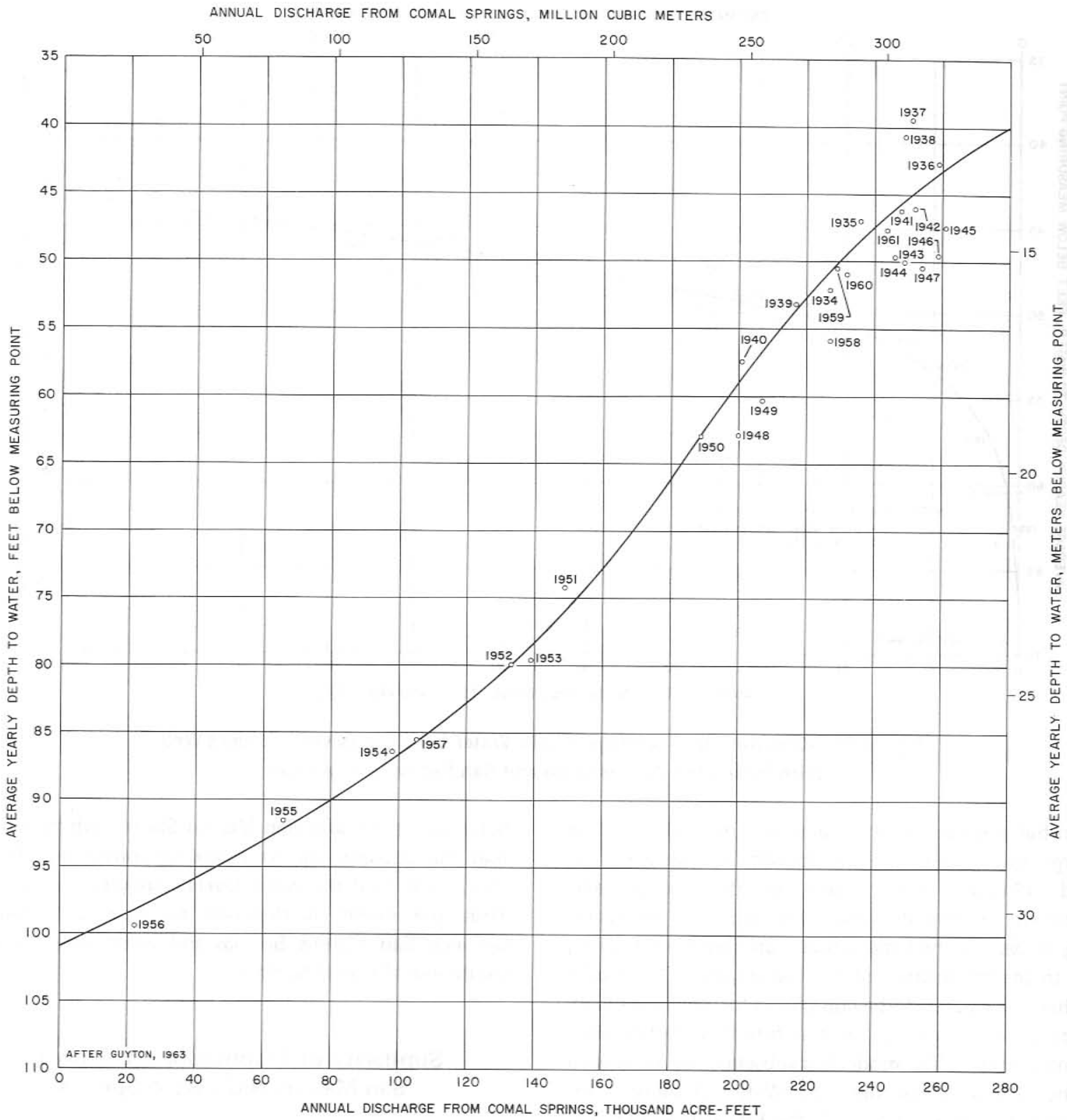

Figure 23.—Correlation of Average Yearly Water Levels in Beverly Lodges Well With Comal Springs Flow

water levels in those pools. The published results of the Bureau of Reclamation projections are not available at this time, but a review of its preliminary memoranda indicate that its method of projection gives results that are reasonably consistent with those that have been made by Guyton & Associates and the Texas Department of Water Resources. The U.S. Bureau of Reclamation estimates assume that both Comal and San Marcos Springs are intimately tied to the entire Edwards aquifer and that both will be directly affected by withdrawals from wells to the southwest.

Digital Model by Texas Department of Water Resources

During the period 1972-75, the Texas Water Development Board (a predecessor of the Department of Water Resources) made a study of the Edwards aquifer and developed a digital model of the aquifer (Klemt and others, 1975). Boundaries, elevations, permeabilities, and storage coefficients were estimated for the aquifer and used to make a mathematical model comprised of 856 cells in a grid superimposed on a map of the aquifer.

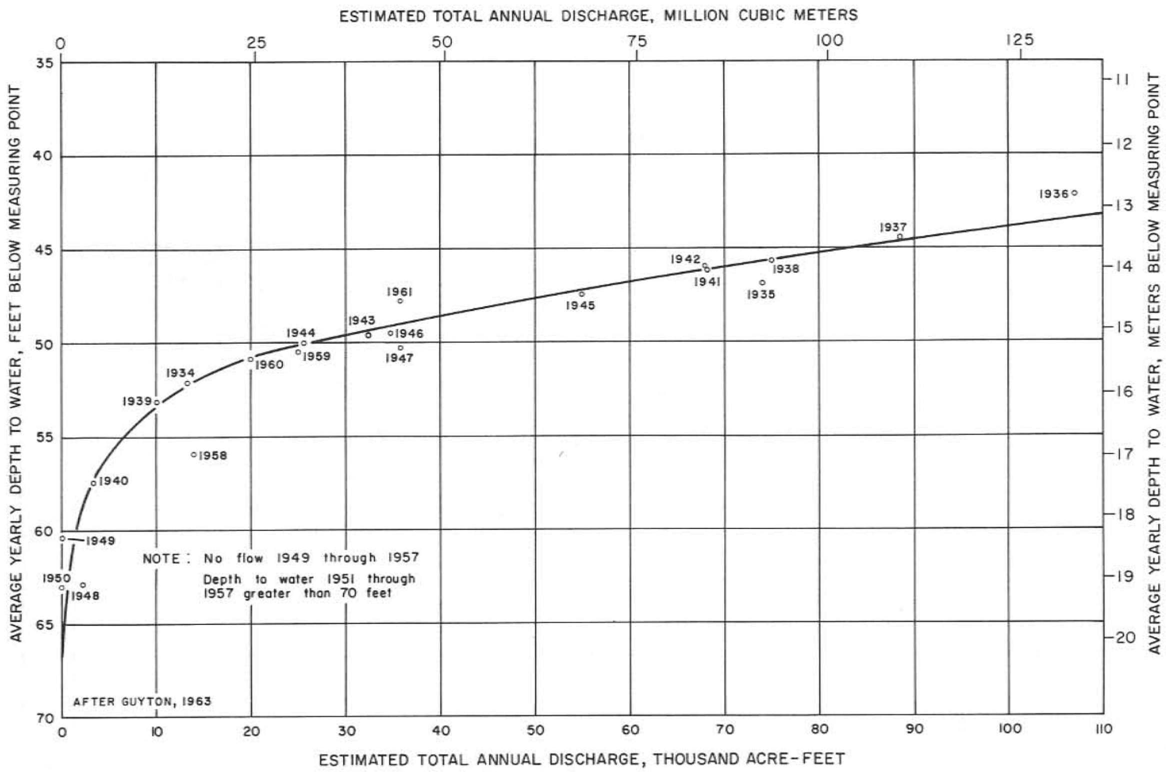

Figure 24.—Correlation of Average Yearly Water Levels in Beverly Lodges Well With Estimated San Antonio and San Pedro Springs Flow

The initial position of the water level in 1947 and the recharge, spring flow, and withdrawals from wells for the period 1947-71 were added to the model, and adjustments were made until computed water levels and spring flows matched the actual water levels and spring flows to the satisfaction of the investigators. The model was then considered to be completed for the time being, subject to modifications in the future as better data become available. The model has subsequently been used by the Texas Department of Water Resources for predicting future water levels in the Edwards aquifer and for predicting spring flows under varying conditions of withdrawals from wells and projected recharge.

Figure 26 is taken from the Department of Water Resources' report and shows the accumulated historical and simulated spring flows from 1947-71. This is a measure of the accuracy with which the model was able to compute the long-term spring flow. The springs included in this analysis are Leona, San Antonio, San Pedro, Comal, and San Marcos Springs. The analysis does not include Hueco Springs because these springs were not included by the U.S. Geological Survey and the Department of Water Resources in the water balance for the Edwards aquifer at the time this study was made.

In making this model, the Department used elevations and permeabilities of the Edwards aquifer between Comal and San Marcos Springs which indicate that the Edwards aquifer would be continuous through this area even if the water levels were greatly depressed. Thus the model is designed to show a connection between San Marcos Springs and water levels in wells southwest of Comal Springs.

Similarity of Fluctuations in Flow of San Marcos and Hueco Springs

A visual examination of the data on Figure 13 indicates that the flows of San Marcos and Hueco Springs correlate reasonably well. As a check on this correlation, the annual flows of these two springs were plotted against each other and are shown on Figure 27. The relatively close correlation of the fluctuations in discharge of these springs indicates that San Marcos Springs may in part be derived from the same source as Hueco Springs and that, in any event, their respective recharges are influenced greatly by the same local factors.

RECHARGE AREAS FOR SPRINGS

Figure 1 shows the recharge area for the entire Edwards aquifer. The recharge area is divided into

AFTER GUYTON, 1963

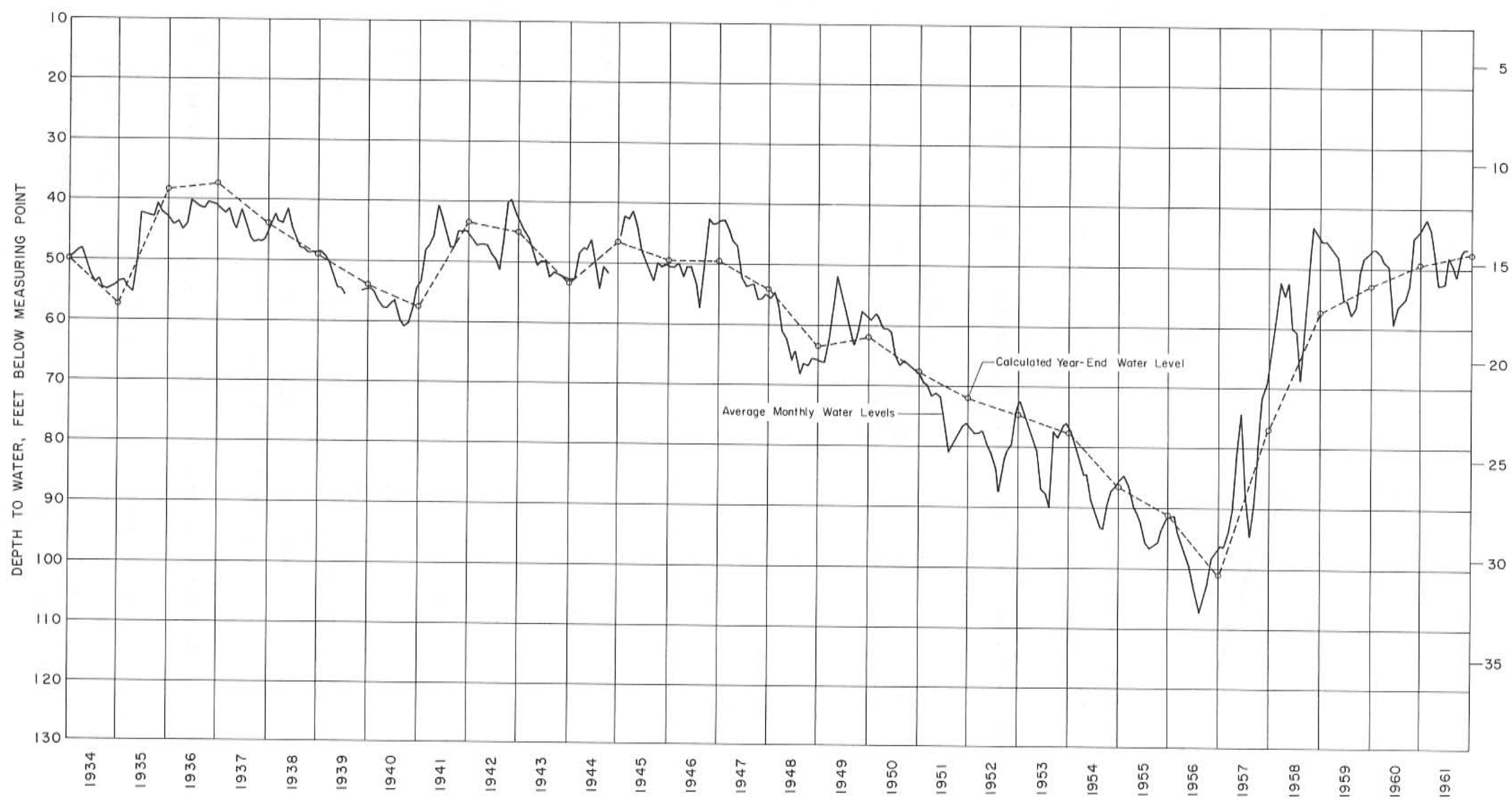

Figure 25
Comparison of Calculated and Measured Water Levels
in Beverly Lodges Well, 1934-1961

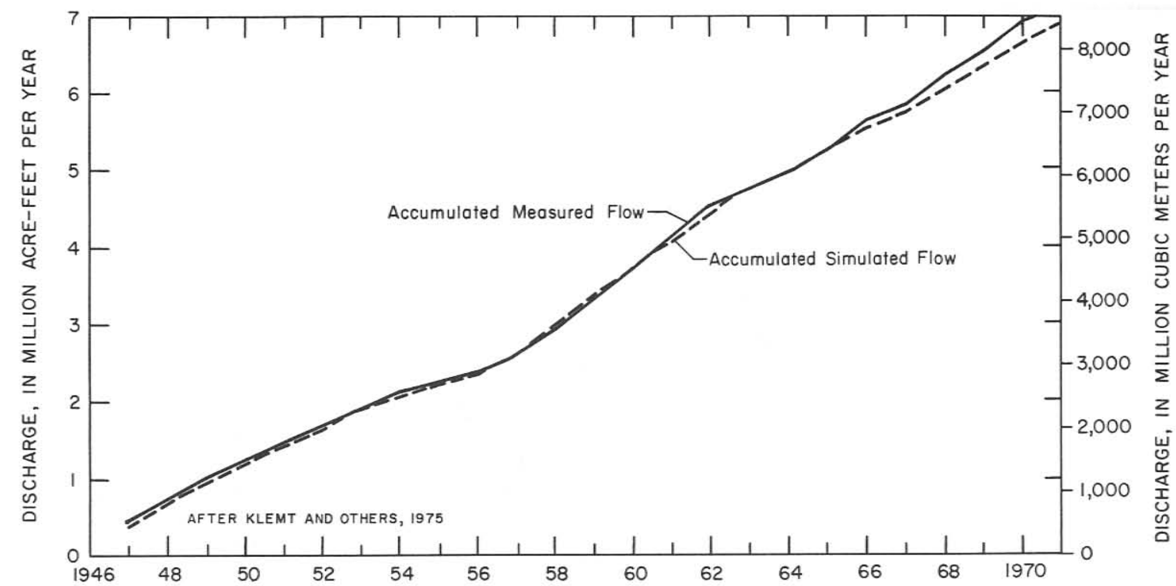

Figure 26.—Historical and Simulated Sum of Spring Flows, 1947-1971

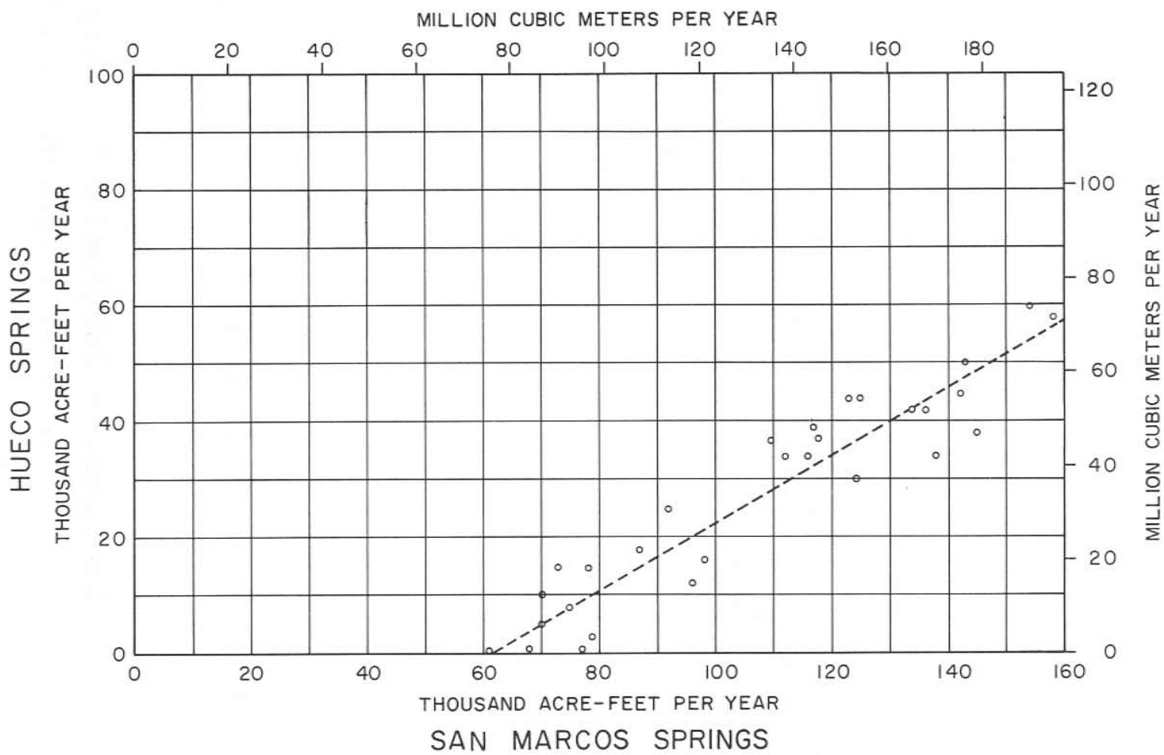

Figure 27.—Annual Flow of San Marcos Springs Versus Annual Flow of Hueco Springs, 1945-1974

subunits for which the U.S. Geological Survey computes recharge. In the primary study area from San Antonio northeastward in Bexar, Comal, and Hays Counties, these are the Cibolo Creek basin; the Dry Comal Creek basin; the Guadalupe River basin; the Sink, Purgatory, York, and Alligator Creek basins; and the Blanco River basin. Dry Comal Creek basin is not named on the map in Figure 1, but is that basin between the Cibolo Creek basin and the Guadalupe River basin. Similarly, the Sink, Purgatory, York, and Alligator Creek basins all comprise one unit which is between the Guadalupe River basin and the Blanco River basin. Recharge amounts computed for these basins or subunits, as well as all the discharge from the Edwards aquifer in Comal and Hays

Counties, are given in Table 1. No recharge is listed for the Guadalupe River basin in Table 1 because it has not been computed by the U.S. Geological Survey. However, as pointed out earlier in this report, there is a small amount of recharge from this basin, estimated to average about 6,000 acre-feet (7.4 million m^3) per year. Also, none of the relatively small amount of recharge which migrates into the Edwards aquifer from the general ground-water body in the Glen Rose Formation is listed.

Comal Springs

All available evidence indicates that the principal recharge area for Comal Springs is all of the recharge area of the Edwards aquifer southwest of the Cibolo Creek basin in the remaining part of the San Antonio River basin and the Nueces River basin. The Comal Springs recharge area probably also includes at least a substantial part of the recharge area of Cibolo Creek basin. In addition, there probably is a small amount of recharge derived from the recharge area of Dry Comal Creek. However, the amount from Dry Comal Creek probably is not large, because this area is so nearby, and the tritium content of the water from Comal Springs indicates that there is very little local water in the discharge from Comal Springs.

It is believed that whatever happens to the recharge, as well as to withdrawals from wells, in the Edwards aquifer southwest of Comal Springs will have an effect on Comal Springs.

San Marcos Springs

It has been concluded that there is a flow in the Edwards aquifer which originates southwest of Comal Springs and goes past Comal Springs to be discharged at San Marcos Springs. Based on U.S. Geological Survey studies, the amount of this by-passing flow, or underflow, is estimated to have ranged from a monthly average as low as about 55 cubic feet per second (1.55 m^3/s) to more than 100 cubic feet per second (2.83 m^3/s). This underflow is supposedly derived from the same sources as the flow of Comal Springs. However, the tritium content of the water from San Marcos Springs may be too great for such a large amount of underflow to come from exactly the same sources as Comal Springs. It appears conceivable that some water may be classed as underflow which originates in the Cibolo Creek recharge area, and possibly the Dry Comal Creek basin. Data are not yet available to resolve this possible anomaly. However, it has been generally concluded by all investigators so far, that there is a large thickness of saturated Edwards aquifer containing fresh water between Comal Springs and San Marcos Springs which is sufficient to carry water past Comal Springs to San Marcos Springs, and that there is a substantial hydraulic gradient in that direction. Thus, the concept of underflow from Comal Springs to San Marcos Springs appears to be sound. The only things that need to be determined are the exact magnitude of the underflow and whether some of the water from the Cibolo Creek and possibly the Dry Comal Creek recharge areas is moving into the main part of the aquifer near Comal Springs and is taking place of water which otherwise would flow to San Marcos Springs as underflow from the larger recharge areas farther to the southwest.

The remaining portion of the water from San Marcos Springs, which is considered to be the local flow component, is believed to be derived primarily from (1) the recharge area of the Blanco River basin; (2) the recharge area of the Sink, Purgatory, York, and Alligator Creek basins; (3) the Guadalupe River basin recharge area east of the river and that small portion west of the river which is south of the Hueco Springs Fault; (4) probably part of the upper part of the Dry Comal Creek basin; and (5) possibly part of the upper part of the Cibolo Creek basin recharge area.

Hueco Springs

The recharge area for Hueco Springs is considered to be relatively local for the most part and to be comprised primarily of the Dry Comal Creek basin north of the Hueco Springs Fault and the Guadalupe River basin recharge area west of the river, with perhaps some water from the upper part of the Cibolo Creek basin recharge area. Studies by Guyton (1958) indicated that some water might be spilled from the main portion of the Edwards aquifer between San Antonio and Comal Springs into the area north of the Hueco Springs Fault, which supplies Hueco Springs, when the water levels in the reservoir are especially high. This can be neither proved nor disproved at this point.

As pointed out earlier in this report, the discharge of Hueco Springs is sufficiently large that it must be taken into account in the water balance for the Edwards aquifer. It seems clear, however, that this is discharge which, at least for the most part, is not directly related to discharge from Comal Springs. Also, because of water level and spring outlet elevation differences, the recharge to Hueco Springs cannot be coming from much of the area from which San Marcos Springs obtains its local recharge. It is believed that no recharge for Hueco Springs occurs from the area east of the Guadalupe River because of the lower water levels in that direction. It seems probable, therefore, that Hueco Springs is the first outlet for a local recharge area to its north, west, and southwest, with the remainder of the water from this area spilling on across the Guadalupe River basin to San Marcos Springs.

Local Water Balance

The question has been raised as to whether there is enough local recharge to supply the water believed to come from local recharge areas, without including the Cibolo Creek basin recharge. Although it is not known whether the Cibolo Creek basin recharge contributes to this portion of the water, the data indicate that there would be enough local recharge, exclusive of the Cibolo Creek basin recharge, if none of the other local recharge went to Comal Springs or was included in the underflow component of San Marcos Springs discharge.

Based on U.S. Geological Survey figures, the underflow to San Marcos Springs has been estimated at an average of 63,000 acre-feet (77.7 million m^3) per year for the period 1956-73, and the local recharge at 50,000 acre-feet (61.7 million m^3) per year. If it is assumed that the same percentages hold for the 1945-73 period, Table 1 indicates that the total discharge of San Marcos Springs, less its underflow from Comal Springs, plus the withdrawals from Hays County wells and the discharge of Hueco Springs for the period 1945-73 averaged about 77,000 acre-feet (94.9 million m^3) per year. This correlates with a total average recharge from the Blanco River basin; the Sink, Purgatory, York, and Alligator Creek basins; and the Dry Comal Creek basin of 67,000 acre-feet (82.6 million m^3) per year. If the average Guadalupe River basin recharge is 6,000 acre-feet (7.4 million m^3) per year as previously estimated, and if there is as much as 4,000 acre-feet (5.4 million m^3) per year available as inflow from the Glen Rose Formation updip, it thus appears that there would be sufficient recharge from the Dry Comal Creek basin northeastward, if none of this recharge was discharged through Comal Springs or became part of the underflow component computed for San Marcos Springs.

POSSIBILITIES OF POLLUTION

Present Records

Table 4 lists all available analyses of minor elements in water from Comal, San Marcos, and Hueco Springs. No evidence of pollution is indicated by these analyses. Nutrients and bacteria in the water are given in Table 5. In addition, all the nitrate analyses which are included in Table 1 are repeated in Table 5. These analyses indicate small amounts of pollution of some of the samples, but the few analyses which are available for each of the springs do not indicate anything especially serious. Table 6 shows the tests which are available for insecticides and herbicides in water from Comal and San Marcos Springs. Only one analysis is available from each spring group, and none of the substances for which tests were made was found in the water.

Legal Control of Pollution

The Texas Department of Water Resources currently has strict regulations in force to protect the recharge area of the Edwards aquifer from pollution. Waste disposal practices are governed by these regulations, and certain other activities, such as the location of animal feedlots and the use of fertilizer, also come under the jurisdiction of the Department. Most reviewers appear to have concluded that if the regulations are strictly followed, there should be a minimum of pollution of the Edwards aquifer as a result of waste disposal practices on the recharge area.

The U.S. Environmental Protection Agency (EPA), under the Safe Drinking Water Act of 1975, has declared the recharge area of the Edwards aquifer under its jurisdiction. As a consequence, it will be necessary that the EPA determine that no project be financed by the federal government which may seriously contaminate the Edwards aquifer through its recharge area.

In addition to the state and federal regulations, various counties and cities within the Edwards aquifer recharge area also have rules and regulations governing waste disposal, for the protection of the quality of ground water in the Edwards aquifer.

Comal Springs

Most of the water moving to Comal Springs is quite old and must first move through the San Antonio area. In view of this, and in view of the strict regulations governing activities which might pollute the Edwards aquifer, it seems very doubtful that Comal Springs will ever be seriously polluted.

San Marcos Springs

The recharge area for much of the San Marcos Springs flow is more local than that for Comal Springs, and the water is younger. Thus, it would appear that San Marcos Springs is more likely to be subject to pollution as the result of man's activities than Comal Springs. On

Table 4.--Minor Elements in Water From Comal, San Marcos, and Hueco Springs

[Results in micrograms per liter (μg/l; 1,000 μg/l = 1 mg/l) and all analyses by U.S. Geological Survey.]

Date of Collection	Aluminum (Al)	Arsenic (As)	Boron (B)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manga-nese (Mn)	Mercury (Hg)	Nickel (Ni)	Strontium (Sr)	Zinc (Zn)
Comal Springs											
1-22-44	--	--	--	--	20	--	--	--	--	--	--
8- 7 -51	--	--	--	--	30	--	--	--	--	--	--
10- 4 -57	--	--	--	--	0	--	--	--	--	--	--
6-18-59	--	--	--	--	30	--	--	--	--	--	--
2-17-71	--	0	--	1	--	0	--	<0.5	--	--	10
7-20-71	--	--	--	--	0	--	0	--	--	600	--
5-12-72	--	0	100	3	0	0	0	0.4	0	--	50
5-15-73	--	--	--	--	0	--	0	--	--	610	--
11-23-73	--	--	--	--	0	--	0	--	--	500	--
4- 2 -74	--	--	--	--	0	--	--	--	--	--	--
12-16-74	--	--	--	--	10	--	--	--	--	620	--
San Marcos Springs											
5-16-47	--	--	--	--	50	--	--	--	--	--	--
6-18-59	--	--	150	--	30	--	--	--	--	--	--
10-31-68	0	--	10	0	0	0	0	--	0	570	20
7-31-72	--	--	--	--	10	--	0	--	--	580	--
3- 7 -73	--	--	80	--	10	--	0	--	--	--	--
5-15-73	--	--	--	--	0	--	0	--	--	610	--
12-16-74	--	--	--	--	0	--	--	--	--	600	--

Table 4.--Minor Elements in Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Aluminum (Al)	Arsenic (As)	Boron (B)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Strontium (Sr)	Zinc (Zn)
Hueco Springs											
10- 4 -57	--	--	--	--	0	--	--	--	--	--	--
10-31-68	0	--	40	0	30	0	0	--	10	370	20
10- 4 -72	--	--	--	--	0	--	0	--	--	390	--
5-15-73	--	--	--	--	0	--	0	--	--	210	--
11-23-73	--	--	--	--	0	--	0	--	--	100	--
12-16-74	--	--	--	--	10	--	--	--	--	310	--

Table 5.--Nutrients and Bacteria in Water From Comal, San Marcos, and Hueco Springs

[Results in milligrams per liter (mg/l) except as otherwise noted and all analyses by U.S. Geological Survey except as noted.]

Date of Collection	Ammonia (NH_4)	Ammonia Nitrogen (N)	Nitrate (NO_3)	Nitrite (NO_2)	Nitrate + Nitrite as Nitrogen (N)	Phos-phate (PO_4)	Total Phos-phorous (P)	Deter-gents (MBAS) 1/	Bio-Chemical Oxygen Demand, 5-day (BOD)	Immediate Coliform (colonies per 100 ml)	Fecal Coliform (colonies per 100 ml)	Strepto-cocci (colonies per 100 ml)	Dissolved Organic Carbon
Comal Springs													
4-10-38	--	--	5.0	--	--	--	--	--	--	--	--	--	--
6-24-41	--	--	3.7	--	--	--	--	--	--	--	--	--	--
9-16-41	--	--	4.4	--	--	--	--	--	--	--	--	--	--
4- 2 -42	--	--	4.0	--	--	--	--	--	--	--	--	--	--
12- 4 -43	--	--	5.8	--	--	--	--	--	--	--	--	--	--
12- 4 -43	--	--	5.5	--	--	--	--	--	--	--	--	--	--
1-10-44	--	--	5.5	--	--	--	--	--	--	--	--	--	--
1-22-44	--	--	5.5	--	--	--	--	--	--	--	--	--	--
10- 9 -45	--	--	5.6	--	--	--	--	--	--	--	--	--	--
2- 1 -47	--	--	4.0	--	--	--	--	--	--	--	--	--	--
8- 7 -51	--	--	4.5	--	--	--	--	--	--	--	--	--	--
6-24-57	--	--	4.8	--	--	--	--	--	--	--	--	--	--
8- 8 -57	--	--	4.8	--	--	--	--	--	--	--	--	--	--
10- 4 -57	--	--	4.2	--	--	--	--	--	--	--	--	--	--
1-14-58	--	--	4.8	--	--	--	--	--	--	--	--	--	--
4- 9 -58	--	--	5.1	--	--	--	--	--	--	--	--	--	--
7-16-58	--	--	5.3	--	--	--	--	--	--	--	--	--	--
1-16-59	--	--	6.8	--	--	--	--	--	--	--	--	--	--
6-18-59	--	--	6.1	--	--	--	--	--	--	--	--	--	--
2-17-71	0.00	0.00	7.1	0.00	1.6	0.03	0.01	0.00	0.7	14	0	0	--
7-20-71	--	--	5.5	--	1.2	--	--	--	--	--	--	--	--
8-12-71	--	--	--	--	--	--	--	--	--	29	0	0	--
10-17-72 2/	--	--	--	--	--	--	--	--	--	0	--	--	--

For footnotes see end of table.

Table 5.--Nutrients and Bacteria in Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Ammonia (NH_4)	Ammonia Nitrogen (N)	Nitrate (NO_3)	Nitrite (NO_2)	Nitrate + Nitrite as Nitrogen (N)	Phos-phate (PO_4)	Total Phos-phorous (P)	Deter-gents (MBAS) 1/	Bio-Chemical Oxygen Demand, 5-day (BOD)	Immediate Coliform (colonies per 100 ml)	Fecal Coliform (colonies per 100 ml)	Strepto-cocci (colonies per 100 ml)	Dissolved Organic Carbon
Comal Springs - continued													
2- 6 -73	--	--	8.0	--	--	--	0.00	0.0	--	16	0	0	--
3-20-73 2/	--	--	--	--	--	--	--	--	--	0	--	--	--
5-15-73	--	--	3.4	--	0.76	--	0.00	--	--	--	--	--	--
9-18-73 2/	--	--	--	--	--	--	--	--	--	0	--	--	--
11-12-73 2/	--	--	--	--	--	--	--	--	--	25	--	--	--
11-23-73	--	--	8.4	--	1.9	--	0.01	--	--	--	--	--	--
4- 2 -74	--	0.02	7.1	--	1.6	--	0.02	--	--	0	0	0	0.0
12-16-74	--	--	7.1	--	1.6	0.00	--	--	--	--	--	--	--
1- 7 -75 2/	--	--	--	--	--	--	--	--	--	0	--	--	--
San Marcos Springs													
5-16-47	--	--	3.0	--	--	--	--	--	--	--	--	--	--
3-23-55	--	--	4.6	--	--	--	--	--	--	--	--	--	--
6-18-59	--	--	8.5	--	--	--	--	--	--	--	--	--	--
10-31-68	0.00	0.00	0.6	0.00	--	0.04	0.01	0.01	0.4	8	--	--	--
10-19-71 3/	--	<1.0	--	--	<1.05	<0.03	--	--	1.0	--	--	--	--
7-31-72	--	--	5.8	--	1.3	--	0.01	--	--	--	--	--	--
3- 7 -73	--	0.06	5.8	--	1.3	--	0.02	0.0	--	67	3	0	--
5-15-73	--	--	4.8	--	1.0	--	0.00	--	--	--	--	--	--
4- 4 -74	--	0.02	5.8	--	1.3	--	0.01	--	--	0	0	0	0.0
6- 6 -74 4/	--	--	--	--	--	<0.01	<0.01	--	--	--	--	--	--

For footnotes see end of table.

Table 5.--Nutrients and Bacteria in Water From Comal, San Marcos, and Hueco Springs--Continued

Date of Collection	Ammonia (NH_4)	Ammonia Nitrogen (N)	Nitrate (NO_3)	Nitrite (NO_2)	Nitrate + Nitrite as Nitrogen (N)	Phos-phate (PO_4)	Total Phos-phorous (P)	Deter-gents (MBAS) 1/	Bio-Chemical Oxygen Demand, 5-day (BOD)	Immediate Coliform (colonies per 100 ml)	Fecal Coliform (colonies per 100 ml)	Strepto-cocci (colonies per 100 ml)	Dissolved Organic Carbon
Hueco Springs													
6-24-41	--	--	9.8	--	--	--	--	--	--	--	--	--	--
9-16-41	--	--	12	--	--	--	--	--	--	--	--	--	--
1-22-44	--	--	12	--	--	--	--	--	--	--	--	--	--
9-14-44	--	--	8.0	--	--	--	--	--	--	--	--	--	--
9-13-45	--	--	1.5	--	--	--	--	--	--	--	--	--	--
10-19-45	--	--	12	--	--	--	--	--	--	--	--	--	--
6-24-57	--	--	23	--	--	--	--	--	--	--	--	--	--
8- 8 -57	--	--	19	--	--	--	--	--	--	--	--	--	--
10- 4 -57	--	--	19	--	--	--	--	--	--	--	--	--	--
1-14-58	--	--	21	--	--	--	--	--	--	--	--	--	--
3- 9 -58	--	--	20	--	--	--	--	--	--	--	--	--	--
7-21-58	--	--	14	--	--	--	--	--	--	--	--	--	--
1-14-59	--	--	18	--	--	--	--	--	--	--	--	--	--
9-10-59	--	--	12	--	--	--	--	--	--	--	--	--	--
10-31-68	0.00	0.00	9.2	0.04	2.1	0.05	0.2	0.00	0.2	24	--	--	--
10- 4 -72	--	--	8.5	--	--	0.00	--	--	--	--	--	--	--
5-15-73	--	--	2.5	--	--	0.00	--	--	--	--	--	--	--
11-23-73	--	--	8.0	--	--	0.00	--	--	--	--	--	--	--

1/ Methylene blue active substance.

2/ Sampled by New Braunfels City Health Department. Analysis by Texas State Health Department Laboratory.

3/ Texas Water Quality Board analysis.

4/ Espey, Huston & Associates, Inc., 1975, analysis by Texas State Department of Health.

Table 6.--Insecticides and Herbicides in Water from Comal and San Marcos Springs [1/]

[Results in micrograms per liter (µg/l; 1,000 µg/l = 1 mg/l) and all analyses by U.S. Geological Survey.]

Date of Collection	Insecticides									Herbicides		
	Aldrin	DDD	DDE	DDT	Diel-drin	Endrin	Hepta-chlor	Hepta-chlor Epoxide	Lin-dane	2,4-D	2,4,5-T	Silvex
Comal Springs												
4-1-68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
San Marcos Springs												
4-1-68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1/] No analyses have been made for insecticides and herbicides in water from Hueco Springs.

the other hand, its local recharge area is much less developed by man than at least part of the recharge area for Comal Springs, and there seems to be less likelihood of development occurring which will contaminate the springs seriously. Furthermore, the same rules and regulations of the Department of Water Resources and the EPA will apply to this area as to the recharge area supplying Comal Springs. Consequently, it is not believed that serious pollution of San Marcos Springs is likely to occur in the reasonably foreseeable future.

Hueco Springs

The relatively high nitrate in the water from Hueco Springs indicates that this group of springs is more likely to receive pollution from the land surface than San Marcos and Comal Springs. Also, the fact that its recharge area is smaller and more local supports this concept. On the other hand, the recharge area for Hueco Springs is the least developed by man of all three, and therefore, the least likely to be adversely affected in the relatively near future. In addition, the same rules and regulations will apply to this recharge area as to the others. Consequently, as in the case of the other two groups of springs, it is not considered likely that serious pollution will occur in the foreseeable future.

EFFECTS ON SPRING FLOW CAUSED BY WITHDRAWALS FROM WELLS

Comal Springs

A substantial portion of the flow of Comal Springs has now been intercepted by wells. Comal Springs show a seasonal fluctuation in flow which they formerly did not have. From July to November 1956, as a result of a combination of severe drought and increased withdrawals from wells, Comal Springs stopped flowing. Withdrawals from the Edwards aquifer through wells totalled 321,000 acre-feet (396 million m^3) for the year 1956. Since then withdrawals from wells have gradually increased, and in 1971 and 1974 they were 407,000 acre-feet (502 million m^3) and 364,000 acre-feet (449 million m^3), respectively. Comal Springs have not stopped flowing again, however, inasmuch as recharge has generally been high. In fact, the highest annual flow ever recorded for the springs was 279,000 acre-feet (344 million m^3) in 1973.

It seems clear that the next time a major drought of the size which occurred in the early 1950's occurs, Comal Springs will again go dry and that it will stay dry for a longer period than it did in 1956. Furthermore, if withdrawals from wells in the Edwards aquifer continue to increase, Comal Springs will go dry even if a major drought does not occur, because average withdrawals from wells are slowly approaching average recharge, which in time will leave little or nothing left to spill out of the reservoir through the springs. Just when this will occur is largely a matter of conjecture because, although estimates can be made of the demands for water in the area of the Edwards aquifer, the fluctuations in recharge cannot be predicted because the future climate cannot be predicted.

On the assumption that historical recharge will be repeated, the Texas Department of Water Resources has made various studies as to when Comal Springs might go dry if pumping continues to increase from wells, and also whether and when it might go dry if withdrawals from wells are held at given rates in the future. Some of these are described in the report by Klemt and others (1975), and other studies are currently being made by use of the Department's digital model of the aquifer.

San Marcos Springs

The only time the effect of withdrawals from wells on San Marcos Springs was very apparent was in the summer and fall of 1956 when Comal Springs were dry. At that time the local recharge component of flow from San Marcos Springs was at a minimum and the underflow past Comal Springs was decreasing because the water level in the reservoir was dropping at Comal Springs and the hydraulic gradient toward San Marcos Springs was becoming less. The lowest average daily flow reached by San Marcos Springs in 1956 was 46 cubic feet per second (1.30 m^3/s), and the annual flow that year, which was the lowest on record, was 48,000 acre-feet (59.2 million m^3).

Intensive studies have been made as part of this investigation, and also have been made by previous investigators, to determine whether there is sufficient aquifer between Comal Springs and San Marcos Springs for the flow, which otherwise would discharge from San Marcos Springs, to be diverted to supply withdrawals from wells to the southwest in the San Antonio area and farther west in Medina, Uvalde, and Kinney Counties. All the studies have indicated that there is sufficient permeable aquifer for this to occur. Consequently, it has been concluded by previous investigators, and is concluded here, that the flow of San Marcos Springs probably can be intercepted by pumping from wells to the southwest. This applies not only to the underflow which now passes Comal Springs and goes to San Marcos Springs, but also applies to the flow from local recharge in the vicinity of San Marcos Springs. In other words, it is believed that the local recharge component of flow can be made to flow to the southwest without ever emerging at San Marcos Springs.

Assuming that this is the case, the effect of withdrawals from wells will be felt on San Marcos Springs whenever Comal Springs are dry. If the water level in the vicinity of Comal Springs is lowered approximately to the elevation of San Marcos Springs, all of the underflow passing Comal Springs will be stopped. Then if the water level is lowered farther, it is believed that water will move toward Comal Springs from San Marcos Springs, and farther southwest and west to the centers of withdrawal. These events are predicted to transpire in the future if and when withdrawals from wells become large enough and in times of major drought. If the average withdrawals from wells become equal to or larger than the total average recharge to the aquifer, the flows of Comal and San Marcos Springs probably will in time be totally intercepted regardless of droughts.

Hueco Springs

Whether Hueco Springs will be affected by pumping is likely to be determined by whether any water spills from the main part of the Edwards aquifer into the area north of the Hueco Springs Fault, as conceived possible by W. F. Guyton & Associates in 1958. Data are not available yet to determine positively whether this is the case. If it is the case, then that portion of the water from the main aquifer can certainly be intercepted by withdrawals from wells. It seems doubtful, however, that the remaining portion of the water which emerges from Hueco Springs can be intercepted by wells completed in the Edwards aquifer in the San Antonio area and farther west. This water is believed to move to the springs through a shallow portion of the Edwards aquifer from recharge areas which are not directly connected to the main portion of the Edwards aquifer. If this is the case, most of the average flow which has emerged from Hueco Springs in historical times likely will continue to occur in the future. There still will be periods when the springs are dry, but for the most part these are likely to be caused by droughts rather than withdrawals from wells.

POSSIBILITIES OF MAINTAINING COMAL AND SAN MARCOS SPRING FLOWS AT PREDETERMINED RATES

Much thought has been given to the possibilities of controlling the discharges of Comal and San Marcos Springs. The purposes of such control would be to maintain an acceptable flow from each of these groups of springs during periods of drought and to keep the springs from flowing at unusually high rates during and after periods of high recharge. Little attention has been paid to Hueco Springs in this regard because they have not been highly developed for recreation, there have been numerous periods of no flow from them in the past, and it does not appear likely that pumping from wells can greatly reduce the flow from them.

Unfortunately, there appears to be no sure way of controlling the high flows of the springs when recharge is great and water levels are high. Any attempt to plug off part of a group of springs and install regulating structures on the flow of the other outlets is likely to be met with the water breaking out of the ground in other places. Such places may or may not be at the same sites as the existing springs. In the case of Comal and San Marcos Springs, wells could, of course, be installed near the springs and pumped heavily during periods of high recharge, thus depleting the flows of the springs. However, there would seem to be little point in doing this in lieu of letting the water emerge from the springs and then diverting it for the same purposes as the well water might be used. Also there would have to be a use for such water at the time, or a place to store it.

At times of low recharge and little or no spring flow, wells could be pumped into the stream channels downstream from the spring outlets. It seems likely, however, that unless the spring outlets were dammed off from the well water at that time, the water would return to the aquifer through these openings. It should be pointed out also that wells cannot be pumped near the springs to supplement the spring flow, because the pumping of the wells themselves will intercept the remaining spring flow, and all the water that is placed in the stream channels leaving the springs will have to be well water if more water is desired than will flow naturally from the springs.

The possibility of artificially recharging the aquifer in the vicinities of the springs has been considered. To the extent that this increases the recharge, it will of course make that much more water available for withdrawal from wells or to flow from the springs. It is believed that it will not be practical, however, to attempt the recharge with the idea that a mound will be built on the piezometric surface of the aquifer in the vicinity of the recharge at each group of springs and thus cause the springs to flow even though the regional water levels are greatly depressed. The transmissibility of the aquifer is too great for this to have much chance of success, as the water probably will flow away underground from the spring outlets if there is a heavy demand for water elsewhere and the water levels are regionally depressed.

It appears, therefore, that if it is desired to keep natural flows from Comal and San Marcos Springs equal to or greater than predetermined minimum amounts, it will be necessary to hold withdrawals through wells from the Edwards aquifer to such a low rate that there will be very high flows from Comal and San Marcos Springs during and after periods of high recharge.

If it is desired to restrict the natural flows of Comal and San Marcos Springs to predetermined maximums, so that maximum withdrawals can be obtained from wells in the Edwards aquifer and still have some flows at the springs, it probably will be necessary to allow the water levels in the Edwards aquifer to seek lower levels so that there will never be high flows from Comal and San Marcos Springs. In this event, if it is desired to keep specified flows going down the stream channels at those points at all times, it will be necessary to pump well water into the stream channels much of the time or to bring it there from outside sources.

There probably is little that can be done to regulate the flow of Hueco Springs. However, it is possible that in the future these springs will be flowing at times when Comal and perhaps San Marcos Springs have been depleted. Because of this, it would be desirable to investigate the possibilities of using the water from Hueco Springs at those times as artificial recharge through wells in the Edwards aquifer south of the Hueco Springs Fault. Also, consideration might be given to constructing a canal from Hueco Springs to Comal Springs, and using the flow from Hueco Springs to supplement or partially replace the flow of Comal Springs.

FUTURE STUDIES

General Edwards Program

Comal, San Marcos, and Hueco Springs are integral parts of the hydrologic system of the Edwards aquifer in the San Antonio region. In studying these springs it is necessary to know as much as possible about the aquifer as a whole, and, vice versa, in studying the aquifer it is necessary to know as much as possible about the springs. Consequently, future studies concerning the springs cannot be separated from future studies concerning other parts of the aquifer in the San Antonio region.

The U.S. Geological Survey currently has underway an intensive program of investigation of the Edwards aquifer in the San Antonio region in cooperation with the Texas Department of Water Resources, the Edwards Underground Water District, and the San Antonio City Water Board. For administrative purposes, these studies are divided into continuing studies and research studies. There are still many unknowns with respect to the Edwards aquifer, and both types of studies should be continued. The continuing studies are primarily concerned with an observation program consisting of periodic measurements of water levels in wells, stream gaging, water-quality sampling, annual pumpage inventory, continuing well inventory, recharge calculations, etc. The research study is designed to investigate various aspects of the Edwards aquifer about which not enough is known, such as the specific yield and permeability of the aquifer at different places and different vertical levels, and relationships between the fresh water and highly mineralized water along the bad water line.

In addition to cooperating in these studies with the U.S. Geological Survey, the Texas Department of Water Resources should, of course, continue with its planning studies for the future water supplies of the entire San Antonio region. Among other things, such studies should include further refinement of the Department's digital model of the Edwards aquifer as better data become available from the Department's studies and the Survey's continuing and research studies. In addition, all practical possibilities of conjunctive use of ground water and surface water, including artificial recharge, should be studied in an effort to devise the optimum use of both, with the least practical waste of water by evapotranspiration and the least practical overall cost of development.

Special Studies Related to Comal, San Marcos, and Hueco Springs

Along with the studies which will be carried out in the vicinities of Comal, San Marcos, and Hueco Springs as part of the general Edwards program, it is specifically recommended that a few special studies be made. The most important of these are more intensive studies of (1) the area in which the artesian portion of the Edwards aquifer occurs between Bexar County and the northeastern limit of the reservoir near Kyle in Hays County; (2) the area within the Cibolo Creek basin where recharge enters the main part of the Edwards aquifer; and (3) the area around Hueco Springs, between it and possible sources of recharge, and between it and San Marcos Springs. These studies should include detailed well inventories, water-level measurements, and sampling for chemical analyses and tritium determinations. At least in the artesian area between Bexar County and Kyle, there should be some additional test drilling. In addition, it is recommended that further studies be made of recharge to the Edwards aquifer in the Guadalupe River basin. This should involve a more intensive study of the geology, water levels in wells, precipitation, and streamflow gains and losses. Also, the possibilities of artificial recharge through wells in this area should be investigated. Finally, with respect to specific observations, it is believed that it probably would be worthwhile to install a continuous-gaging station on Hueco Springs, and to sample the water approximately every 3 months from Comal, San Marcos, and Hueco Springs for monitoring and studies of possible pollution. Analyses should be made of all of the items for which a major public water supply is analyzed. At the time the samples are taken, careful and more accurate temperature measurements also should be made at each group of springs.

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