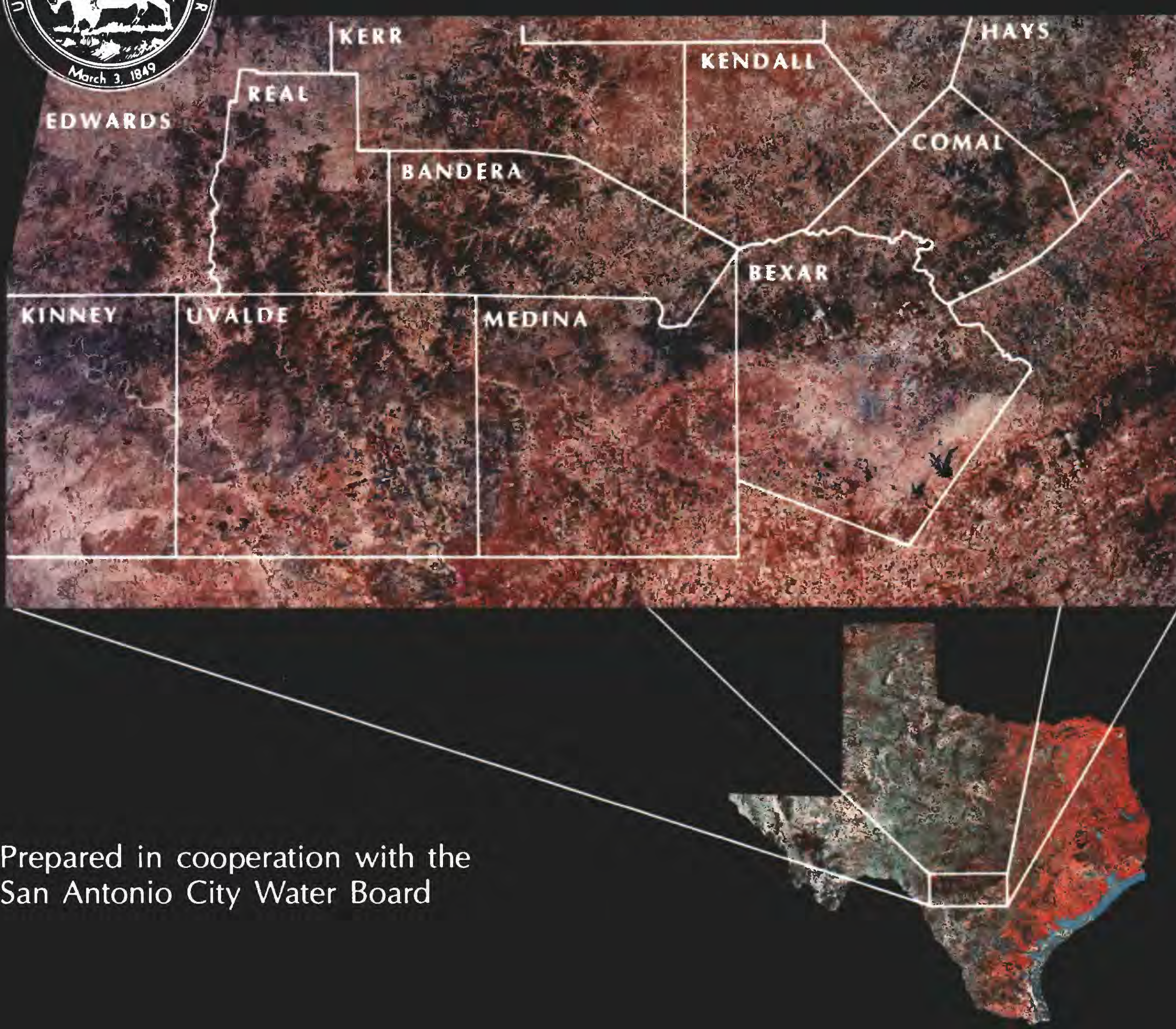
Simulation of Flow in the Edwards Aquifer, San Antonio Region, Texas, and Refinement of Storage and Flow Concepts

THE EDWARDS-TRINITY AQUIFER SYSTEM,
SAN ANTONIO REGION, TEXAS

United States Geological Survey Water-Supply Paper 2336–A



Prepared in cooperation with the
San Antonio City Water Board

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Chapter A

Simulation of Flow in the Edwards Aquifer, San Antonio Region, Texas, and Refinement of Storage and Flow Concepts

By R.W. MACLAY and L.F. LAND

Prepared in cooperation with the
San Antonio City Water Board

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2336

THE EDWARDS-TRINITY AQUIFER SYSTEM,
SAN ANTONIO REGION, TEXAS

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
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Metric Conversions

The inch-pound units of measurement used in this report may be converted to metric units (International System) by the following factors:

Multiply inch-pound unit	By	To obtain metric units
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06308	liter per second
gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square foot per day (ft^2/d)	0.0929	square meter per day
square foot per second (ft^2/s)	0.0929	square meter per second
square mile (mi^2)	2.590	square kilometer

Simulation of Flow in the Edwards Aquifer, San Antonio Region, Texas, and Refinement of Storage and Flow Concepts

By R.W. Maclay *and* L.F. Land

Abstract

The Edwards aquifer is a complexly faulted, carbonate aquifer lying within the Balcones fault zone of south-central Texas. The aquifer consists of thin- to massive-bedded limestone and dolomite, most of which is in the form of mudstones and wackestones. Well-developed secondary porosity has formed in association with former erosional surfaces within the carbonate rocks, within dolomitized-burrowed tidal and evaporitic deposits, and along inclined fractures to produce an aquifer with transmissivities greater than 100 ft^2/s. The aquifer is recharged mainly by streamflow losses in the outcrop area of the Edwards aquifer and is discharged by major springs located at considerable distances, as much as 150 mi, from the areas of recharge and by wells. Ground-water flow within the Edwards aquifer of the San Antonio region was simulated to investigate concepts relating to the storage and flow characteristics. The concepts of major interest were the effects of barrier faults on flow direction, water levels, springflow, and storage within the aquifer.

A general-purpose, finite-difference model, modified to provide the capability of representing barrier faults, was used to simulate ground-water flow and storage in the aquifer. The approach in model development was to conduct a series of simulations beginning with a simple representation of the aquifer framework and then proceeding to subsequent representations of increasing complexity. The simulations investigated the effects of complex geologic structures and of significant changes in transmissivity, anisotropy, and storage coefficient. Initial values of transmissivity, anisotropy, and storage coefficient were estimated based on concepts developed in previous studies.

Results of the simulations confirmed the original estimates of transmissivity values (greater than 100 ft^2/s) in the confined zone of the aquifer between San Antonio and Comal Springs. A storage coefficient of 0.05 in the unconfined zone of the aquifer produced the best simulation of water levels and springflow. A major interpretation resulting from the simulations is that two essentially independent areas of regional flow were identified in the west and central part of the study area. Flows from the two areas converge at Comal Springs. The directions of computed flux vectors reflected the presence of major barrier faults, which locally deflect patterns of ground-water movement. The most noticeable deflection is the convergence of flow through a geologic structural opening, the Knippa gap, in eastern Uvalde County. A second significant interpretation is that ground-water flow in northeastern Bexar, Comal, and Hays Counties is diverted by barrier faults toward San Marcos Springs, a regional discharge point. Simulations showed that several barrier faults in the northwestern part of the San Antonio area had a significant effect on storage, water levels, and springflow within the Edwards aquifer.

INTRODUCTION

The Edwards Limestone of Early Cretaceous age in south Texas contains one of the most permeable and productive carbonate aquifers in the United States. The Edwards aquifer in the San Antonio region is the sole source of municipal water for the city of San Antonio (fig. 1). In addition to providing drinking water to more than a million people, the aquifer supplies large quantities of irrigation water to the agricultural industry in Bexar, Medina, and Uvalde Counties and to major springs that are attractions for a tourist industry at New Braunfels and San Marcos. A knowledge of the geologic controls on ground-water flow is needed for planning, protection, and management of the aquifer.

Investigative Background

Historic use of water from the Edwards aquifer by Europeans began when the missions of San Antonio were built near perennial streams that were sustained by springflow from the aquifer. These springs provided the water for human, stock, and agricultural needs for many years. Water wells in the region were first drilled in the late 1800's so that the water supplies could be expanded to areas not adjacent to streams and springs. Subsequently, an ever-increasing number of wells have been completed in the Edwards aquifer, and consequently, total withdrawals from the aquifer have increased significantly. Former perennial springs—San Pedro and San Antonio Springs—have become intermittent in recent years because ground-water levels near the springs have been lowered by ground-water withdrawals.

With the increase in withdrawals and the realization of the effects of well discharge on springflows and water levels throughout the aquifer, the need for hydrologic information concerning the movement of ground water within and the extent of the Edwards aquifer was recognized by the City Water Board of San Antonio. Initially, hydrologic information on the extent and depth of the Edwards aquifer was needed to locate water-supply wells. As a result, early ground-water reports on the Edwards aquifer described the occurrence of ground water in the San Antonio area

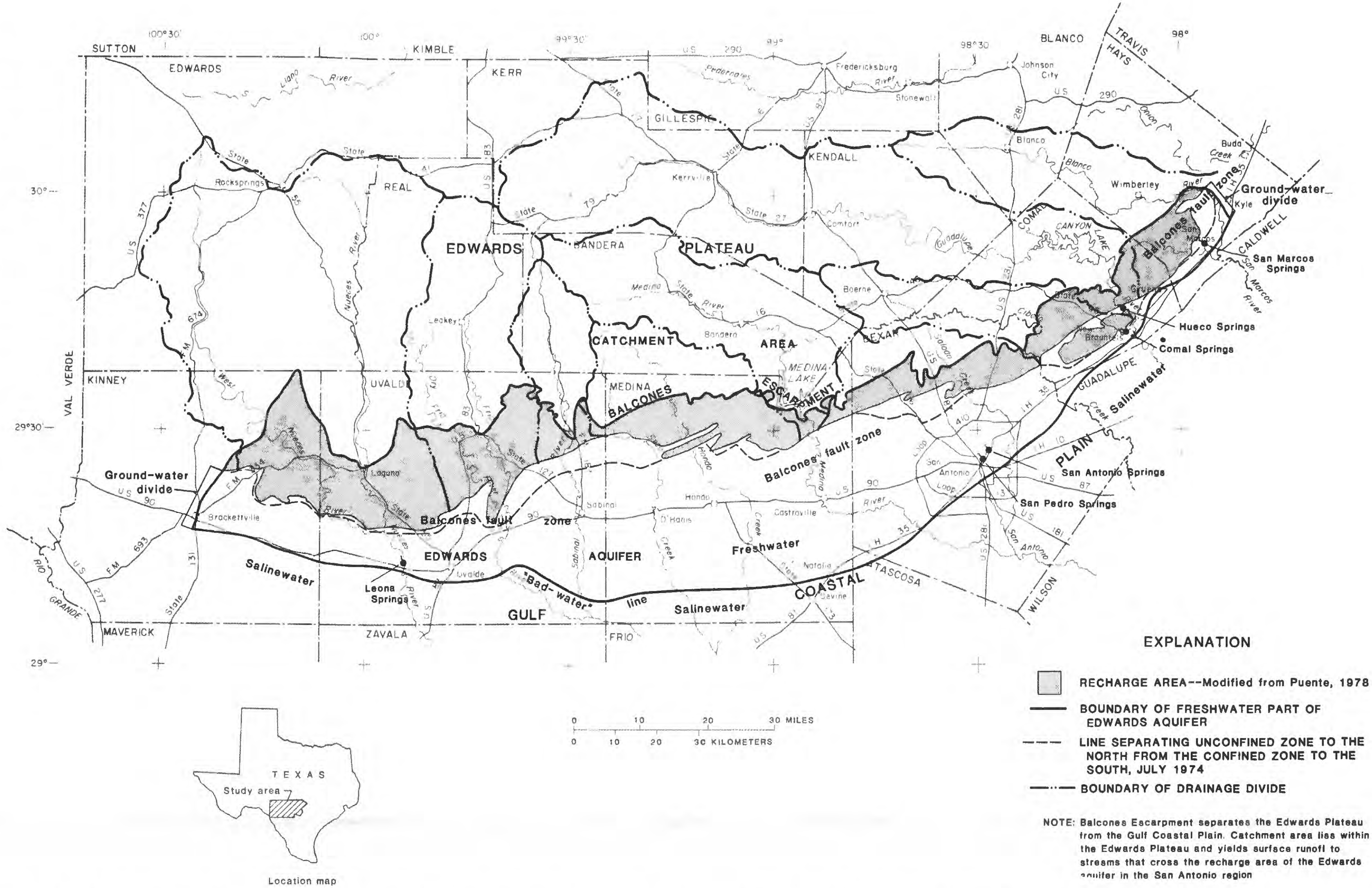


Figure 1. Location of San Antonio region, physiographic regions, and drainage basins that contribute recharge to Edwards aquifer.

(Livingston and others, 1936). In the 1940's, Sayre and Bennett (1942) made a fundamental observation on the regional extent of circulation within the Edwards aquifer and indicated that ground-water flow was regionally eastward through the confined aquifer, from recharge areas in Medina and Uvalde Counties to natural discharge areas at the major springs in Comal and Hays Counties. These important studies provided the initial knowledge and insight on the extent, productivity, and flow patterns of the Edwards aquifer in the San Antonio region. In the 1950's, hydrologic studies were begun to quantify the recharge and discharge from the aquifer and to relate changes in hydrologic conditions to water level or storage within the aquifer (Garza, 1962).

Beginning in the early 1960's and continuing to the present (1986), a continuing program of collecting geologic and hydrologic data has been conducted by the U.S. Geological Survey in cooperation with the Edwards Underground Water District and intermittently by several State agencies, including the Texas Water Commission, the Texas Water Development Board, and the Texas Department of Water Resources. Data-collection activities for this program include measuring discharge and collecting water-quality samples of major streams crossing the recharge zone, continuing and periodic water-level measurements in wells, water-quality sampling and analyses of the Edwards aquifer, and geologic mapping in local areas. Annual recharge and discharge data are collected, computed, and compiled. In recent years, an annual data report has been prepared to present the data collected in the previous year and to present the trends in recharge and discharge.

In 1970, the City Water Board of San Antonio through their private technical consultant, William F. Guyton, made a formal request to the Geological Survey for a cooperative program to obtain information so that they could address management questions about the Edwards aquifer. As a consequence of these informational needs, a cooperative agreement was made between the Geological Survey and the City Water Board of San Antonio to conduct the necessary hydrologic and geologic studies. The initial charge to project personnel was to obtain data relating to the nature of the aquifer framework and to review previous hydrologic methods used to investigate recharge to the aquifer.

From 1970 to 1976, primary emphasis was given to data collection, documentation review, and modification of the historic methods used for computing recharge. Relationships between precipitation and recharge were determined (Puente, 1975, 1978). Puente (1976) also showed the statistical relationship between water levels, springflow, and streamflow. During this period, the program was expanded when the Texas Department of Water Resources and the Geological Survey entered into a separate cooperative agreement. Data were obtained from investigations at eight cored test holes that penetrated the entire thickness of the aquifer (Maclay and Small, 1976). A report by Maclay and Rettman (1973) discussed the regional specific yield.

From 1976 to 1981, interpretative studies were conducted using available geologic, hydrologic, and hydrochemical data to determine the extent of the hydrostratigraphic units, the locations of internal boundaries, the hydrogeologic and hydrochemical properties of the Edwards aquifer, and the flow patterns within the aquifer (Maclay, Rettman, and Small, 1980; Maclay, Small, and Rettman, 1980; Maclay and Small 1984). Studies continued on the use of natural and man-made tracers to determine hydrogeologic properties of the aquifer and flow paths in the aquifer (Thompson and Hayes, 1979; Maclay, Rettman, and Small, 1980).

In the late 1970's, the Texas Department of Water Resources conducted an investigation to determine the occurrence, availability, and dependability of water from the Edwards aquifer in the Nueces, San Antonio, and Guadalupe–Blanco River basins and to develop a ground-water resources management tool for use in a total water-resources management program for the three river basins (Klemt and others, 1979). As part of their investigation, a two-dimensional ground-water flow model that covers the same study area as that of this report was developed, verified, and used to simulate several ground-water withdrawal and climatic scenarios from 1972 through 2049.

From 1981 to 1985, the main thrust of research has been directed toward testing and expanding hydrogeologic concepts by using mathematical simulation. This report documents the findings of this research.

Purpose and Scope

The primary objective of this report is to expand the ground-water storage and flow concepts of the Edwards aquifer in the San Antonio region by using simulation techniques. All pertinent geologic, hydrologic, and hydrochemical data that were collected during the previous phases of the cooperative program were used.

Secondary objectives are (1) to determine the effect of faults on ground-water storage and flow and on aquifer anisotropy on a regional scale, (2) to quantify the transmissivity, anisotropy, and storage coefficient of the aquifer, (3) to determine the major geologic controls on the aquifer, and (4) to test different hypotheses regarding ground-water storage and flow.

Approach

The major steps of the approach used in the study are (1) to state the initial storage and flow concepts of the aquifers as they were understood at the beginning of this study, (2) to apply ground-water-flow modeling techniques as a tool to mathematically simulate and test these concepts, (3) to analyze and interpret the results of the modeling study, in consideration of existing hydrology and geologic data, and

(4) to modify, expand, and restate the storage and flow concepts of the aquifer. The initial flow and storage concepts were presented by Maclay and Small (1984). One of their concepts related significant faults and ground-water movement and storage. These faults were termed barrier faults because they offset permeable layers of the aquifer and restricted ground-water flows across them.

A general-purpose, two-dimensional, finite-difference ground-water-flow model provided the framework of the mathematical representation of the aquifer (Trescott and others, 1976). In order to represent the special circumstances associated with the Edwards aquifer, minor modifications were made to the code to provide the features needed to test some of the components and concepts, to facilitate data entry into the model, and to analyze the computed results. The general approach used in model development and testing was to start with a rather simple representation of the aquifer framework and to add complexities. The simulations were organized into several series, each having a given set of boundary, hydrologic, or hydraulic constraints. Once simulations of a given series ceased to make marked improvements in the results, another complexity would be added to formulate another series. Near the end of the study, a series of simulations was developed to test the sensitivity of the model to variations in transmissivity and anisotropy. The model was improved by trial-and-error adjustment of transmissivity, anisotropy, and storage coefficient. Under some conditions, sources of inflow and outflow were added. The test for acceptability of simulation was based on a comparison of computed and measured values for water levels at widely distributed wells and for springflows at Comal and San Marcos Springs. The hydrologic data set selected for model development was collected during 1972–76, a period for which comprehensive data sets were available. During 1972, recharge approximately equaled discharge, thus approximating steady-state conditions for that year; during 1973, recharge greatly exceeded discharge.

The initial concepts were refined by simulating numerous hydrologic and geologic framework characteristics and comparing the results with available hydrologic and hydrogeologic data. The tests considered changes in transmissivity and anisotropy in subareas, the effectiveness and extent of barrier faults, and global changes in storage coefficients.

Physiographic and Hydrologic Setting

The surface-drainage system contributing water to the Edwards aquifer (the catchment area) within the San Antonio region extends from San Marcos in Hays County to Rocksprings in Edwards County and to Brackettville in Kinney County (fig. 1). The drainage system lies within two physiographic provinces—the Edwards Plateau and the Gulf Coastal Plain. The Balcones Escarpment separates the two provinces and generally coincides with the northern boundary of the Balcones fault zone. The surface-drainage area contributing water to the Edwards aquifer is about 6,500 mi^2. Runoff to most streams on the Edwards Plateau is lost downstream where these streams cross the outcrop of the Edwards aquifer within the Balcones fault zone. Most of the base flow and much of the storm runoff of streams recharge the Edwards aquifer through open solution channels in the unsaturated zone.

The Edwards Plateau consists of an elevated, flat to rolling upland surface capped by a thick mantle of partially saturated carbonate rocks of the Edwards Limestone, which has a moderate permeability and a large infiltration capacity. The Edwards Limestone of the Edwards Plateau contains a major unconfined aquifer that is hydrologically isolated from the Edwards aquifer within the San Antonio region. The plateau is bordered on the east by a lower, moderately dissected upland underlain by the Cretaceous Glen Rose Formation, which consists of marls, shale, and carbonate rocks of relatively low permeability. The headwaters of the streams providing recharge occur within the reentrant valleys cut into the margins of the elevated limestone-capped uplands. In these valleys, many contact springs emerge near the geologic contact between the moderately permeable limestone strata and the underlying, poorly permeable marls and shales. The small size of the present-day streams appears to be inconsistent with the large size of the valleys in which they occur; for example, the valley of the West Nueces River is about a half-mile wide and is occupied by an intermittent stream. These wide valleys probably were eroded by fluvial processes during Pleistocene time. Most of the catchment area for the Edwards aquifer in the Edwards Plateau is sparsely populated ranch land with a limited population. Moderate population increases have occurred at isolated places; these are primarily recreational areas located in the vicinity of the picturesque cypress-lined streams in Uvalde, Medina, and Bandera Counties.

The Balcones fault zone is marked by a prominent escarpment that generally rises from an altitude of 600 to 900 ft along the terraced, sloping lowlands of the Gulf Coastal Plain to an altitude of 1,400 to 2,300 ft in the uplands of the Edwards Plateau.

The Gulf Coastal Plain in the San Antonio region is characterized by a rolling to hilly surface of prairies and brush land. Much of the area is very suitable for farming. Some of the crops are irrigated with water from the Edwards aquifer or from Medina Lake. Major population centers have developed along the northwest limits of this physiographic region.

The average annual precipitation within the study area ranges from about 34 in. near Wimberley in the eastern part to about 21 in. near Rocksprings in the western part. Evapotranspiration returns about 80 to 90 percent of the annual precipitation to the atmosphere.

Acknowledgments

Many of the concepts used in this report have been developed as a result of discussions with associates of the U.S. Geological Survey Texas District, and with Dr. William L. Guyton of William F. Guyton Associates, Inc. The work is a continuation of that supported through a cooperative agreement between the City Water Board of San Antonio and the U.S. Geological Survey. Special appreciation is extended to Robert Van Dyke, manager of the City Water Board, whose sustained interest and support of technical studies have provided funding and encouragement that has resulted in this report.

GEOLOGIC FRAMEWORK

The Edwards Limestone of Early Cretaceous age is exposed throughout the Edwards Plateau and underlies the Gulf Coastal Plain at depth. The Edwards Limestone in the San Antonio region consists of 400 to 600 ft of thin- to massive-bedded carbonate rocks and contains several stratigraphic zones with several permeable beds characterized by well-developed vuggy porosity. These permeable and porous zones of carbonate rocks are vertically separated by beds of dense to chalky limestone of small to moderate permeability and very small to large porosity. At places, the permeable strata are hydraulically interconnected by open, inclined fractures. The lateral continuity of the permeable strata is made discontinuous by normal, high-angle faults that, at places, displace the entire thickness of the Edwards Limestone.

The sediments comprising the Edwards Limestone and its stratigraphic equivalents were deposited on the margin of the Central Texas platform, a low-lying carbonate surface, by shallow transgressing and regressing Early Cretaceous seas. The now deeply buried Stuart City reef, a rudistid barrier reef, formed the offshore margin of this platform (Rose, 1972). The Devils River trend, another rudistid barrier reef, developed around the Maverick basin during a later period of deposition (fig. 2). The Maverick basin was a site of continuous deposition during most of Edwards time.

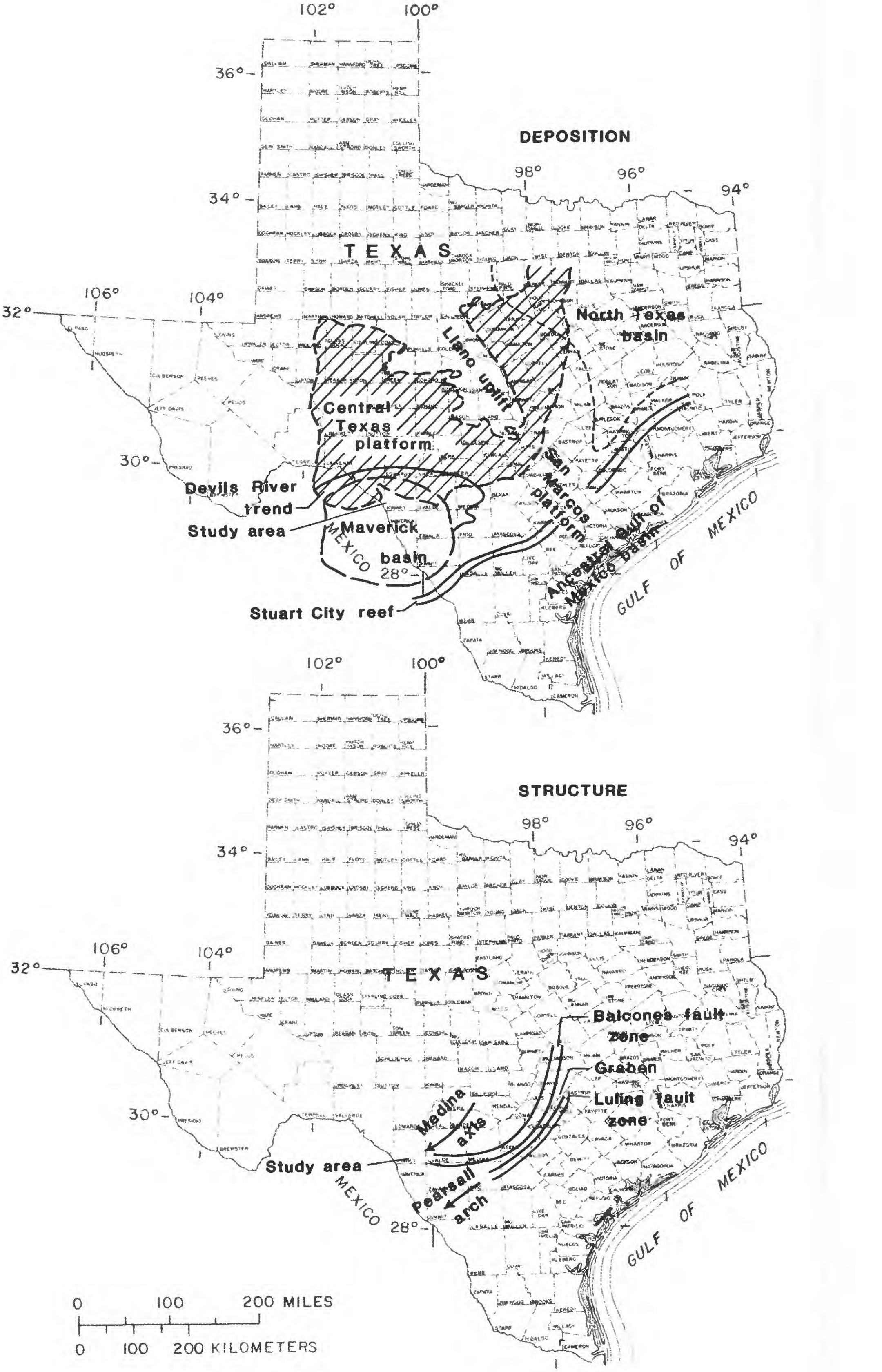
A broad lagoonal area behind the Stuart City reef in the vicinity of the San Marcos platform became the site of cyclic deposition. Cycles began with transgression of the sea, followed by progradation of subtidal, intertidal, and supratidal sediments from the north and west. Evaporites, the final stage of a sedimentation cycle, were deposited on the hot, supratidal flats and were subsequently wholly or partly removed by circulating ground waters. Within these deposits, collapse breccias of high porosity and permeability were formed. During late Edwards time, subaerial erosion removed about 100 ft or more of the deposits from the San Marcos platform, resulting in extensive karstification of the limestones and dolomites. Shorter periods of subaerial exposure occurred during several cycles of carbonate deposition on the platform, and meteoric water circulating through the rocks selectively leached or cemented the sediments. During these periods of erosion, much of the early texture-controlled secondary porosity was developed.

These and other depositional and structural features that were influential in the geologic development of the Edwards Limestone are shown in figure 2 and described in table 1.

Regional stratigraphic studies of the Edwards Limestone, the Edwards Group of Rose (1972), and equivalent rocks in south Texas by Fisher and Rodda (1969), Lozo and Smith (1964), Rose (1972), and Tucker (1962) have resulted in subdivisions within the major depositional basins and correlations among the basins. Rose (1972) raised the Edwards Limestone to the rank of a stratigraphic unit. The stratigraphically equivalent units that compose the Edwards aquifer in this report are the Edwards Group, consisting of the Kainer and Person Formations, and the overlying Georgetown Formation in the San Marcos platform; the Devils River Limestone of the Devils River trend; and the West Nueces, McKnight, and Salmon Peak Formations of Lozo and Smith (1964) in the Maverick basin. The correlations of stratigraphic units of part of the Cretaceous System in south Texas are shown in figure 3. The geologic unit stratigraphically below the Edwards aquifer or Group and equivalents is the Glen Rose Formation. It is composed of a thick sequence consisting of marl, shale, and dolomite in the upper part and massive-bedded limestone and dolomite in the lower part. The upper part of the Glen Rose Formation is the lower confining unit of the Edwards aquifer. The unit above the Edwards aquifer, the Del Rio Clay, is relatively impermeable and confines the stratigraphically lower units.

Rock Properties

The Edwards Group consists mostly of calcitic mudstones and wackestones with lesser amounts of grainstones. Lithofacies that contain permeable strata include (1) tidal, burrowed mudstone or wackestone in which the materials filling the burrows were dolomitized and were subsequently leached to produce a highly porous and permeable honeycombed rock; (2) supratidal, evaporitic breccias formed by leaching of bedded gypsum; and (3) reefal, rudistid grainstones that have been fractured and leached. The Edwards and associated limestones in the San Marcos platform contain more strata having the above-mentioned lithofacies than equivalent rocks in the Devils River trend or the Maverick basin (fig. 2). Many of the recrystallized calcitic rocks were dedolomitized by circulating ground water having a dissolved-ion-concentration ratio of calcium to magnesium greater than 1. The source producing the excessive concentration of dissolved calcium was the gypsum contained within rocks forming the Edwards aquifer. As a consequence of the



Modified from Rose, 1972

Figure 2. Depositional provinces and geologic structure of south Texas.

Table 1. Major structural and depositional features

Name of feature	Description
Central Texas platform	A broad elongate swell bearing southeasterly from Tom Green County across the Llano uplift to the Stuart City reef. The southeastern end is the San Marcos platform. This feature was part of a vast, flat, generally submerged plain upon which lower Cretaceous rocks in central Texas were deposited. The water was shallow in this plain, although two main depressions developed on the southwest and northeast--the Maverick basin and the North Texas basin, respectively. The Central Texas platform became the swell that separated these depressions and was the dominant element that controlled depositional patterns for the carbonate complexes exhibited by the Edwards Limestone.
Llano uplift	An area of exposed Paleozoic and Precambrian rocks that directly underlie the Cretaceous rocks throughout the Edwards Plateau. This major regional uplift may be intermittently active. Movement of major faults along the Balcones fault zone may be associated with intermittent uplift of the Llano area. Edwards Limestone and other Cretaceous rocks are eroded away near the crest of the Llano uplift.
Ancestral Gulf of Mexico basin	A subsiding depositional basin ringed by a barrier reef. It consists of dense, basinal carbonate rocks that contain fluids under high geopressure. These pressures are much higher than measured pressures in the Edwards aquifer updip from the geopressured area.
Stuart City reef	A deeply buried ancestral reef that separated two major depositional environments--back-reef platform carbonate rocks and the fore-reef basinal carbonate rocks. It is a segment of an extensive Cretaceous reef that extends from Mexico around the ancestral Gulf of Mexico to the Florida peninsula. Deep structural faulted troughs (the Karnes and the Atascosa troughs) lie on the platform side of the reef in south Texas. These troughs contain a thick sequence of rocks of the Edwards Limestone or its stratigraphic equivalents. Fluids in the Cretaceous rocks extending gulfward of the reef are under very high potentiometric head caused by compaction of gulf coastal sediments and associated pressure buildup due to fluid movement across ion-selective permeable membranes. Deep subsurface liquids move very slowly northward and updip toward the meteoric water of the freshwater part of the Edwards aquifer.
North Texas basin	The basin has a similar depositional history as that of the south Texas region. However, the hydrogeologic system of the North Texas basin is independent of that of south Texas. Southern and western boundaries of the basin mark the pinchouts of Cretaceous stratigraphic units of south Texas.
Maverick basin	A deep-water marine basin where medium- to massive-bedded carbonate rocks consisting mostly of micrites having little primary porosity or permeability were deposited. Rocks were not exposed to subaerial environment during their depositional history, and therefore little secondary porosity development occurs within these deposits. Lithofacies represent a low-energy depositional environment.
Devils River trend	A reef formed by medium- to massive-bedded, reefal and shallow-water carbonate rocks of the Devils River Limestone. These rocks were intermittently exposed during their depositional history. Lithofacies represent a high-energy depositional environment and a moderately to highly permeable unit. Permeable zones are variably distributed throughout the unit, but they occur in greater numbers in the upper two-thirds of the unit. Permeable zones are associated with collapsed breccias, dolomitized burrowed tidal-flat sediments, and rudist packstones. Owing to a higher permeability of this unit, ground-water flow is significantly greater through this unit than through the deposits of the Maverick basin.
San Marcos platform	A southeastern extension of the Llano uplift. Uplift along the platform increases in magnitude toward the Llano uplift. An area of active subaerial erosion during intermittent periods of Cretaceous time. Enhanced development of secondary porosity occurred within carbonate rocks.
Back-reef carbonate rocks of the San Marcos platform	These carbonate rocks represent a series of thin- to medium-bedded carbonate rocks and interbedded evaporites occurring at different vertical positions that are separated by disconformities. These disconformities represent periods of subaerial exposure and development of significant secondary porosity in the immediate underlying carbonate rocks. Major solutional zones occur within the dolomitic rocks. Lithofacies represent a low- to moderate-energy depositional environment.

Table 1. Major structural and depositional features—Continued

Name of feature	Description
Balcones fault zone	A zone of high-angle normal faults, most of which have their downthrown blocks on the gulfward side. Some structural horsts and grabens occur in the Balcones fault zone. Several scissor faults occur within major fault blocks. The en echelon pattern of faults in the Edwards aquifer outcrop reflects a structural fault system that contains several major rotated fault blocks that are differentially uplifted toward the Llano uplift and the San Marcos platform. This has been a zone of active, but intermittent, faulting or uplift since Cretaceous time. Geomorphic features that suggest recent faulting and uplift are high relief of the Balcones fault scarp, the unusual shapes of drainage divides (such as Cibolo Creek), and offsets of the alluvial deposits along major faults. Movement along fault planes enhanced the opportunity for porosity development in the confined part of the Edwards aquifer by exposing unaltered rock to solution action. The faults within the Balcones and Luling fault zones possibly are related to movement in the basement rocks of of the underlying Ouachita fold belt.
Luling fault zone	High-angle normal faults having the upthrown block on the gulfward side. Fault zone may act as a barrier to gulfward flow of meteoric water and could also block updip movement of fluids from the downdip direction.
Unnamed regional graben	A structural depression formed between the Balcones fault zone and the Luling fault zone. Regional ground-water flow may move northeastward through the regional graben in the salinewater zone toward discharge areas in the vicinity of the Colorado River valley near Austin, Texas, or toward overlying deposits in the lower Tertiary Carrizo Sand within the Gulf Coastal Plain. The ground-water flow may contain a mixture of mostly meteoric water from the updip extensions of the aquifer in the western part of the San Antonio region and water originating from the consolidation process of Gulf Coastal sediment gulfward from the Stuart City reef.
Pearsall arch and Medina axis	The trends of the Pearsall arch and the Medina axis are consistent with the trends of the Balcones and Luling fault zones. These trends may be affected by possible periodic wrenching movement of the basement rocks of the Ouachita fold belt and concomitant subsidence of the ancestral Gulf of Mexico basin. The Medina axis and the Balcones fault zone may be related to control and uplift of the Edwards Plateau starting with the Laramade orogeny at the end of Cretaceous time. These uplifts may influence the rock textextures along the trends of the structures, which probably enhance permeability.
Trend of paleovalley eroded into top of Early Cretaceous rocks	Trend of valley was interpreted from the isopachous map of Georgetown Formation prepared by Rose (1972). Possible zone of enhanced secondary porosity in carbonate rocks may exist along course of paleovalleys extending from the San Marcos platform toward the Maverick basin. These valleys could affect the direction of flow in the San Marcos platform.

process of dedolomitization, many of the formerly dolomitic rocks of the Edwards Group within the freshwater zone of the Edwards aquifer developed into dense, recrystallized rocks containing large, irregularly shaped voids.

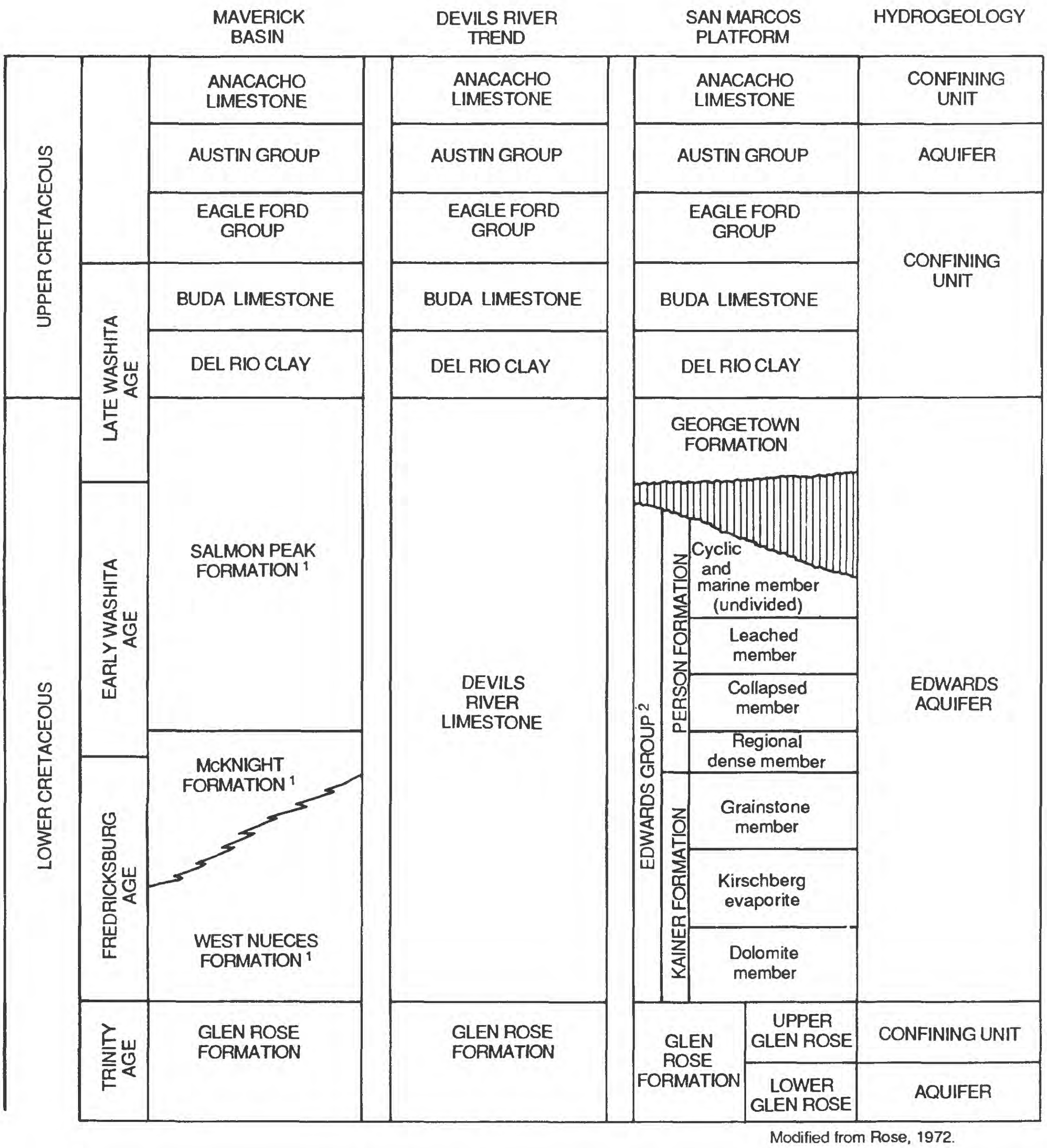
Fractures are common throughout the entire thickness of the Edwards Group. Open fractures commonly cross several strata, but many fractures are discontinuous or partially closed within massive-bedded dense mudstones, such as those that exist in the middle or basal nodular sections of the Edwards aquifer. The walls of fractures are commonly iron stained and partially covered by dogtooth spar (calcite). These fractures are believed to hydraulically interconnect the permeable strata and openings developed along bedding planes.

Unconformable contacts that occur within the Edwards Group represent periods of subaerial erosion. Some of these unconformable contacts, such as the Georgetown Formation and Edwards Limestone contact, are associated with cavernous porosity that was formed by karstic solutioning during the Cretaceous period.

Voids within the rocks of the Edwards Group range widely in size, shape, and degree of interconnection depending upon the textural and diagenetic history of the rock. The porosity of the rock forming the Edwards Group results mostly from small voids between and within the particles that compose the rock matrix (Maclay and Small, 1984). Much of the secondary porosity has developed by solutioning and dedolomitization processes that have been occurring below a thick cover of confining rock. It is speculated that the solutioning and dedolomitization processes have been accelerated by intermittent movement along active faults within the Balcones fault zone. This movement has increased the opportunity for contact between unaltered rocks composed of permeable dolomites and circulating ground water that has a large ratio of dissolved calcium to magnesium concentrations.

Structural Properties

The Edwards Group and its stratigraphic equivalents occur at the surface in an irregular band along the southern edge of the Balcones Escarpment (fig. 1). It dips toward the southeast, and thus older rocks are exposed north of the band and younger rocks south of the band (fig. 4). The Edwards Group has undergone extensive faulting, as shown in figure 5. These faults generally are downthrown to the south and southeast, and trend east-northeast. The faults form a complex system of fault blocks that are differentially rotated and rise toward the San Marcos platform. This pattern is



[1] Of Lozo and Smith (1964).

[2] The Edwards Limestone was raised to a stratigraphic group by Rose (1972) and includes Kainer and Person Formations in the subsurface.

Figure 3. Correlation of Cretaceous stratigraphic units in south Texas.

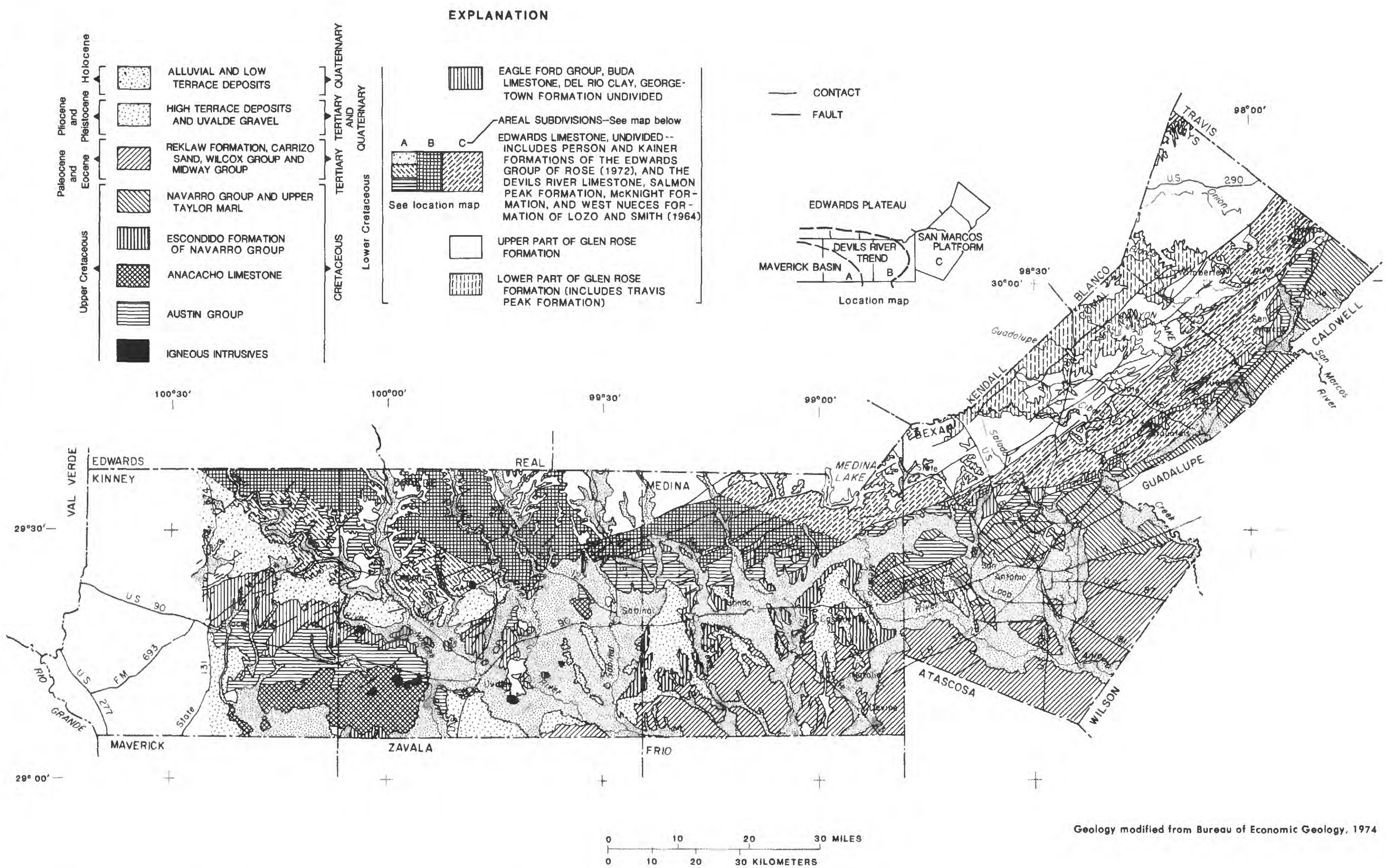


Figure 4. Surface geology of study area.

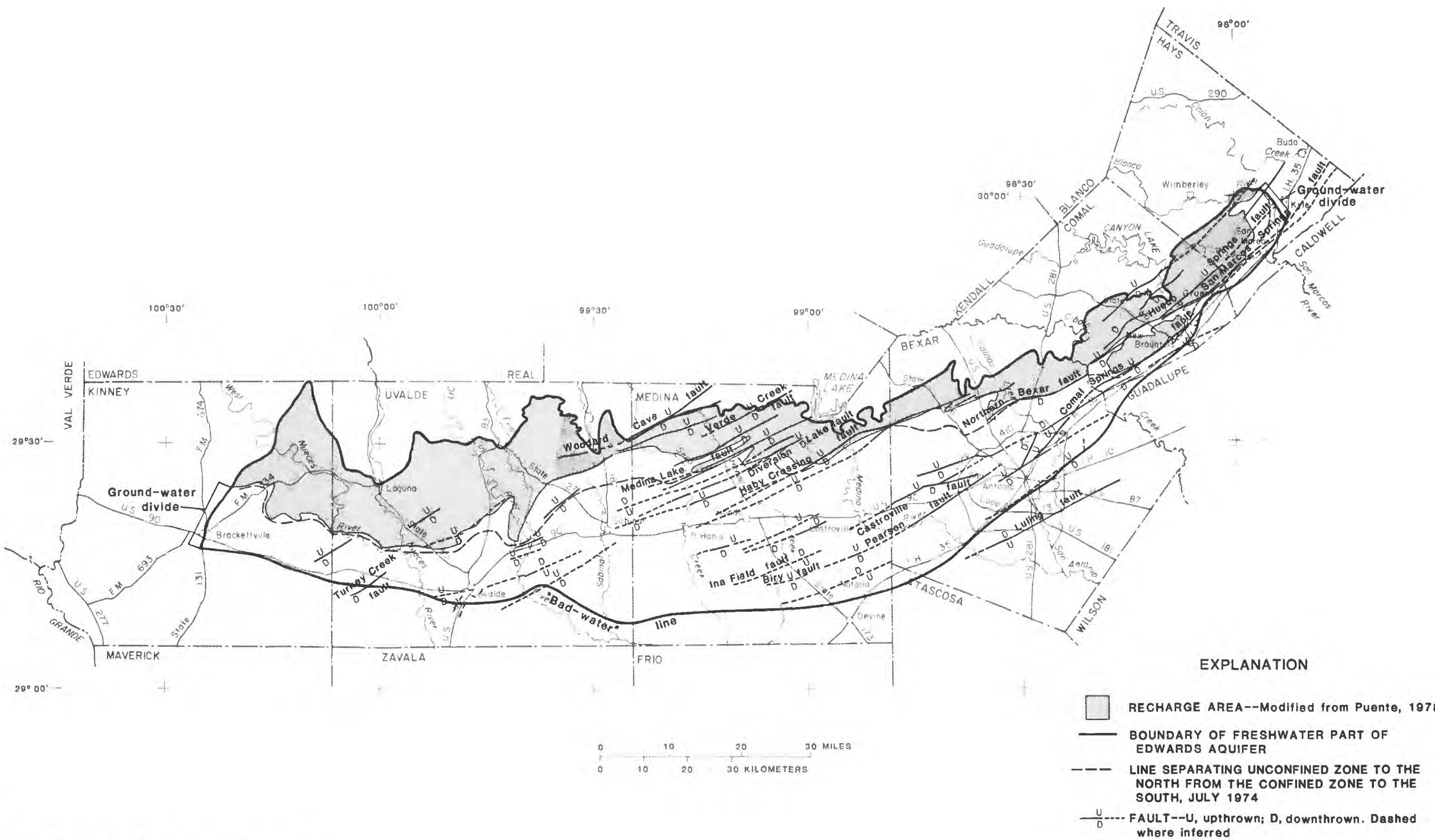


Figure 5. Major faults in study area.

illustrated with a surface configuration map of the base of the Del Rio Clay (fig. 6). The map shows many disruptions and great local relief. Along the strike of some major faults, the displacement across the fault plane is sufficient to disrupt the continuity of the Edwards Group. Also, cross faults intersect at acute angles at many locations. These differentially uplifted and rotated fault blocks result in the general en echelon areal pattern that can be observed from a geologic map (fig. 4). The major fault blocks may result from wrench faulting during Late Cretaceous and early Cenozoic time that involved rejuvenation of faults in the basement rocks of the Ouachita fold belt. This deduction is supported by seismic data (Sams, 1983).

HYDROGEOLOGIC FRAMEWORK

The Edwards aquifer within the San Antonio region consists of the Edwards and associated limestones of Early Cretaceous age (fig. 3). The part of the Edwards aquifer included in this study is bounded on the west and east by ground-water divides in Kinney and Hays Counties, respectively; on the north by the updip limits of the Balcones fault zone; and on the south by a line commonly referred to as the "bad-water" line. The latter separates freshwater from salinewater in the aquifer and coincides with the isoconcentration line of 1,000 mg/L (milligrams per liter) dissolved solids. The location of the aquifer and regional water levels are shown in figure 7. Two typical hydrogeologic sections are shown in figure 8.

The base of the Edwards aquifer is confined by the upper part of the Glen Rose Formation, and in the subsurface the top of the Edwards aquifer is confined by the Del Rio Clay (figs. 3, 6). The small permeability of these confining units greatly restricts vertical leakage from or to overlying and underlying aquifers, although some water probably moves across strata along open inclined fractures and faults.

Some water is believed to move into the salinewater part of the Edwards aquifer in Kinney and Uvalde Counties and then flow in the salinewater part east and northeast either toward the regional discharge areas that probably occur in the vicinity of the Colorado River near Austin in Travis County or to areas where upward leakage can occur to overlying aquifers. The downdip movement of water in the salinewater part is prevented by high potentiometric heads in the Edwards Limestone downdip from the Luling fault zone and in the vicinity of the Stuart City reef. These heads are higher than those occurring within the freshwater part of the Edwards aquifer. Because of these high heads, salinewater moves very slowly updip from the Stuart City reef; however, the rate of flow is restricted by the low transmissivity of the aquifer and by differences in water densities. The salinity of the water within the saline part grades from more than 250,000 mg/L of dissolved solids to 1,000 mg/L at the "bad-water" line. The salinity distribution is the result both of mixing of freshwater of meteoric origin and salinewater resulting from the geopressure process and of equilibrium reactions between fluids and minerals within the salinewater part of the aquifer.

Hydrology

Recharge to the Edwards aquifer in the San Antonio region occurs within the outcrop of the Edwards and associated limestones, where water quickly seeps from the streams to the aquifer. All major streams in the region, except the Guadalupe River, lose water to the Edwards aquifer as they cross the recharge area (defined by Puente, 1978, as infiltration area). The recharge from the Guadalupe River along with the inflow from the updip lower Glen Rose aquifer are believed to approximately equal the discharge from Hueco Springs. Thus, these components are not included in the hydrologic analysis of the Edwards aquifer. Additional recharge is from infiltration of precipitation in the interstream areas. Within most drainage basins, however, the percentage of recharge occurring along the stream channels is greater than the percentage of recharge occurring in the interstream areas; the difference between these two percentages varies according to climatic conditions.

A part of the Geological Survey studies of the Edwards aquifer includes the collection of data, which began in 1934, and the calculations to determine the annual recharge and discharge. The recharge data are computed and compiled by river basin. The discharge data are compiled by major uses within each county. The methods for computing recharge are documented by Puente (1978). Pumpage of most irrigation wells is estimated by using power-consumption records, while pumpage by industrial and municipal users is determined from meters. The annual recharge, discharge, and accumulated recharge and discharge are shown in figure 9.

Water entering the aquifer in the outcrop generally moves toward the confined zone of the aquifer but often is diverted by faults that interrupt the continuity of the aquifer (fig. 7). After reaching this zone, the water moves by low hydraulic gradients and in materials with high permeabilities toward the east and northeast, where it is discharged through wells and springs. The approximate altitudes of water levels in the Edwards aquifer for the winter of 1973 are shown in figure 7.

The water in the aquifer is discharged by springs at the following locations: (1) the Leona Springs near Uvalde, (2) San Antonio and San Pedro Springs in San Antonio, (3) Comal Springs in New Braunfels, and (4) San Marcos Springs in San Marcos. These springs issue along faults that have developed into open cracks and solution channels. Several hundred large-yield wells in Uvalde, Medina, Bexar, Comal, and Hays Counties discharge water from the aquifer.

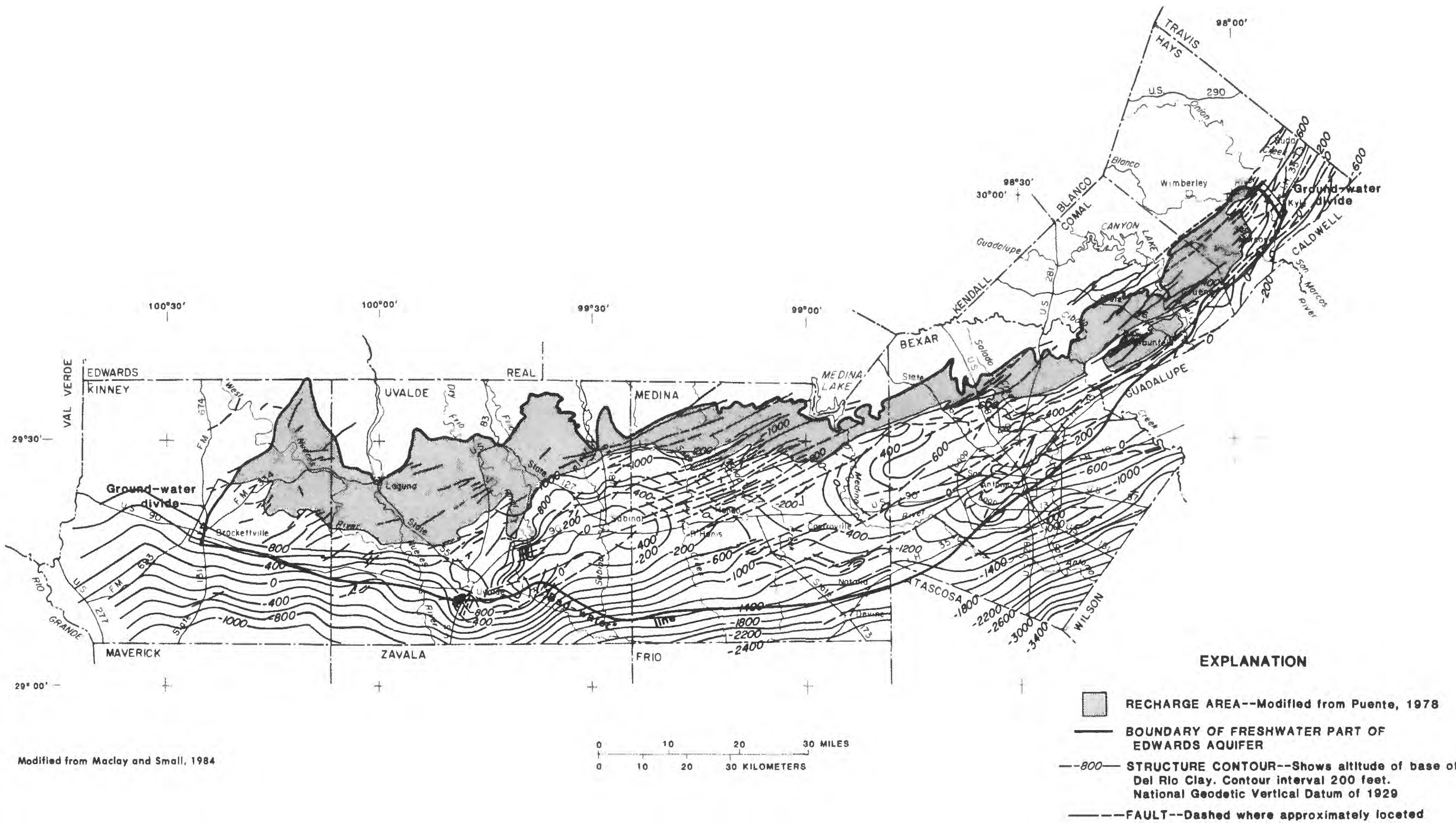


Figure 6. Configuration of base of Del Rio Clay.

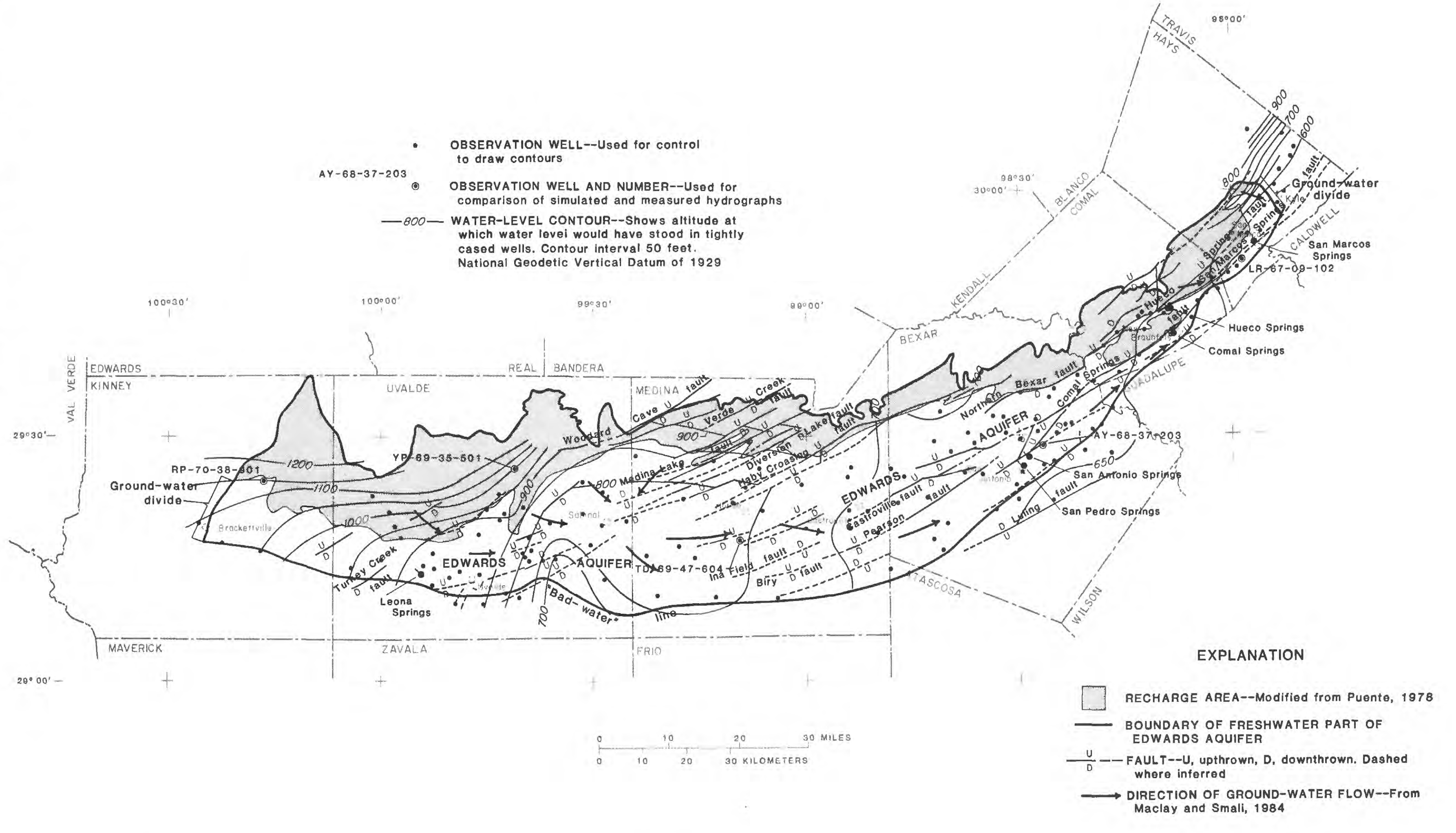


Figure 7. Regional water levels during winter of 1973, regional ground-water-flow pattern, and location of selected observation wells.

The water is used for irrigation, industrial, and municipal purposes. Cities and towns that rely solely on the Edwards aquifer for their water include Uvalde, Sabinal, D'Hanis, Hondo, Castroville, San Antonio, New Braunfels, San Marcos, and Kyle.

The relationship between the springflow and well discharge is highly variable and is dependent on climatic conditions, which control recharge and influence pumpage. In the recent past, springflow slightly exceeds well discharge (fig. 9). In addition to the water movement described above,

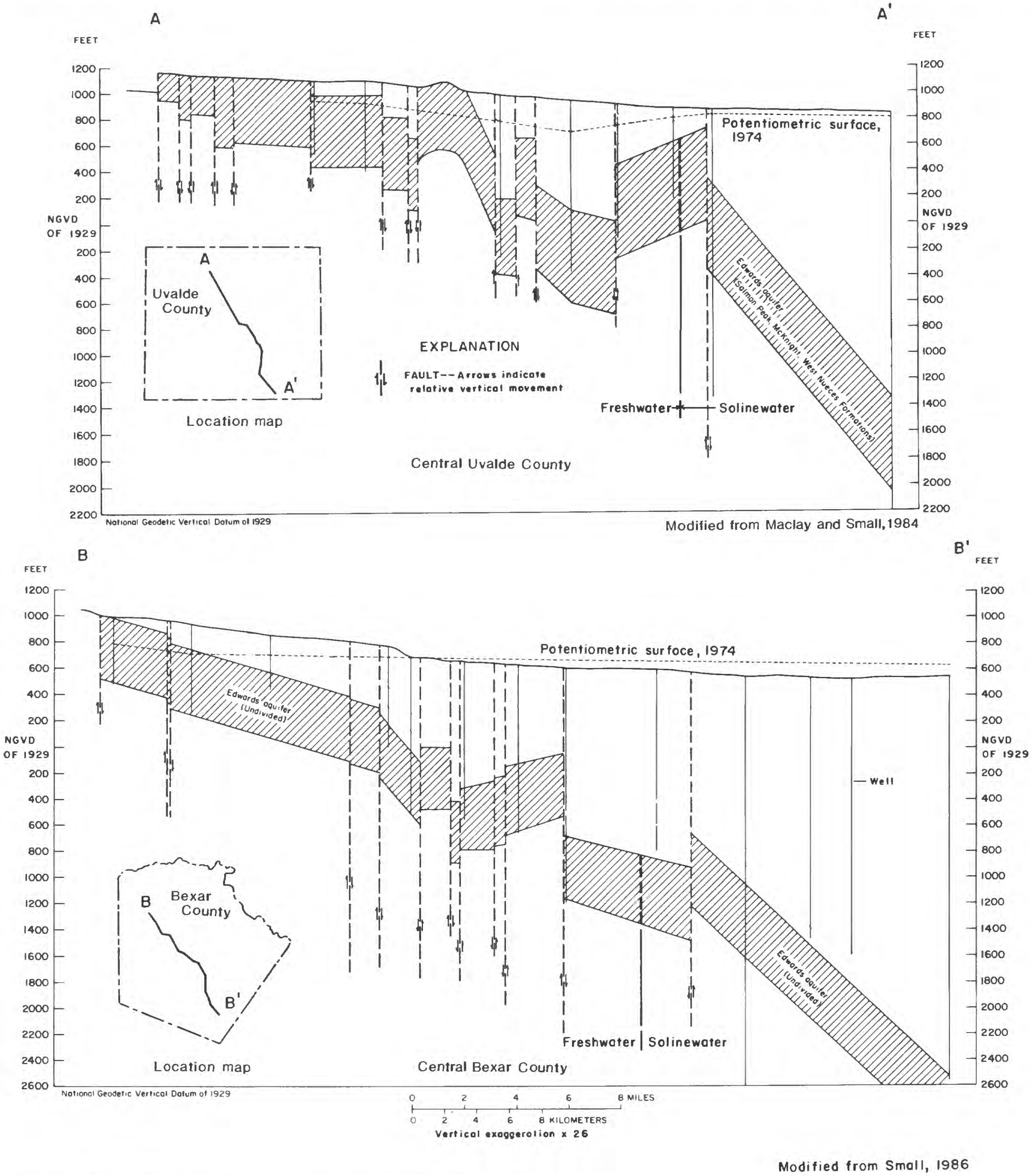


Figure 8. Two typical hydrogeologic sections along geologic dip.

minor quantities of water move across lateral boundaries at several localities. Significant inflow may occur along the northern edge of the Balcones fault zone, where the Edwards aquifer is downfaulted against the lower permeable rock of the Glen Rose Formation; the quantity is believed to be least in the area west of the Nueces River. Some flow probably moves from the freshwater to the salinewater part of the aquifer in Uvalde and western Medina Counties, and from the salinewater to the freshwater part of the aquifer in Hays and Travis Counties. The quantity of flow is relatively small

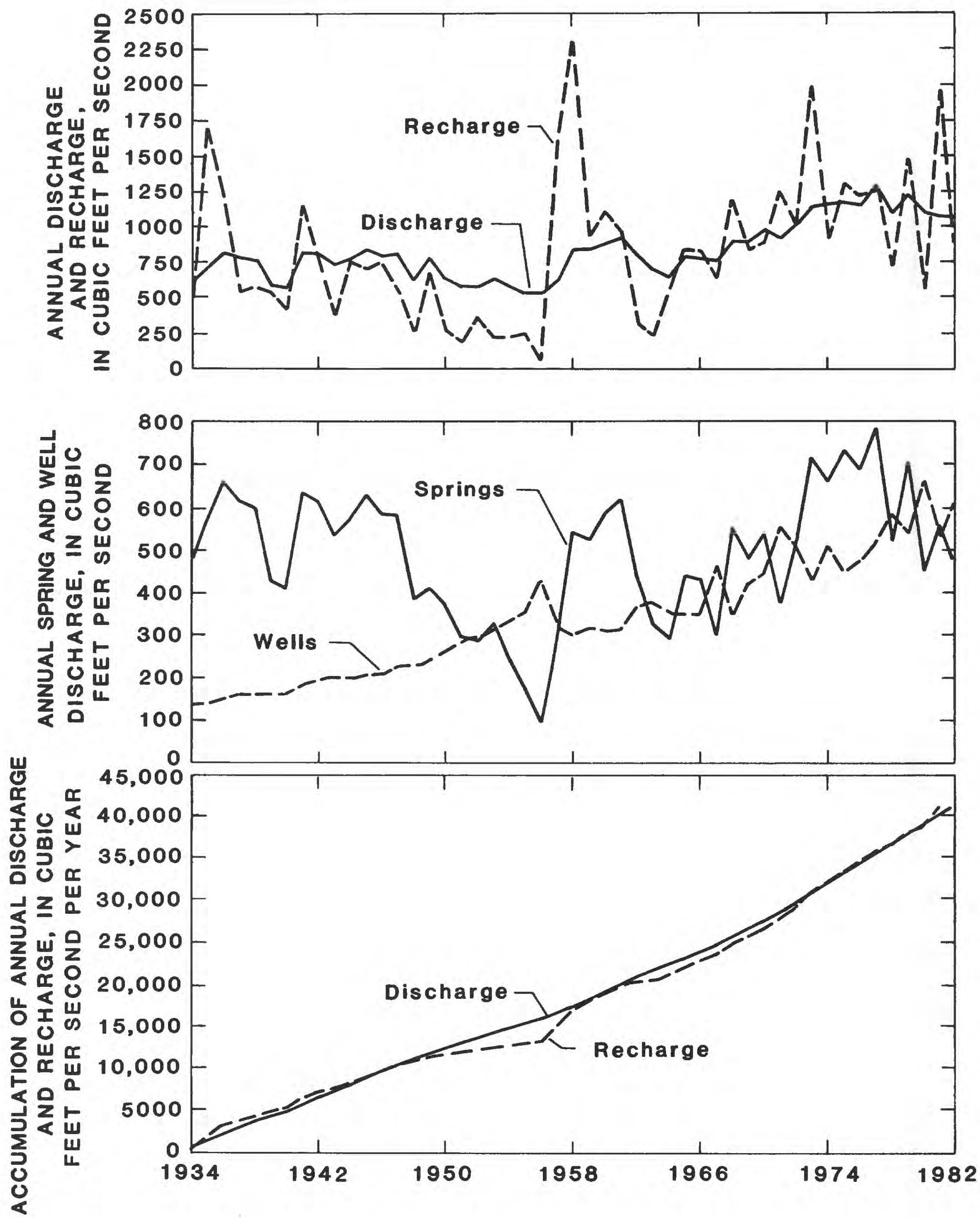


Figure 9. Annual recharge, discharge, and accumulated recharge and discharge, 1934–82.

because of the small transmissivity of the Edwards aquifer and low hydraulic gradients in the salinewater zone. An undetermined flow probably crosses the poorly defined ground-water divides near Brackettville in Kinney County and near Kyle in Hays County. In Kinney County, some inflow from the Edwards aquifer in the Edwards Plateau occurs. In comparison to the large quantities of recharge and discharge within the San Antonio region, these quantities probably are negligible.

Hydraulic Characteristics

The capacity of the Edwards aquifer to transmit large quantities of water is indicated by the occurrence of hundreds of very productive wells that are present thoughout the San Antonio region. Many of the wells yield several thousand gallons of water per minute, and pumping at this rate results in a lowering of the water level at most wells of only a few feet. The great transmissive capability of the aquifer in the confined zone is indicated by very low hydraulic gradients, excellent correlation of water levels among widely spaced wells, a large—ranging from about 100 to more than 500 ft^3/s—combined discharge from Comal and San Marcos Springs, and uniform quality and temperature of water within the aquifer. The large storage capacity is illustrated by the sustained high rates of springflow and withdrawals during several years of below-normal rainfall.

Flowing wells that discharge more than 10,000 gal/min can be drilled within the city of San Antonio. Live blind catfish have been netted from the surface discharge of flowing wells that were drilled to depths of approximately 1,500 ft and which are located near the transition between the freshwater and salinewater parts (''bad-water'' line) at a distance of more than 15 mi from the unconfined zone of the aquifer (Longley, 1981). The occurrence of catfish in these wells suggests that interconnected cavernous openings occur at great depth within the deeply buried carbonate aquifer. These deep cavernous openings may be associated with a paleokarst developed during Cretaceous time.

Aquifer performance-test data for determining the hydraulic properties of the Edwards aquifer in the San Antonio region have been compiled and summarized by Maclay, Small, and Rettman (1980). This report presented data on specific capacities, well yields, a limited number of aquifer tests, and regional water-level fluctuations caused by well withdrawals and recharge from a major storm. Klemt and others (1979) prepared a digital ground-water-flow model for management purposes of the Edwards aquifer that is common to this study. Earlier, they reviewed and analyzed existing data for starting values in their model. Major products of their model include the selection of storage coefficients and transmissivity and anisotropy maps. Garza (1968) investigated the transmissivity of the Edwards aquifer in the metropolitan area of San Antonio using well fields as loci for pumping centers. Results of his studies indicated the transmissivities in the confined part of the aquifer in the vicinity of San Antonio to be in the range of 1 to 2 million ft^2/d. Estimates of the relative transmissivities of the aquifer within subareas of the San Antonio region were made by Maclay and Small (1984, p. 48–53). These estimates, based on available geologic, hydrochemical, and hydrologic information, are shown in figure 10.

The anisotropy of the aquifer is largely unknown except as influenced by faults. The disruption to ground-water flow by faults is strongly influenced by major disruptions in the lateral continuity of highly permeable strata. Schematic diagrams that illustrate several of the common fault displacements are shown in figure 11. Because several of the fault blocks are rotated within the overall geologic framework, the degree of disruption varies along each fault. Vertical displacements at places along major faults exceed the thickness of the aquifer, which averages about 500 ft.

The capacity of the Edwards aquifer to supply water during extended droughts is controlled by the storage coefficient, transmissivity, and extent of the unconfined part of the aquifer. The water yield from a given lowering of water level in the unconfined (water-table) zone is about 500 times greater than that for the confined (artesian) zone. The relatively large areal extent of the unconfined zone of the aquifer in the western part of the San Antonio region and the associated larger storage coefficient are the physical properties that significantly affect the long-term availability of water in the Edwards aquifer. The highly transmissive characteristics of the confined zone aid in readily distributing the water moving from the unconfined zone to the confined zone.

The storage coefficient for the unconfined zone is not accurately known, but it probably ranges from less than 0.05 to about 0.20 depending principally upon the textural rock types (Maclay and Small, 1976). The storage coefficient due to elastic response for the confined zone of the Edwards aquifer is estimated by Maclay and Small (1984) to range from 10^{-4} to 10^{-5} and will vary depending upon the porosity and thickness of the aquifer.

INITIAL STORAGE AND FLOW CONCEPTS

The initial storage and flow concepts in the Edwards aquifer in the study area are considered to be the discussion by Maclay and Small (1984, p. 57–65) on what influences ground-water storage and flow at several locations and areas. Their discussion was concluded with a map showing the regional ground-water-flow pattern, reproduced here in figure 7. The following discussion summarizes that of Maclay and Small (1984).

In eastern Kinney and western Uvalde Counties, ground-water levels are the highest in the study area. This subarea encompasses a large part of the unconfined zone and

SUBAREA	ESTIMATED RELATIVE TRANSMISSIVITY (ORDINAL RATING)	SUBAREA	ESTIMATED RELATIVE TRANSMISSIVITY (ORDINAL RATING)
A	1-3	L	3-4
B	0-5	M	3-5
C	0-4	N	4-7
D	0-1	O	4-6
E	0-4	P	6-8
F	0-3	Q	2-3
G	0-2	R	9-10
H	3-5	S	6-8
I	3-7	T	7-8
J	1-3	U	1-2
K	3-6		

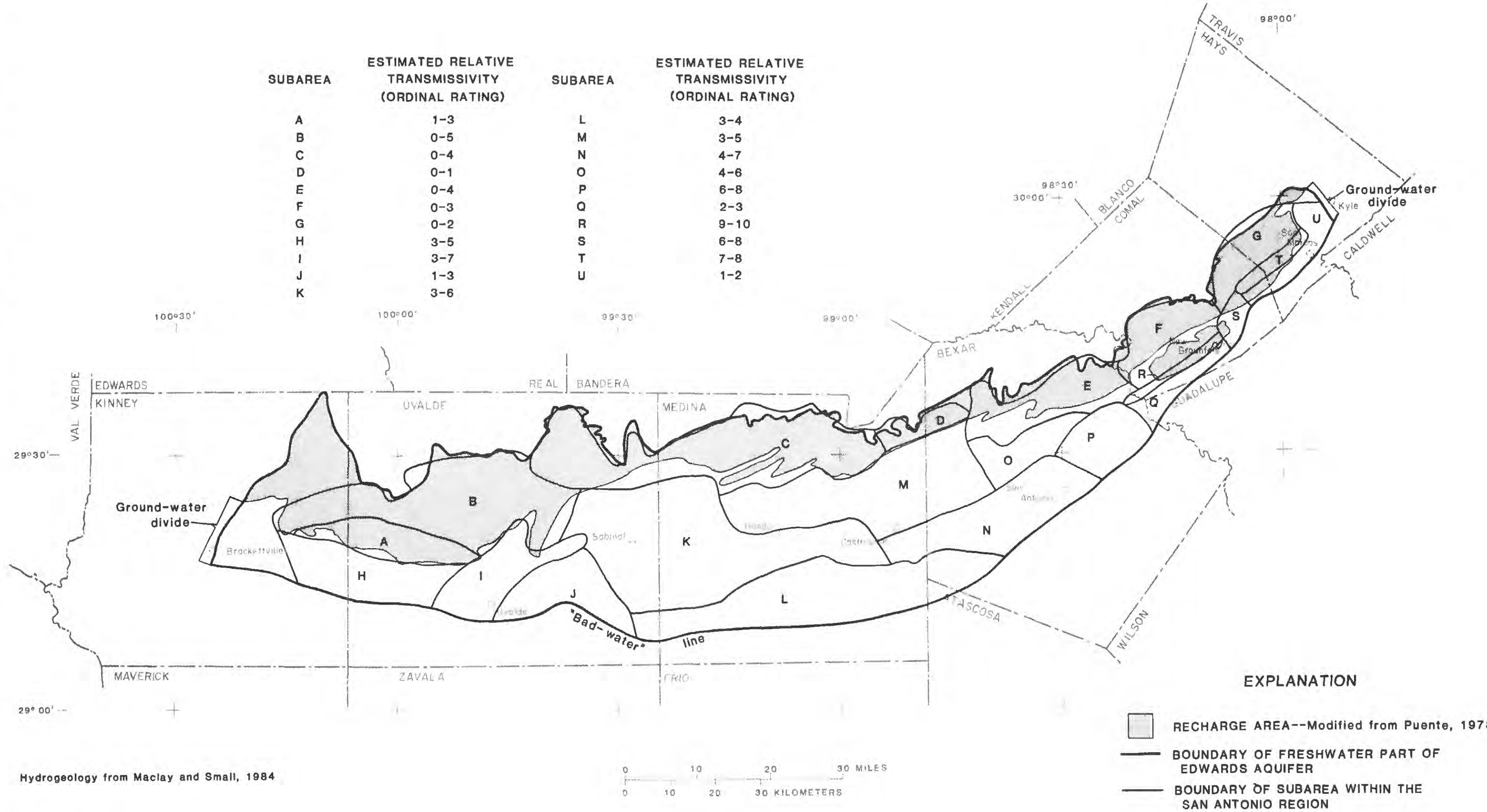


Figure 10. Relative transmissivity values by subareas.

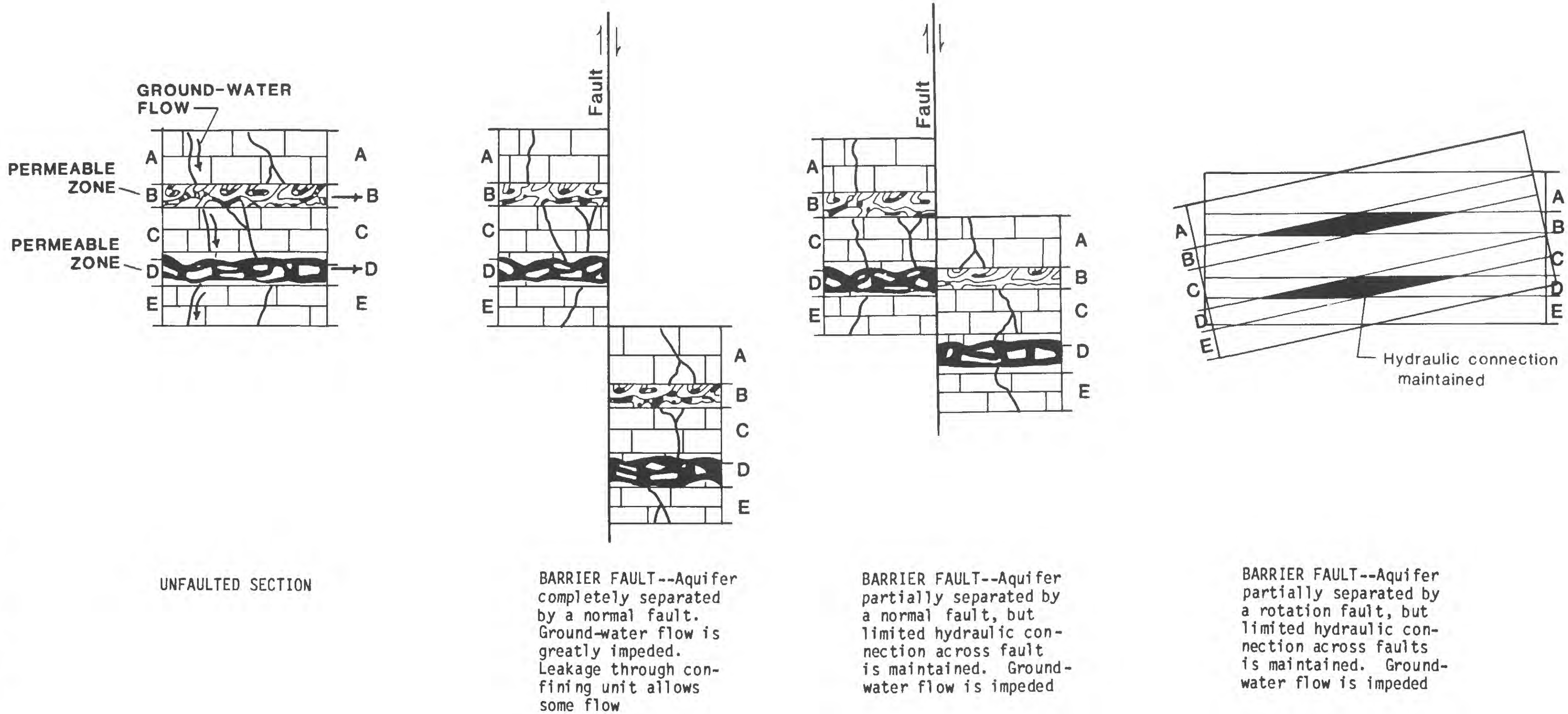


Figure 11. Schematic diagrams showing possible hydraulic restrictions and connections across faults.

includes the West Nueces and Nueces River basin, which has the second largest rate of recharge. From this area, ground water moves to the southeast and then turns eastward north of Uvalde. During high water-level conditions, some water is discharged at Leona Springs. The largest rate of recharge from any basin occurs in central Uvalde County. From this area, ground water flows toward the confined zone in eastern Uvalde and western Medina Counties.

In southeastern Uvalde County, ground water moves toward a large cone of depression south of U.S. Highway No. 90. This cone of depression is intermittently developed by pumping for irrigation. The area where the cone develops is intensively faulted and contains many poorly permeable, intrusive igneous rocks. The lateral continuity of the Edwards aquifer is disrupted by the many faults that strike in different directions and form numerous barriers to ground-water flow. These geologic factors have lessened the capacity of the aquifer to transmit water through this area.

In northern Medina County, the direction of ground-water flow is affected primarily by parallel northeastward-striking faults that divert the flow toward the southwest. The steep regional slope of the potentiometric surface is toward the southeast, but these faults, being local barriers to southeastward flow, cause ground water to remain in storage for a longer period of time. The altitudes of the water levels change abruptly across segments of the major faults in northern Medina County (Holt, 1959). These barriers cause ground water in this unconfined area to remain in storage longer than what would be expected if it was able to take the most direct route. A relatively large portion of the ground water also is stored and recharged in this area.

From the major sources of recharge, in northwest Uvalde County and northern Medina County, ground water moves toward a gap in the major faults immediately east of Sabinal. This flow is combined with some of the flow from north-central Uvalde County. A relatively large flow moving through a small area forces the water to move far southward into the confined zone. No major fault barriers occur within the confined zone to obstruct the southward movement of ground water in this area.

The Haby Crossing fault in northeast Medina County and northwest Bexar County vertically separates the continuity of the Edwards aquifer. This fault is the dividing line between the recharge area and the confined zone. Thus, ground water cannot readily move from the recharge area directly into the confined zone in this area.

In southern Medina County, ground water moves eastward toward Bexar County. At places along segments of the Castroville and Pearson faults, the aquifer is completely or almost completely displaced vertically, which restricts or prevents ground-water circulation perpendicular to the faults. Most of the ground-water flow from Medina County into Bexar County probably occurs south of the Castroville fault. The chemistry of the water south of the Castroville fault typically is similar to that of the main zone of circulation, whereas the chemistry of the water to the north is different from that of the main zone of circulation (Maclay, Rettman, and Small, 1980).

In northeast Bexar County, water moves southward or southeastward from the unconfined zone toward the confined zone of the aquifer. In the vicinity of Cibolo Creek, water may move from Bexar County through the unconfined zone into Comal County.

In the confined zone in Bexar County, ground water generally moves northeastward toward an aquifer constriction in the vicinity of Cibolo Creek and Interstate Highway 35. However, when water levels are high, some ground water is diverted locally toward San Pedro Springs and San Antonio Springs, which are intermittent. These springs occur along a fault that marks the southeast boundary of a horst that probably diverts ground-water flow locally to the northeast and to the southeast.

In northwestern Comal County, water in the unconfined zone northwest of the Hueco Springs fault moves toward Hueco Springs. A narrow and complexly faulted graben that extends northeastward from the vicinity of Cibolo Creek and Comal Springs fault may act as a ground-water drain that collects water northwest of the Hueco Springs fault. In the area between the Hueco Springs fault and Comal Springs fault, ground water is diverted northeastward; however, some flow is discharged locally at Comal Springs.

The confined freshwater zone in Comal County occupies a narrow band that extends along the Comal Springs fault from the downthrown side of the fault to the "bad-water" line. A substantial flow of ground water moves northeastward toward Comal Springs. Along most of the length of Comal Springs fault between Bexar County and Comal Springs, the confined part of the aquifer is vertically separated from the unconfined aquifer on the upthrown side of the fault. However, near Cibolo Creek, the confined and unconfined zones are not clearly separated. Most of the flow of Comal Springs is sustained by ground water along the downthrown side of the Comal Springs fault.

In southern Hays County, substantial ground-water flow moves northeastward through the confined aquifer within a narrow strip between the Hueco Springs and Comal Springs faults and discharges at San Marcos Springs. Part of the flow of San Marcos Springs also is sustained by water moving southeastward from the recharge area in east-central Hays County. In northeastern Hays County, a poorly defined ground-water divide separates the Edwards aquifer in the San Antonio area from the Edwards aquifer to the northeast.

MATHEMATICAL MODEL

A general-purpose, finite-difference digital model for aquifer simulation in two dimensions was selected for testing the initial concepts of the Edwards aquifer in the San Antonio region. The finite-difference model was documented by

Trescott and others (1976) for the U.S. Geological Survey, Water Resources Division.

The finite-difference model simulates ground-water flow in a confined aquifer, an unconfined aquifer, and a combined confined and unconfined aquifer. The aquifer may be heterogeneous and anisotropic and have irregular boundaries. The recharge/discharge from the aquifer may be from wells and springs, be uniformly constant over the entire aquifer, include leakage through confining beds, and include evapotranspiration.

For a confined aquifer system, the digital model uses the ground-water-flow equation written in the following form:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S \frac{\partial h}{\partial t} + W_{(x,\,y,\,t)}, \quad (1)$$

where T_x, T_y = vector components of transmissivity;
h = hydraulic head;
t = time;
S = storage coefficient; and
$W_{(x,\,y,\,t)}$ = volumetric flux of recharge or withdrawal per unit surface area of the aquifer.

The assumption is made that one of the Cartesian coordinate axes of the applied model is aligned along the principal component of the transmissivity.

To represent an irregular aquifer system, derivatives in the continuous equation (eq. 1) are replaced by finite-difference approximations. This equation is written for the center of each cell in the finite-difference grid. The storage and flux terms for a given cell are independent of similar terms for adjacent cells, but the transmissivity terms depend on the values of transmissivity components at this cell and at adjacent cells in the *x*- and *y*-directions. The model uses the harmonic mean of the transmissivities of two adjacent cells to represent the transmissivity between the centers of the two cells. Cells may be designated inactive (no flow) or specified head. For specified-head cells, the model takes out or adds the flow of water needed to maintain the head in the cells at fixed values.

Simulating the response of an aquifer system to a given hydrologic stress, which usually is a change in withdrawals and recharge, involves the following steps: (1) designing a finite-difference grid network, (2) estimating values of the aquifer's hydraulic properties, (3) estimating the initial head, (4) subdividing the test period into simulation intervals during which recharge and withdrawals can be assumed to be constant, (5) estimating the recharge and withdrawals, (6) estimating appropriate time steps during the simulation periods, (7) assembling several simulation periods into a single test period, and (8) executing the computer program. The results of simulation are heads at each cell, fluxes at specified-head cells, and mass water balances of the system. If the model is an acceptable representation of the aquifer, it will compute results that are consistent with measurements of the aquifer's head, recharge, and discharge.

Comparison of the generalized ground-water-flow model, the conceptual model of the Edwards aquifer, and the available recharge/discharge data suggested that several modifications of the computer program (the model) were needed in order to adequately represent the concepts, to readily use the available hydrologic data, and to examine the results of the model's output. To test the concepts, an option was added to allow the user to vary the anisotropy of the transmissivity at individual cells rather than being restricted to a single global value of anisotropy. This modification allowed the placement of flow barriers in the aquifer that could partially or completely restrict flow along one axis and allow free flow along the other axis. The 21 subareas delineated by Maclay and Small (1984) were expanded to 26 subareas and were identified in the computer program so that a single multiplier could be used to uniformly change transmissivity and anisotropy in all cells in any one of the subareas. This aided the adjustment of hydraulic parameters for new simulations.

To readily use the existing recharge/discharge data, the computer program was changed to allow the entry of annual recharge data by stream basins (as grouped by Puente, 1978). This modification consisted of first assigning the cells in the recharge area to one of eight stream basins (fig. 1), and then assigning a percentage of each basin's recharge to each cell. A large percentage was assigned to cells coinciding with the streams. The balance was distributed uniformly over the remainder of the area. Additional modifications were made to allow the recharge and discharge to be changed by multiplication factors during simulation periods.

Modifications of the program in order to compute and print the discharge from the specified-head cells (springs) and the flux between individual cells permitted a more detailed examination of the results. Computer-drawn plots of head and values of hydraulic properties also were made available by modifying the original modeling program.

Representation of the Aquifer

In any numerical modeling study, compromises are necessary between detail and data availability, data handling, and computer resources. In developing the rectangular grid, the modeled perimeter was placed slightly outside the natural boundaries of the system (fig. 12). These external boundaries are assumed to be the updip limits of the recharge area to the north and northwest, the transition between the freshwater and salinewater zones on the south and southeast, and the ground-water divides to the west and northeast. The selected orientation of the grid is about 65 degrees east of north in order to achieve the best alignment with the faults in the Balcones fault zone; however, preference was given to the orientation of faults west of Cibolo Creek. With the alignment established, several trial row and column widths were considered in an attempt to provide an appropriate amount

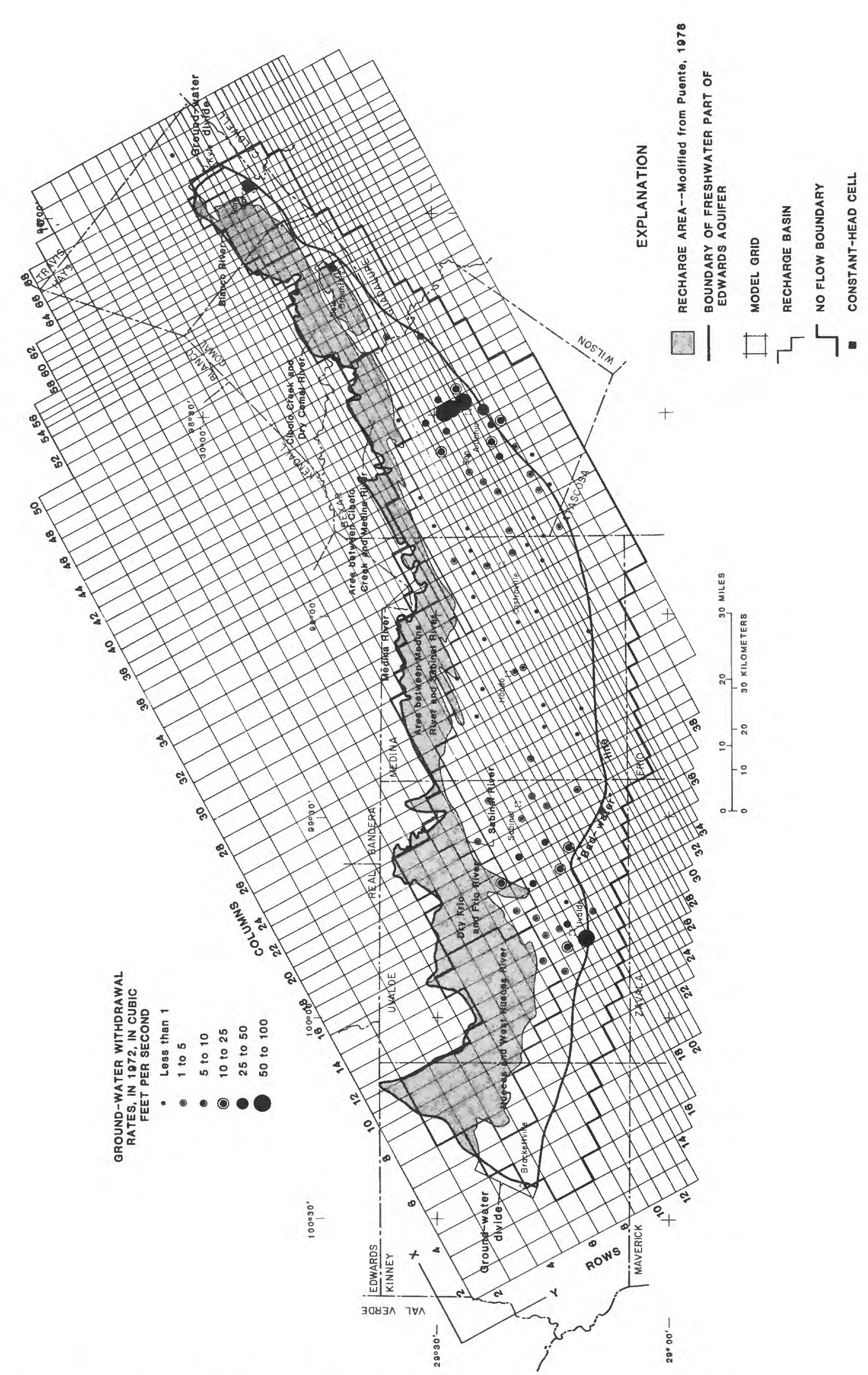


Figure 12. Model grid and recharge and discharge areas.

of detail in the geologically and hydrologically complicated areas and yet to keep the number of cells at a manageable size. The selected grid has 40 rows and 72 columns. Because the model requires the active area to be surrounded by no-flow boundary cells, the active area is limited to the internal 38 rows and 70 columns. Row widths ranged from 0.79 to 6.31 mi; column widths ranged from 1.18 to 3.95 mi. This modeled area is about 75 mi wide and 280 mi long; about 50 percent of the modeled area overlies the Edwards aquifer (fig. 12).

After the regional grid was designed, cells within the eight recharge basins and areas of ground-water withdrawals (fig. 12) were identified for purposes of entering recharge and discharge data into the model. Comal and San Marcos Springs are the major natural discharge points. Cells at these points were set as specified-head boundaries and were assigned ground-water levels that approximated the natural water level in the area (fig. 12). The model computed the discharge at these two springs. When Leona Springs was simulated, its discharge was estimated and assigned as a well (fig. 12). The amount of discharge from Leona Springs was estimated because most of the water goes directly into the alluvial gravels. Leona Springs consists of a number of springs along Leona Creek south of Uvalde that flow at different aquifer stages of the Edwards aquifer.

Cells within the 26 transmissivity and anisotropy subareas are identified in figure 13. The magnitude of hydraulic properties (transmissivity and storage) used in the initial coding was based on data and reports (Klemt and others, 1979; Maclay, Small, and Rettman, 1980; Maclay and Small, 1984). The storage properties were represented by two values, one characterizing the unconfined zone and the other, the confined zone.

Hydrologic Data

The hydrologic events that occurred from January 1972 to January 1977 were selected for simulation because of the high variability of annual recharge and the availability of detailed hydrologic data. During the first year (1972), recharge approximately equaled discharge, thus establishing a possibility of approximately steady-state conditions for that year. Hydrologic conditions in 1973 were unusual in that recharge was exceptionally large and greatly exceeded discharge. The hydrologic records for 1973 provided a suitable situation to investigate the storage properties of the Edwards aquifer.

Records of annual recharge to the Edwards aquifer from 1934 to the present (1986) are available for each of the eight major recharging streams and their interstream areas in the recharge area (fig. 1). Methods of computing the recharge are based on streamflow characteristics of the interstream areas (Puente, 1978). The distribution of the recharge for 1972–76 by stream basin is shown in figure 14*A*. The amount of recharge varies significantly between basins, and most of the recharge occurs in the basins west of Bexar County. About 60 percent of the annual recharge for a recharge basin was assigned to those cells that represented the recharging streams, and the remaining 40 percent was assigned on a uniform basis to those cells in the remaining area of each drainage basin. This distribution is based upon analysis of streamflow hydrographs and records of recharge.

Records of annual discharge from the Edwards aquifer within the San Antonio region are available beginning with 1934 (Maclay and Small, 1984). Ground-water withdrawals are published for municipal and military, irrigation, industry, and domestic, livestock, and miscellaneous uses for five of the six counties forming the San Antonio region. The sixth County (Kinney) is grouped with Uvalde County. The distribution of withdrawals and spring discharge for 1972–76 by county is shown in figure 14*B*. The areal distribution of withdrawals within a county was proportioned to individual cells on the basis of unpublished data on locations and discharges of individual wells and on springflow data.

Records of water levels at widely distributed wells tapping the Edwards aquifer within the San Antonio region are available (Maclay, Small, and Rettman, 1980). Potentiometric or water-level maps for the Edwards aquifer in the San Antonio region are available for 23 different periods from 1930 to 1976. The hydrologic conditions range from the drought in 1950–56 to times of unusually high recharge in 1958 and 1973. Water levels for February 1973 that document the stage of the aquifer following calendar year 1972 are shown in figure 7. Representative water-level hydrographs from widely spaced observation wells tapping the Edwards aquifer and discharge hydrographs for the two major springs from 1972 to 1976 also are available. Most hydrographs indicate relatively little change in water levels between the winter of 1972 and 1973.

Inspection of ground-water levels and spring discharge shows long-term fluctuations. The major rises in water levels are in response to large recharge events of short-term duration. Because the selected model requires the assigned recharge and discharge to be constant during simulation periods, the test period was subdivided into several simulation periods to provide some definition of the irregular recharge events. All temporal subdivisions were on an annual basis except during 1973, when major seasonal changes in recharge occurred. The distributions of the total assigned recharge and withdrawals by simulated periods are shown in figure 15.

Hydrogeologic Data

The hydrogeologic parameters in this model (transmissivity, anisotropy, and storage coefficient) control the quantity of water stored and the movement of water in the aquifer from the area of recharge to the area of discharge.

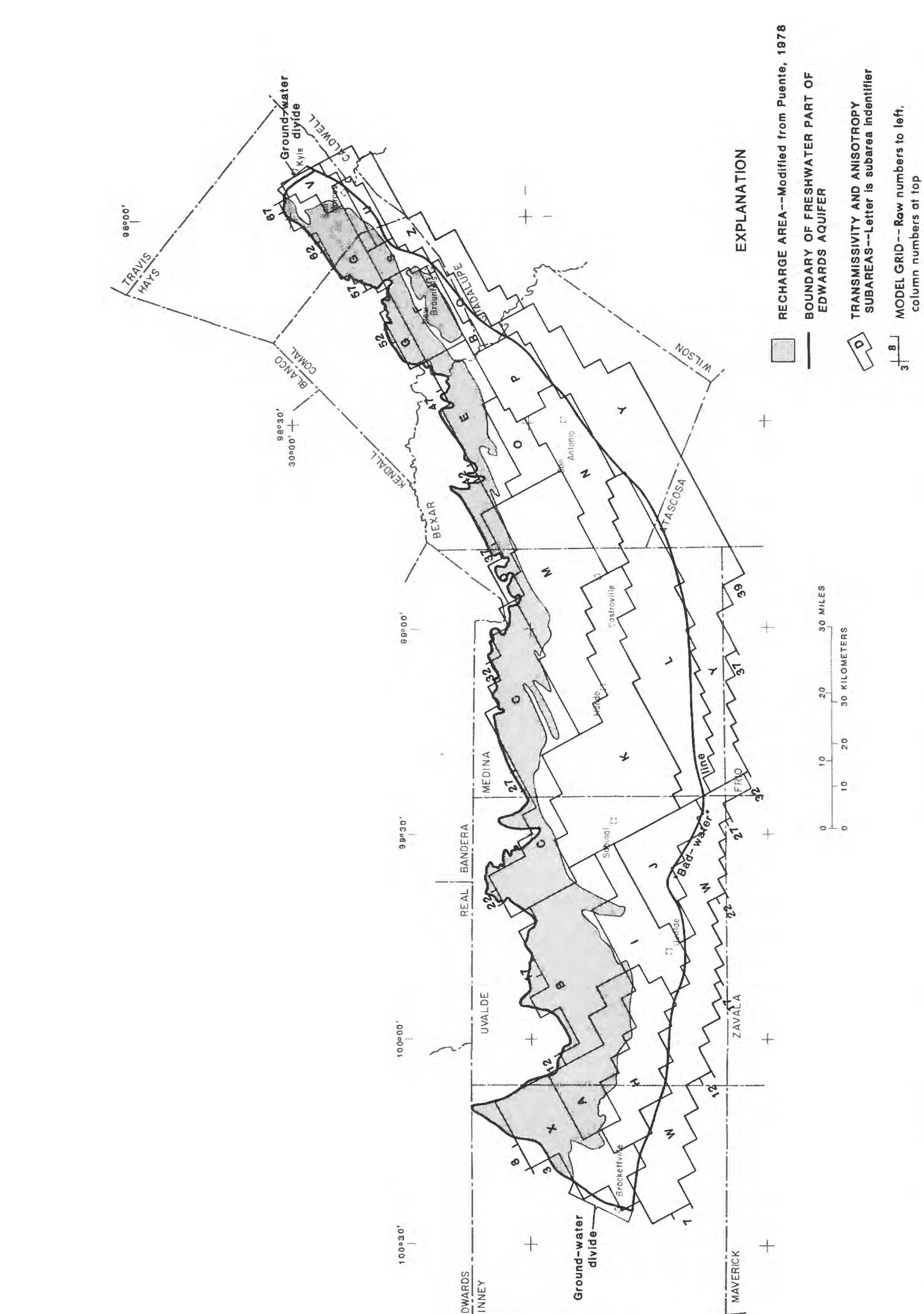


Figure 13. Delineation of transmissivity subareas.

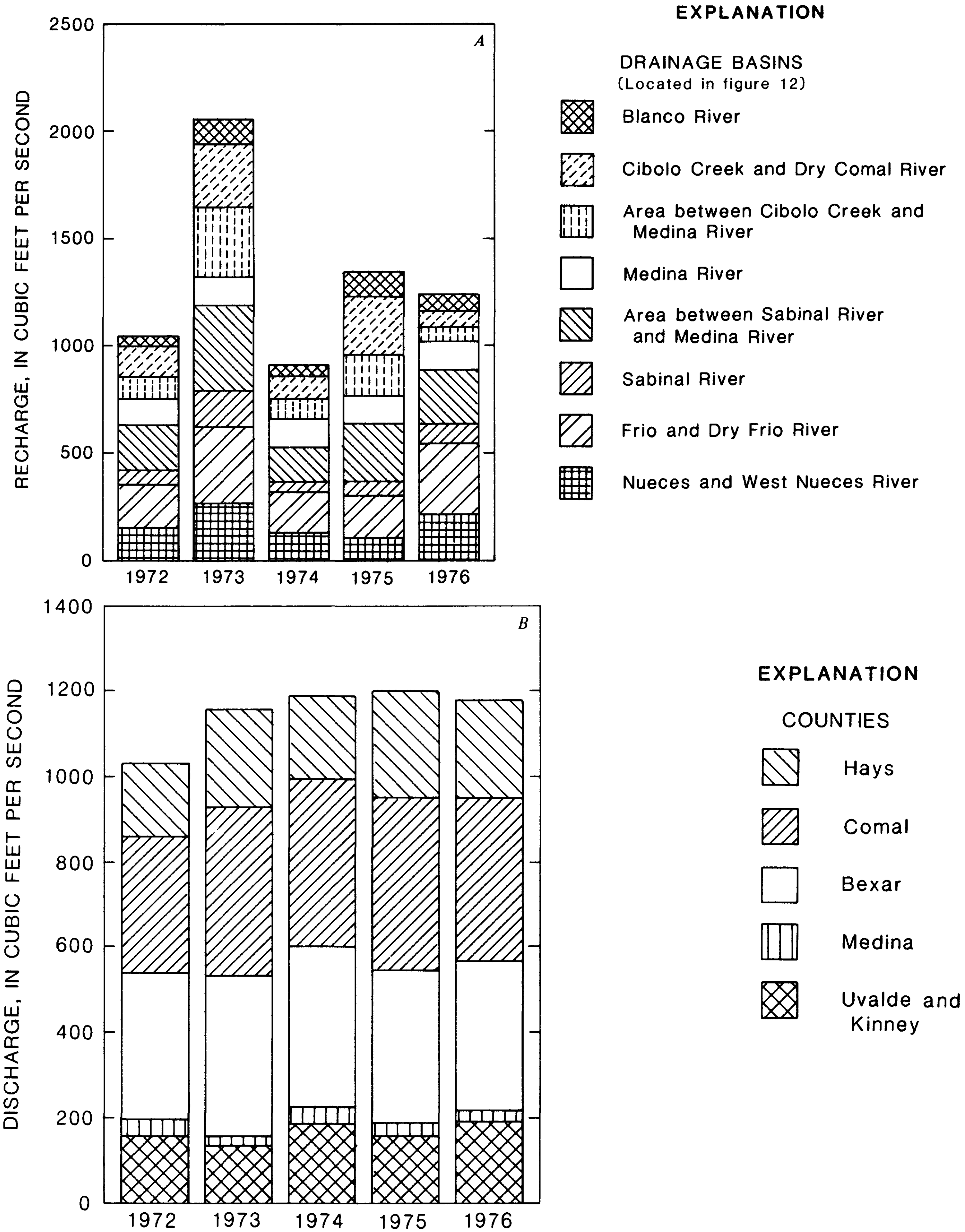


Figure 14. *A*, distribution of recharge by drainage basin, 1972–76 and *B*, distribution of combined ground-water withdrawals and spring discharge by county, 1972–76.

Numerical values for these parameters originally were estimated on the basis of an initial concept of water storage and movement in the aquifer. All available geologic, hydrochemical, and hydrologic information was used to prepare the initial concepts. Using these concepts, large values of transmissivity (as much as 10 million ft^2/d) were originally selected for those cells located along major flow paths. The local direction of ground-water flow is strongly affected by anisotropic properties of the rocks that control the orientation of the larger interconnected pores. Anisotropy within a carbonate aquifer is related to the solubility of the rocks. Water circulation causes the solutioning to develop along the main flow paths in carbonate aquifers. Also, the orientation and occurrence of faults indicate the possible locations for large values of transmissivity and anisotropy. Values of anisotropy were assigned to those grid cells believed to function as major barrier faults.

Original estimates of the hydrogeologic parameters were adjusted during the calibration process. These estimates were varied within reasonable limits dictated by deductions made from the conceptual model and by knowledge of the geology of the aquifer, and they resulted in the computation of heads, springflow, and storage that compare satisfactorily with available data.

Estimates of transmissivity for individual grid cells ranged from small values of 0.001 to 0.1 ft^2/s for cells representing the slightly saline zone of the aquifer, to intermediate values of 0.1 to 20 ft^2/s for cells representing the unconfined zone, to large values of 20 to 100 ft^2/s for cells representing the confined zone of the aquifer. Most of the published information forming the basis for these estimates is from Maclay and Small (1984) and Maclay, Small, and Rettman (1980).

Allowable estimates of anisotropy normal to and along barrier faults ranged from 0:1, where the Edwards aquifer is completely offset by faulting, to 0.5:1, where the Edwards aquifer is partially offset. The initial estimate for anisotropy associated with faults is from Maclay and Small (1984). Regional and subarea anisotropy was allowed to range from 0.5:1 to 1:1. The unit anisotropy is in the x-direction, and the fraction is in the y-direction.

Specific yield estimates range from 2 to 20 percent in the unconfined zone of the aquifer. The storage coefficient in the confined zone was allowed to range from 1×10^{-4} to 10^{-5}. Storativity values for the confined and unconfined parts of the aquifer were estimated using the findings of Maclay and Small (1984).

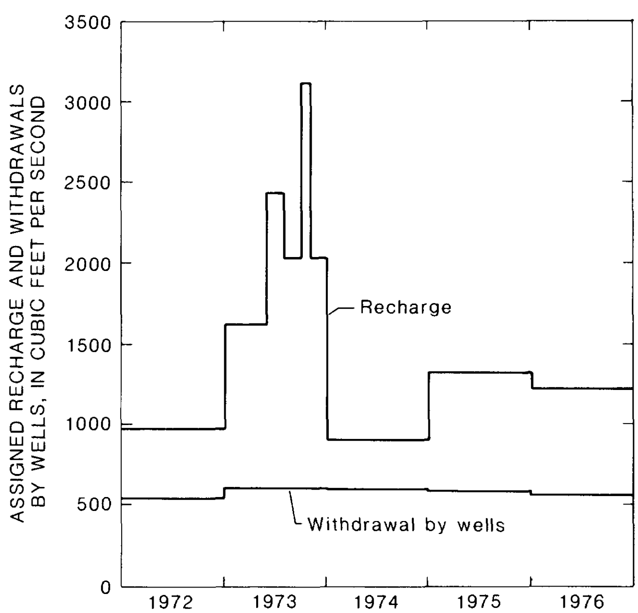


Figure 15. Temporal distribution of total recharge and ground-water withdrawals assigned to model.

SIMULATION OF FLOW

For purposes of this report, a simulation is defined as a test using quantified hydrologic data (recharge and withdrawals) and hydrogeologic parameters (transmissivity and storage) in which the results (hydraulic head and spring discharge) are computed with a mathematical ground-water-flow model. The analysis of an individual simulation was made by comparing the computed results with measured data. A total of approximately 300 simulations were made during the investigation to develop the most acceptable model that was consistent with geologic and hydrologic data. The experiments were conducted in such a manner that subsets of simulations were grouped into a series. Each series included those simulations that had similar constraints on data or were representative of different test periods.

General Description of Simulations

In the process of achieving the most acceptable model, simulations were grouped into series that had similar hydrologic or boundary representations. Each series had its own objective of testing some concept or quantifying hydrogeologic properties.

A brief description of the objectives and constraints of each series follows. Series I, II, and III tested the original estimates of transmissivity as determined from previous geologic and hydrologic studies. In general, a change in transmissivity for a single cell, or for a few cells, within the confined zone had relatively little effect on computed head or springflow. Also, during these series it was noted that computed heads in the recharge area in Comal County generally were significantly lower than the measured heads. Ground-water inflow from the lower Glen Rose Formation to the Edwards aquifer was found to be a reasonable assumption along faults where the lower Glen Rose is juxtaposed against the Edwards Limestone.

Series IV and V were conducted primarily to investigate the storage characteristics of the aquifer. A significant effect of anisotropy on retaining water within the unconfined part of the aquifer was noted. The presence or absence of major barrier faults strongly affected both the amount of ground water that was temporarily retained within the unconfined zone and the computed springflow.

Series VI investigated the sensitivity of computed springflows and heads to uniform changes of transmissivity and anisotropy for individual subareas or combinations of subareas. Also, the effect of varying the length of certain barrier faults on storage and springflow was noted. The high sensitivity of the simulated length of the Haby Crossing fault to the computed discharge of Comal Springs was determined. By varying the length of this barrier fault, the springflow could be significantly changed.

Series VII and VIII investigated the effect of varying anisotropy within the unconfined zone and assumed isotropy within the confined zone of the aquifer. Anisotropy aligned with the geologic structure in the unconfined zone caused computed water levels to be higher within the unconfined zone. Also, simulations were made to investigate leakage across barrier faults.

Series IX investigated the effect of no subarea anisotropy (that is, assumed isotropy). The series showed that a reasonable simulation could be achieved by assuming the aquifer to be isotropic on a global basis and anisotropic only along barrier faults.

Series X was conducted to select the simulation that best represented the Edwards aquifer. The selection was based on matching the model and its simulation results with water-level and springflow hydrographs and the regional potentiometric surface. A summary of each series is given in table 2.

Selected Simulation

The selected simulation is considered to be the best representation of ground-water flow in the Edwards aquifer during 1972–76. It was selected on the basis of matching measured and simulated water-level and springflow hydrographs, as well as the measured and simulated regional potentiometric surface in the winter of 1977. Some other simulations produced results for one or two of the calibration criteria with lesser differences than those of the selected simulation, but other criteria had greater differences. These simulations were judged as a less realistic representation of the aquifer. To indicate the goodness-of-fit, a comparison of simulated and measured water levels at selected observation wells (fig. 16) and springflows (fig. 17) were made. A simulated water-level map for the end of 1972 is given in figure 18. Measured water levels during the winter of 1973 from selected wells have been included in figure 18 to facilitate comparison of simulated and measured values, and this map can be compared with that of measured water levels given earlier in figure 7.

The simulated springflows of Comal and of San Marcos Springs (fig. 17) compare reasonably well with the measured springflows. The time distribution of simulated springflows is moderately out of phase with the measured springflows for 1974–76. The major cause of the phase error probably is the use of annual average recharge and discharge for these years. Some of the error may result both from using only a single value of specific yield in the unconfined zone of the aquifer and from the lack of information on barrier faults occurring in the unconfined zone. However, the error is probably of minor significance because of the goodness-of-fit between measured and simulated discharge rates and timing for 1973 and the long-term average discharge rates for 1974–76.

The long-term simulated water levels of five widely distributed observation wells for 1972–76 (fig. 16) approximate the long-term measured water levels. As in springflow, the poorest fit was for 1974–76. For 1973, the magnitudes of the calculated water-level altitudes and changes are consistent with that of the measured values.

The general pattern of water-level contours on the simulated regional potentiometric map for the end of 1972 (fig. 18) is consistent with that of measured values. The simulation demonstrates the effect of major barrier faults on the regional distribution of the potentiometric surface. A comparison of the simulated and measured water levels (figs. 16, 18) shows that the discrepancies are in an area northwest of Sabinal. This is in the area of very complex faulting and the convergence of ground-water flow from northern Uvalde County and northwest Medina County.

The distribution of transmissivities used in the selected simulation is shown in figure 19. Using the initial distribution of transmissivities with some cell-by-cell adjustments of transmissivity as a base, subarea multipliers ranged from 0.15 to 5.00; eight of the subareas used a multiplier of 1.00. In general, the transmissivities used in the selected simulation increase from west to east in the confined part of the aquifer. The greatest value of transmissivity is 112 ft^2/s along flow lines leading to Comal Springs, and the least value is 0.0015 ft^2/s in the slightly saline zone.

The distribution of anisotropy is given in figure 20. As expected, it was necessary to designate the anisotropy at cells representing the major barrier faults. The anisotropy at these cells ranged from 0.0:1 to 0.5:1. The effect of the anisotropy across faults resulted in directional changes of ground-water flow and impoundment of water. Designation of a value for anisotropy on a subarea scale was not needed; thus, all the anisotropy could be accounted for by the barrier faults.

Table 2. Summary of series of simulations
[ft^2/s, square foot per second; ft, foot; ft^3/s, cubic foot per second]

Series	Purpose of series	Modification of model	Simulation condition	Best simulation of series	
				Input	Results
I. Steady state; eastern half of the San Antonio region.	To improve original estimates of transmissivities.	Rearrangement of output matrices for readability.	Used recharge and discharge data for 1972. Initial heads were winter of 1972-73 data. Underflow to Bexar County is represented by simulated injection wells along western Bexar County line. Varied regional anisotropy in x-direction (row) for the entire area by multiplication factors that range from 1 to 10. Varied estimates of transmissivity for individual cells. Original estimate of maximum transmissivity was about 12 ft^2/s. For numerical purposes, steady state was approximated by a very low storage coefficient and a 2-year simulation.	Anisotropy multiplication factor of transmissivity in x-direction (row) was 1.2. Varied transmissivity at individual cells up to 50 percent from original estimates. In general, the model transmissivities were about 20 percent higher than those originally estimated for cells in the confined zone of the aquifer in Bexar County.	Simulated heads were much too high along eastern and western boundaries, too low in most of confined zone, and much too low in unconfined zone of the aquifer.
II. Steady state; western half of the San Antonio region.	Same as series I.	None.	Outflow from Medina County was represented by simulated pumping wells along eastern Medina County line. Varied anisotropy in the x-direction for the entire area from 1 to 10. Varied estimates of transmissivity for individual cells.	Regional transmissivity increased by 20 percent over original estimate. Varied cell estimates of transmissivity up to 100 percent.	Simulated heads were 5 to 20 ft too high in confined zone and about 20 to 60 ft too low in unconfined zone of the aquifer.
III. Steady state; entire San Antonio region.	Same as series I.	None.	Initial experiment used transmissivity derived from previous best experiments.	Anisotropy multiplication factor for transmissivity in x-direction (row) was 1.4. Varied transmissivity in individual cells up to a factor of 10.	Not very satisfactory. Simulated heads were 100 ft too high in the west. No combination of transmissivities produced reasonable results.
IV. Transient, 1972-73.	To refine estimates of transmissivity and to improve estimates of storage coefficients.	Features to change all transmissivities in any of the 26 subareas by a subarea multiplier, to input recharge by basin, and to change recharge and discharge by separate multipliers. Subdivided the San Antonio region into 26 areas.	Simulated hydrology of calendar years 1972 and 1973. To reduce model start irregularities, continued to start the model simulation using winter of 1972-73 water-level data and repeated the simulation of 1972. Simulated results were compared with winter of 1972-73 measurements. Subdivided 1973 into 150-, 65-, 60-, and 30-day simulation periods. The recharge distribution included identifying the cells in each of the drainage basins, estimating the percent of recharge for those cells overlying streams, and inputing recharge by drainage basin.	No satisfactory solution. The following parameters were varied: transmissivity and anisotropy for each of the 26 subareas, transmissivity value of individual cells, and storage coefficients for unconfined and confined zones of the aquifer.	Excessive springflows were computed for 1973. Simulated Comal Springs discharge usually was several times too high. Simulated heads were too high in the western part of the San Antonio region. Could not adequately control simulated storage within the recharge area using transmissivity and anisotropy multipliers by subsrea.
V. Transient, 1972-73; barrier faults.	To test the significance of barrier faults on water levels and springflow.	Feature to allow anisotropy in y-direction to be changed cell by cell. Value must be greater than zero.	Delineated significant barrier faults. The anisotropy factor is equivalent to the fraction of water that would flow across the cell for an expected hydraulic gradient and transmissivity if the barrier fault did not exist. Varied anisotropy	Subarea multipliers for transmissivity (T) and anisotropy in y-direction: T / Anisotropy / T / Anisotropy A 0.60 0.80 C 0.40 0.40 B 0.40 0.50 D 1.00 0.60	For 1972, the simulated heads were about 10 ft below measured heads in the confined zone of the aquifer and 10 to 50 ft above them in the recharge area in the west (Uvalde and Kinney Counties).

Table 2. Summary of series of simulations—Continued

Series	Purpose of series	Modification of model	Simulation condition	Best simulation of series: Input	Best simulation of series: Results
V.--Continued			factor by subareas from 0.4 to 1.0 in the *y*-direction. Varied transmissivity vslues of individual cells in accordance with revised concepts of possible flow patterns. Redistributed cell-by-cell recharge percentage to add more water near the downstream part of the recharge area. Varied specific yields for unconfined zone of aquifer from 0.01 to 0.10.	*T* Anisotropy / *T* Anisotropy E 0.60 0.60 / P 1.50 0.50 F 0.60 0.60 / Q 1.50 0.75 G 0.50 0.60 / R 1.00 0.75 H 2.00 1.00 / S 2.00 1.00 I 0.85 0.75 / T 2.00 0.75 J 1.50 0.75 / U 1.50 1.00 K 2.00 0.85 / V 1.00 1.00 L 3.00 0.75 / W 1.00 1.00 M 2.00 0.75 / X 0.50 1.00 N 1.50 0.75 / Y 1.00 1.00 O 1.50 0.50 / Z 1.00 1.00 Storsge coefficient of aquifer in unconfined zone of aquifer was 0.05.	
VI. Sensitivity tests.	To test the sensitivity of computed springflow and heads to changes in transmissivity and anisotropy in subareas and to the occurrence and length of selected barrier faults.	None.	Used the results from transient 1972-73, with fault barrier series as base run for sensitivity studies. All parameters except one were held constant. The varied parameter was then investigated by making changes of the values and then studying the computed results.	--	When isotropy was assigned to subaress representing the confined zone of the aquifer, the match of computed and measured springflow snd water levels improved. Computed very excessive springflow when simulated barrier fsult at Haby Crossing fault was removed. The additions of a simulated subsurface spring near Uvalde (Leona Springs) lowered the discharge at Comal Springs in April 1973 from 367 to 348 ft^3/s. This alteration also lowered the head in western Uvalde County. Simulated springflows are very sensitive to presence and effectiveness of barrier faults.
VII. Transient, 1972-73; barrier faults included, anisotropy varied by subareas in unconfined zone and set to 1.00 in confined zone of the aquifer.	To test need for anisotropy away from faults in unconfined zone of the aquifer.	Festure to print fluxes across cell boundaries and to plot velocity vectors.	Adjusted anisotropy for cells representing barrier faults. Added additional minor bsrrier faults in the recharge area. Storage coefficient of recharge area set at 0.05.	Subarea multipliers for transmissivity (*T*) and anisotropy in *y*-direction: *T* Anisotropy / *T* Anisotropy A 0.60 0.80 / N 1.50 1.00 B 0.40 0.50 / O 1.50 1.00 C 0.40 0.40 / P 1.50 1.00 D 1.00 0.60 / Q 1.50 1.00 E 0.60 0.60 / R 1.00 1.00 F 0.60 0.60 / S 2.00 1.00 G 0.50 0.60 / T 2.00 1.00 H 2.00 1.00 / U 1.50 1.00 I 0.85 1.00 / V 1.00 1.00 J 1.50 1.00 / W 1.00 1.00 K 2.00 1.00 / X .50 1.00 L 3.00 1.00 / Y 1.00 1.00 M 2.00 1.00 / Z 1.00 1.00	Spring — Springflow (ft^3/s) Simulated / Measured End of 1972 Comal 265 / 310 San Marcos 139 / 161 May 1973 Comal 336 / 365 San Marcos 178 / 211 For 1972 the simulated heads were 5 to 10 ft too low throughout the confined zone and 10 to 30 ft too high in the unconfined zone of the aquifer.

Table 2. Summary of series of simulations—Continued

Series	Purpose of series	Modification of model	Simulation condition	Best simulation of series: Input	Best simulation of series: Results
VIII. Transient, 1972-73; isotropic except for barrier faults.	To test the significance of leakage across barrier faults on springflow and water levels. To locate the most significant barrier faults.	Feature to allow *y*-direction anisotropy to be set at 0.00.	Sets anisotropy for individual cells along mapped barrier faults between 0.0 and 0.5 and isotropic elsewhere. Storage coefficient of aquifer held at 0.05 for the recharge area. Tested the effects of barrier faults in northern Uvalde County on springflow. Changes were made in simulated length of selected faults.	--	Springflow (ft^3/s), Simulated / Measured: End of 1972: Comal 269 / 310; San Marcos 138 / 161 May 1973: Comal 343 / 365; San Marcos 177 / 211 Major convergences of flow were noted in the Nueces area and in the vicinity of Sabinal. In 1972, water levels were about 5 to 10 ft too low in the confined zone of the aquifer.
IX. Transient, 1972-76; isotropic except for barrier faults, specific yield set at 0.08.	To refine calibration of transmissivity and anisotropy of faults using a storage coefficient of 0.08 for the recharge area.	None.	Set discharge at Leona Springs to 75 ft^3/s in 1973. Varied transmissivity estimates in vicinity of Comal Springs to increase simulated flow to San Marcos Springs.	Transmissivity subarea and its multiplier: A 0.40, B 0.40, C 0.40, D 1.00, E 1.40, F 1.40, G 0.50, H 3.00, I 0.85, J 1.50, K 2.00, L 3.00, M 1.25, N 1.25, O 1.50, P 1.50, Q 1.50, R 1.00, S 2.00, T 2.00, U 1.50, V 1.00, W 1.00, X 1.50, Y 1.00, Z 1.00	Springflow (ft^3/s), Simulated / Measured: End of 1972: Comal 260 / 310; San Marcos 160 / 161 May 1973: Comal 375 / 365; San Marcos 210 / 211 Barrier fault along row 10 is a very significant control on springflow. Simulated water levels within confined zone of aquifer are within a few feet of measured heads. Simulated water levels in northern Uvalde are about 10 to 30 ft too high.
X. Transient, 1972-76; final selection of transmissivity, anisotropy, and storage coefficient.	To achieve best simulation.	None.	Any combination of minor changes to any or all aquifer properties.	Subarea multipliers for transmissivity (*T*): A 0.15, B 0.15, C 0.50, D 1.00, E 1.40, F 1.40, G 0.20, H 4.00, I 5.00, J 1.30, K 2.00, L 4.00, M 1.00, N 2.50, O 1.00, P 2.50, Q 1.50, R 1.00, S 2.00, T 2.00, U 1.50, V 1.00, W 1.00, X 0.50, Y 1.00, Z 1.00	Described in text.

The storage coefficient was determined to be 0.05 in the unconfined zone and 1×10^{-4} in the confined zone of the aquifer. The complexity of the aquifer and the interrelation of the several parameters prevented additional refinement of these values.

The direction and relative magnitude of flow at each cell of the selected simulation are indicated by the orientation and relative length of arrows shown in figure 21. The directions of the flux vectors reflect the presence of nearby barrier faults. Most noticeable is the concentration of flow that is southward through Knippa gap, a few miles west of Sabinal.

REFINEMENT OF STORAGE AND FLOW CONCEPTS

The results of the simulation study and knowledge of hydrogeologic features that may affect ground-water flow in the aquifer have led to refinement of the initial storage and flow concepts. A description of the current (1986) concepts is presented by means of tables that name and describe the hydrologic and geologic components. The concepts are divided into the following categories: storage units, flow units, flow across external boundaries, and geologic structures restricting or conveying ground-water flow. The discussion in the tables generally follows a west to east order.

Delineation of Storage Units

Water stored between the historical range of water levels in the Edwards aquifer in the San Antonio region is contained primarily within the unconfined zone. Changes in

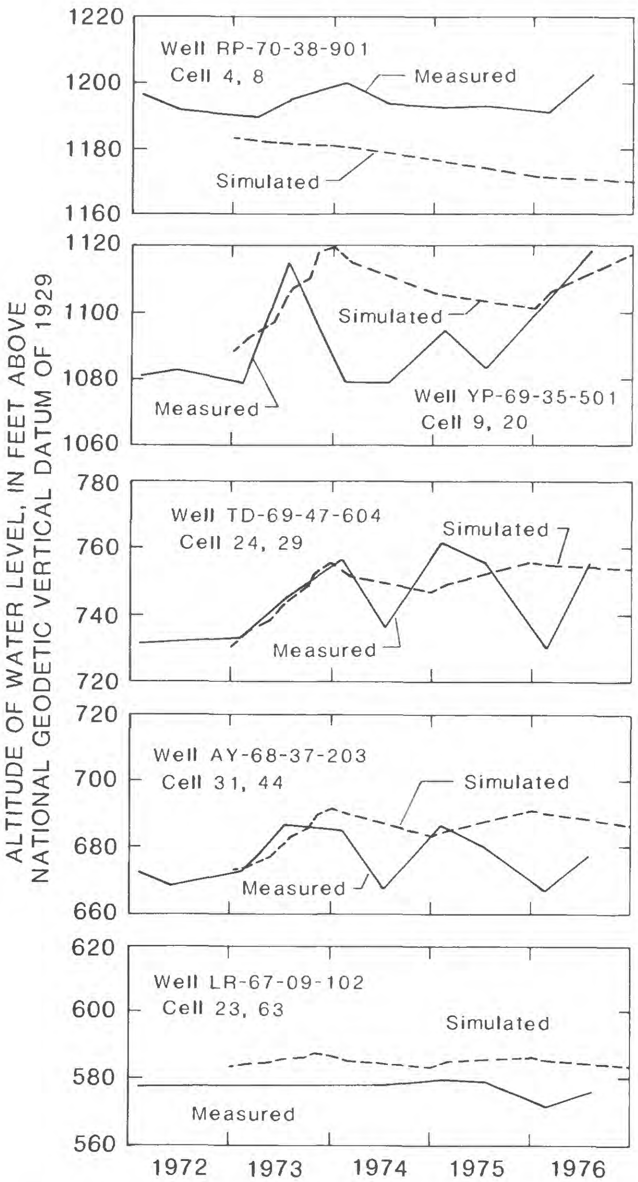


Figure 16. Hydrographs showing comparison of simulated and measured water levels in selected observation wells.

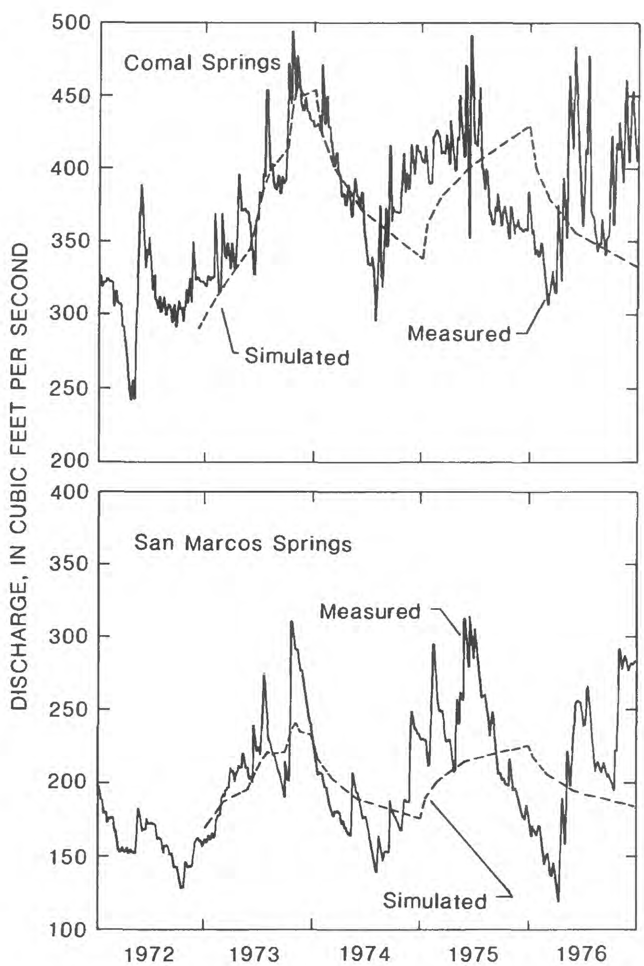


Figure 17. Hydrographs showing comparison of simulated and measured discharge at Comal and San Marcos Springs.

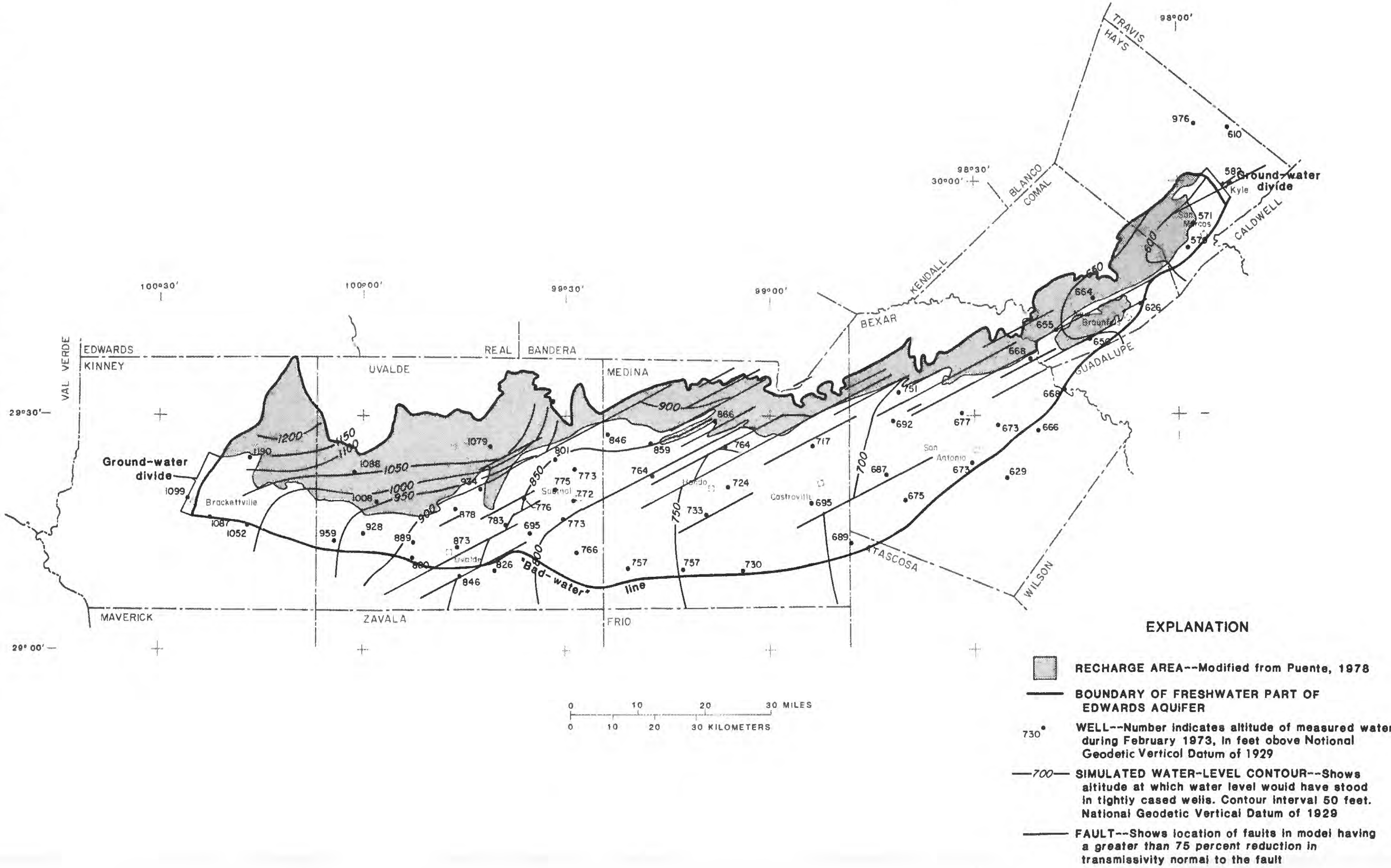


Figure 18. Simulated regional water levels, end of 1972.

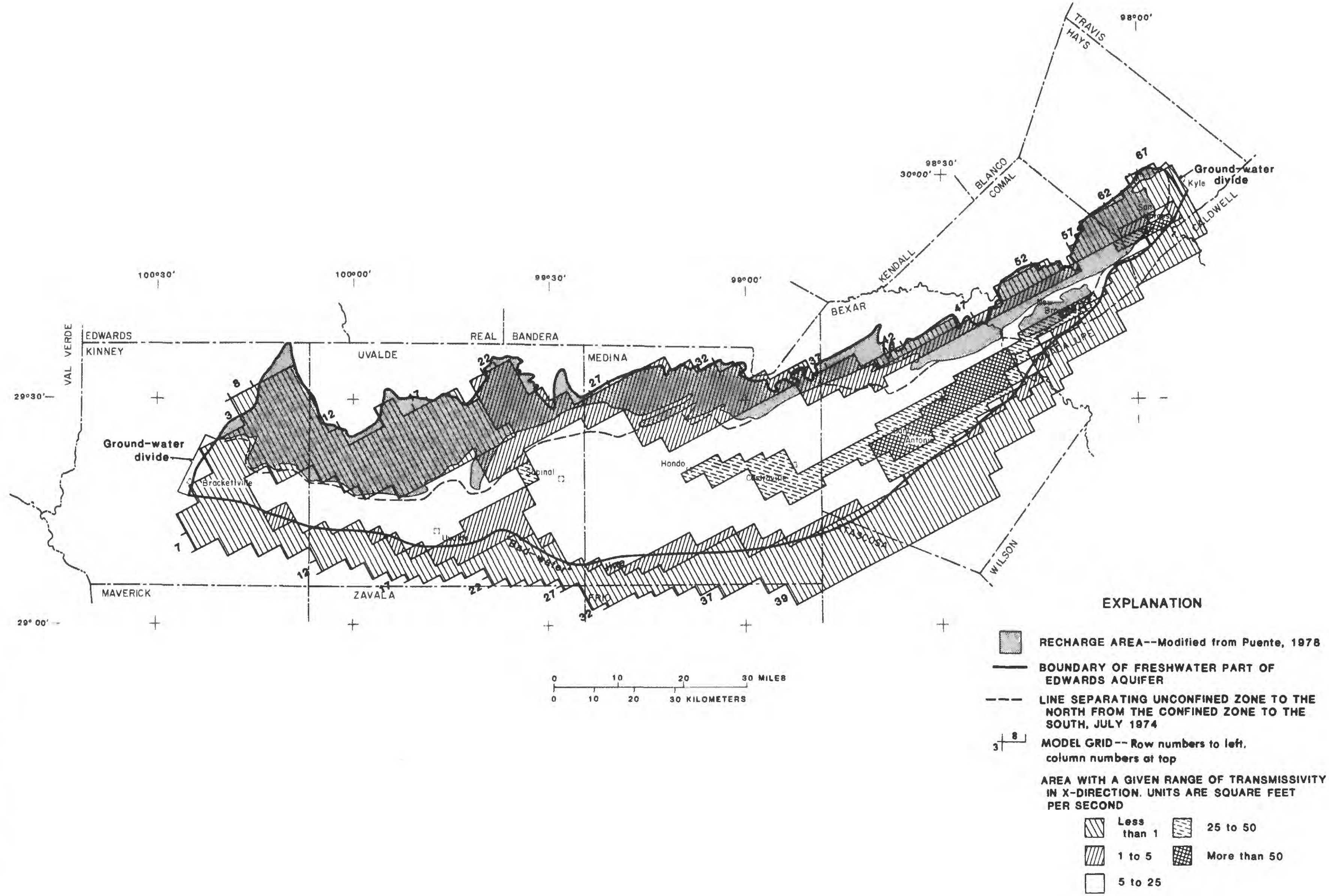


Figure 19. Transmissivities used in selected simulation

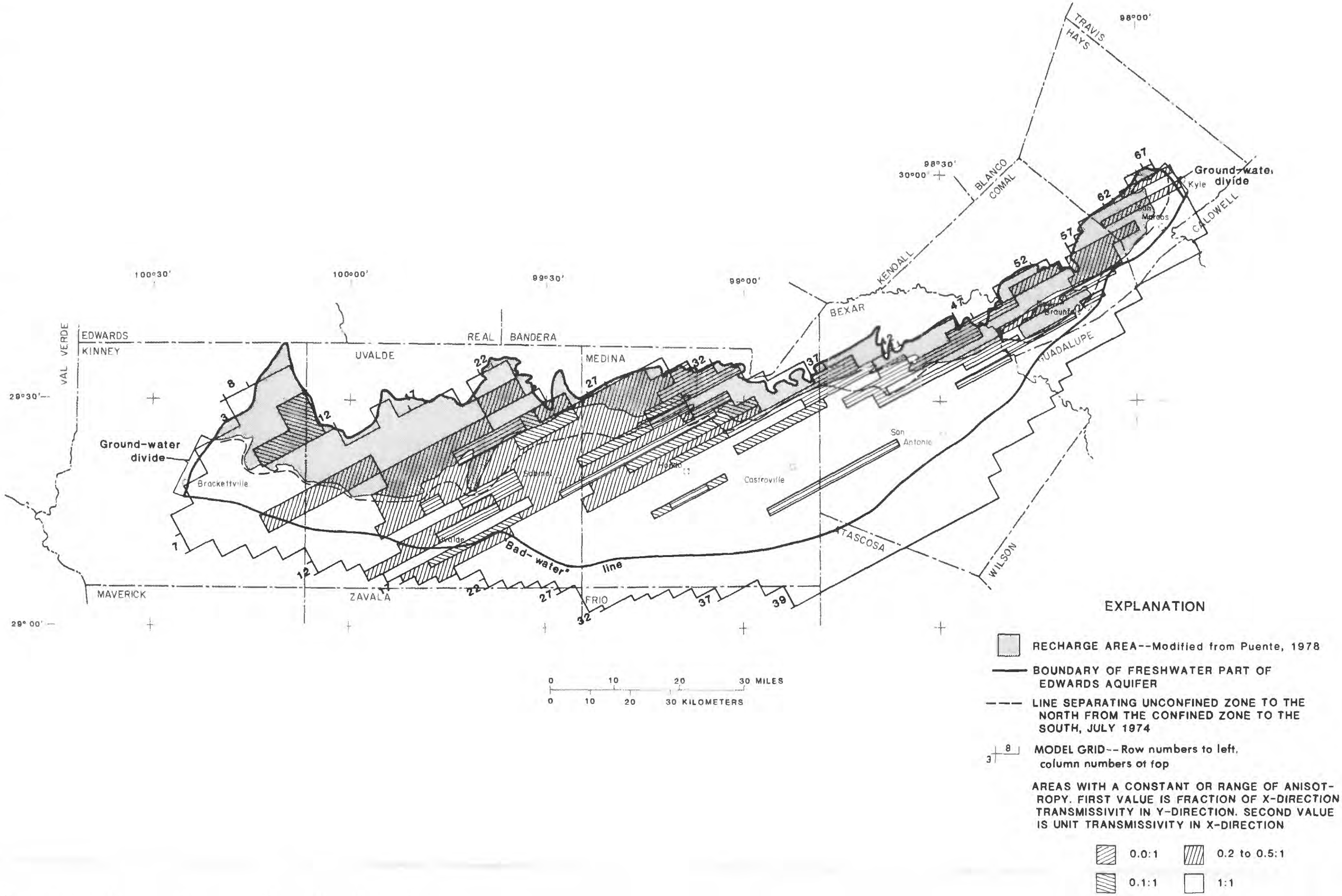


Figure 20. Anisotropy factors used in selected simulation.

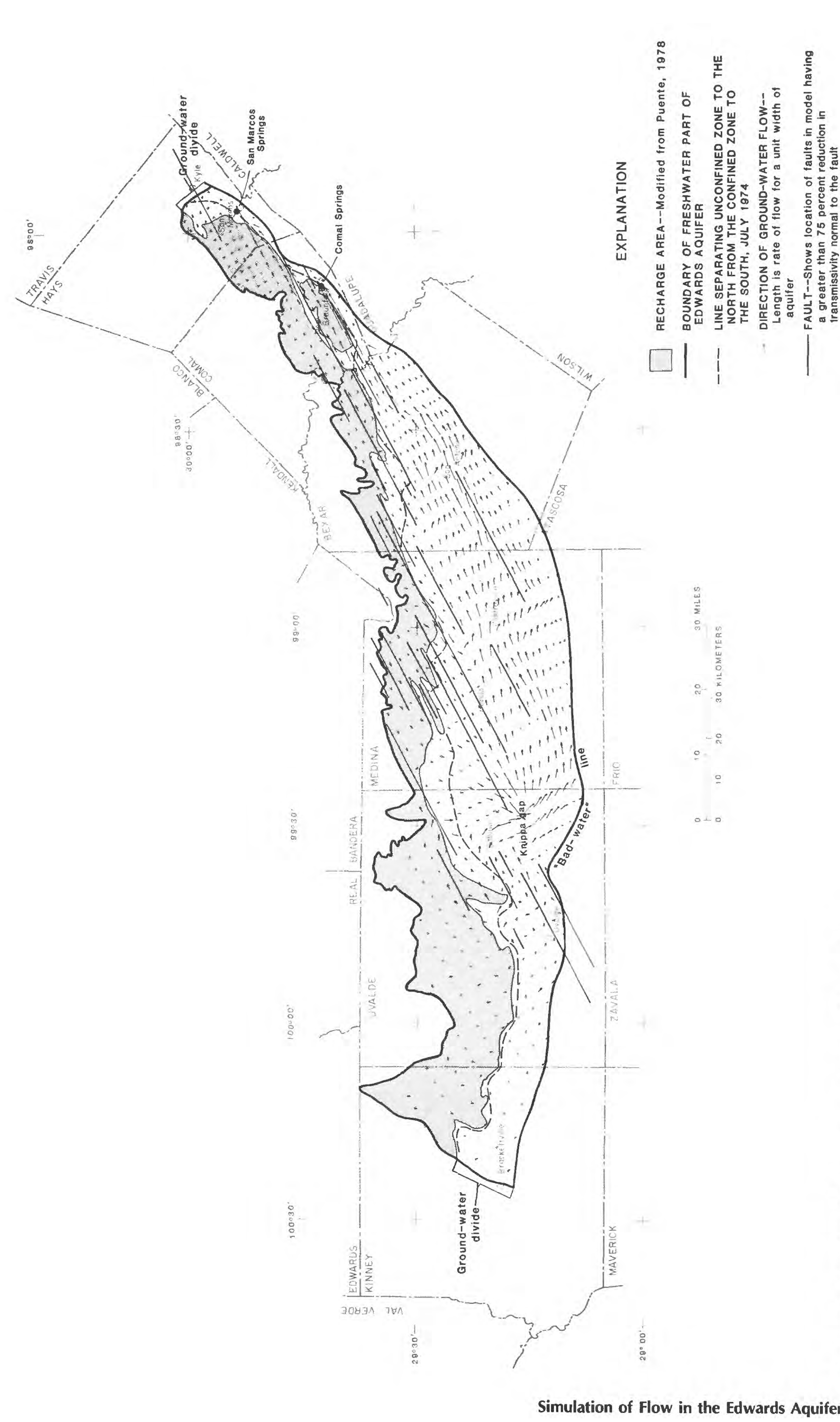


Figure 21. Simulated flow vectors at each cell in model.

water levels in the unconfined zone represent significant changes in the volume of water stored within the aquifer, whereas comparable changes in water levels within the confined zone represent only very small changes in volume of water stored within the aquifer. Because the area of the unconfined zone represents a significant part (30 to 40 percent) of the aquifer, a very large percentage of the water released from storage for a historical range in water levels comes from this zone.

The quantity of water temporarily retained in storage within the unconfined zone between recharge events is affected strongly by the geologic structure of the aquifer. A system of parallel faults are oriented in a manner to obstruct the flow of ground water from the unconfined zone to the confined zone. Because of these obstructions, water movement from the unconfined zone to the confined zone is slowed, thus causing the quantity of water in storage to remain there for longer periods.

During this study, it was noted that four subareas of the unconfined zone tended to function as independent storage units because of faults. They are identified as the western, western Medina, eastern Medina, and eastern storage units. The division between these units is strongly influenced by major faults, a narrowing of the recharge area, and a change from one stream basin to another basin. These units are described in table 3 and are shown in figure 22. They are delineated with the aid of the flow-vector map (fig. 21), maps of the unconfined zone and recharge area, and the location of the major barrier faults.

Delineation of Flow Units

For purposes of this report, a flow unit of the Edwards aquifer in the San Antonio region is defined as an area of the aquifer that includes a storage unit and a zone in which water is transmitted from this storage unit to major points of discharge. Some interchange of ground water from one flow unit to another probably occurs at different water-level conditions. Owing to the configuration of the aquifer, the controlling geology, and the stable locations of ground-water withdrawals, the flow units are not expected to vary substantially with historical changes in water levels.

A study of the selected simulation identified four generally independent ground-water-flow units—the western-southern, south-central, north-central, and eastern flow units. Downgradient major faults and ground-water discharge were influential in the delineation of the flow units. The flow units are described in table 4, and their locations are shown in figure 22. They were delineated primarily with the aid of the flow-vector map and using the locations of barrier faults and storage units.

Identification of Possible Flow Across External Boundaries

Not all inflow and outflow of ground water to the Edwards aquifer in the San Antonio region can be determined from available data. However, the long-term balance

Table 3. Major storage units

Name	Description
Western	Includes the unconfined zone west of the Woodard Cave fault and the complex of faults in the Uvalde area that is an extension of the Medina Lake fault. Eastern limit is the topographic divide between Sabinal River and Seco Creek. Most of the recharge comes from losses of flow in the Nueces, West Nueces, Frio, Dry Frio, and Sabinal Rivers. Has the largest storage capacity of the four units. Is the most remote from the major discharge points. Yields water to the confined zone rather sluggishly.
Western Medina	Includes the unconfined zone between the western storage unit and the Medina Lake fault. Most of the recharge comes from Hondo and Seco Creeks and from Medina Lake.
Eastern Medina	Includes the unconfined zone between the western Medina storage unit and generally along the Haby Crossing fault. Receives most of its recharge from Medina River, Medina Lake, and several small creeks.
Eastern	Includes the unconfined zone east of the eastern Medina storage unit. The storage in this unit is strongly influenced by the Northern Bexar fault and the Hueco Springs fault. The recharge is primarily from several small streams, especially Cibolo Creek.

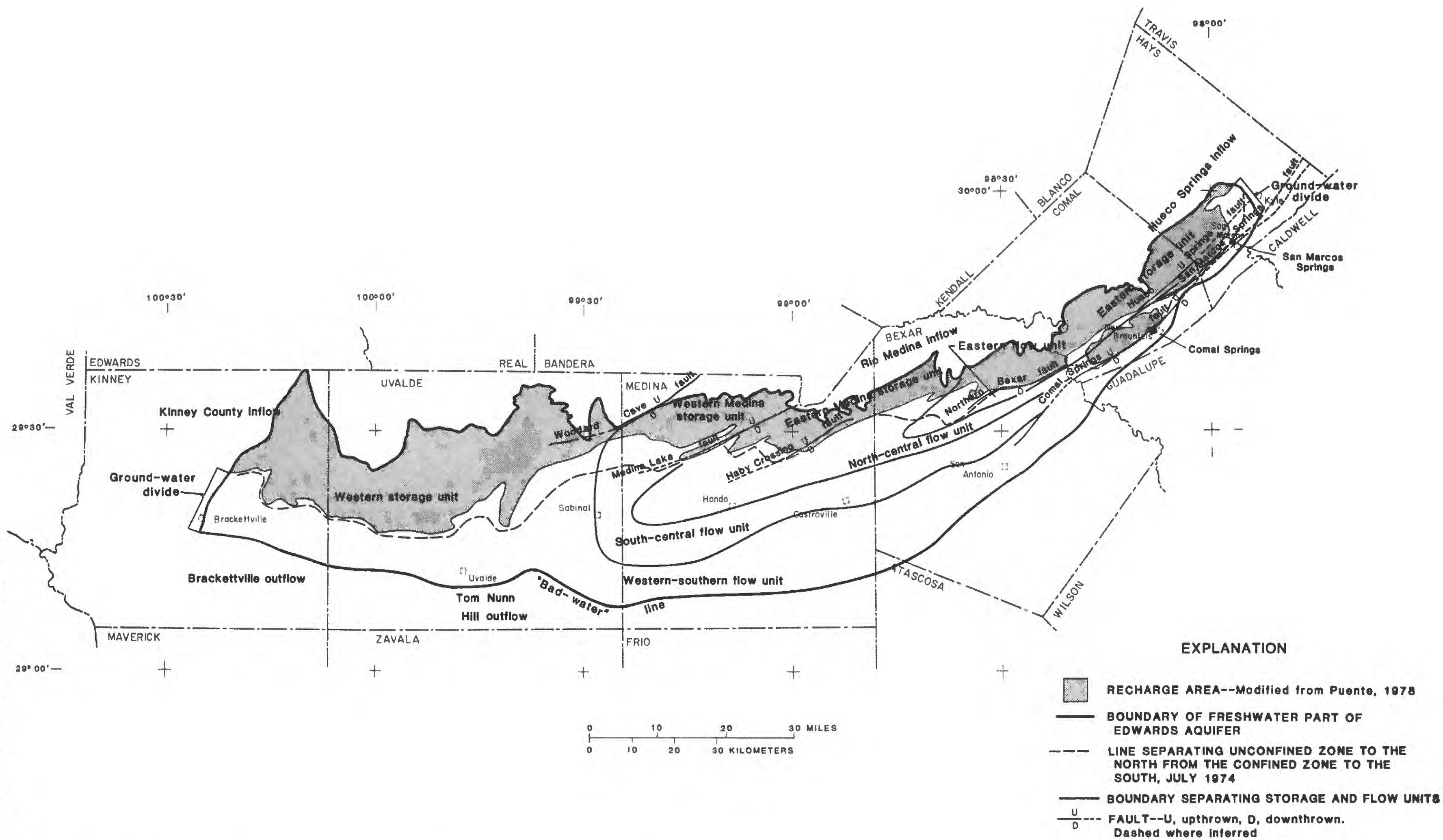


Figure 22. Storage and flow units and areas of flow across external boundaries.

Table 4. Major flow units

Name	Description
Western-southern	Source of water is the western storage unit. Geometry of the aquifer causes the water to take the southernmost route from the area of recharge to points of discharge that extend to Comal Springs. Large portion of water moves through the western part of an opening (Knippa gap) in the Medina Lake fault-Uvalde horst complex near Sabinal and a graben in the Uvalde area. Most or all of this flow is withdrawn by irrigation wells in Medina County and for the city of San Antonio water supply.
South-central	Source of water is the western Medina storage unit. The Medina Lake fault functions as a major barrier of ground-water flow and diverts the water to the southwest, where it moves through the eastern part of the Knippa gap near Sabinal that is described above. After the water moves past the opening, it turns sharply to the east. The major discharge points are irrigation wells in Medina County and municipal wells in San Antonio and Comal Springs.
North-central	Source of water is the eastern Medina storage unit. Much of the flow is diverted to the southwest by the Haby Crossing fault before it turns to the east. Major discharge points are municipal wells in San Antonio and Comal and San Marcos Springs. Flow merges with the two southern flow units at Comal Springs.
Eastern	Source of water is the eastern storage unit. Water in the western part of the unit is diverted to the southwest by barrier faults but in a short distance turns to the northeast. During normal water-level conditions, most of this flow discharges at San Marcos Springs.

between measured inflow and outflow and trends of water levels suggest that these fluxes are small or approximately balanced. Also, it is known that water levels in the salinewater part of the aquifer respond to water-level changes in the freshwater part. Thus, flow of unknown significance across the "bad-water" line is possible. The limited water levels in the salinewater part in Bexar and Uvalde Counties are lower than nearby water levels within the freshwater part, indicating a hydraulic gradient toward the salinewater part of the aquifer from the freshwater part. The modeled area extended about 5 mi into the salinewater part of the aquifer and allowed lateral flow in this zone. The magnitude of flux across the limits of the modeled area probably is very small and is not considered significant in this study. Thus, it was ignored.

Some inflow to the Edwards aquifer in the San Antonio region occurs from the Edwards-Trinity aquifer in the Edwards Plateau region, especially in Kinney County (Long, 1962; Walker, 1979).

Leakage from or to the Edwards Limestone from the Austin Group (fig. 3) occurs along faults at a few places in the San Antonio region. The leakage is indicated by water-level changes in wells of the Austin Group that appear to be in response to recharge or pumping in the Edwards aquifer. The quantity of water leaked is unknown, but it is probably insufficient to make a major difference in the interpreted regional ground-water-flow pattern.

The simulation study suggests at least three areas of possible ground-water inflow along the updip limit of the aquifer. One is at Rio Medina, another is along the Hueco Springs fault, and the third is in Kinney County. Two areas of possible outflow also were noted. One is into the salinewater part in the Brackettville area, and the other is into surficial gravels at Tom Nunn Hill. These sources of inflow and outflow are described in table 5, and their locations are shown in figure 22. Because of the lack of data to quantify the exchange of water across the external boundaries and of the reasonable hydrologic balance, fluxes of this nature were not coded into the model. However, comparisons of computed and measured water levels in several locations would support the possibilities of water movement across the external boundaries.

Description of Geologic Structures That Restrict and Convey Ground Water

The previous study by Maclay and Small (1984) identifies the importance of faults on ground-water flow in a qualitative sense. To provide a better understanding of the regional and local flow, Small (1986) prepared 26 hydrogeologic sections along the dip of the Edwards aquifer. These sections and regional maps of water levels, geologic structure, and surface geology indicate that many geologic features

Table 5. Ground-water flow across external boundaries

Name	Description
Kinney County inflow	The Edwards and associated limestones that compose the Edwards aquifer in the San Antonio region are continuous to the Edwards Plateau in Kinney County. The formations are exposed at the land surface in this area. Water levels are continuout and have gradients to the south and southwest. The division of this inflow between the Edwards aquifer in the San Antonio region and the region to the west is unknown.
Rio Medina inflow	In the vicinity of northeastern Medina County, the Edwards aquifer is downthrown by the Haby Crossing fault to a position where it is juxtaposed opposite the lower Glen Rose aquifer. Regional water-level maps of the lower Glen Rose aquifer and the Edwards aquifer indicate consistent water levels, suggesting that flow from the lower Glen Rose may occur across the fault.
Hueco Springs fault inflow	Updip from the Hueco Springs fault, the Glen Rose Formation locally contains thick beds of dolomite and limestone that are fully saturated and appear to be in hydraulic connection with the Edwards aquifer. Much of the inflow probably discharges at Hueco Springs.
Brackettville outflow	Outflow probably occurs near the regional ground-water divide near Brackettville. Ground water is believed to be diverted into the salinewater part of the aquifer by the presence of northeast-trending faults that function as partial barriers to ground-water flow.
Tom Nunn Hill outflow	Southwest of Uvalde, a complex network of normal faults trending in different directions appears to cause ground water to discharge into surficial gravel deposits during periods of excessive recharge. Some outflow in this area may go into the salinewater part of the aquifer.

control ground-water flow. The model was designed to incorporate many of the more important features. Only a few of them were directly tested by placing them in and taking them out of the model and noting the difference. However, many simulations were made that included changes in the transmissivity and anisotropy at these structures.

The structures influencing ground-water flow were divided into two groups—those that tend to restrict flow (barrier faults, horsts, and so forth) and those that tend to convey flow (gaps, grabens, and so forth). The locations of these structures are shown in figure 23. The structures restricting flow are described in table 6, and the structures conveying ground water are described in table 7. They are generally presented from west to east. Many of the effects are interpreted from a study of the pattern of computed flow vectors given in figure 21.

The model simulations are sensitive to variations of transmissivity and anisotropy. In the areas with large transmissivity (generally in the confined zone), modest changes in transmissivity and anisotropy cause only minor changes in heads and springflow (insensitive). The inverse is true in the small-transmissivity areas (generally in the unconfined zone). As a result, most of the testing of geologic structures restricting or conveying ground-water flow was done in Medina and Uvalde Counties, where the placement and effectiveness (degree of anisotropy) of barrier faults were most sensitive. The restricting structures that received the most attention in the simulation study and probably exert the most influence on the regional ground-water flow are the Uvalde horst, the Woodard Cave fault, the Medina Lake fault, the Haby Crossing fault, the Northern Bexar fault, and the Comal Springs fault. As expected, simulating these restrictions caused the water levels to rise upgradient, to fall downgradient, and to reduce or retard springflow. The conveying structures that received the most attention and probably exert the most influence on the regional ground-water flow are the Knippa gap, the Leona Springs gap, the Uvalde graben, the Dry Frio–Frio River gap, and the Hunter channel.

In the simulations, many of the restricting and conveying structures appear to function as a system instead of individually or as isolated structures in controlling ground-water movement. Further complexities occur because some structures conveying ground water are part of or parallel to restrictive structures. Some of the structures have pronounced regional influence, whereas others primarily affect local flow. Limited data and a rather coarse model grid prevented a quantitative analysis of many of these structures.

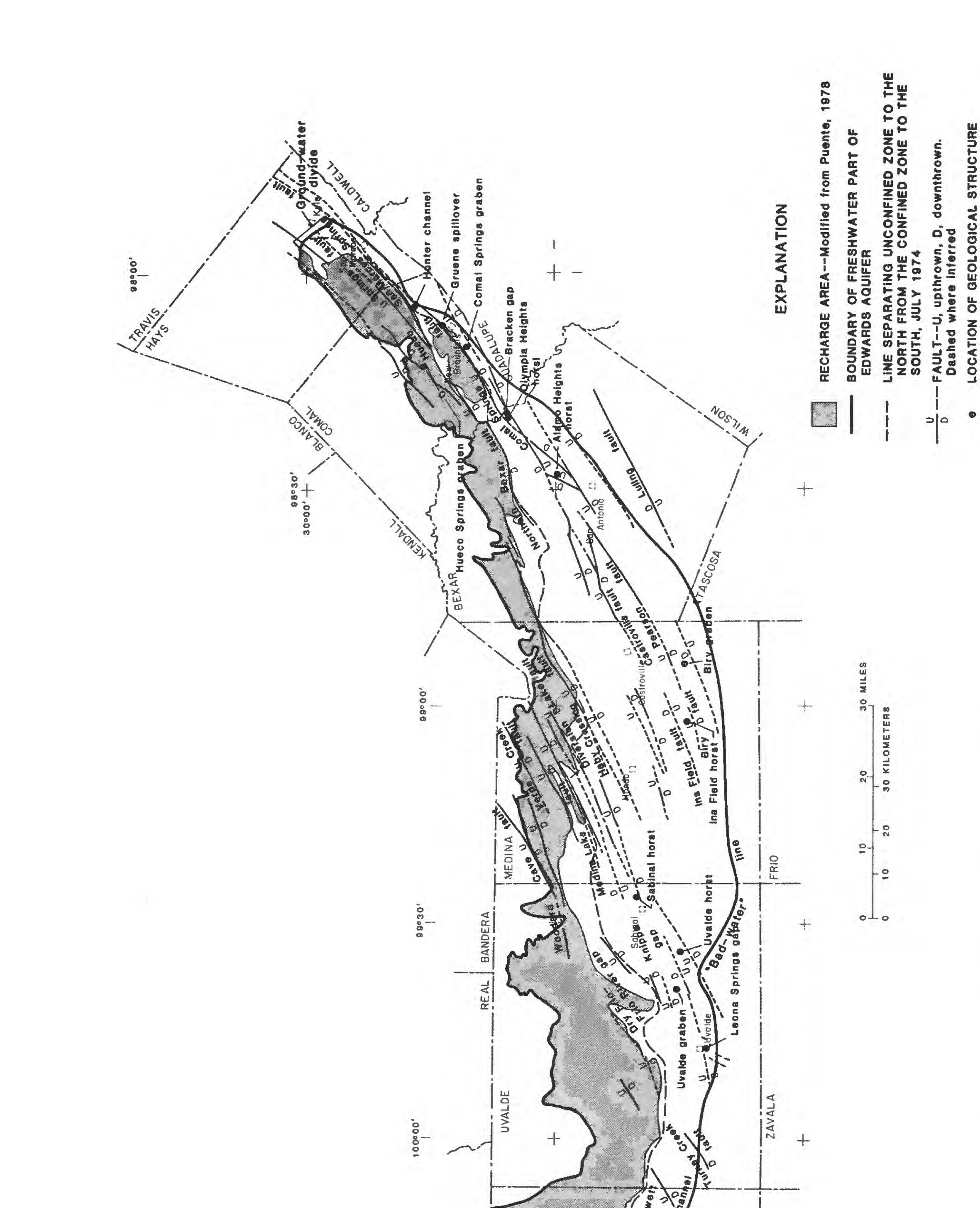


Figure 23. Locations of selected geologic structures restricting and conveying ground water.

Table 6. Major geologic barriers that restrict ground-water flow
[ft, foot]

Name	Description
Woodard Cave fault	Marks the southeastern boundary of a large, rotated fault block that is inclined toward the Llano uplift to the northeast and is associated with a complex system of local faults that intersect at oblique angles with this fault. Local grabens occur to the southeast. Erosion has removed most of the Edwards Limestone updip and in the eastern half. Prevents direct movement of ground water to the confined zone in northeastern Uvalde County. Also, functions to retain the amount of water held in temporary storage within the area to the northwest of the fault.
Turkey Creek fault	Vertical displacement along the fault is 200 to 300 ft, which is sufficient to separate permeable zones. It is an extension of Woodard Cave fault. Partially restricts and diverts ground-water flow from the Blewett channel into the Uvalde area.
Uvalde horst	Formed by a complex of local uplifted blocks of the Edwards Limestone and associated stratigraphic units. Leona Springs occurs within the horst. Prevents direct ground-water flow to the south and diverts ground water eastward through the Uvalde graben.
Sabinal horst	Formed by a wedge of rocks that dips toward the northwest. The southeastern boundary of the horst has vertical displacement of more than 400 ft and is immediately southeast of Sabinal. Marks the northeastern boundary of the Knippa gap.
Medina Lake fault	Marks the southeastern boundary of a major rotated block of the Edwards Limestone. Partly separates ground water from the western Medina storage unit from that of the eastern Medina storage unit. Diverts recharge from Hondo and Seco Creeks to the southwest. Controls the volume of water held in temporary storage northwest of the barrier.
Haby Crossing fault	Marks the southeastern boundary of a major rotated block of the Edwards Limestone. Vertical displacements are more than 500 ft. Displacement in the vicinity of Medina Lake is sufficient to juxtapose the Edwards aquifer and the lower Glen Rose aquifer, allowing cross-formational flow. Other northeasterly trending faults occur in the rotated block that hydraulically separates flow on opposite sides of the fault in local areas. Diverts recharge in the vicinity of Medina Lake southwestward. Hydraulically isolates the unconfined zone of the Edwards aquifer in northwestern Bexar County from the confined zone immediately to the southeast.
Castroville fault	The downthrown fault block lies on the gulfward side. Vertical displacement is several hundred feet.
Pearson fault	A vertical displacement of more than 500 ft partitions ground water in the western-southern flow unit.
Ina Field horst	A local horst adjacent to Biry graben that has a vertical displacement of several hundred feet. Directs ground water in western-southern flow unit to the northeast.
Northern Bexar fault	A northeasterly trending (previously unnamed) fault having a vertical displacement from 200 to 300 ft along much of its length. Diverts ground water from recharge area in northeastern Bexar County toward Comal County.

Table 6. Major geologic barriers that restrict ground-water flow—Continued

Name	Description
Luling fault	The upthrown fault block lies on the gulfward side. Vertical displacement is several hundred feet. Probably restricts flow in the freshwater part of the aquifer from moving directly into the downdip salinewater part. May be a partial barrier that could restrict salinewater from moving directly into the freshwater part under certain hydraulic conditions.
Alamo Heights horst	Local horst that is structurally uplifted by 300 to 500 ft. Diverts ground water to the northwest and southeast around the horst. Functions as a "bottleneck" in the regional flow pattern. San Antonio and San Pedro Springs occur along the southern boundary of this horst.
Olympia Heights horst	A northeast-trending block of rocks that extends into the northwest corner of Guadalupe County near Cibolo Creek. Restricts ground-water flow to the south and forms the gulfward boundary of the Comal Springs graben. Some flow move northeastward along the southeastern boundary of the horst toward the Comal Springs graben.
Comal Springs fault	Vertical displacement up to 500 ft occurs near New Braunfels. A transverse fault intersects this fault immediately northeast of New Braunfels. Restricts flow from the unconfined zone in Comal County into the confined aquifer.
San Marcos Springs fault	Southern boundary of the eastern flow unit in Hays County. Intersected at an oblique angle by a major fault northeast of San Marcos Springs. Combines and directs ground-water flow from the "spillover" across Comal Springs fault near New Braunfels and ground water from the recharge area in Bexar and Comal Counties toward San Marcos Springs.

TOPICS FOR FUTURE INVESTIGATION

Topics for future investigations on factors affecting the water movement in and storage capacity of the Edwards aquifer are based on several speculative concepts concerning the Edwards aquifer. These concepts and inferences are based on knowledge of the geology and hydrology of the aquifer, on geologic and hydrologic properties, and on intuition developed from field observations and studies of the aquifer. These topics are derived from the following speculative concepts.

1. Cross-formational flow probably exists where one aquifer is juxtaposed against another. The Edwards aquifer within the San Antonio region is the principal aquifer within a multi-layered aquifer system consisting of aquifers in three geologic groups—the lower Glen Rose Formation, the Edwards Group of Rose (1972) or its stratigraphic equivalent, and the Austin Group (fig. 3). Hydraulic connection between the aquifers is believed to be principally along fault planes.

To better understand and evaluate the possibility of crossformational flow, the following types of data are needed: potentiometric heads for each aquifer, the chemistry of the water within each aquifer, structure maps of each aquifer, the internal stratification and porosity development within each aquifer, mineralogic and textural characteristics of each aquifer and confining bed, and the location of regional recharge and discharge areas.

A significant amount of flow may move across the Haby Crossing fault from the lower Glen Rose Limestone to the Edwards aquifer. Recharge to the lower Glen Rose aquifer can occur in the valley of the Medina River near Bandera in Bandera County (fig. 1). Flow through the lower Glen Rose aquifer in Bandera County is southward toward Medina Lake. Hydraulic heads in the lower Glen Rose aquifer and the Edwards aquifer are regionally consistent with each other in the vicinity of Medina Lake (Ashworth, 1983). Elevated sulfate concentrations in the lower Glen Rose aquifer and large concentrations of sulfate in the Edwards aquifer near the Haby Crossing fault (Maclay, Rettman, and Small, 1980) suggest that water from the lower Glen Rose aquifer is entering the Edwards aquifer.

Flow from the lower Glen Rose aquifer to the Edwards aquifer also may occur in the vicinity of Cibolo Creek and

Table 7. Major geologic gaps and channels that convey ground water

Name	Description
Blewett channel	Many northeast-striking faults locally retard ground-water flow within the channel. The lesser transmissivity within the salinewater part of the aquifer limits ground-water flow into this part of the aquifer. Receives ground water from westernmost part of western storage unit. Conveys ground water toward the Uvalde graben.
Uvalde graben	Directs ground-water flow to the main confined zone of the aquifer in Medina County. Complicated by several transverse faults and volcanic plugs that retard outflow from the graben. Major barrier horst (Uvalde horst) prevents ground water in the Uvalde graben from moving directly downdip toward the salinewater. Transmits ground water from the Blewett channel and the Dry Frio-Frio River gap toward the Knippa gap.
Leona Springs gap	Small structural gap within the Uvalde horst. Permits water to readily move from the vicinity of Uvalde to Leona Springs. Springs may discharge into surficial gravel deposits along Leona Creek along fault planes. Local unnamed barrier faults and rocks of lower transmissivity within the salinewater part restrict movement of ground water from the freshwater part into the salinewater part of the aquifer.
Dry Frio-Frio River gap	Complex network of normal faults and local uplifted blocks of the Edwards Limestone that are exposed at the land surface. Some ground water from western storage unit moves across the Woodard Cave fault at this gap to join the ground water in the Uvalde graben.
Knippa gap	Narrow opening within an extensive, complex barrier system that includes the combination of the Uvalde and Sabinal horsts and the Medina Lake fault. Through this opening, ground water flows from the western and western Medina storage units southward and downdip toward the southernmost part of the aquifer in southeastern Uvalde and southwestern Medina Counties. The gap occurs in the Devils River Limestone and lies near the less-permeable rocks of the Maverick basin.
Biry graben	Occurs between the Pearson fault and an unnamed fault to the southeast.
Bracken gap	The Comal Springs fault does not fully offset the entire thickness of the aquifer at this location. At higher water levels, some ground water from the eastern flow unit enters the Comal Springs graben to combine with ground water from the north-central flow unit.
Comal Springs graben	Narrow graben containing extremely transmissive rocks. Occurs between the Comal Springs fault on the northwest and a complex system of upthrown fault blocks on the southeast. Northeastern end of graben is cut by a transverse fault that forms a partial barrier to ground-water flow. Transmits ground water to Comal Springs.
Hueco Springs graben	Narrow graben that contains the complete thickness of the Edwards aquifer, whereas area to the northwest and southeast of the graben are underlain by only a fraction of the stratigraphic thickness of the aquifer. Cut by many transverse faults that may retard ground-water flow. Hueco Springs occurs near one of these transverse faults and may be partially fed by ground water from the Glen Rose Formation that enters the Hueco Springs graben as cross-formational flow. Receives recharge from Cibolo Creek watershed northwest of Hueco Springs fault. Transmits this water toward Hunter channel.

Table 7. Major geologic gaps and channels that convey ground water—Continued

Name	Description
Gruene spillover	A transverse fault cuts across the Comal Springs graben immediately northeast of the Guadalupe River. Prevents flow from continuing northeastward in the Comal Springs graben and forces water to flow upward along the fault plane of the Comal Springs fault near Comal Springs. Flow from the Comal Springs graben that has bypassed Comal Springs joins flow in the northern part of the eastern flow region.
Hunter channel	Narrow channel between the Comal Springs and San Marcos Springs faults containing extremely transmissive rocks. Most of the ground water probably is transmitted through the stratigraphic units above the regional dense member. Transmits flow from Gruene spillover near Comal Springs and from the eastern flow unit toward San Marcos Springs.

along northeasterly trending faults in the outcrop area in Comal and Hays Counties.

2. The total availability of water from storage should also include parts of the lower Glen Rose and Austin Group aquifers in addition to the Edwards aquifer because of hydraulic connections among these three aquifers. The storage capacity of an integrated system that includes the Edwards aquifer and its hydraulic connection with the Austin and lower Glen Rose aquifer may be significantly larger than that formed solely within the Edwards aquifer. Most of the additional storage is believed to be in the lower Glen Rose aquifer that occurs in the Edwards Plateau, updip of the Edwards aquifer. The reasons are the extent of the unconfined conditions in this area and the better hydraulic flow connection. The availability of this potentially larger storage capacity to supply water to the Edwards aquifer is greatly dependent upon the hydraulic characteristics of the rocks in the vicinity of the hydraulic connection between the aquifers.

3. Flow within the Edwards aquifer from the freshwater to the salinewater part may occur locally where the geology is not complicated by barrier faults. Flow may move between and along the parallel faults that lead from the freshwater part to the salinewater part of the aquifer.

SUMMARY AND CONCLUSIONS

The flow of the Edwards aquifer in the San Antonio region was mathematically simulated to refine the ground-water storage and flow concepts. The analyses resulted in a better understanding of the significance of faults on ground-water storage and flows and of the magnitudes of aquifer hydraulic properties.

The Edwards aquifer lies in the Balcones fault zone and underlies an area of about 3,200 mi^2. It is recharged by streams draining the Edwards Plateau that lose streamflow by infiltration in the recharge area of the Edwards aquifer. The dominant regional pattern of ground-water flow in the Edwards aquifer is generally southward in the unconfined zone and then eastward toward major discharge areas.

The Edwards aquifer consists of variably stratified and faulted carbonate rocks that transmit water principally through selected zones that have well-developed secondary porosity and permeability. At places, the permeable strata are hydraulically interconnected by open, inclined fractures. The lateral continuity of the permeable strata is interrupted by normal, high-angle faults that, at places, displace the entire thickness of the Edwards aquifer. The Edwards aquifer is partly composed of the regionally extensive Edwards Limestone and stratigraphic equivalent rocks of Early Cretaceous age. These rocks are exposed throughout the Edwards Plateau and underlie, at depth, the Gulf Coastal Plain of Texas. The Edwards Limestone in the confined zone of the aquifer is 400 to 600 ft thick.

The structure of the Edwards aquifer has many disruptions caused by a complex system of differentially rotated fault blocks that rise toward the San Marcos platform. The faulting produces local barriers that have significant control on ground-water movement and serve as water impoundments.

The Edwards aquifer is very permeable. The transmissivity is estimated to be greater than 100 ft^2/s. The storage coefficient of the Edwards aquifer is estimated to range from 1×10^{-4} to 10^{-5} for the confined part and generally from less than 0.05 to about 0.20 for the unconfined part.

The approach for simulating and refining the storage and flow concepts of the aquifer was to use a two-dimensional, finite-difference ground-water-flow model to represent the system. The general approach in the development of the model was to start with a rather simple representation of the aquifer framework and to increase the complexity of the model in steps.

The ground-water-flow model was tested against hydrologic data for 1972–76. Discharge approximately equaled recharge in 1972. Recharge was unusually large in 1973 and more than the long-term average for 1974–76.

The boundary of the model was placed slightly outside of the natural boundaries of the flow system. External boundaries were defined as the updip limits of the recharge area to the north and northwest, the transition zone between the freshwater and salinewater parts of the aquifer to the south and southeast, and ground-water divides to the west and northeast. The orientation of the model grid, which was 40 rows and 72 columns, is about 65 degrees east of north in order to achieve the best alignment with the strike of the faults in the Balcones fault zone. Numerical values for the hydrogeologic parameters (transmissivity, anisotropy, and storage coefficient) originally were estimated on the basis of initial concepts of storage and flow within the aquifer and are based on available geologic, hydrochemical, and hydrologic information.

The model was considered an acceptable representation of the aquifer when simulations produced the best match between measured and simulated head and springflows and produced a reasonable representation of the regional potentiometric surface. The largest values of transmissivities were 112 ft^2/s along flow lines that lead to Comal Springs; the smallest values were 0.0015 ft^2/s in the slightly saline zone. The storage coefficient was estimated to be 0.05 in the unconfined zone and 0.0001 in the confined zone of the aquifer. The direction of ground-water flow vectors for February 1973 demonstrates the effect of major barrier faults on the regional potentiometric surface. The most noticeable pattern of flow vectors is the concentration of flow vectors that represent the southward flow through the Knippa gap, a few miles west of Sabinal.

The major interpretations that resulted from simulation studies are the following:

1. Four major storage units were defined. Most of the storage that affects ground-water flow to the San Antonio area is contained within the unconfined zone of the aquifer (western and western Medina storage units), which is northwest of the Haby Crossing barrier fault complex that extends to the southwest.

2. Four flow units were defined. Two flow units occur in the western and central part of the region and converge at Comal Springs. The two other units converge toward Comal Springs or San Marcos Springs.

3. Subsurface springs discharge along faults and to gravel deposits along Leona Creek in Uvalde County. They occur in the vicinity of, and are controlled by, a horst located south of Uvalde.

4. The Uvalde graben, which lies between the Woodard Cave barrier fault and the Uvalde horst, transmits ground water from the west to the extensive confined zone of the aquifer in the central and southern part of the San Antonio region.

5. The area of largest transmissivity in the Edwards aquifer occurs within a narrow graben (Comal Springs graben), which extends along the downthrown side of the Comal Springs fault in Comal County.

6. Significant quantities of ground water probably cross the Comal Springs fault in Comal County near the Bexar County line. Depending on the water levels of the aquifer, pumpage in San Antonio, and recharge conditions in Bexar and Comal Counties, the direction of flow across this fault may reverse.

7. Ground water in the unconfined zone of the aquifer in northeastern Bexar, Comal, and Hays Counties is diverted by barrier faults toward San Marcos Springs.

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GLOSSARY

Anistropic aquifer. An aquifer is anistotropic if the hydraulic conductivity varies with the direction of measurement at a point within the aquifer.

Cell. A rectangular subarea that results from segmenting the aquifer system by a ground-water-flow model.

Collapse breccia. Formed where soluble material has been partly or wholly removed by solution, thereby allowing the overlying rock to settle and become fragmented.

Cone of depression. A depression in the potentiometric surface of a body of ground wtaer that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of effect of a well.

Confined aquifer. An aquifer contained between two rock units that retard but do not prevent the flow of water to or from an adjacent aquifer.

Conformable. An unbroken stratigraphic sequence is conformable if the layers are formed one above the other in parallel order by regular, uninterrupted deposition under the same general conditions.

Dedolomitization. The replacement of dolomite by calcite in water with a very small magnesium to calcium ratio, which removes magnesium ions from the dolomite.

Diagenesis. All the chemical, physical, and biological changes, modifications, or transformations undergone by a sediment after its initial deposition and during and after lithification, exclusive of surficial weathering and metamorphism.

Dolomitization. The process by which limestone is wholly or partly converted to dolomite or dolomitic limestone. The replacement of the original calcium carbonate (calcite) by magnesium carbonate, usually through the action of magnesium-bearing water.

En echelon faults. Faults that are in an overlapping or staggered arrangement.

Evaporite. A nonclastic sedimentary rock composed primarily of minerals chemically precipitated from a saline solution that became concentrated by evaporation.

Fault scarp. A steep slope or cliff formed directly by movement along one side of a fault and representing the exposed surface of the fault before modification by erosion and weathering.

Fissile. Capable of being easily split along closely spaced planes.

Graben. An elongate, relatively depressed crustal unit or block that is bounded by faults on its long sides.

Horst. An elongate, relatively raised crustal unit or block that is bounded by faults on its long sides.

Hydraulic conductivity. The volume of water at the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Karstification. Action by water (mainly chemical but also mechanical) that produces features of a karst topography, including caves, sinkholes, and solution channels.

Lithofacies. The general aspect or appearance of the lithology of a sedimentary bed or formation considered as the expression of the local depositional environment.

Marl. Earthy and semifriable or crumbling unconsolidated deposits consisting chiefly of a mixture of clay and calcium carbonate in varying proportions formed under either marine or especially freshwater conditions.

Porosity. The ratio of the aggregate volume of interstices (openings) in a rock or soil to its total volume, usually states as a percentage.

Potentiometric surface. A surface that represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Rudist. A bivalve mollusk, characterized by an inequivale shell, that lived attached to the substrate and formed mounds or reefs during Cretaceous age.

Specific capacity. The rate of yield of a well per unit of drawdown, usually expressed as gallons per minute per foot (gal/min/ft) of drawdown. If the yield is 250 gal/min and the drawdown is 10 ft, the specific capacity is 25 gal/min/ft. It varies with duration of discharge.

Specific yield. The quantity of water that an aquifer will yield by gravity if it is first saturated and then allowed to drain; the ratio expressed in percentage of the volume of water drained to the volume of the aquifer that is drained.

Supratidal. Describes the region of the ocean shore found just above the high-tide level.

Transmissivity. The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined aquifer. An aquifer in which the water table forms the upper boundary.