EDWARDS AQUIFER—NORTHERN SEGMENT,

TRAVIS, WILLIAMSON, AND BELL COUNTIES, TEXAS

C. M. Woodruff, Jr., Fred Snyder, Laura De La Garza, and Raymond M. Slade, Jr.,
Coordinators

GUIDEBOOK 8

AUSTIN GEOLOGICAL SOCIETY
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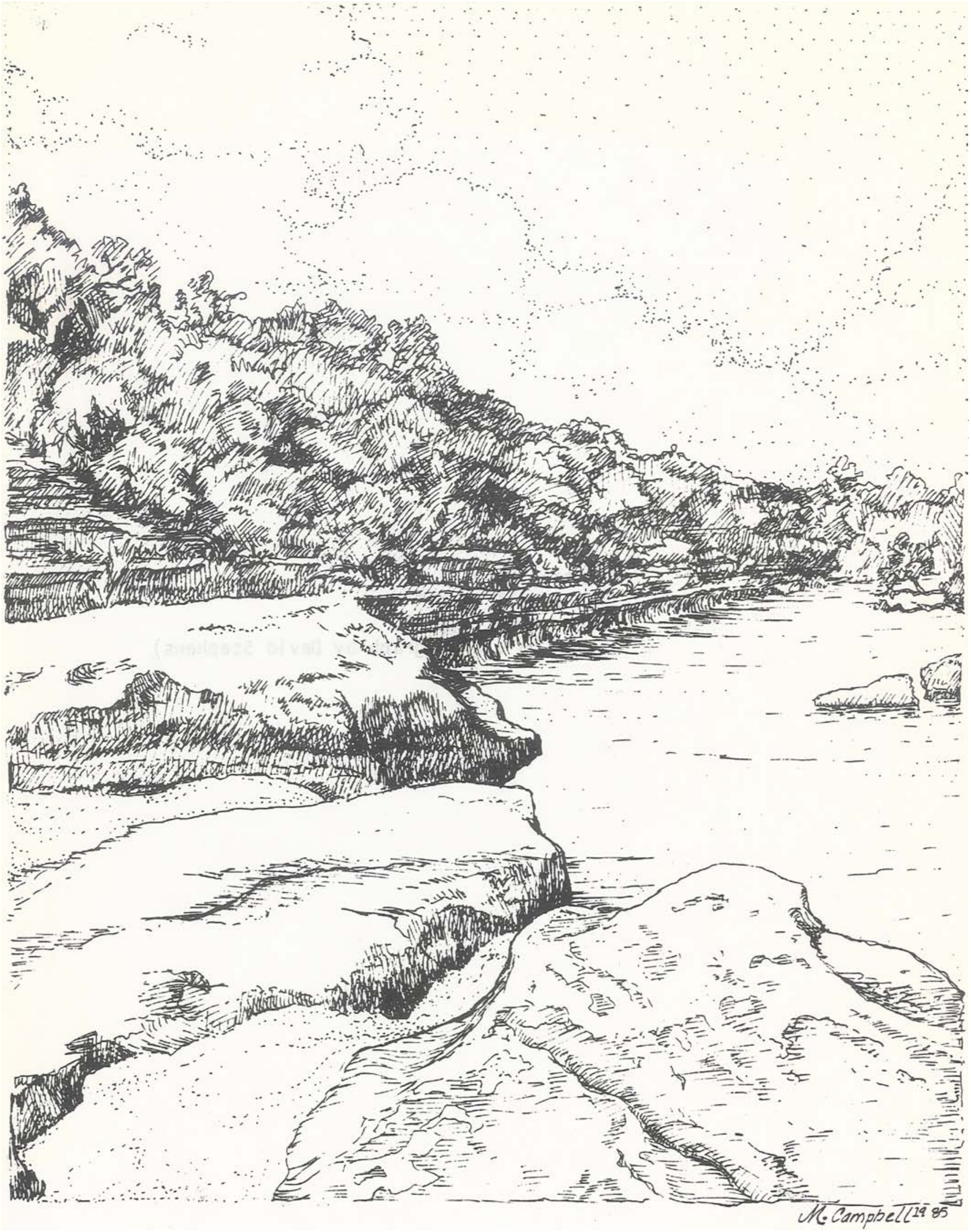
Austin, Texas 78767

1985


M. Campbell 1985

Frontispiece:
"Along Bull Creek"
By Margaret Campbell
(based on a photograph by David Stephens)

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EDWARDS AQUIFER, NORTHERN SEGMENT--

Introduction to Field Trip

The Edwards aquifer is a vast underground water reservoir. It is mainly contained within the Edwards Limestone, a Lower Cretaceous rock unit that once extended unbroken from the inner Gulf Coastal Plain into the Panhandle and Trans-Pecos regions of West Texas. Today, this once-continuous limestone unit has been flexed and broken by tectonic events, dissected by surface erosion, and dissolved by the actions of percolating water. The chemical interactions between rock and the water contained within its pore spaces have largely dictated porosity and permeability development, and hence, local hydrodynamic evolution. The vagaries of erosion and of structural deformation have resulted in different hydrodynamic regimes within the various geologic/ geographic provinces of the state.

The Edwards Plateau comprises a water-table aquifer that extends beneath much of the southwestern and west-central parts of Texas. This Plateau aquifer is largely distinct from the part of the Edwards aquifer that lies along the Balcones Fault Zone, although along the western part of the Nueces watershed and adjacent parts of the Rio Grande basin, the outcropping Edwards Limestone continues unbroken between the Plateau terrain and the Fault Zone. In that area, hydrologic communication may exist between the Plateau aquifer and the Fault Zone aquifer. In most areas, however, water discharges from the edge of the Edwards Plateau and flows across the Glen Rose Limestone terrain of the dissected Central Texas Hill Country, only to feed the Fault Zone aquifer where the limestone is downfaulted to stream level.

The Balcones Fault Zone is where the Edwards aquifer yields water most abundantly. There, it is a major water table/ artesian system supplying potable water for more than one million people. Recharge occurs mainly along major stream courses that flow roughly perpendicular to the Edwards outcrop. Once under- ground, the dominant direction of water flow is along strike of major faults. Most recharge occurs along the topographically high areas in the western parts of the various surface watersheds. Natural discharge occurs via springs where downcutting surface streams have intersected the aquifer at low topographic levels, forming drains for the aquifer.

East of the Balcones fault system, the Edwards Limestone is displaced abruptly downward into the Gulf Coast Basin. There, it is no longer a fresh-water aquifer. Instead, it is a zone of upwelling, deep basin brines (with local accumulations of hydrocarbons); the "bad-water line" is a major discontinuity between two distinct hydrologic regimes: the fresh-water, artesian system that continually renews itself by the processes of recharge and discharge; and a stagnant, saline-water system that results from the slow upward percolation of formation fluids derived from deep in the Gulf Coast Basin.

Within the Balcones Fault Zone, there are several distinct segments of the Edwards aquifer. The main (central) segment is defined by researchers of the Texas Department of Water Resources (Klemt and others, 1979) as extending from the Nueces/Rio Grande divide in Kinney County to the Guadalupe/ Colorado divide in Hays County. This central segment supplies the water for the City of San Antonio, the largest city in the United States dependent entirely on groundwater for its municipal water needs. It also supplies water for some of the largest springs in the state: Comal Springs, San Marcos Springs, San Antonio Springs, San Pedro Springs, Leona Springs, Los Moras Springs, and others. Because of its extent and importance to a large population that depends on it as a source of drinking water, this segment of the aquifer has been accorded the most scrutiny. Recently, however, with the rapid growth in the Austin area, considerable attention has been focused on the Barton Springs segment of the aquifer (see Woodruff and Slade, 1984). Studies by several government bodies have focused on this area (for example, Andrews and others, 1984; Baker and others, 1985; City of Austin, 1983, and City of Austin, 1985). Also, moves are afoot to establish an underground water district aimed at protecting this segment of the aquifer. Heretofore, little attention has been accorded to the northernmost segment of the aquifer, the part extending north of the Colorado River into northern Travis, Williamson, and Bell Counties. But rapid growth is also occurring there, just as in southwestern Travis County, and thus there is a need for critical evaluations of the land and water in that area to ascertain the exact limits of the aquifer and to understand the specific processes active there.

This guidebook is viewed as a beginning step in filling this need for information on the northern segment of the Edwards aquifer. The field trip will consist of 5 stops (see back cover of guidebook for map showing stop locations). Highlights of the day include a visit to Inner Space Caverns and to the Texas Crushed Stone quarry. In Inner Space Caverns we are able to walk around in part of the localized mega-porosity system of the aquifer. Moreover, the discussion (by Ernie Lundelius) on the vertebrate fossils found in the cave provide clues as to the general time frame when the cavern first became air-filled and accessible to fauna then existing in Central Texas. The Texas Crushed Stone quarry affords a remarkable view of the three-dimensional geometry of lithic variations within the Edwards Limestone and of the localized porosity within this limestone. This view is especially valuable to emphasize the distribution of solution porosity that occurs at a smaller scale than that seen in the Inner Space Caverns. Besides these two major stops, we will also view a sinkhole in the bed of Brushy Creek; a spring and municipal water well in Georgetown; we will cross the recharge zone across the Jollyville Plateau and note the lack of drainage development there as contrasted to the deep dissection by surface streams in the Lake Austin watershed; and finally we will view strata-bound porosity development (and interesting multiple land use) in an abandoned quarry near Murchison Junior High School in northwest Austin.

The guidebook presents a road log for these stops. But more than that, it contains several original papers on the geology and hydrology of the northern segment of the aquifer. Articles include a geomorphic overview of the Jollyville Plateau in terms of its hydrologic evolution; a hydrogeologic overview of this part of the aquifer; a discussion of the geologic history of the Edwards Limestone; a presentation on the springs issuing from these terrains; the Quaternary history of the caves as indicated by their vertebrate fauna; two papers presenting case studies of well completion and testing for the development of water supplies; and papers on the current attempts to manage the recharge zone of the aquifer.

ACKNOWLEDGMENTS

Besides the contributors of articles that appear separately in this guidebook, several authors--besides the trip coordinators--provided descriptions for individual stops. These include Sam Pole and Ernie Lundelius for Inner Space Caverns; and Tom Patty for the Texas Crushed Stone quarry. We are especially indebted to William B. Sneed, Jr., for allowing us access to the Texas Crushed Stone Company's quarry. This allows a perspective not gained in any other way.

We are grateful to Chet Garrett and his co-workers at the Bureau of Economic Geology, The University of Texas at Austin, for employing their talents in the layout and design of this guidebook.

This guidebook has been enhanced by Margaret Campbell's drawings of native flora and her fine rendering of a landscape scene along Bull Creek (see frontispiece). We also thank David Stephens for furnishing the photograph on which that drawing was based. Finally, we are grateful to Harold Billman for contributing to the "liquid assets" of this field trip.

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Austin, Texas
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JOLLYVILLE PLATEAU--GEOMORPHIC CONTROLS ON AQUIFER DEVELOPMENT

C. M. Woodruff, Jr.

INTRODUCTION

A geologic map of the Austin area (Garner and Young, 1976) discloses a peculiar outcrop geometry for the Edwards Limestone. South of the Colorado River, the Edwards crops out as a continuous belt east of the Mount Bonnell Fault. North of the river, the Edwards occurs at the surface west of that fault. This geometry in map view creates the appearance of a major dislocation of the Edwards. But this apparent dislocation is not structural; it is merely an accident of erosion--a local expression of topography. In brief, the land south and west of the Colorado River is much more highly eroded than that to the north and east.

Irrespective of cause, the Colorado River separates the Edwards aquifer into two discrete segments. South of the river is the Barton Springs segment, a roughly triangular "watershed" of sorts, with Barton Springs as its mouth (Woodruff and Slade, 1984). North of the river, the outcroping Edwards is the catchment area (the recharge zone) for the Jollyville Plateau segment of the aquifer, where groundwater flows to the northeast. Most of this groundwater discharges from wells and springs near Round Rock, Georgetown, and Salado.

The Jollyville Plateau stands out as a nearly flat upland north of the river. It occurs precisely because the Edwards Limestone remains there in an unbroken belt. The Edwards is a rock unit that resists mechanical erosion even while it is being sapped from within owing to dissolution by groundwater. The Jollyville Plateau is a remnant of the Edwards Plateau that once extended unbroken all the way from the Balcones Escarpment to at least as far as the High Plains and the Stockton Plateau in West Texas. Today, however, much of the Plateau country has been breached by surface streams forming the classic Central Texas Hill Country, with the typical stairstep hills formed on the Glen Rose and Walnut Formations (rock units that lie beneath the Edwards). Across the Hill Country terrain east of the contiguous Edwards Plateau, there are only occasional outliers of Edwards Limestone capping the tops of hills and forming narrow ridgelines along drainage divides. South of the Colorado River in the Austin area, a few remnants of Edwards Limestone may be seen west of the Mount Bonnell Fault in the vicinity of Westlake Hills and near Barton Creek along State Highway 71 (Dittmar Hill, for example). These outliers represent remnants of what was once the contiguous Edwards Plateau before it was breached by the aggressively eroding drainage courses.

GEOMORPHIC EVOLUTION OF THE JOLLYVILLE PLATEAU

The Jollyville Plateau constitutes an outlier of the Edwards Plateau, although compared to other remnants of isolated Plateau terrain its areal extent is anomalously large. The extent of this outlier is due to its straddling the Brazos/Colorado drainage divide. It remains as a relict upland because of the geometry of the major drainage systems and the differences in long-term downcutting and erosion by streams in the two watersheds.

Abrupt slope breaks occur along the southern margin of the Jollyville Plateau. There, tributaries of the Colorado River have incised deeply into the Plateau, giving rise to remarkable scenic vistas. On the northern side of the Colorado/Brazos drainage divide (which coincides with the Travis/Williamson County Line) this deep dissection does not occur. Instead, tributaries of Brushy Creek (the southernmost tributary of the San Gabriel River within the Brazos drainage basin) form low-gradient drainageways that cross the gentle slopes of the Plateau. Differences in drainage densities illustrate the varying rates of downcutting across this drainage divide: Within the Brazos watershed (that is, within Williamson County) drainage density is low, as are stream gradients and overall ground slope values; on the Colorado River side of the divide, drainage densities and stream gradients are high, as are typical slope values.

Hypsometric data further illustrates the differences in drainage development across the Brazos/Colorado divide. The Colorado River crosses the Balcones Escarpment at an elevation of about 450 ft above mean sea level (msl), at a distance of about 11 miles from the nearest 900-ft contour on the Brazos/Colorado divide. The North and South Forks of the San Gabriel River flow together where they cross the Escarpment at an elevation of 750 ft above msl, which is about 16 miles from the same 900-ft datum on the divide. The overall topographic gradient for these Colorado River tributaries in the vicinity of the Balcones Escarpment is approximately 0.78 percent, whereas for the San Gabriel river system the value is 0.17 percent. It is apparent that the abrupt landscape changes across the Brazos/Colorado divide are due mainly to the proximity of the Colorado River, which forms a low-lying base level that controls the degree of landscape dissection by its tributary streams. The Brazos River, on the other hand, is almost 100 miles away.

Throughout Central Texas, the Colorado River basin is markedly asymmetrical. Most major tributaries (the Concho, San Saba, Llano, and Pedernales Rivers) flow into the main stream from the west. As the hypsometric data show, the Colorado River, where it traverses the Hill Country, lies only a few miles from the Brazos/Colorado divide. This overall geometry of watersheds within the Colorado basin suggests long-term structural control on drainage. The Colorado River appears to have been gradually moving east off the Llano granitic massif into the Strawn Basin to the north. Such gradual movement could account for the elongated tributary watersheds that originate from the west, while to the east the headwaters of the Brazos basin have been systematically diverted by stream piracy into the Colorado watershed.

Geometry of drainage nets is the main evidence for this ongoing stream capture by tributaries of the Colorado River. Bull Creek provides an excellent example of a stream whose headwaters were probably once a part of the Brazos drainage system. But these headwaters have been diverted by piracy, and a sharp deflection in direction of flow marks the probable location of capture. Accompanying the capture, rapid incision occurred, and this contributed to the abrupt topographic breaks that developed along the southern edge of the Jollyville Plateau.

JOLLYVILLE PLATEAU AS AQUIFER REGION

The Edwards Limestone--where it holds up the rim of the Jollyville Plateau--is riven by solution; prevalent sinkholes and caves provide the porosity for a shallow water-table aquifer. A water budget has not been computed for the Jollyville Plateau, but it is likely that--as with the watersheds supplying Barton Springs--most rainfall occurring on the Plateau is cycled through the biophysical processes of evapotranspiration. A relatively minor fraction of incident rainfall probably contributes to runoff and to recharge into the water-table aquifer. But, along the Plateau edge, where drainageways have breached the resistant limestone caprock, runoff is probably a much more important process. These slope breaks are also loci of discharge from the water-table aquifer; numerous seeps and springs issue forth from the base of the Edwards Limestone where it is exposed in bluffs. The underlying, less permeable Walnut Formation forms a seal preventing further downward percolation of this groundwater.

As already mentioned, the Jollyville Plateau comprises a disjunct segment of the aquifer; it is physically disconnected from the area providing recharge to Barton Springs. In addition to geographic separation, there are other differences between this northern part of the aquifer and the Barton Springs segment:

1. Much of the Jollyville Plateau terrain is underlain by the bottom few tens of feet of the Edwards Limestone. In places, streams have eroded away all this basal part of the Edwards, exposing the underlying rock units. In such areas, little or no recharge is occurring in the stream bottoms--unlike in other parts of the aquifer, where most recharge occurs via water loss into streams.

2. As mentioned at the outset, the Jollyville Plateau aquifer segment lies west of the main fault line, whereas the Barton Springs segment lies east of the Mount Bonnell Fault. Some faults occur across the Jollyville Plateau, but their displacement is relatively minor. This lack of faulting maintains the relatively thin section of Edwards beneath most of the Plateau; only near the main fault line is there abrupt thickening of the Edwards owing to the downfaulting of the several-hundred-foot section that makes up the total limestone package. Minor faults that do occur farther west probably provide some controls on cavern development beneath the Jollyville Plateau. But only where the main fault line is crossed are the same effects seen as those occurring farther south. There, the aquifer is compartmentalized into discrete segments owing to selective dissolution along major faults. Groundwater is thus channelled along faults bounding the eastern edge of the Jollyville Plateau toward discharge points to the northeast: Georgetown Springs, Berry Springs, and Salado Springs.

3. The Jollyville Plateau owes its presence, its persistence despite erosion, to the resistant stratum of Edwards Limestone. In other words, the southern part of the Jollyville Plateau (that is, the part of the Plateau draining into the Brushy Creek watershed, or into the Colorado River basin) and the water-table aquifer are one and the same, except for the above-mentioned situation where streams have cut entirely through the Edwards. In this southern part of the plateau, there is no distinct "contributing zone," no watershed areas where collection of surface waters occurs upstream from the recharge zone. Thus, the water budget operates differently in the southern part of the Jollyville Plateau, in contrast to the Barton Springs segment of the aquifer. Recharge on the Jollyville Plateau is probably distributed more diffusely because potential recharging waters are not presented to the aquifer in bulk via a series of well-developed surface streams. Some inflitration may occur where sinkholes dot the uplands. Other seepage into the Plateau aquifer probably occurs within the smallest subdivisions of the drainage network as soon as surface water begins to be collected into discrete channels. This diffusion of recharge within the headwaters of the drainage systems adds negative feedback for erosion by the Plateau streams: The immediate water loss into the Edwards prevents much sustained flow across this terrain; such flow loss has precluded the development of an effective system of surface streams, hence surface erosion is lessened.

4. Few data exist on the hydrology or geology of the Jollyville Plateau terrain. Unlike in the part of the Edwards aquifer that drains to Barton Springs, there have been few systematic programs of monitoring rainfall, or of gaging streams crossing the recharge area. Nor have there been major efforts at charting and analyzing geologic and topographic features. In order to recognize areas having differing sensitivities to human uses of the land, however, inventories of the water and land resources of the Jollyville Plateau are needed.

5. Finally, the area of most rapid erosion is along the southern margin of the Plateau, within the Colorado River watershed. Rapid erosion there has dissected this terrain into small, isolated water-table aquifer segments, each filling and draining independently of one another and independent of the contiguous part of the Plateau aquifer.

CONCLUSIONS

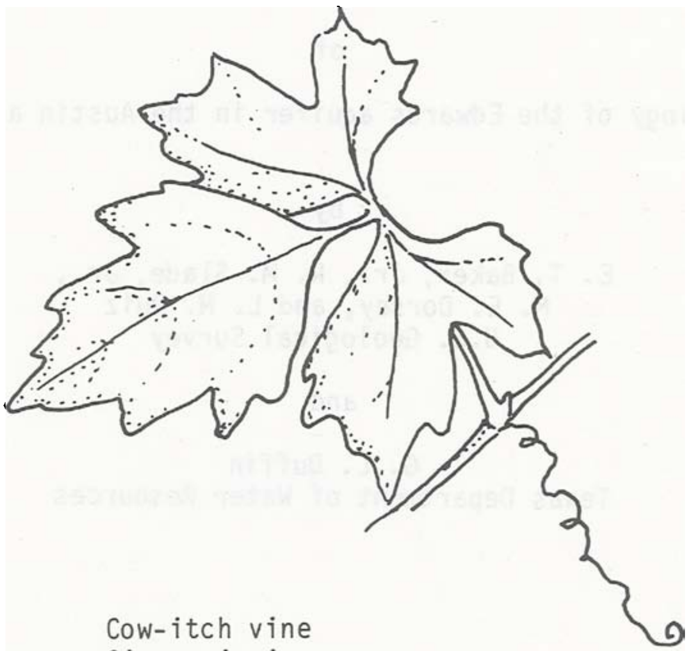
The Jollyville Plateau is an anomalous landscape. It is part of a relict terrain, underlain by a few tens of feet of the bottommost part of the Edwards Limestone. Abrupt slope breaks occur along the southern margin of the Jollyville Plateau. There, ongoing stream piracy has resulted in tributaries of the Colorado River having incised deeply into the Plateau. On the northern side of the Colorado/Brazos drainage divide (in Williamson County) this deep dissection does not occur. Instead, tributaries of Brushy Creek form low-gradient drainageays that cross the gentle slopes of the Plateau. The Jollyville Plateau is a karst upland; that is, it is pitted by sinkholes that indicate the presence of collapsed caverns beneath this area. These sinks--along with stream channels--act as loci of recharge into this northern segment of the Edwards aquifer.

The main difference between the Barton Springs segment and the Jollyville segment of the Edwards aquifer is the terrain. The Barton Springs segment owes its geometry to the bounding faults, whereas to the north, the recharge zone owes its geometry to the less aggressive erosion of the streams composing the Brushy Creek/San Gabriel/Brazos River system in contrast to most tributaries flowing into the Colorado River. Owing to the vagaries of erosion, there is no significant "contributing zone" to the southern reaches of the Jollyville Plateau segment of the aquifer (the area within the Brushy Creek watershed). For this reason, almost the entire Plateau terrain constitutes part of the recharge zone. Thus, almost all the southernmost Plateau area is likely to collect recharging waters, which are channelled underground toward the discharge areas to the northeast. In this way, drainage evolution is a control on aquifer development on the Jollyville Plateau just as it is in the central part of the Edwards aquifer (Woodruff and Abbott, 1979), and in the Barton Springs segment (Woodruff, 1984).

The main environmental issues for the Jollyville Plateau segment of the Edwards aquifer involve hydrologic processes--both surface and subsurface--that affect both quality and quantity of waters within the local hydrologic system. Protection of the quality of waters recharging the northern segment of the Edwards aquifer entails many of the same measures that are being employed in the southwest (Barton Springs) part of the aquifer. The key to aquifer protection is twofold: (1) maintenance of the integrity of the drainageways (i.e., prevent pollutants from entering the watercourses); and (2) delineation of the localized high-porosity zones on the uplands that might be amenable to recharge--specifically sinkholes, caverns, and loci of abnormal fracture density. Although insufficient data exist to construct a detailed water budget for the rainfall/runoff/recharge "account" on the Jollyville Plateau, the overall allocation of incident rainwater is probably similar for both recharge areas. The predominant amount of incident water will be cycled through the biophysical processes of evapotranspiration. Only a small fraction (about 15 percent) is likely to contribute to streamflow and recharge. Thus, natural water-cycling through soils and vegetation should be used to mediate adverse effects on water quality and stream runoff.

Methods of employing natural cycling of water entails innovative design to minimize impervious cover. And rather than channelizing the headwaters of the drainage system to promote immediate downstream conveyance of surface flow, incident rainfall on any given site should be retained on vegetated areas as much as possible. Even having an overstory of vegetation above impervious cover will help, as some of the rainfall will thus be intercepted by the leaves and branches and may evaporate directly from those surfaces. Every drop of water that is cycled through this evapotranspiration loop is water that need not be subjected to the various structural (or other) measures aimed at upgrading the quality of urban runoff. Note, however, that the prescription for retention of incident rainfall on a given tract operates counter to another natural phenomenon that is all too active in this area:

extraordinary rainfall events. The Balcones Escarpment is the locus of the largest flood-producing storms in the conterminous United States. In designing for spreading incident rainfall for use by plants (very effective for small to moderate rainfall events), there sould be some sort of threshold device for routing the occasional runoff from these expected, infrequent high-magnitude rains.



Cow-itch vine
Cissus incisa

Hydrogeology of the Edwards aquifer in Bell,
Williamson, and northern Travis Counties, Texas

Edited by

R. M. Slade, Jr.

Abridged version

of

Geohydrology of the Edwards aquifer in the Austin area, Texas

by

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The information contained in this report is primarily from the above-referenced report which concerns the Edwards aquifer in northern Hays, Travis, Williamson, and Bell Counties. Information from that original report is abridged to present information for the Edwards aquifer only in Bell, Williamson, and northern Travis Counties. The only information in this report not from the original report concerns the following subjects: Population projections, characteristics of the geologic units (table 1), the divide between the confined and unconfined areas of the aquifer, the maximum measured water-level fluctuations (fig. 6), and the water levels for wells developed in the Trinity aquifers (fig. 7).

BACKGROUND

The Edwards aquifer supplies at least 10 counties in central and southern Texas with water. However, there are many hydrologic divides that separate the aquifer into independent or relatively independent systems. The Edwards aquifer south of the city of Kyle is referred to as the San Antonio part; the aquifer from Kyle to the Colorado River discharges to Barton Springs and thus is referred to as the Barton Springs part (Andrews and others, 1984); and north of the Colorado River, in Bell, Williamson, and northern Travis Counties, the aquifer is referred to as the "northern" Edwards aquifer, and is the subject of this field trip (fig. 1). The northern Edwards aquifer contains water having less than 3,000 milligrams per liter dissolved solids.

The northern Edwards aquifer underlies about 1,000 square miles and, as of 1980, provided about 35,000 people with municipal, industrial, agricultural, and domestic supplies. Recent population projections by the city of Austin indicate that about 250,000 more people will live in the area underlain by the aquifer by 2000, many of who may depend on the aquifer for water (Planning and Growth Management Department, City of Austin, written commun., 1984). Hydrogeologic and water-quality data and information are needed to aid managers in making decisions regarding present and long-range planning of water use and management.

In 1978, the U.S. Geological Survey (USGS) and Texas Department of Water Resources (TDWR) began a hydrologic-investigations project of the Barton Springs part and the northern part of the Edwards aquifer. Baker and others (1985) presented the hydrogeologic framework of both Edwards aquifer areas, based on hydrogeologic sections that are supplemented by structure and thickness maps of the aquifer. Also presented in that report are hydrologic findings such as the extent of water use, position of water levels in the subsurface and changes in those level, the quality of Edwards water throughout the aquifer, and important interrelationships of streamflow with the aquifer. As part of the study, a steady-state model of the two-dimensional ground-water flow is being developed to determine the transmissivity of the northern Edwards aquifer (R. M. Slade, Jr., W. L. Boettner, and D. L. Slagle, USGS, written commun., 1985). Measured water levels, recharge, pumpage, springflow, and subsurface discharge were used to develop the model.

Water-resources data have been gathered in the northern Edwards aquifer area by the USGS and TDWR as well as other governmental and private entities during the course of regional, county-wide, or local investigations in the past several decades. A statewide inventory of springs is presented by Brune (1975, 1981).

A well-inventory report of Travis County by George and others (1941) contains records of wells and springs that were collected from 1937 to 1940. This inventory was updated by Arnow (1957), who presented similar data that were collected through 1955. Information on wells and springs in Travis County was

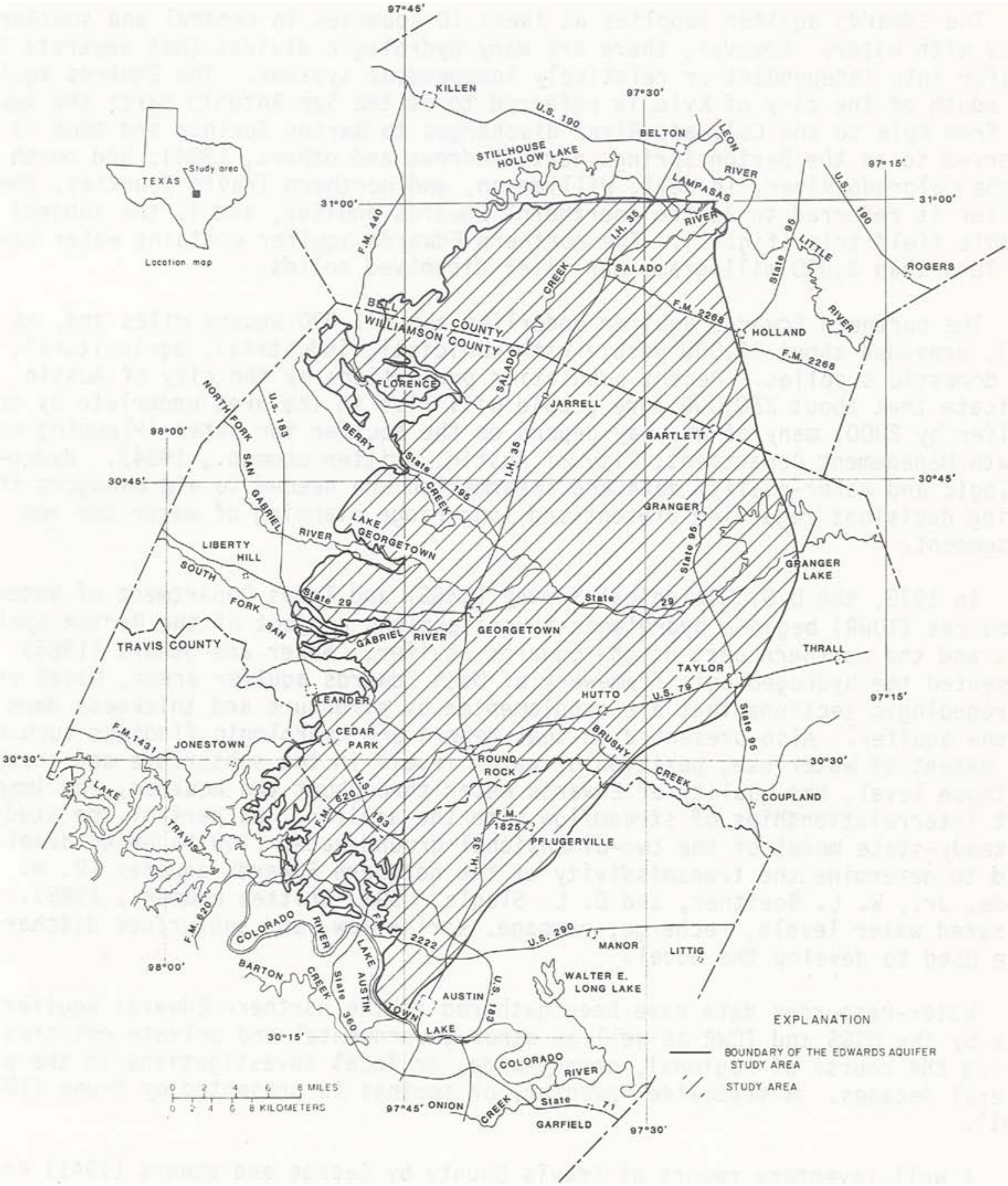


Figure 1.--Location of northern Edwards aquifer

updated again during the 1970's, and an interpretive report on the occurrence, availability, and quality of the ground water was prepared (Brune and Duffin, 1983). An annual report presenting ground-water levels and quality collected by the USGS in northern Travis County was prepared by Slade and others (1980, 1981, 1982, 1983, 1984).

The first county-wide well and spring inventory in Williamson County was made during 1940 by Cumley and others (1942). These hydrologic data were supplemented by additional data that were collected sporadically during the next 30 years and presented by Klemt and others (1975, 1976) for the central Texas region, which included Williamson County.

The only county-wide ground-water investigation of Bell County was made by Klemt and others (1975, 1976). These interpretive and hydrologic-data reports were regional in scope, but included substantial information for Bell County.

HYDROGEOLOGIC FRAMEWORK

The location of the outcrop of the geologic formations comprising the Edwards aquifer is shown in figure 2. The outcrop includes the Edwards Limestone, the underlying Comanche Peak Limestone, and the overlying Georgetown Formation. The stratigraphic nomenclature used in this report was determined from several sources and may not necessarily follow the usage of the USGS. A summary of the characteristics of the geologic units of the Edwards aquifer and adjoining formations is presented in table 1. The total outcrop area is about 400 square miles.

The Edwards aquifer is bounded on the west by Cretaceous-age rocks that are older than the aquifer. These rocks include from youngest to oldest, the Walnut Formation with its associated members and the Glen Rose Limestone. All of these rocks yield relatively little water when compared to the Edwards aquifer. The Glen Rose Limestone yields mostly small to moderate quantities of water, but is an important aquifer where the Edwards is not available.

Cretaceous rocks younger than the Edwards aquifer adjoin the aquifer on the east and extend eastward on the surface. These rocks include from oldest to youngest, the Del Rio Clay, and Buda Limestone. They yield either no water or a very small amount of water to mostly shallow dug wells.

The bedrock of the Edwards aquifer outcrop consists of mostly hard to soft limestone but some interbedded marl is present on the outcrop and in the subsurface. The limestone and dolomite on the outcrop typically is dense, grayish to white, and massive. In some areas, thin beds create a flaggy appearance. Chert is common in the limetone as hard nodules. In zones of intense weathering, honeycombing is characteristic, and in a few areas sinkholes and caves or caverns may be seen.

Solution features, such as honeycombing, sinkholes, and caverns, allow for rapid infiltration of water on the outcrop as wells as for rapid movement of ground water within the aquifer. Intensive faulting throughout the outcrop is an important feature that causes many of the solution features to develop.

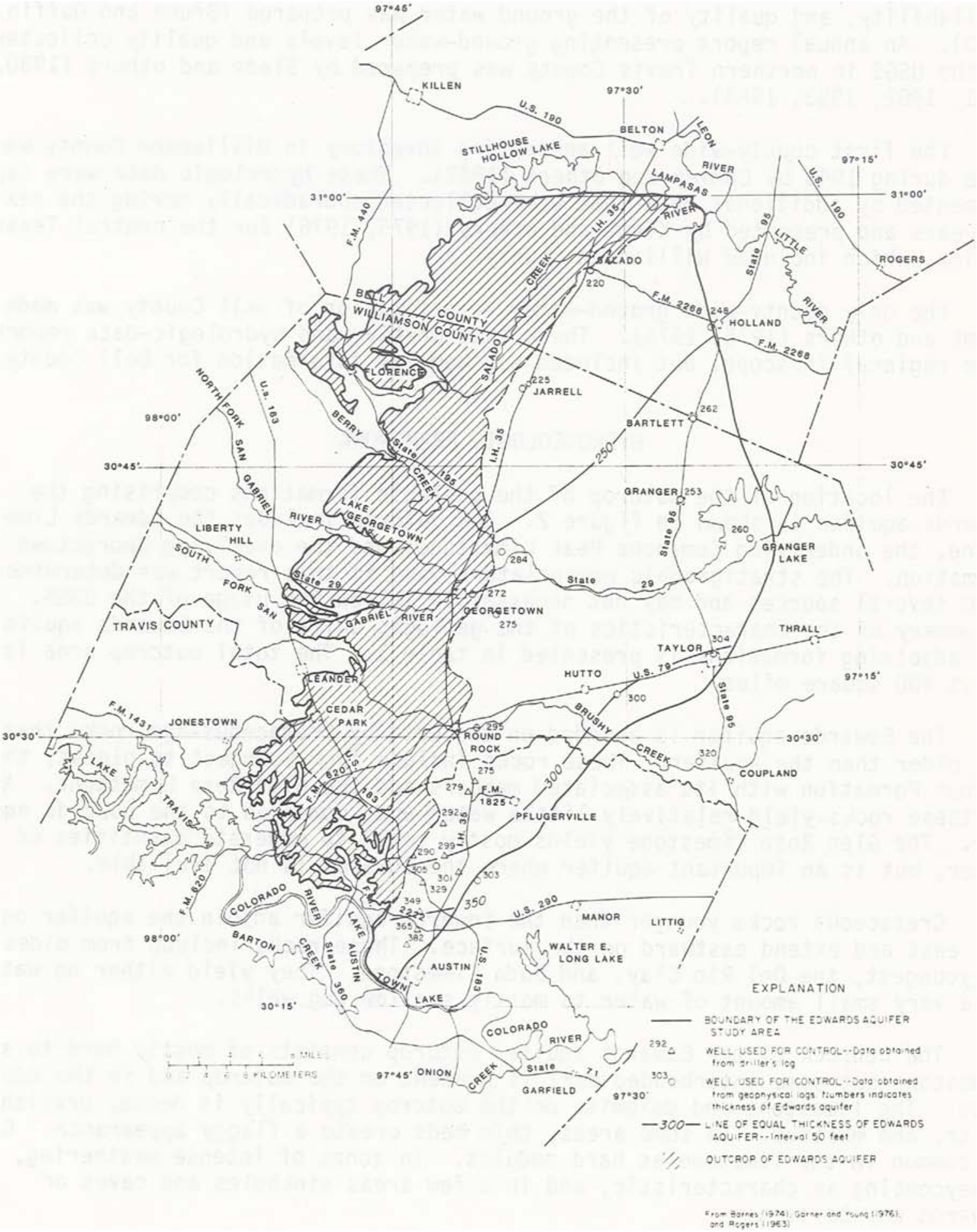


Figure 2.--Outcrop and thickness of northern Edwards aquifer

Table 1.--Summary of characteristics of geologic units

Age	Series	Group	Formation	Hydrogeologic unit	Thickness	Lithology
Cretaceous	Comanche	Washita	Buda Limestone	Confining bed	5-40 feet; generally thinning to the north in the study area.	Gray to tan, hard, resistant glauconitic shell-fragment limestone and a lower marly, nodular and less resistant limestone.
			Del Rio Clay		60-150 feet; generally thinning to the south in the study area.	Dark grey to olive-brown, calcareous fossiliferous clay containing selenite and pyrite.
			Georgetown Formation	Edwards	85-160 feet; generally thinning to the south in the study area.	Thin interbeds of gray to tan, fine-grained, fossiliferous limestone with layers of marly limestone and marl.
		Fredericksburg	Edwards Limestone: Person, Member 4		225-400 feet; thickest at the Colorado River and gradually thinning to the north in the study area.	Hard, dense, thick- to thin-bedded, fine-grained limestone; soft dolomitic limestone and solution collapse zone near middle.
			Edwards Limestone: Person, Member 3			Soft, nodular, marly limestone and marl interbedded locally with flaggy limestone.
			Edwards Limestone: Kainer, Member 2			Fine- to medium-grained, hard, thick- to thin-bedded limestone. Lower beds folded and fractured as a result of collapse in Member 1.
			Edwards Limestone: Kainer, Member 1			Porous dolomite and dolomitic limestone. Nodular chert common. A solution collapse zone within this member creates cavernous and vugular porosity.
			Comanche Peak Limestone		20-25 feet in the northwest, gradually thins and pinches out to the east and south.	Gray to tan, fine-grained, nodular limestone, marly limestone and marl.
			Walnut: Keys Valley, Whitestone, Cedar Park, Bee Cave, Bull Creek		30-150 feet; each member approximately 30 feet thick. The formation as a whole generally thins to the south in the study area.	Gray to tan, hard, fine- to medium-grained fossiliferous limestone with layers of fine-grained marl, marly limestone, and nodular limestone.
		Trinity	Glen Rose Limestone: Upper Member	Upper Trinity	500-900 feet	Alternating beds of limestone, dolomite, and marl. Some anhydrite and gypsum.
			Glen Rose Limestone: Lower Member	Middle Trinity		Massive fossiliferous limestone and dolomite at base grading upward into thin beds of limestone, shale, marl, and gypsum.
			Travis Peak: Hensell Sand Member		70 feet	Sand, gravel, conglomerate, sandstone, siltstone and shale, clay, limy clay, and limestone.
			Travis Peak: Cow Creek Limestone Member		100 feet	Massive, often sandy, dolomitic limestone, frequently forming cliffs and waterfalls. Contains gypsum and anhydrite beds.
			Travis Peak: Hammett Shale Member		60 feet	Shale and clay with some sand, dolomitic limestone, and conglomerate.
			Travis Peak: Sycamore, Sand: Sligo Member	Lower Trinity	300 feet	Limestone, dolomite, occasionally sandy, and shale. Thins to the west and is not present in northwest Travis County.
			Travis Peak: Sycamore, Sand: Hosston Sand Member		800 feet	Basal conglomerate grading upward into a mixture of sand, siltstone, and shale, with some limestone beds. Sycamore in outcrop. Hosston in subsurface.

Adapted from: Baker and others (in press), Brune and Duffin (1983), and Young (1977).

Geophysical well logs, lithologic descriptions of wells, and surface geology were used to determine the position of the Edwards aquifer in the subsurface. Three hydrogeologic sections along the dip of the aquifer and two sections along strike were developed as well as contour maps of the base and top of the aquifer. The hydrogeologic section along dip in southern Williamson County is presented in figure 3, and a section along northern Travis County is presented in figure 4. The aquifer dips to the east-southeast at a rate that averages from 70 to 75 feet per mile. Large variations in the rate of dip, as well as variations in the elevation and depth of the top, locally occur within short distances due the effect of faulting, which normally is stair-stepped downward in the dip direction. Because of erosion in the outcrop area, the full thickness of the aquifer is not present in that area. The thickness of the aquifer in the subsurface was obtained from drillers' and geophysical logs (fig. 2). In this area, the thickness varies from about 400 feet at the Colorado River to about 225 feet in southern Bell County.

WATER LEVELS IN THE AQUIFER

Water levels in the Edwards aquifer fluctuate in relation to changes in the quantity of water recharged to and discharged from the aquifer. In relatively wet years (when precipitation is substantial), greater-than-normal additions of water to the aquifer exceed the discharge and cause water levels to rise. These additions of water come from streamflow entering the outcrop in the stream channels and from infiltration of precipitation directly on the outcrop of the aquifer. During relatively dry years, discharge exceeds the less-than-normal recharge and causes the quantity of ground water that is stored in the aquifer to decrease, which is shown by a decline in water levels.

The potentiometric surface in the Edwards aquifer during January-February 1981 is shown in figure 5, and indicates the general direction of ground-water flow to be easterly. In a zone of the aquifer where substantial anisotropy exists, such as along faults, the direction of local ground-water movement may be substantially different from the regional hydraulic gradient.

The confined part of an aquifer occurs where the water level is higher than the base of the confining bed overlying the aquifer. For the Edwards aquifer, the Del Rio Clay forms the confining layer. A contour map of the altitude of the top of the aquifer (Baker and others, 1985) was compared to the January 1981 potentiometric surface in order to determine the confined and unconfined zones of the aquifer. The divide between the two zones is shown in figure 5. As the illustration shows, the divide approximates the eastern boundary of the outcrop of the Edwards aquifer.

Water-level fluctuations between high and low streamflow conditions vary substantially. The USGS and TDWR collectively have about 100 observation wells that are measured annually and about 45 wells that are measured monthly within the study area (Baker and others, in 1985). The maximum measured water-level fluctuations for all observation wells developed in the Edwards aquifer with more than 5 years of measurements are shown in figure 6. Beginning in 1980, the TDWR began measuring many wells in the outcrop area of the Edwards aqui-

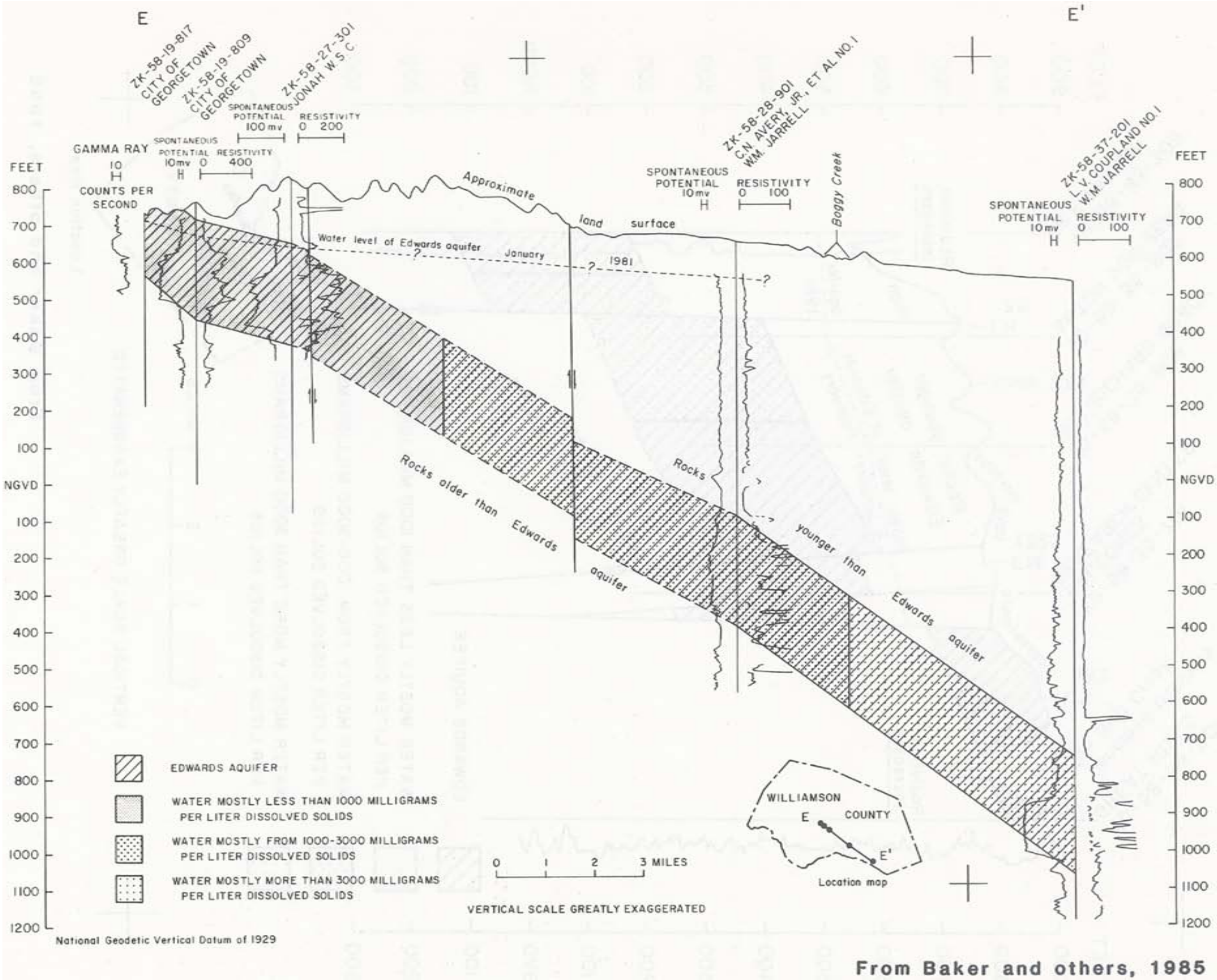


Figure 3.--Hydrogeologic dip section through southern Williamson County

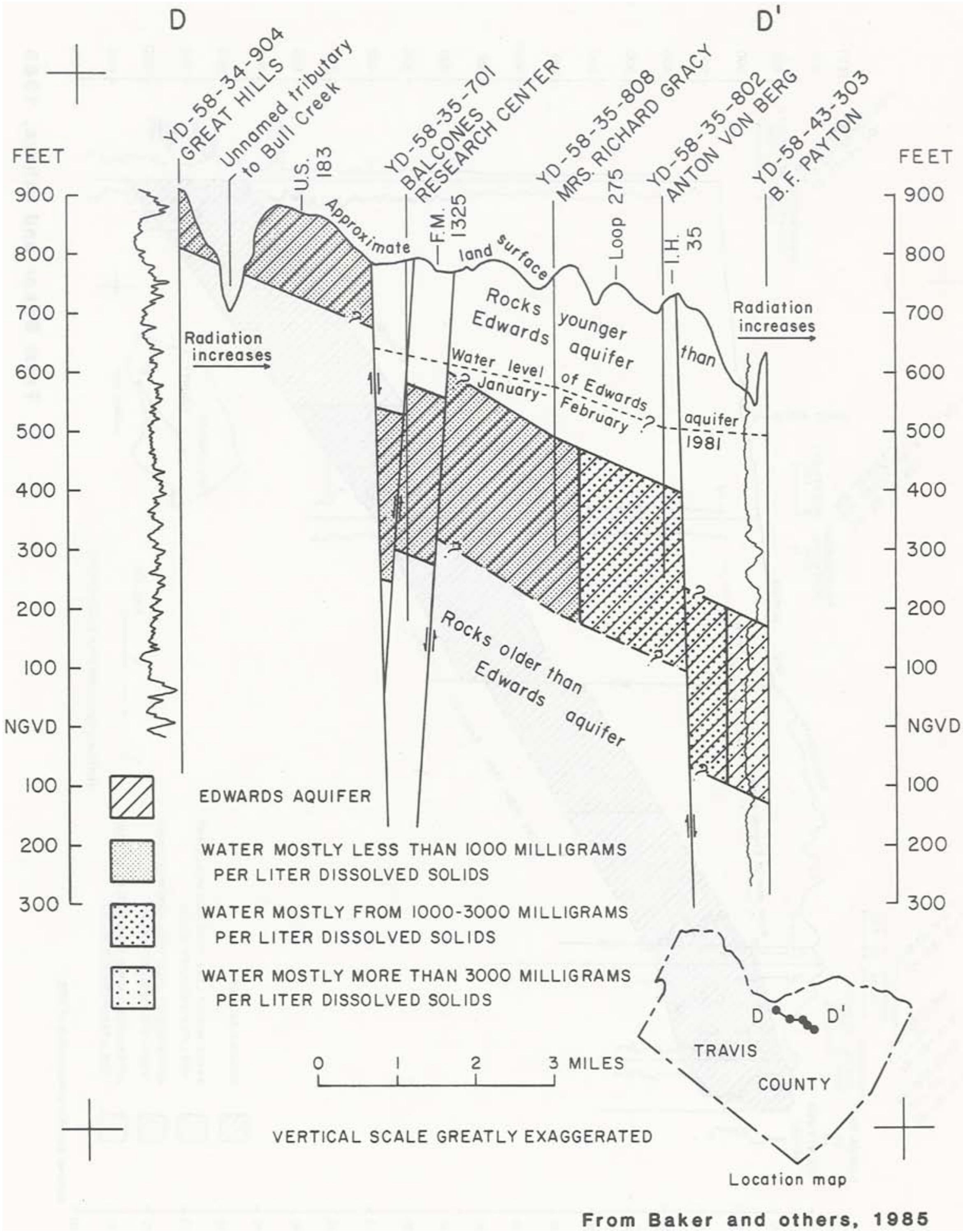
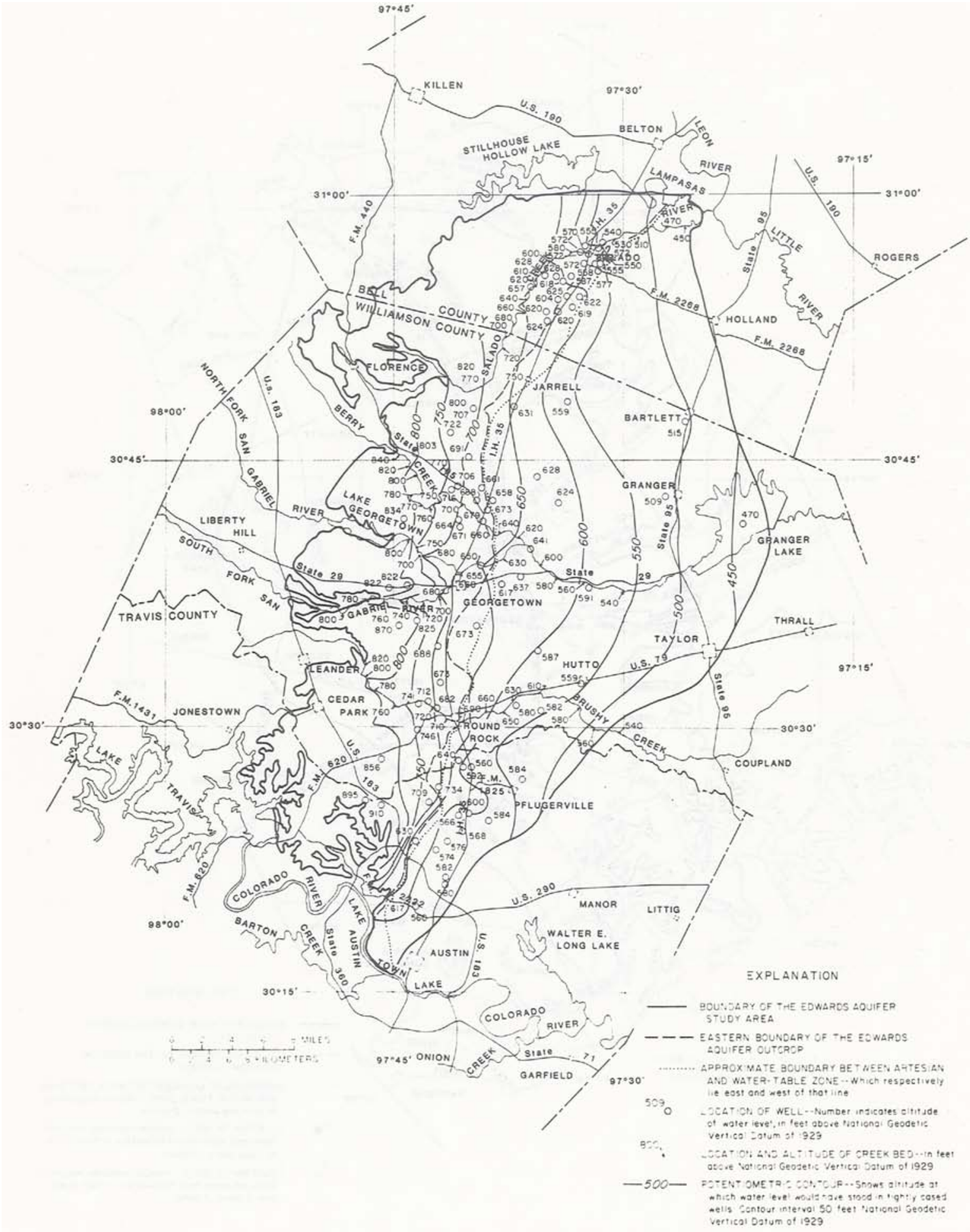


Figure 4.--Hydrogeologic dip section through northern Travis County



Modified from Baker and others, 1985

Figure 5.--Potentiometric surface of the Edwards aquifer, January-February 1981

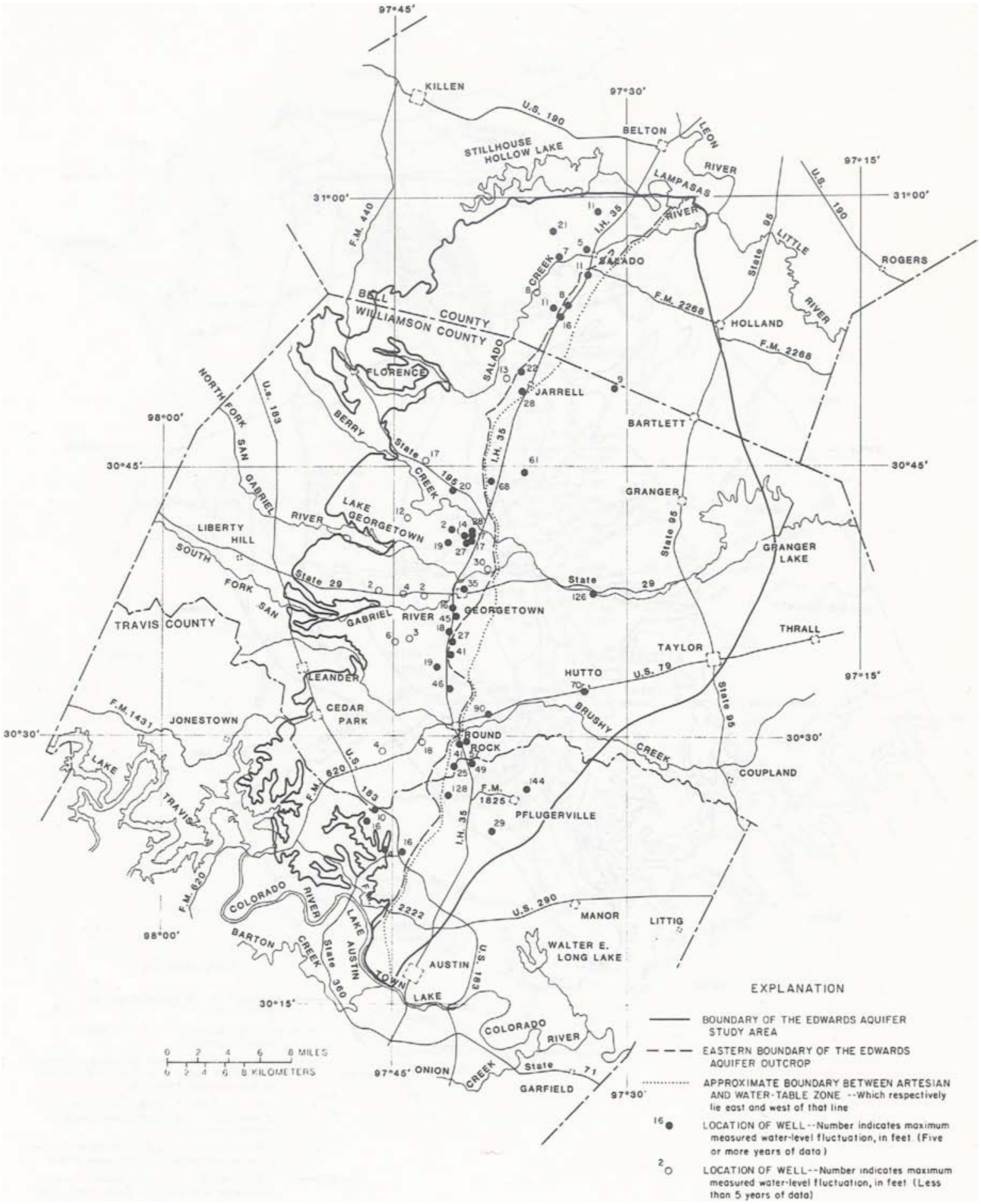


Figure 6.--Maximum water-level fluctuations of selected Edwards aquifer wells

fer. The maximum measured water-level fluctuations for those wells, based on 2 to 4 years of measurements, also are shown in figure 6. As of 1982, no trends of ground-water declines had been identified because of annual pumpage increases, thus the fluctuations are thought to be caused by variations in recharge and periodic variations in withdrawals. Generally, water-level fluctuations increase from the western part of the aquifer to the east. In the outcrop area of the aquifer, maximum fluctuations in individual wells range from about 2 to 40 feet. East of the outcrop area, fluctuations generally are greater, with a maximum of 145 feet.

Water levels in the three Trinity aquifers were compared to levels in the overlying Edwards aquifer. Water levels from wells developed in the Trinity aquifers within and near the study area are presented in figure 7, along with all the water levels in wells developed in the Edwards aquifer that were measured in January and February 1981. The water levels for the wells developed in the Trinity aquifers were obtained from Cumley and others (1942) and Klemt and others (1975). All of the measurements from Cumley and others (1942) were made in 1940, and most of the measurements from Klemt and others (1975) were made in 1966-68. The wells from these reports are identified as being developed in the Glen Rose Limestone, Travis Peak Formation, or are undifferentiated between those two formations. The Glen Rose Limestone is shared by the Upper and Middle Trinity aquifers, whereas the Travis Peak Formation is shared by the Middle and Lower Trinity aquifers (table 1).

SURFACE-WATER AND GROUND-WATER RELATIONSHIPS

The surface-water and ground-water subsystems are related, especially in the outcrop of the Edwards aquifer where there is an interchange of surface water and ground water. In some localities where streams cross the outcrop, surface water as streamflow is lost to the aquifer and becomes ground water. This process contributes a substantial part of the total recharge to the aquifer. In Williamson and Bell Counties and near the eastern edge of the outcrop, springs are common.

In 1978-79, four flow studies were made on each of five streams that cross the Edwards aquifer outcrop. These streams are Salado and Berry Creeks, North and South Forks San Gabriel River, and Brushy Creek. The primary objective of the investigations was to determine changes in the quantity of the streamflow throughout the reaches that were studied, with a secondary objective being to determine changes in the quality of the flow. Some of the streams were studied during low-flow periods when flow was small or even zero at certain sites along the stream. Others were studied when there was sufficient water after runoff-producing rains to provide flow throughout the reach of the channel. From these studies the recharge and discharge zones of the Edwards aquifer were defined more accurately.

The four Salado Creek investigations were made in April and August 1978 and in February and August 1979. About 26 miles of the main channel and additional tributary mileage were studied during these times under different flow conditions. The 1979 investigations showed that there were substantial losses

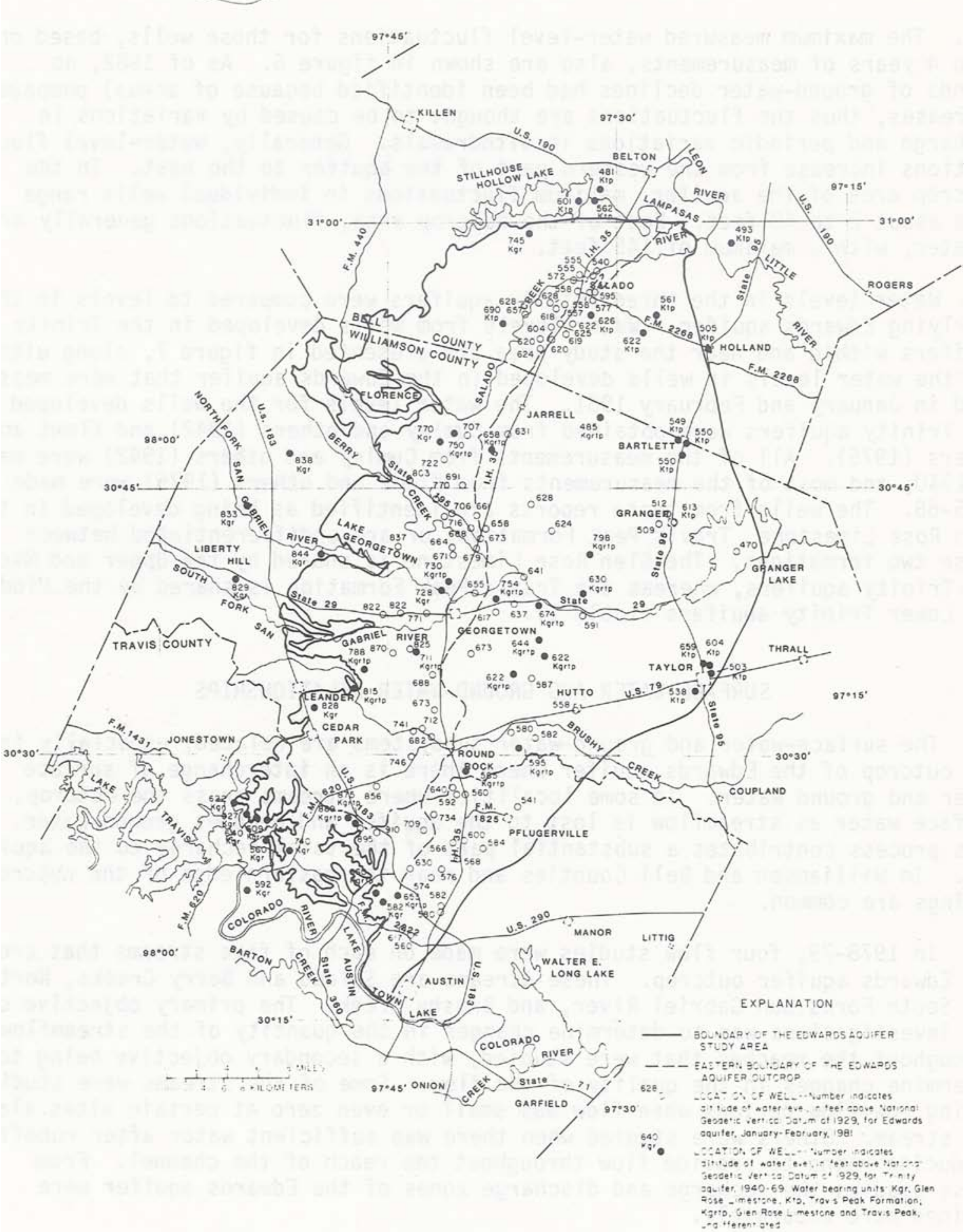


Figure 7.--Water levels for wells developed in the Edwards and Trinity aquifers

of streamflow in a reach near the western boundary of the outcrop of the Edwards aquifer. These losses are attributed to at least two faults in the Edwards aquifer that intercept the streambed in this reach. Downstream from the faults the, streamflow increased because of ground-water discharge for the next 14 miles. At Salado, streamflow increased substantially from the discharge of Salado Springs, located just east of Salado, which issues from the Edwards aquifer.

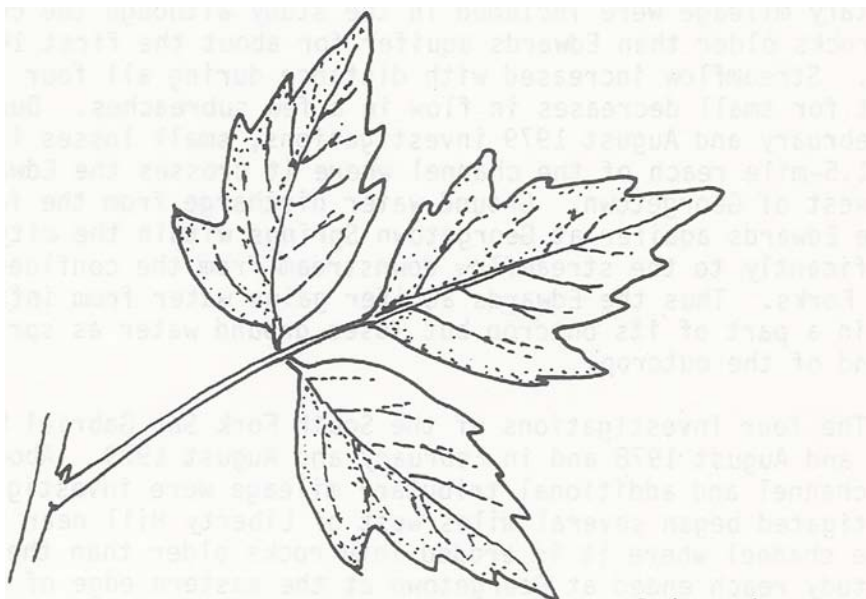
The four Berry Creek investigations were made in April and August 1978 and in February and August 1979. About 30 miles of the main channel and some tributary reaches were studied. Flow was zero at most of the measurement sites during the two 1978 investigations, but near the junction with San Gabriel River, streamflow increased substantially, due to the flow of Berry Springs. Berry Springs, at the eastern edge of the Edwards aquifer outcrop, is a major discharge site for ground water in the area. During the 1979 investigations, flow was mostly continuous through the reach. Streamflow consistently increased in the main channel except for a loss in about 1.5 miles between sites near the western boundary of the outcrop. These losses are attributed to a fault that cuts the channel between the two sites.

The four North Fork San Gabriel River investigations were made in April and August of 1978 and 1979. About 28 miles of the main channel and additional tributary mileage were included in the study although the channel was eroded into rocks older than Edwards aquifer for about the first 14 miles of the total reach. Streamflow increased with distance during all four investigations, except for small decreases in flow in a few subreaches. During the August 1978 and February and August 1979 investigations, small losses in streamflow occurred in a 1.5-mile reach of the channel where it crosses the Edwards aquifer outcrop just west of Georgetown. Ground-water discharge from the faulted eastern edge of the Edwards aquifer at Georgetown Springs within the city of Georgetown adds significantly to the streamflow downstream from the confluence of the North and South Forks. Thus the Edwards aquifer gains water from infiltration of streamflow in a part of its outcrop but loses ground water as springflow at the eastern end of the outcrop.

The four investigations of the South Fork San Gabriel River were made in April and August 1978 and in February and August 1979. About 30 miles of the main channel and additional tributary mileage were investigated. The reach investigated began several miles west of Liberty Hill near the upstream reach of the channel where it is eroded into rocks older than the Edwards aquifer. The study reach ended at Georgetown at the eastern edge of the aquifer's outcrop. Except for minor decreases in flow in only a few subreaches during the April 1978 investigation, the streamflow gradually increased throughout the investigated reach.

The four Brushy Creek investigations were made in April and August 1978 and in February and August 1979. About 20 miles of the main channel and additional tributary mileage were studied during different rates of streamflow. The reach investigated began about 4 miles west of Leander where Brushy Creek is eroded into rocks older than the Edwards aquifer and ended about 4 miles east of Round Rock on rocks younger than the Edwards aquifer. Throughout the reach, streamflow increased with the exception of some losses near Round Rock during the April 1978 and February 1979 investigations. Within the 1-mile reach near Round Rock, the stream crosses a major fault in the Edwards aquifer. The losses may be attributed to inflow into the aquifer at the fault.

For each of the four flow studies, the difference in flow at the upstream and downstream boundaries of the outcrop area was determined and summed for all five creeks. For all four studies, the differences indicated a gain in flow. The studies, conducted in April and August 1978 and in February and August 1979, indicated gains of 33, 10, 205, and 90 cubic feet per second, respectively. These gains represent springflow to the streams. The gains in streamflow generally are gradual between adjacent measuring sites, indicating that many seeps and small springs occur, rather than a few large springs. However, there are several major springs in the study area. The location and discharge for the major springs are presented by Snyder in this publication.



Poison ivy
Rhus toxicodendron

DEVELOPMENT OF THE NORTHERN SEGMENT OF THE EDWARDS AQUIFER AS A MAJOR WATER SUPPLY

Ted L. Harringer

HISTORICAL DEVELOPMENT

The early settlers in the part of Central Texas that overlies the northern segment of the Edwards aquifer relied primarily on the flow of streams, rivers, and springs for their water supplies. The majority of the population at that time was rural and concentrated communities were small, so water supplies from these sources were adequate. As the area became more populated and settlements grew into towns and cities, a need developed for centralized water systems which could supply water to the populace, even when the streams and rivers quit flowing during dry spells. For many years, these needs were partially met by individual house wells or privately owned wells which supplied several nearby houses.

Publicly owned or municipal water systems which obtain their supply from wells are a relatively recent development in this part of the state. An exception to this is a well drilled at the State Capitol in 1858 (Hill and Vaughn, 1898). This well, which may have been the first deep water well drilled in the state, is reported to have been drilled into the Edwards aquifer to a depth of 471 feet. The well, which has since been abandoned, was located beneath the present Capitol. Due to the presence of the Colorado River and the numerous springs located along it, the Edwards never became heavily developed by wells in Austin.

The major development of this segment of the Edwards has occurred north of Austin, and primarily in Williamson County. As can be seen from Figure 1, which shows the areal extent of the northern segment of the Edwards aquifer, the majority of the aquifer lies in Williamson County. Although the two present largest users of Edwards wells are the Cities of Georgetown and Round Rock, some of the smaller communities such as Bartlett, Jarrell, and Pflugerville had drilled Edwards wells for public water supplies before or at about the same time as the larger cities. This is probably because these outlying communities were not located at Edwards springs as Georgetown and Round Rock were.

The City of Georgetown's first public supply well, located about three blocks southwest of the courthouse, was dug by hand to a depth of 90 feet in 1910. Prior to the construction of this well, the City's organized system pumped water from springs located in the San Gabriel River on the northeast edge of town. Use of the springs has long since been discontinued and the City now relies exclusively on Edwards wells for its water supply.

The City of Round Rock drilled its first public supply well in 1934. Before that time, there was no organized system in the city. Privately owned wells located around town were used to supply water to surrounding houses.

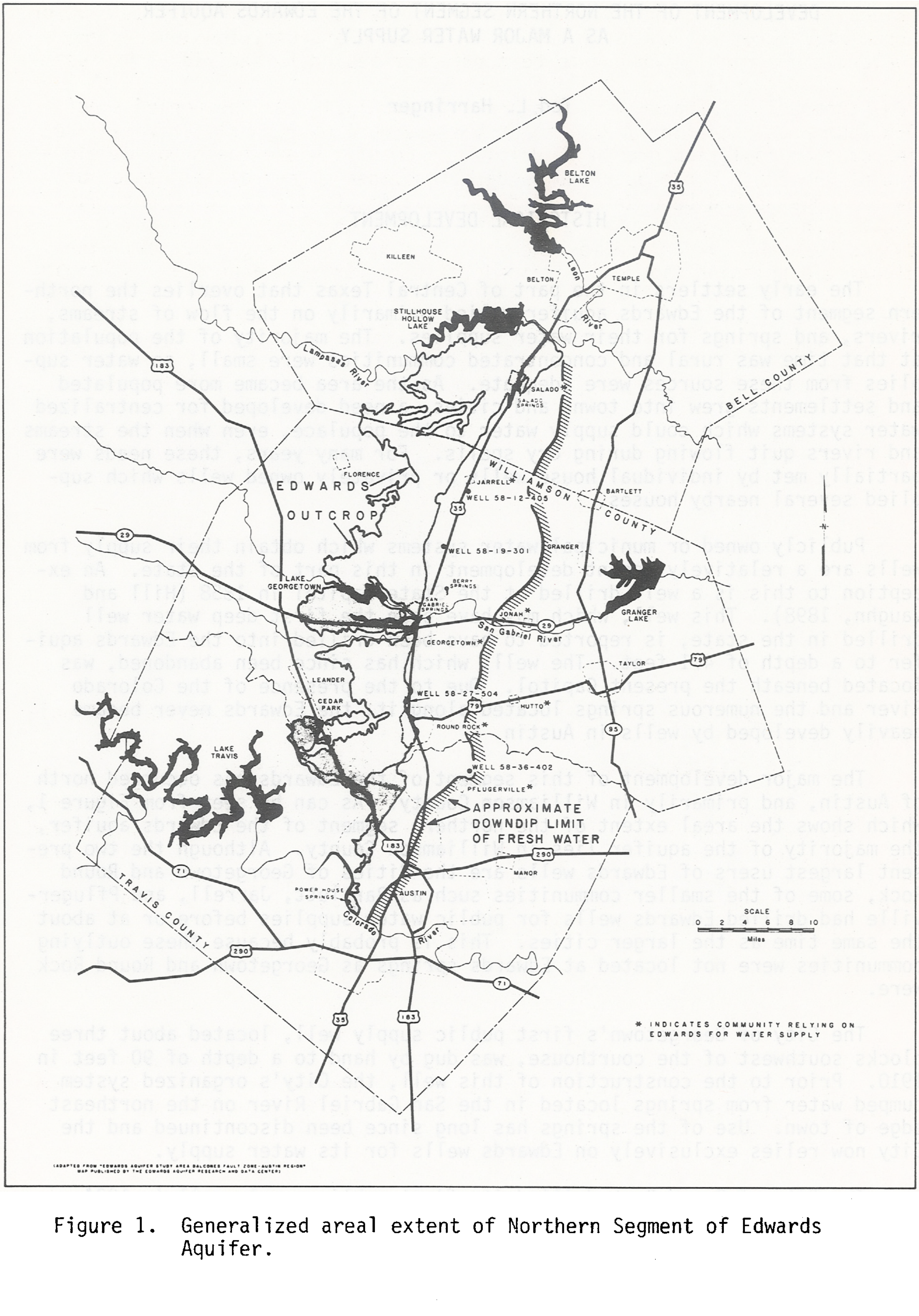


Figure 1. Generalized areal extent of Northern Segment of Edwards Aquifer.

Springs located along Brushy Creek were also used by the community as a major source of water. Without an organized collection and distribution system, however, the spring water had to be carried or hauled to individual houses.

Since accurate water-use data are only available for the period since 1955, pumpage in earlier years can at best be determined qualitatively. Review of the population growth of Williamson County, where the major development of the Edwards has occurred to date, provides a general indication of how the Edwards had been developed during the first half of this century. Even though only a portion of the county lies on the Edwards aquifer, the Edwards has been by far the most heavily relied upon source of water. The following population figures, obtained from the Texas Almanac (Dallas Morning News, 1967), the Handbook of Texas (Branda, 1976), and the Williamson County Appraisal District (personal communication, 1985) show the general growth trend of the area.

Williamson County Population

Year	Population
1900	38,072
1910	42,228
1920	42,934
1930	44,146
1940	41,698
1950	38,853
1960	35,044
1970	37,305
1980	76,507
1990*	132,800

*1984 projection by the Capital Area Planning Council (personal communication, 1985).

The population of Williamson County had until recently been based on agriculture and, as a result, had changed little through most of the century. From the numbers above, it can be seen that the major growth of this area and resultant development of the Edwards occurred within the last 10 to 15 years. The following sections discuss the recent development of the aquifer as a water supply, the interrelated effects of precipitation, pumpage, and springflow, and the corresponding changes in water levels.

PUMPAGE

As mentioned above, although Georgetown and Round Rock have been the major pumpers from the Edwards, numerous other communities, water supply companies, industries, and individuals also produce water from this aquifer. The locations of several of the entities are shown on Figure 1.

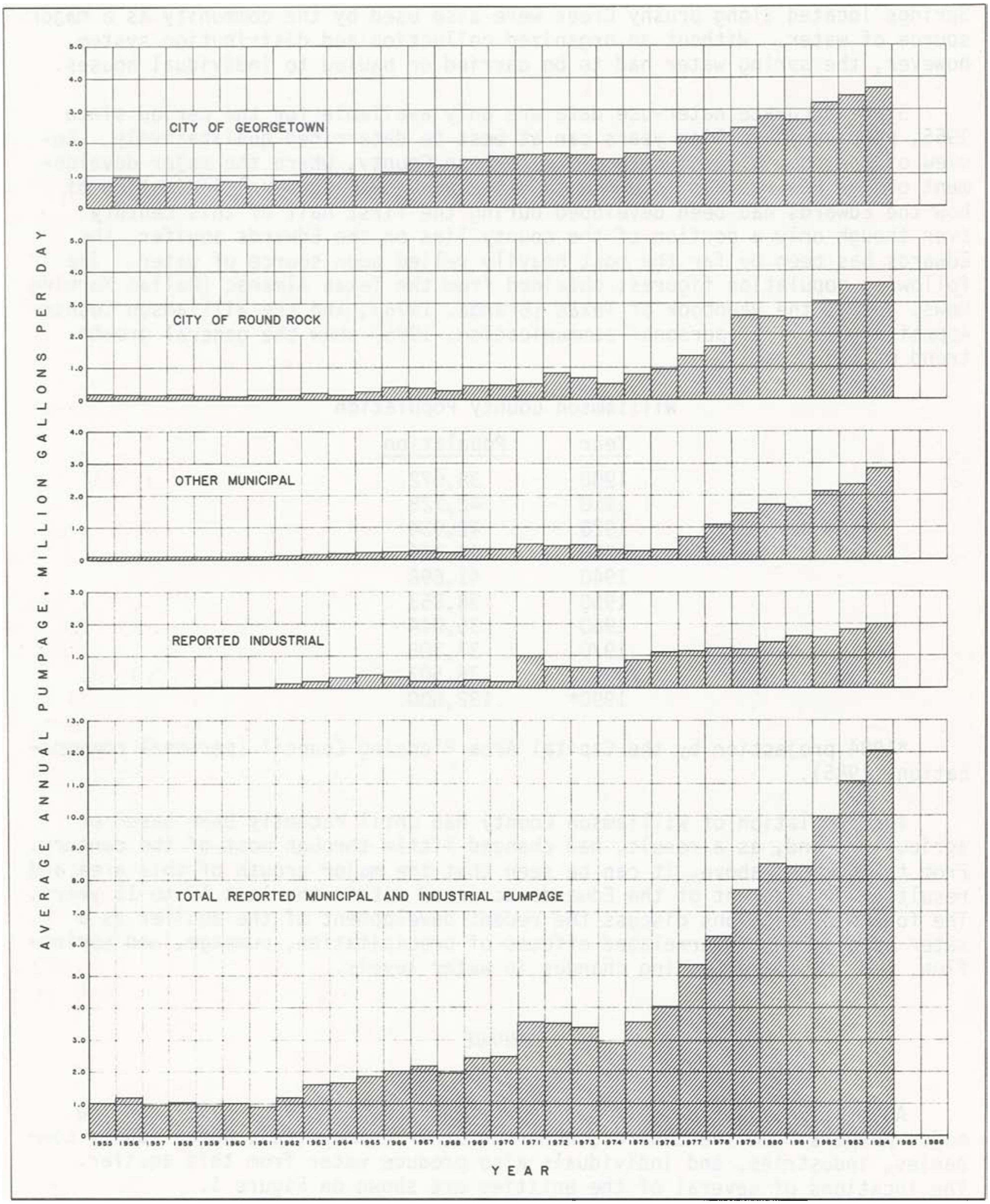


Figure 2. Reported municipal and industrial pumpage from Northern Segment of Edwards Aquifer, 1955-1984.

The reported pumpage from this northern segment of the Edwards aquifer from 1955 through 1984 is shown on Figure 2 by major municipal, other municipal, industrial, and total reported pumpage. The annual pumpage information was obtained from the Texas Department of Water Resources and modified to correct errors in reported values. The average annual pumpage shown on the graphs was calculated by dividing the total pumpage for each year by the number of days in that year. Since peak summer pumpage is often more than twice the annual average and winter pumpage is accordingly reduced, the pumpage on any specific day would rarely equal the values shown. It should be noted that the total reported pumpage shown on Figure 2 does not include individual domestic, stock and irrigation, or some industrial and commercial pumpage. The plots showing "Other Municipal" and "Reported Industrial" pumpage include some estimated values for 1984 because not all of the reporting entities had submitted pumpage data for that year.

As illustrated in Figure 2, the City of Georgetown has been the single largest Edwards user throughout recent history. Its pumpage increased steadily from 1961 to 1976, and at a much faster rate since that time. Georgetown's average annual increase since 1976 has been 0.24 million gallons per day (mgd). This recent annual increase, albeit several times larger than the increases in previous years, is somewhat less than that for other municipal water supply systems which are closer to Austin and have been affected more by its growth.

The City of Round Rock's pumpage was only a fraction of Georgetown's for many years, but Round Rock's rapid growth in the late 1970's and early 1980's changed that condition. Since 1976, Round Rock's annual pumpage has increased at an average rate of 0.33 mgd. By the end of 1983, the effects of Round Rock's growth increased the City's annual pumpage to a value that exceeded Georgetown's. Round Rock placed its surface-water treatment plant into operation in late 1983, and as a result, its yearly increase in ground-water use slowed in 1984. Georgetown's ground-water pumpage continued to increase, and in 1984 it again exceeded the amount pumped by Round Rock.

The total pumpage reported by other public supplies has developed in a pattern similar to Round Rock's, but at a reduced level. Rapid growth near but outside the service areas of Austin has resulted in major pumpage increases. Since 1976, the combined annual pumpage by these other municipal and public systems has increased at an average rate of 0.31 mgd. Some of the larger of these other public supplies are the Johah and Manville Water Supply Corporations, Williamson County M.U.D. #2 (Brushy Creek subdivision), and the City of Pflugerville.

The reported industrial pumpage has exhibited a steady but much slower rate of increase. As shown by the graphs on Figure 2, the time at which industrial pumpage began increasing predated the increase in municipal pumpage by 5 to 6 years. Since most of the reported industrial pumpage is water used by quarries and limestone processors, the earlier increase of industrial pumpage appears to reflect increased mining and processing of limestone used for construction in areas not relying on the northern segment of the Edwards for water.

The bottom graph, showing the total reported Edwards pumpage, largely reflects the net effect of rapid growth in the area overlying the Edwards. Average daily withdrawals have recently been increasing at a rate of more than 0.9 mgd each year and have more than tripled in the last 10 years. The total average pumpage in 1975 was just under 3.6 mgd, compared to over 12 mgd in 1984.

As noted earlier, these values do not include pumpage from individual domestic wells, stock and irrigation wells, and some industrial and commerical wells, for which accurate values are not available. The Texas Department of Water Resources estimated that approximately 1.9 mgd was pumped from such Edwards wells in 1981. If the recent increases in this unreported pumpage had been the same as that indicated for reported pumpage, unreported pumpage in 1984 would have been about 2.7 mgd. Adding this pumpage to reported pumpage results in an estimated total withdrawal of about 14.7 mgd in 1984.

PRECIPITATION

The role of precipitation in relation to the Edwards aquifer system is, as would be expected, primarily one of supplying recharge to the aquifer. The mechanisms by which recharge occurs and estimates of the volumes of water involved are addressed by others in this guidebook and are not presented here. Two other factors relating to and being affected by rainfall are pumpage and springflow. These are discussed in the following paragraphs.

PRECIPITATION AND PUMPAGE

Ground-water pumpage normally increases when rainfall is deficient. Since there is no major amount of agricultural irrigation within this segment of the Edwards, pumpage for agricultural use increases only minimally during dry periods. Pumpage for household gardens increases, but this is believed to be a relatively small volume. The main cause of the increased pumpage which occurs during dry periods appears to be watering of lawns and landscapes. Again, this is a result of the type of growth that has been experienced in this area. A comparison of the recorded precipitation presented in Figure 3 and pumpage through the years supports this idea. (Records for Pflugerville and Round Rock are combined on the same graph because the one station was discontinued before the other was established.)

During the severe drought of the 1950's, most of the area outside of Austin was still primarily rural. At that time, lawns were either maintained as dirt that was swept smooth with a broom, or were native grasses that required little care. The practice of maintaining a well-watered lawn, even during drought conditions, was fairly restricted to urban or suburban areas. In 1956, the last and one of the driest years of the drought, the City of Georgetown was the only municipal user of record in the area that reported appreciably higher pumpage of ground water than in previous or following years. It is probably not a coincidence that Georgetown was the largest, most urban community producing from the Edwards at that time.

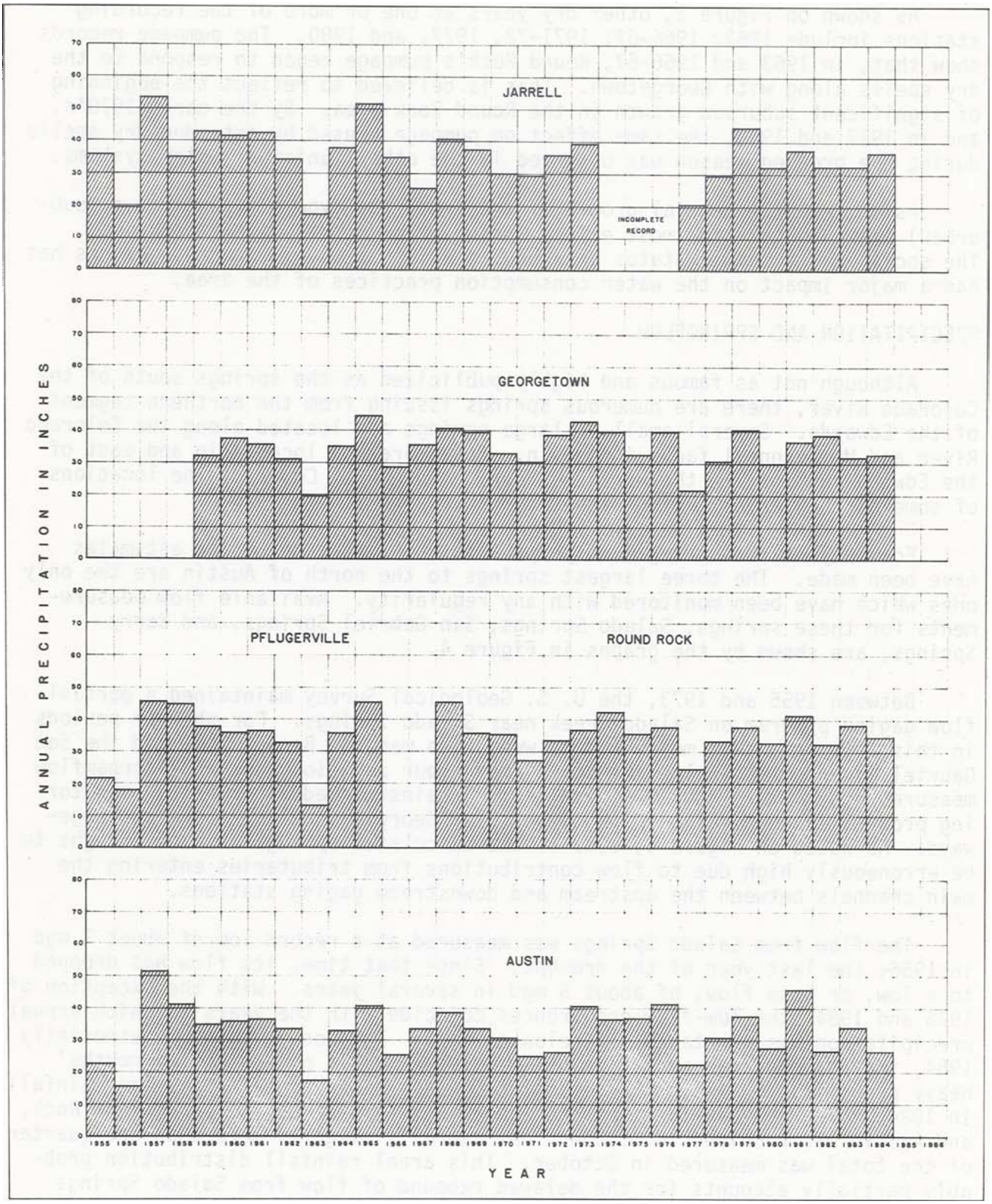


Figure 3. Annual precipitation at recording stations near outcrop of Northern Segment of Edwards Aquifer, 1955-1984.

As shown on Figure 3, other dry years at one or more of the recording stations include 1963, 1966-67, 1971-72, 1977, and 1980. The pumpage records show that, in 1963 and 1966-67, Round Rock's pumpage began to respond to the dry spells along with Georgetown. This is believed to reflect the beginning of significant suburban growth in the Round Rock area. By the early 1970's, and in 1977 and 1980, the same effect on pumpage caused by extended dry spells during the growing season was observed in the other municipal water systems.

Aside from the general growth of the area, the type of growth (i.e. suburban) seems to have the most effect during below-normal rainfall periods. The social and economic status attached to a lush lawn of imported grasses has had a major impact on the water consumption practices of the area.

PRECIPITATION AND SPRINGFLOW

Although not as famous and highly publicized as the springs south of the Colorado River, there are numerous springs issuing from the northern segment of the Edwards. Several small to large springs are located along the Colorado River and Mt. Bonnell fault in Austin. Many more are located in and east of the Edwards outcrop to the north, extending into Bell County. The locations of some of the larger springs are shown on Figure 1.

For many of the springs, only sporadic flow measurements or estimates have been made. The three largest springs to the north of Austin are the only ones which have been monitored with any regularity. Available flow measurements for these springs, Salado Springs, San Gabriel Springs, and Berry Springs, are shown by the graphs in Figure 4.

Between 1955 and 1973, the U. S. Geological Survey maintained a partial-flow gaging program on Salado Creek near Salado Springs. For shorter periods in this interval, flow measurements were also made on Berry Creek and the San Gabriel River. The Geological Survey made four additional sets of streamflow measurements in 1978 and 1979, and in 1984 reinstituted an organized monitoring program in cooperation with the City of Georgetown along these drainageways. As noted on Figure 4, some of the calculated springflows are thought to be erroneously high due to flow contributions from tributaries entering the main channels between the upstream and downstream gaging stations.

The flow from Salado Springs was measured at a record low of about 2 mgd in 1956, the last year of the drought. Since that time, its flow has dropped to a low, or base flow, of about 5 mgd in several years. With the exception of 1978 and 1984, the low-flow occurrences coincide with the years in which annual precipitation was substantially below average. In these two years, especially 1984, the near average annual rainfall was the result of one or two months' heavy precipitation, with the rest of the year recording below average rainfall. In 1984, more than one-third of the annual rainfall at Georgetown, Round Rock, and Austin was received in October. At Jarrell, slightly more than one-quarter of the total was measured in October. This areal rainfall distribution probably partially accounts for the delayed rebound of flow from Salado Springs from 1984 to 1985, while the other two springs responded more rapidly.

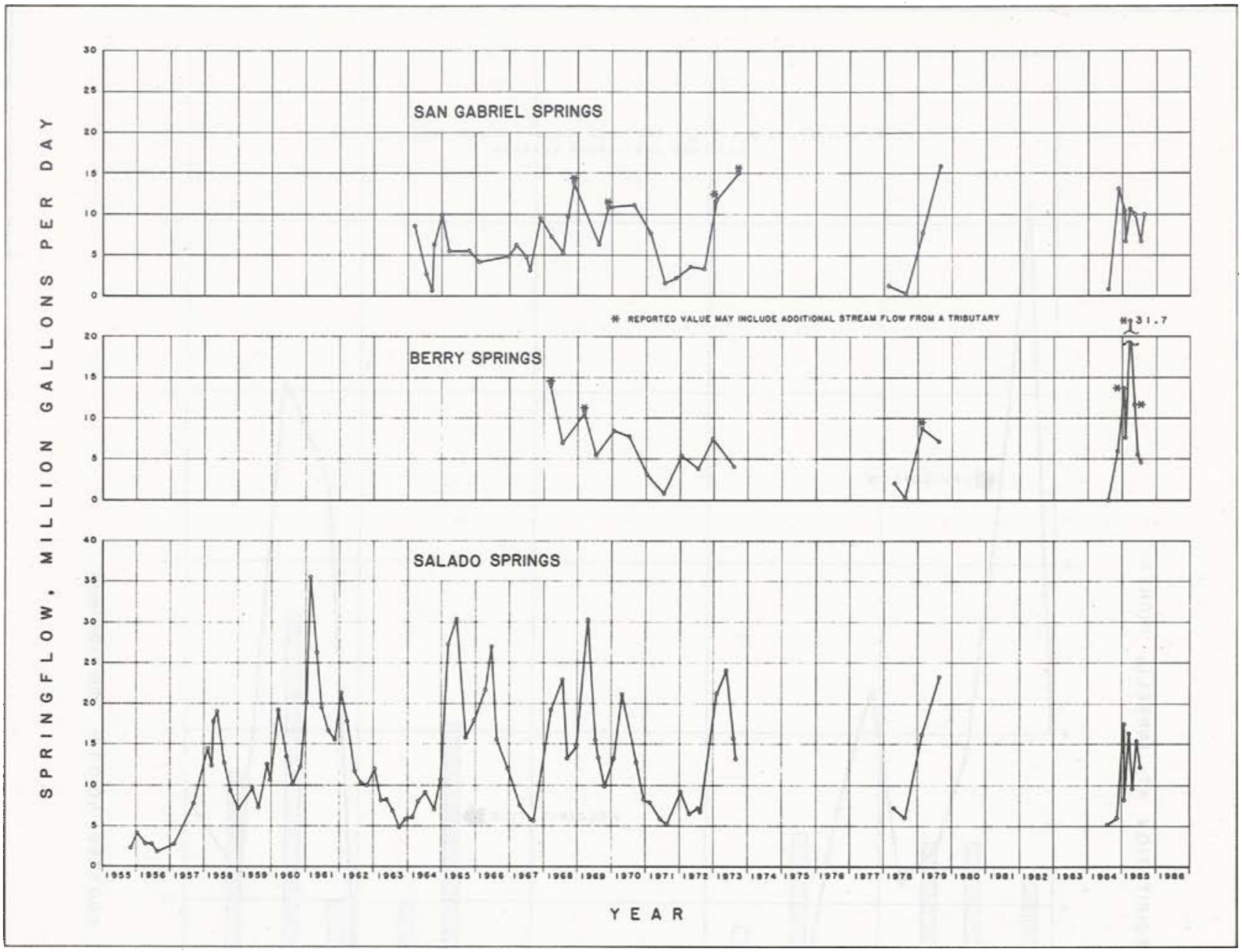


Figure 4. Flow of major springs issuing from Northern Segment of Edwards Aquifer, 1955-1985.

Although records of flow from Berry and San Gabriel Springs are available for shorter periods, they also show reduced flows during dry years. Since these springs are at substantially higher elevations than Salado Springs, and have smaller local contributing areas from which to obtain water, their low flows are correspondingly less. In addition, the flows from Berry and San Gabriel Springs in recent years probably have been reduced by pumpage by the City of Georgetown and new development just north of it.

Comparison of Figures 3 and 4 shows that there is a general correlation between rainfall and springflow on an annual basis, but annual rainfall data do not provide the detail needed to illustrate how "flashy" the discharge from the springs is. Figure 5, which presents springflow measurements and monthly precipitation, shows this in a better time perspective. The interval from 1961 to 1965 was chosen for Salado Springs, as it presents the most numerous measurements of flow available during a wide range of precipitation values.

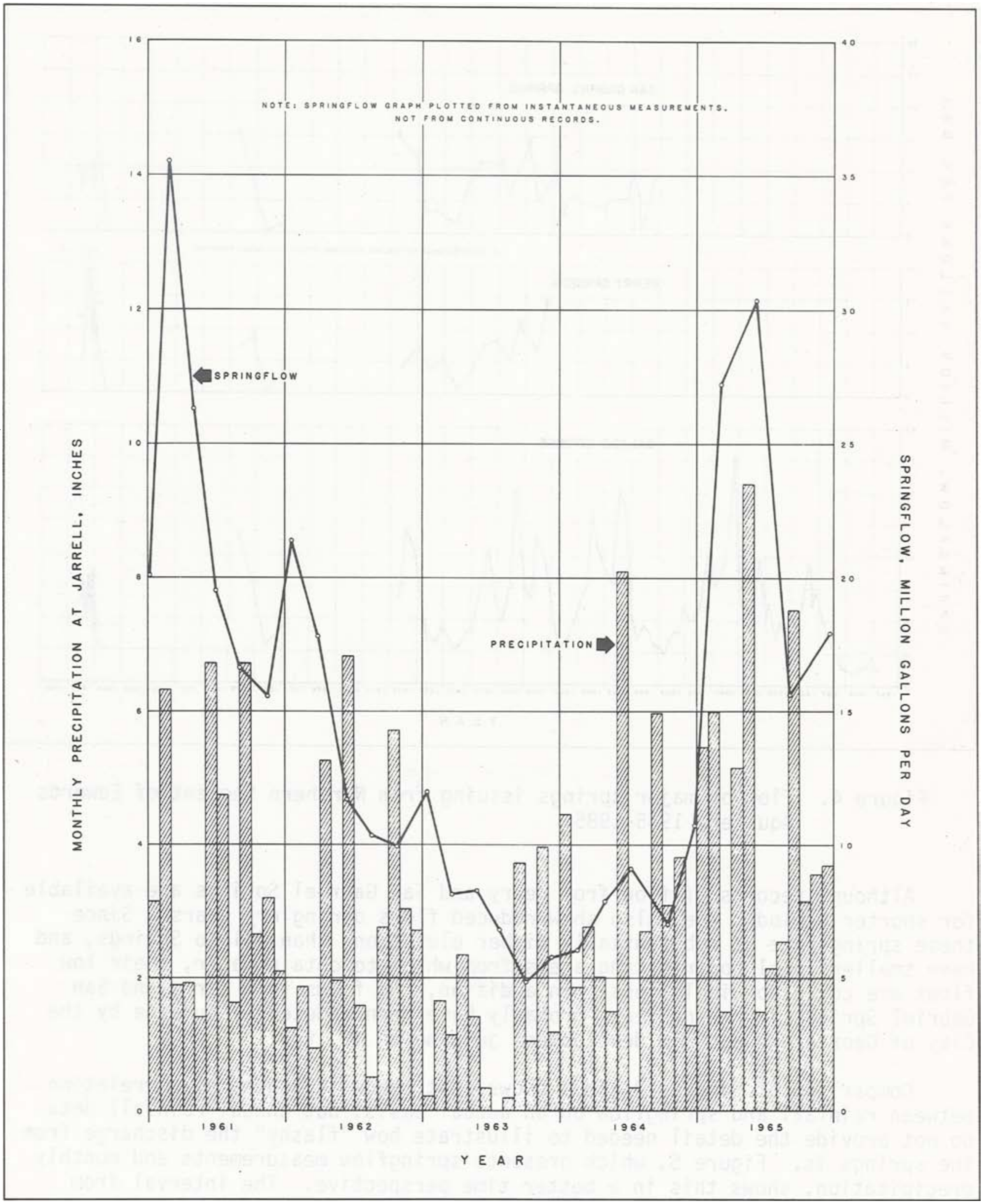


Figure 5. Monthly precipitation and flow from Salado Springs, 1961-1965.

Even on this scale, however, the flow measurements lack the frequency to catch the high peaks and base flows from day to day, or even month to month. Such definition should become available as the reactivated gaging program for these springs progresses.

WATER LEVELS

A more obvious indicator of the effects of changes in pumpage and variations in precipitation over the years is the fluctuation of water levels in wells. Hydrographs of four wells completed in the Edwards are presented in Figure 6. The locations of these wells are shown on Figure 1.

As with the springflows, water levels have been low in years of low rainfall and reduced recharge, and have recovered in wet years. Until recently, the levels of the mid-1950's were considered to be record lows. The major increases in pumpage since the mid- to late 1970's have, however, produced water levels that are lower than those of the 1950's.

Well 58-12-405 has exhibited the least amount of water-level fluctuation over the years. This is probably due to it being located away from centers of major pumpage and relatively near to the Edwards outcrop. Being under water-table conditions, the aquifer in the outcrop area acts as a storage reservoir which receives recharge and makes it available to the artesian portion of the aquifer. This storage capacity tends to buffer wide fluctuations in nearby water levels.

Wells 58-19-301 and 58-27-504 are located much nearer the pumpage around Georgetown and Round Rock, but they are also located near the Edwards outcrop and near springs. As described above, the proximity to the outcrop area attenuates water-level fluctuations in these wells. In addition, some of the water normally discharged at the springs is intercepted by the Cities' production wells, further attenuating the water-level fluctuations in these observation wells.

In 1984, the water level in Well 58-36-402 fell to almost 10 feet below the previous record low of 1956. This well is located near the pumpage for Pflugerville, relatively far from the outcrop, and not near any major Edwards springs. Because it is located in the artesian portion of the aquifer and away from natural recharge, its water levels are subject to wide fluctuations as a result of pressure changes created by nearby pumpage.

One of the most illustrative points of the hydrographs is the magnitude of water-level declines and the quickness with which they have occurred in the last several years, especially 1984 and 1985. Even though the recent "droughts" have been less severe than that of the 1950's, the effect of the more than tenfold increase in pumpage becomes evident. The stress that is put on the aquifer by the increased pumpage causes large and rapid declines in water levels, both near the pumpage centers and areally as pumpage exceeds recharge.

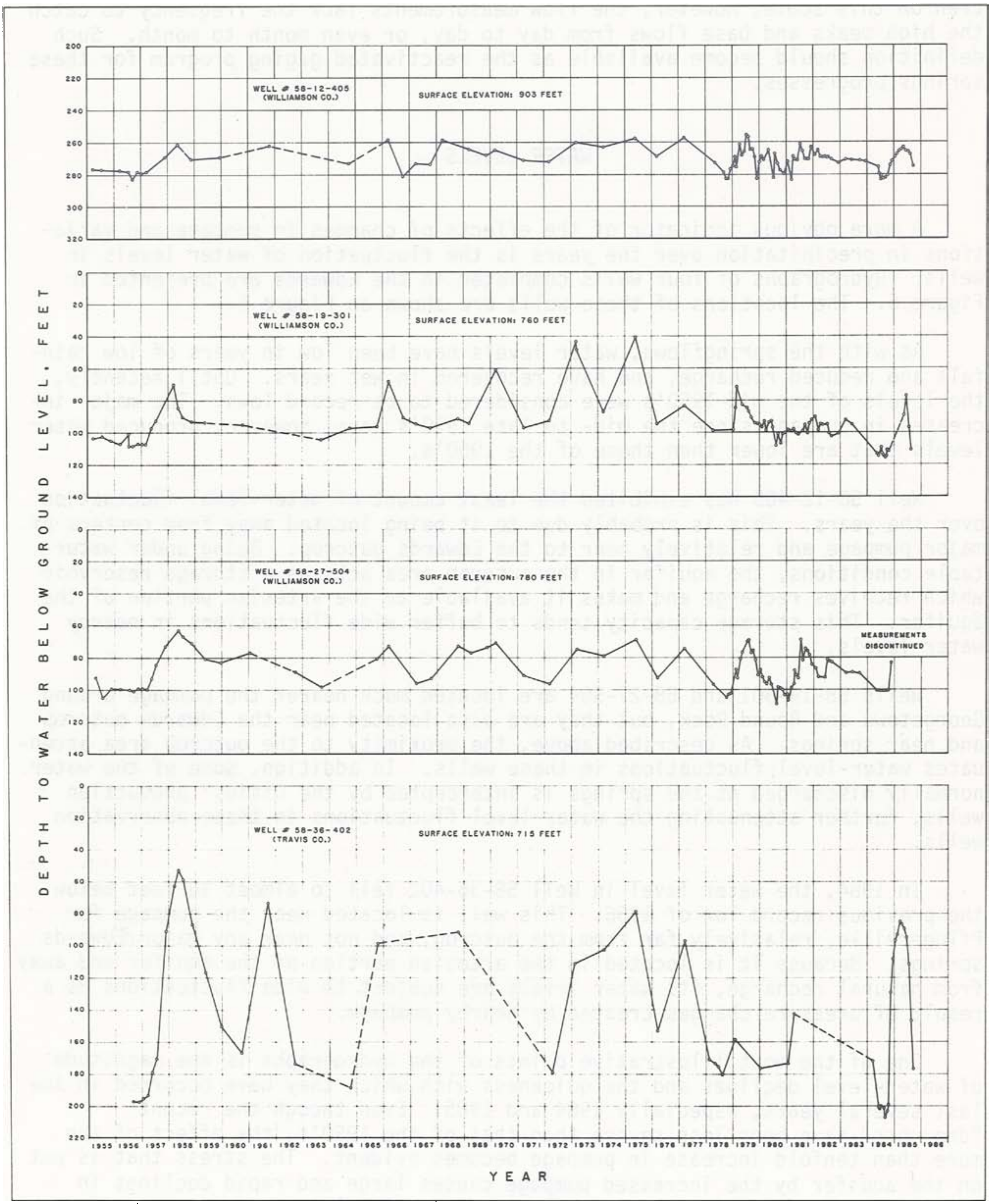


Figure 6. Hydrographs of selected Edwards wells, 1955-1985.

OVERVIEW

The development of the northern segment of the Edwards aquifer as a major water supply did not occur until the mid-1970's. Prior to that time, springflow and areal water levels generally reflected and were controlled by climatic conditions. More recently, however, the effects of pumpage from wells have become more noticeable and, during short "droughts", have almost become the controlling factor. Springflows have reached historical base levels, with some completely ceasing to flow, water levels in wells have fallen below record lows, and reports of water shortages and wells "drying up" have become more more numerous during periods of below average precipitation lasting only 1 to 2 years.

To date, most of the municipal water shortages leading to voluntary or mandatory water rationing and failure to meet water use demands have resulted from mechanical failures, inadequacy of a water system to keep pace with its population growth, or the locating of wells too close to each other, causing excessive water-level drawdowns in a concentrated area. A few exceptions to this occurred in 1984 when use of some outcrop wells had to be curtailed or totally discontinued because the water being pumped became excessively turbid or muddy. Since these occurrences were primarily restricted to shallow outcrop wells, this situation appears to have resulted from turbulence being created in the producing cavities of the formation as they were partially unwatered by the heavy pumpage in concert with reduced recharge.

If current withdrawal rates continue to be maintained, it is anticipated that a drought of the magnitude of the 1950's drought would result in major water shortages for many of the existing municipal water systems relying on the Edwards. New large municipal water systems that will use the Edwards are already being planned and constructed in this area. The addition of these systems, some of whose pumpage will be exceeded by only Georgetown and Round Rock, will increase the frequency of "water shortages" by reducing the duration and intensity of the droughts required to initiate the problems.

Although Round Rock has added surface-water capabilities to its system and Georgetown is planning to do the same, these supplemental supplies may only compensate for some of the future growth of the two cities, without effectively reducing their present ground-water pumpage. Much of the projected additional development of the aquifer will occur at the expense of springflow. It is likely that, as the expanded pumpage lowers water levels and intercepts the natural discharge of the springs, San Gabriel and Berry Springs will cease to flow or become only intermittent. Salado Springs will probably continue to flow for a much longer time than these smaller springs, but at rates that are substantially less than those observed in the past.

LOWER CRETACEOUS REGIONAL SETTING--TEXAS CRUSHED STONE QUARRY

Don G. Bebout

Here at the quarry just south of Georgetown we are standing near the top of the Lower Cretaceous (Albian and lower Cenomanian) Edwards Limestone. Several major paleotopographic features dominated the Lower Cretaceous setting at the time of deposition of these carbonates (Fig. 1). Seventy-five miles to the southwest an almost continuous shelf margin (the Stuart City Reef Trend) constructed of rudist-coral-stromatoporoid banks and carbonate bars, beaches, and tidal channels separated this extensive, shallow-water platform from the deeper water (hundreds of feet) ancestral Gulf basin. The nature of the extensive platform on the landward side of the shelf margin was controlled by the more positive Central Texas Platform (Llano Uplift) to our southwest and its seaward extension, the San Marcos Platform. On either side of this feature are the more rapidly subsiding North Texas-Tyler Basin, to the northeast, and the McKnight (Maverick) Basin, to the southwest. The broad Comanche and Devils River Platforms lie between the Central Texas Platform and these subsiding basins. We are in the center of this shallow-water platform.

The Edwards Formation dips gently to the southeast at about 300 to 400 feet per mile (3 to 4 degrees) except where interrupted by the en echelon faults of the Balcones and Luling fault zones, considered to be middle to late Tertiary in age. The Balcones fault system lies immediately to the east of this quarry just across the highway (I-35); total displacement of the fault system is approximately 900 feet in this area. The Luling fault system has less offset with a total displacement of about 450 feet.

The Edwards is the upper formation of the Fredericksburg Group (Fig. 2). The Fredericksburg Group is about 280 feet thick in the Austin to Georgetown area. Near Austin the Edwards Formation is composed of more than 230 feet of the Fredericksburg, and the underlying Walnut Shale (Cedar Park Limestone and Bee Cave Marl Members) makes up the remaining 50 feet. In contrast, in the Georgetown area the Edwards Formation is only about 130 feet thick, and the remaining 150 feet is made up of the Comanche Peak Limestone and Walnut Shale (Keys Valley Marl, Cedar Park Limestone, and Bee Cave Marl Members). This southwest-northeast change in thicknesses of the Fredericksburg formations represents the progradation of the shallow-water platform carbonates of the Edwards Formation over the slightly deeper water, argillaceous carbonates of the North Texas-Tyler Basin. High-energy carbonates of the Whitestone Member and Moffat Mound occur at the transition, representing shoal-water deposits at the edge of this shallow basin.

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*Publication authorized by the Director, Bureau of Economic Geology, The University of Texas at Austin.

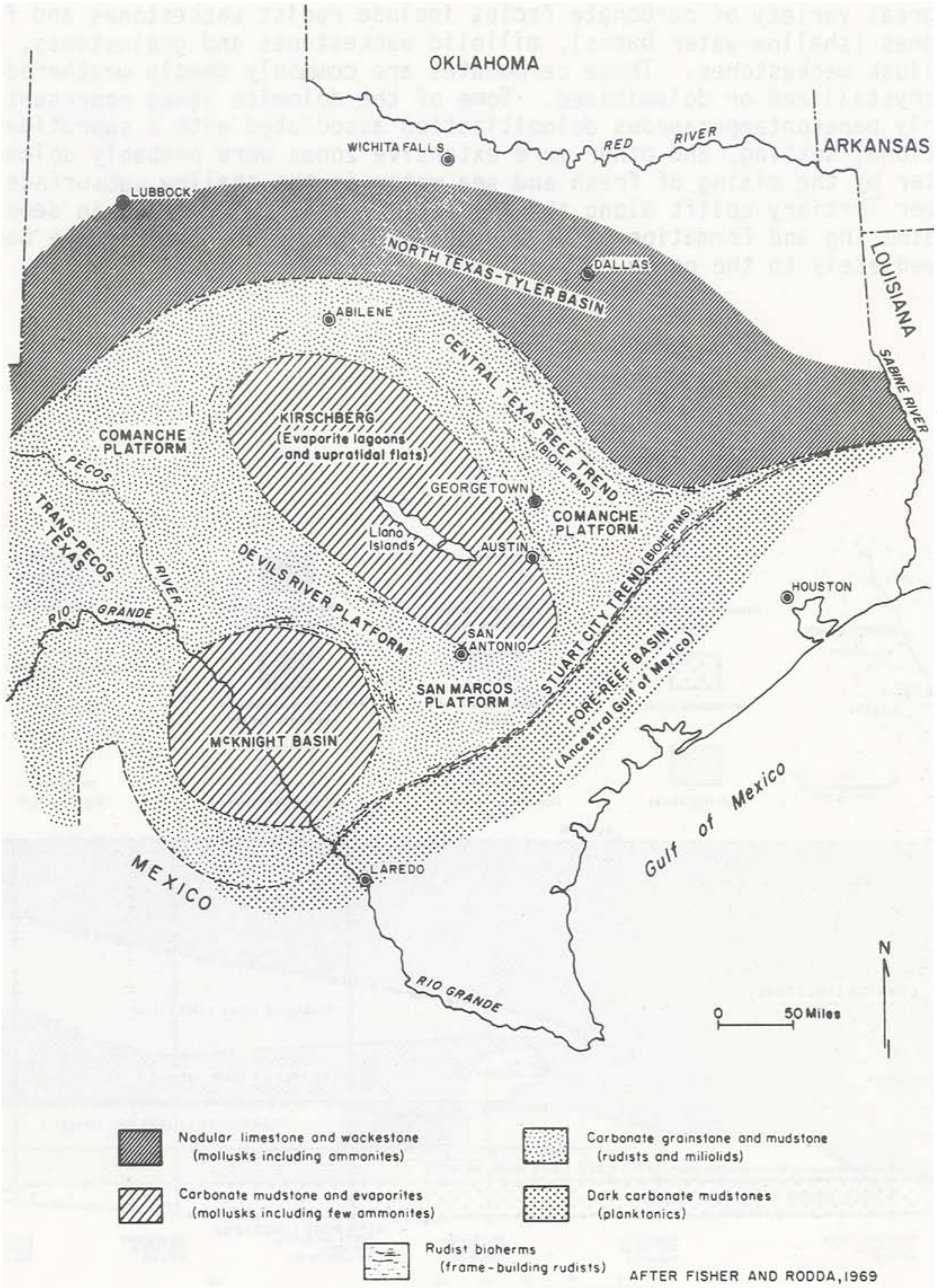


Figure 1. Paleogeographic setting during deposition of the Lower Cretaceous Fredericksburg formations. From Fisher and Rodda, 1969.

The Edwards Formation at this quarry is approximately 130 feet thick. A great variety of carbonate facies include rudist wackestones and framestones (shallow-water banks), miliolid wackestones and grainstones, and mollusk wackestones. These carbonates are commonly deeply weathered and recrystallized or dolomitized. Some of the dolomite zones represent very early penecontemporaneous dolomitization associated with a supratidal depositional setting, and other more extensive zones were probably dolomitized later by the mixing of fresh and sea water in the shallow subsurface. The later Tertiary uplift along the Balcones fault zone resulted in deep weathering and formation of cave systems, such as the Inner Space Caverns immediately to the north.

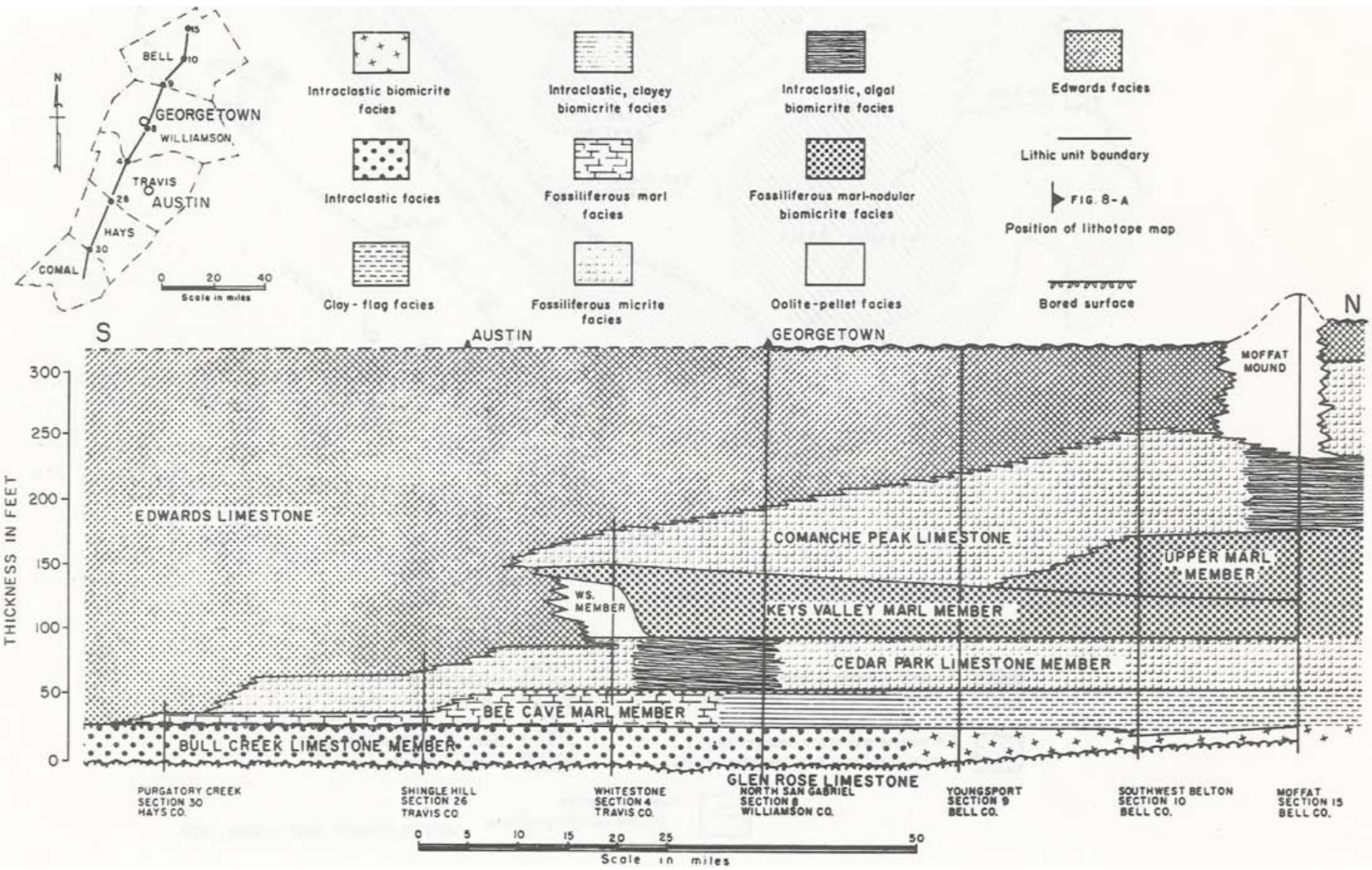


Figure 2. Cross section showing the distribution of Fredericksburg formations through the Austin and Georgetown areas. From Moore, 1964.

PLEISTOCENE VERTEBRATES FROM LAUBACH CAVE

Ernest L. Lundelius, Jr.

INTRODUCTION

Inner Space Cavern, formerly known as Laubach Cave, was discovered in the fall of 1963 by the Texas Highway Department which was drilling exploratory holes for overpass footings on Interstate Highway 35. When they encountered voids about 30 feet below the surface, a 24 inch diameter hole was drilled into what proved to be a sealed cave system. Speleologists from the Dallas-Ft. Worth Grotto and the University of Texas Speleological Society began exploration and mapping of the cave. The first fossil bones were found by Pete Linsley and Norman Robinson of the Dallas-Ft. Worth group at Laubach 1 (Bone Sink 1 of Slaughter, 1966). Subsequent exploration resulted in the discovery of fossil bones at a number of locations in the cave system.

LOCATION OF BONES AND TAPHONOMY

All the fossil bones are associated with debris cones marking former entrances into the cave (see map). Bones are rare or absent in those parts of the cave that are away from these former entrances. This agrees with the observation that, aside from bats, most animals that enter caves voluntarily do not go far beyond the lighted areas.

A number of animals such as bats, wolves, coyotes, peccaries and jaguars, whose bones are found in the cave, are known to frequent caves at times. Others such as deer, antelope, prairie dogs, and possibly camel and horse were probably brought into the cave by avian and/or mammalian predators. Some such as the mammoth and glyptodont may have fallen into the sink holes and died.

At Laubach 5 many of the bones of the large extinct peccary, *Platygonus compressus*, are those of juvenile individuals. It is tempting to speculate that at least some of them may have been brought into the cave by jaguars whose bones were also found in the cave. A careful survey of all the bones has not been done but some of the peccary bones show marks that could have been made by a carnivore.

AGE OF THE FAUNA

All of the bones are of late Pleistocene age. The fact that they came from different places associated with different former openings raises the possibility that they may not all be the same age. This is supported by the fact that the debris cone of Bone Sink 3 is heavily cemented by travertine.

One radiocarbon date on bone is available from each of the following localities: Laubach 1 (TMM loc. no. 40673), 15,850 + 500 YBP; Laubach 2 (TMM loc. no. 40722), 13,970 ± 310 YBP; Laubach 3 (TMM loc. no. 41343) 23,230 ± 490 YBP. Although radiocarbon dates on bone are not as reliable as those based on other materials such as charcoal (Haas et al., 1980; Hassan et al., 1977; Haynes, 1968), these dates are consistent with the conclusion that the material associated with Laubach 3 is older than those of the other two localities.

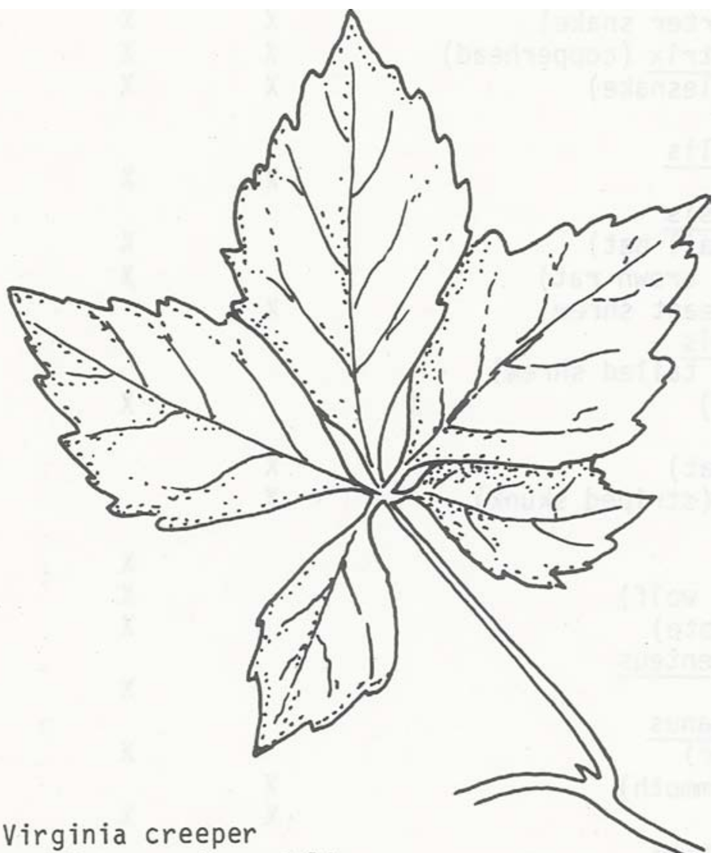
ENVIRONMENTAL INTERPRETATION

The Pleistocene faunas from the various localities in Laubach Cave contain three groups of species: extinct species such as the mammoth, sabertoothed cat, glyptodont, sloth etc.; extant species such as prairie dog, short tailed shrew and microtine rodents that no longer live in Central Texas; and extant species that are part of the modern fauna of this region. It is difficult to use the extinct species in environmental interpretations because their tolerances are not known. Some suggestions can be made by an examination of the geographic distributions of these species. Glyptodonts of late Wisconsinan age are almost entirely restricted to the Gulf and Atlantic coastal plains and no records are known north of the Red River. This suggests the existence of some climatic zonation in North America at that time.

Extant species are much more reliable indicators of environmental conditions. The short tailed shrew, *Blarina carolinensis*, and the microtine rodent, *Microtus* sp., and the prairie dog, *Cynomys ludovicianus*, no longer occur in Central Texas. The first two species are found in areas of higher rainfall and lower evaporation rates to the north and east of Laubach Cave. The presence of their remains in late Pleistocene deposits in this cave indicate more moist conditions at that time than at present. This is in agreement with conclusions based on a number of late Pleistocene faunas from most parts of Texas. The environmental significance of the presence of the prairie dog is less clear. The modern distribution of this species apparently did not extend southeastward past the northwest edge of the Llano Uplift. It is also known from late Wisconsinan deposits in Kendall and Bexar counties.

One characteristic of late Pleistocene faunas that is not well represented in the faunas of Laubach Cave is the co-occurence of species that are now allopatric (i.e. species whose geographical distributions do not overlap today). Only one such pair of species, *Dipodomys elator* and *Microtus ochrogaster*, are known so far from Laubach 3. These assemblages have been interpreted as an indication that Pleistocene climates were less seasonal than the present (Hibbard 1960, Lundelius, 1974). This is based on the observation that species involved in such associations that are primarily northern in their distribution appear to have their southern limits controlled by the summer aridity and temperature maxima while the species that are primarily southern in their distribution appear to have their northern limits controlled primarily by the winter temperature minima. The reason for the scarcity of such assemblages from Laubach Cave is almost certainly due to the poor sample of small extant mammals so far recovered.

The differences in age between the bones found in Laubach 1 and 2 and those found at Laubach 3 opens the possibility of obtaining information about environmental changes during the late Wisconsinan. Unfortunately, although there are differences in the faunal lists of the localities, these lists are too limited to allow any meaningful conclusions to be drawn.



Virginia creeper
Parthenocissus quinquefolia

TABLE 1
FAUNAL LIST FROM LAUBACH CAVE

TAXON	LAUBACH 1	LAUBACH 2	LAUBACH 3	LAUBACH 4	LAUBACH 5
Class Amphibia					
Rana pipiens (leopard frog)		X	X		
Class Reptilia					
Terrapene carolina (eastern box turtle)		X			
Sceloporus sp. (fence lizard)		X	X		
Coluber sp. (racer)		X	X		
Elaphe sp. (rat snake)		X			
Heterodon sp. (hog nosed snake)		X			
Pituophis sp. (bull snake)		X	X		
Thamnophis sp. (garter snake)		X	X		
Agkistrodon contortrix (copperhead)		X	X		
Crotalus sp. (rattlesnake)		X	X		X
Class Mammalia					
Didelphis marsupialis (o'possum)		X	X		
Tadarida brasiliensis (Mexican free-tail bat)			X		
Myotis sp. (little brown rat)			X		
Cryptotis parva (least shrew)		X		X	
Blarina carolinensis (southern short tailed shrew)				X	
Felis onca (jaguar)	X		X		
*Homotherium serum (sabertoothed cat)		X			
Mephitis mephitis (striped skunk)		X			
Spilogale putorius (spotted skunk)			X		
*Canis dirus (dire wolf)			X		
Canis latrans (coyote)			X		
Urocyon cinereoargenteus (gray fox)			X		
*Tremarctos floridanus (spectacled bear)			X		
*Mammuthus sp. (mammoth)		X			X
*Equus sp. (horse)		X	X		
*Platygonus compressus (extinct peccary)	X		X		X
Odocoileus virginianus (whitetail deer)			X		
*Tetrameryx shuleri (four horned antelope)			X		X

TABLE 1 (CONTINUED)
FAUNAL LIST FROM LAUBACH CAVE

TAXON	LAUBACH 1	LAUBACH 2	LAUBACH 3	LAUBACH 4	LAUBACH 5
**Camelops* sp (camel)		X			
**Dasypus bellus* (large armadillo)			X		
**Glyptotherium floridanus* (glyptodont)			X		
**Megalonyx jeffersoni* (ground sloth)			X		
Cynomys ludovicianus (prairie dog)	X		X		
Microtus sp. (vole)		X	X	X	
Microtus ochrogaster (prairie vole)			X		
Neotoma sp. (packrat)		X	X		
Peromyscus sp. (deer mouse)		X	X		
Sigmodon hispidus (cotton rat)		X	X		
Geomys sp. (gopher)		X	X	X	
Perognathus hispidus (hispid pocket mouse)				X	
Perognathus flavus (silky pocket mouse)				X	
Dipodomys sp. (kangaroo rat)		X			
Dipodomys elator (Texas kangaroo rat)			X		
Lepus californicus (jackrabbit)		X	X		X
Sylvilagus sp. (cottontail)	X	X	X		

*Denotes extinct taxa

HYDRAULIC PROPERTIES OF A PART OF THE EDWARDS AQUIFER NEAR PFLUGERVILLE, TEXAS

Michael E. Bentley

The artesian Edwards Aquifer is the only sizeable, readily available source of fresh water in much of north-central Travis County. The movement of urban Austin into this area has created a steadily increasing demand for water from the Edwards. It would be desirable to be able to predict the effects of pumpage on surrounding water levels as part of evaluations of the feasibility of obtaining additional supplies of groundwater.

In order to estimate the drawdown of water levels in the more common, relatively homogeneous granular aquifer, well locations and pumping schedules are usually identified and then the transmissivity and storativity of the groundwater reservoir are used to make a simple analytical wellfield model. This method could be applied to part of the artesian, "nonhomogeneous" Edwards if the network of pores and fractures had reasonably similar characteristics over a wide area.

It is a common experience of well drillers in this area to make several test holes at a project site in order to locate a place where the aquifer has high transmissivity. It is not unusual to drill test holes with yields of a few gallons per minute a few tens of feet away from wells that will yield several hundred gallons per minute. When the aquifer is considered on a small scale, the extreme nonhomogeneity of the porosity and permeability of the rock is readily apparent. However, there is considerable evidence that a well-integrated system of high permeability water-transmitting features has shaped the development of major springs, their contributing segments of the aquifer, and even the courses of surface streams. The results of recent pumping tests in the vicinity of Pflugerville indicate that several relatively widely-spaced water wells may communicate within such a hydraulically contiguous, high-transmissivity porous system.

Pumping tests are commonly used to measure transmissivity and storativity. Standard pumping-test analysis methods are based on the assumption that the aquifer is an isotropic, homogeneous porous media of large areal extent bounded above and below by impermeable beds. The transient response of water levels to constant-rate pumping of water from such an aquifer is predictable and is described by the "exponential integral solution" (Theis, 1935). If a heterogeneous "block and fissure" geologic media is areally large and consists of an extensive network of hydraulically similar fractures and approximately equidimensional blocks, then flow during a pumping test will eventually become generally "radial" and the pressure response at the pumping well will eventually follow the Theis curve (Gringarten, 1982). The result is that although little detailed information on characteristics of individual fractures will be obtained, analysis of late-time data can yield gross properties of the aquifer as a whole.

The locations of the three pumping tests are shown in Figure 1. Public

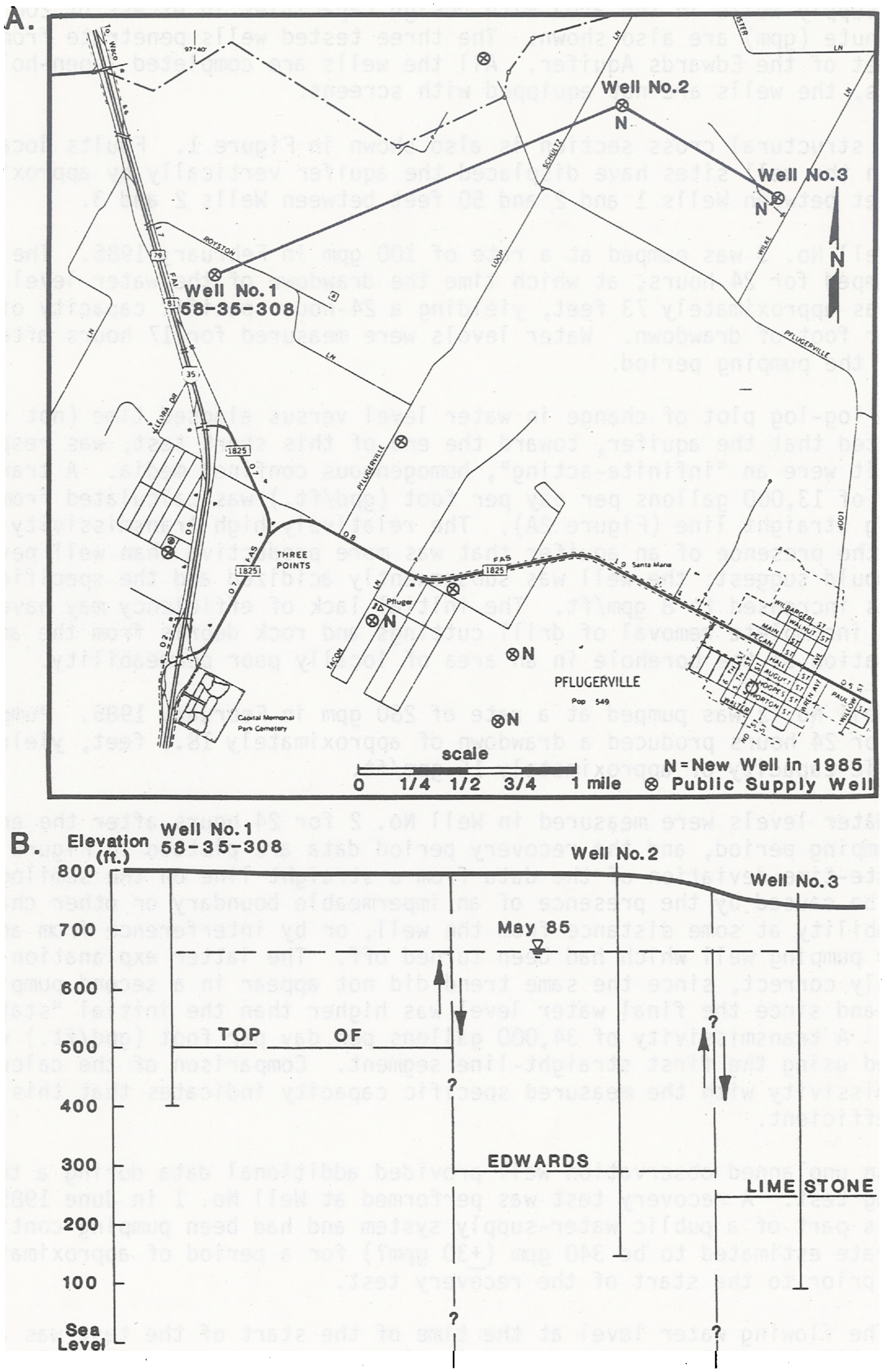


Figure 1A. Locations of Wells
1B. Geologic Cross Section

water supply wells in the area with design capacities in excess of 200 gallons per minute (gpm) are also shown. The three tested wells penetrate from 100 to 150 feet of the Edwards Aquifer. All the wells are completed "open-hole", that is, the wells are not equipped with screens.

A structural cross section is also shown in Figure 1. Faults located between the well sites have displaced the aquifer vertically by approximately 200 feet between Wells 1 and 2 and 50 feet between Wells 2 and 3.

Well No. 3 was pumped at a rate of 100 gpm in February 1985. The well was pumped for 24 hours, at which time the drawdown of the water level in the well was approximately 73 feet, yielding a 24-hour specific capacity of 1.37 gpm per foot of drawdown. Water levels were measured for 17 hours after the end of the pumping period.

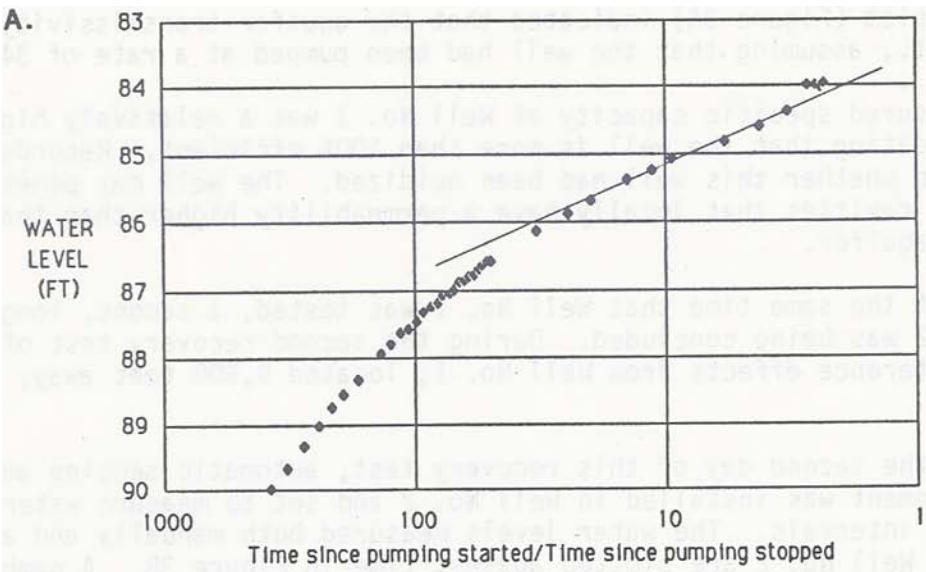
A log-log plot of change in water level versus elapsed time (not shown) indicated that the aquifer, toward the end of this short test, was responding as if it were an "infinite-acting", homogeneous confined media. A transmissivity of 13,000 gallons per day per foot (gpd/ft.) was calculated from the semilog straight line (Figure 2A). The relatively high transmissivity indicated the presence of an aquifer that was more productive than well performance would suggest; the well was subsequently acidized and the specific capacity was increased to 8 gpm/ft. The initial lack of efficiency may have been due to incomplete removal of drill cuttings and rock debris from the aquifer, or location of the borehole in an area of locally poor permeability.

Well No. 2 was pumped at a rate of 280 gpm in February 1985. Pumping the well for 24 hours produced a drawdown of approximately 18.5 feet, yielding a specific capacity of approximately 15 gpm/ft.

Water levels were measured in Well No. 2 for 24 hours after the end of the pumping period, and the recovery period data are plotted in Figure 2B. The late-time deviation of the data from a straight line on the semilog plot could be caused by the presence of an impermeable boundary or other change in permeability at some distance from the well, or by interference from another nearby pumping well which had been turned off. The latter explanation is probably correct, since the same trend did not appear in a second pumping test, and since the final water level was higher than the initial "static" level. A transmissivity of 34,000 gallons per day per foot (gpd/ft.) was calculated using the first straight-line segment. Comparison of the calculated transmissivity with the measured specific capacity indicates that this well is 100% efficient.

An unplanned observation well provided additional data during a third pumping test. A recovery test was performed at Well No. 1 in June 1985. This well is part of a public water-supply system and had been pumping continuously at a rate estimated to be 340 gpm ($\pm$30 gpm?) for a period of approximately two weeks prior to the start of the recovery test.

The flowing water level at the time of the start of the test was approximately 157 feet below grade. Water levels were measured in this well for 41



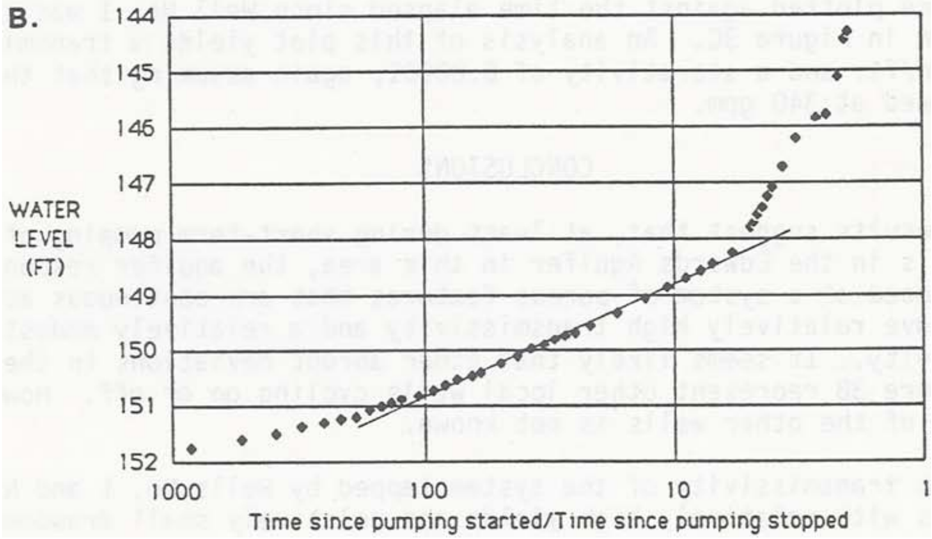


Figure 2A. Semilog Data Plot For Recovery Test of Well No. 3.
2B. Semilog Data Plot For Recovery Test of Well No. 2

hours, at which time the level had risen a total of 10.9 feet. Analysis of the semilog plot (Figure 3A) indicated that the aquifer transmissivity was 40,000 gpd/ft., assuming that the well had been pumped at a rate of 340 gpm.

The measured specific capacity of Well No. 1 was a relatively high 30 gpm/ft, indicating that the well is more than 100% efficient. Records are unclear as to whether this well had been acidized. The well may penetrate fractures or cavities that locally have a permeability higher than that of the bulk of the aquifer.

At about the same time that Well No. 1 was tested, a second, longer test of Well No. 2 was being concluded. During the second recovery test of Well No. 2, interference effects from Well No. 1, located 9,500 feet away, were noted.

During the second day of this recovery test, automatic sensing and recording equipment was installed in Well No. 2 and set to measure water levels at 30-minute intervals. The water levels measured both manually and automatically in Well No. 2 are plotted against time in Figure 3B. A number of abrupt changes in the trend of water levels versus time are evident. Arrows indicate when Well No. 1 was turned off and then on again.

The water-level data recorded in Well No. 2 during the period shown on Figure 3B were plotted against the time elapsed since Well No. 1 was turned off, as shown in Figure 3C. An analysis of this plot yields a transmissivity of 25,000 gpd/ft. and a storativity of 0.00001, again assuming that the pumping well flowed at 340 gpm.

CONCLUSIONS

These results suggest that, at least during short-term pumping of high-capacity wells in the Edwards Aquifer in this area, the aquifer responds as if it were composed of a system of porous features that are continuous across faults and have relatively high transmissivity and a relatively modest artesian storativity. It seems likely that other abrupt deviations in the hydrograph of Figure 3B represent other local wells cycling on or off. However, the identity of the other wells is not known.

The high transmissivity of the system tapped by Wells No. 1 and No. 2 enables wells with relatively high yields and relatively small drawdowns to be made. Apparently, however, this will occur only where wells intersect the primary network of fractures and/or vugs, or where wells can be treated to improve connections with the system.

Additional pumping tests could be conducted with multiple observation wells completed in different parts of the aquifer that have a wide range of apparent transmissivities. Responses of water levels in these wells should produce an improved picture of the aquifer's "plumbing". However, such tests would probably require cooperation of all operators of public water systems in the area.

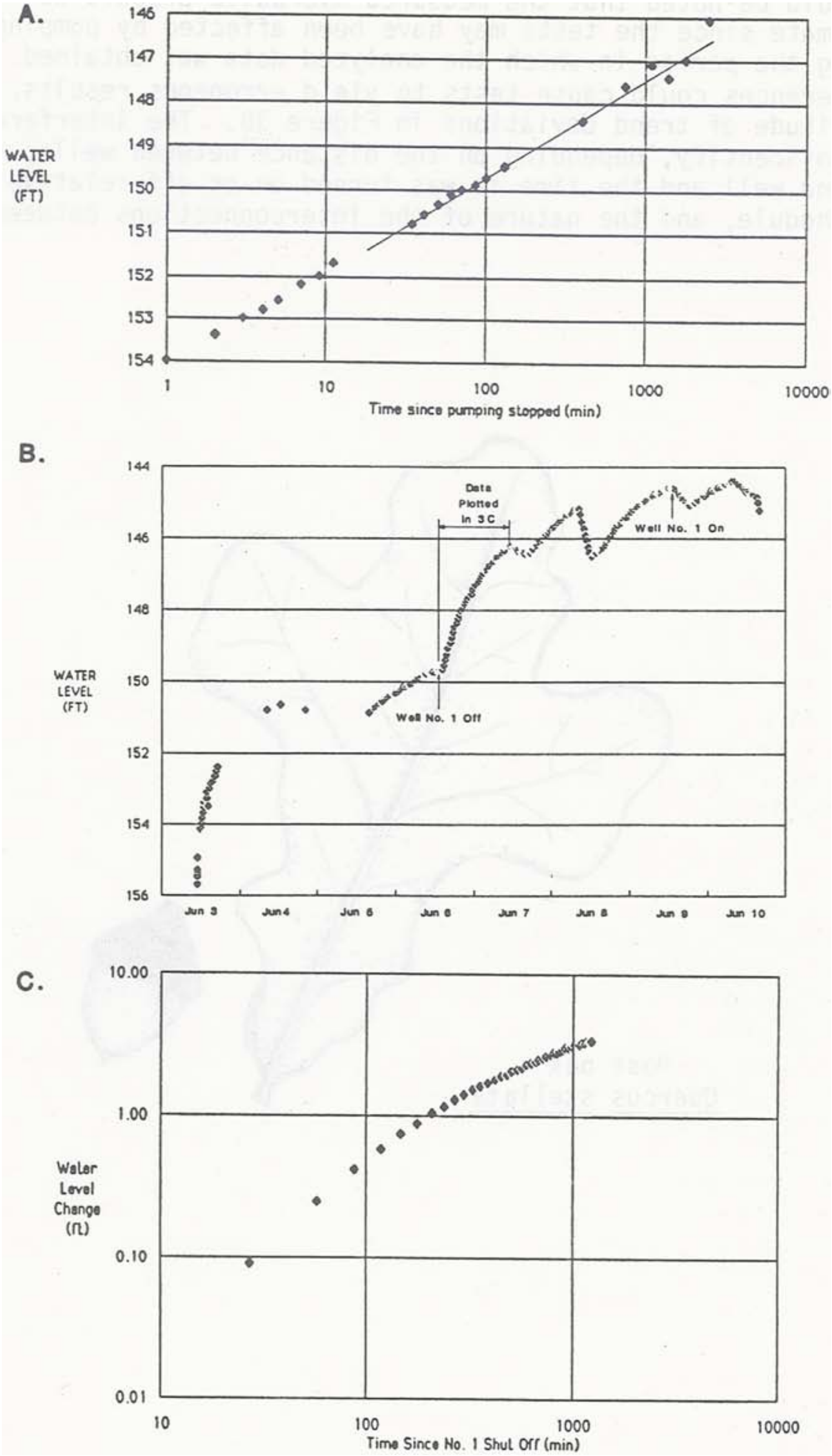
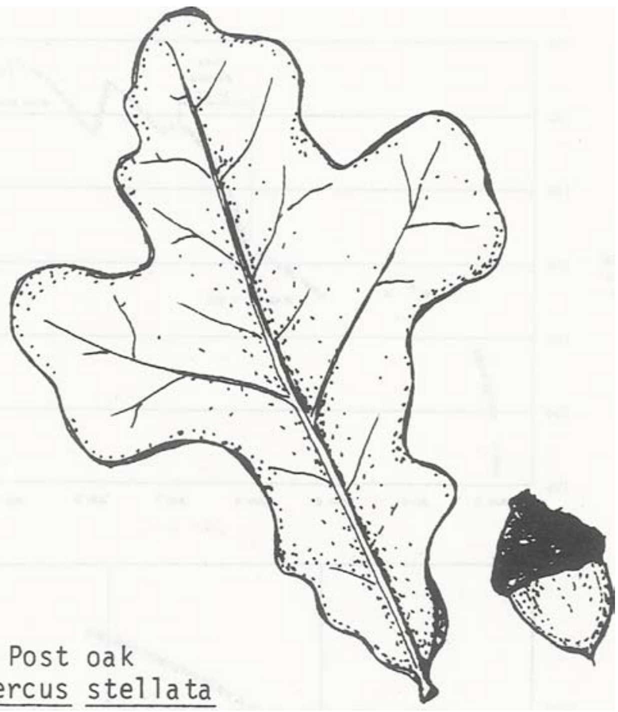


Figure 3A. Semilog Data Plot For Recovery Test of Well No. 1

3B. Water-Level Record for Well No. 2 Showing Interference by Well No. 1 and Other Wells.

3C. Log-Log Data Plot of Water Levels from Period Shown in 3B.

It should be noted that the measured hydraulic properties reported above are approximate since the tests may have been affected by pumping of other wells during the period in which the analyzed data was obtained. The potential interferences could cause tests to yield erroneous results, as suggested by the magnitude of trend deviations in Figure 3B. The interference could be difficult to identify, depending on the distance between wells, the flow rate of the second well and the time it was turned on or off relative to the pumping test schedule, and the nature of the interconnections between the wells.



Post oak
Quercus stellata

SPRINGS IN THE NORTHERN SEGMENT OF THE EDWARDS AQUIFER

Fred Snyder

INTRODUCTION / REGIONAL SETTING

The Edwards Aquifer, which extends from near Del Rio, northward along the Balcones Fault Zone to Bell County, is divided into three hydrologically distinct segments or regions. The San Antonio segment of the Edwards Aquifer extends from near Del Rio, northward to a groundwater flow divide (delineated by the surface water drainage divide between the Guadalupe and Colorado River basins) near the City of Kyle, approximately 20 miles south of Austin. The Barton Springs segment of the aquifer extends northward from the groundwater flow divide to the Colorado River, which has incised through the Edwards Limestone creating a no-flow boundary. The Northern Segment of the aquifer extends from the Colorado River and progressively thins to the north through Williamson County until it ultimately pinches-out in Bell County.

Basically, conditions occurring in one segment of the Edwards Aquifer have little or no effect on conditions in the other segments of the Aquifer. In the spring and fall of 1984, the Austin Geological Society sponsored field trips concerning the San Antonio and Barton Springs segments of the Edwards Aquifer. Thus, this field trip, which examines the northern-most segment, is the final chapter in the story of the Edwards Aquifer.

Travis, Williamson and Bell Counties straddle the Balcones Fault Zone, a major geo-cultural break in the earth's crust, which has resulted in abrupt bedrock changes that profoundly affect the distribution and occurrence of soils, vegetation, wildlife, surface water, groundwater, terrain, and even the weather. The Balcones Escarpment, a well-watered area where the west truly begins, separates the Hill Country rancher to the north and west from the Blackland farmer to the south and east. For the Northern Segment of the Edwards Aquifer, Balcones faulting has separated the water-table portion of the aquifer to the west from the artesian portion of the aquifer to the east.

The water-table zone of the aquifer is the area where the Edwards and Georgetown Limestones are exposed at the surface (Figure 1). It is here that surface waters can directly infiltrate and recharge the aquifer (as discussed by Slade and others - this volume). The water-table zone is characterized by countless low flowing springs that discharge along the base of the Edwards Limestone. Underlying geologic units, the Comanche Peak Limestone, Walnut Formation and the Glen Rose Limestone, are relatively impermeable compared to the Edwards, so that downward flowing groundwater moves laterally until it is discharged as spring flow in the stream valleys. Typically, with this type of groundwater system, flow distances from areas of recharge to discharge sites are relatively short.

The water-table zone of the Edwards Aquifer, being exposed at the surface, has been subjected to a great deal of erosion and is relatively thin in this area; therefore, the limestone does not possess the capability to store and transmit the quantities of water it could if its full thickness were present. Many of the springs in the water-table zone of the aquifer

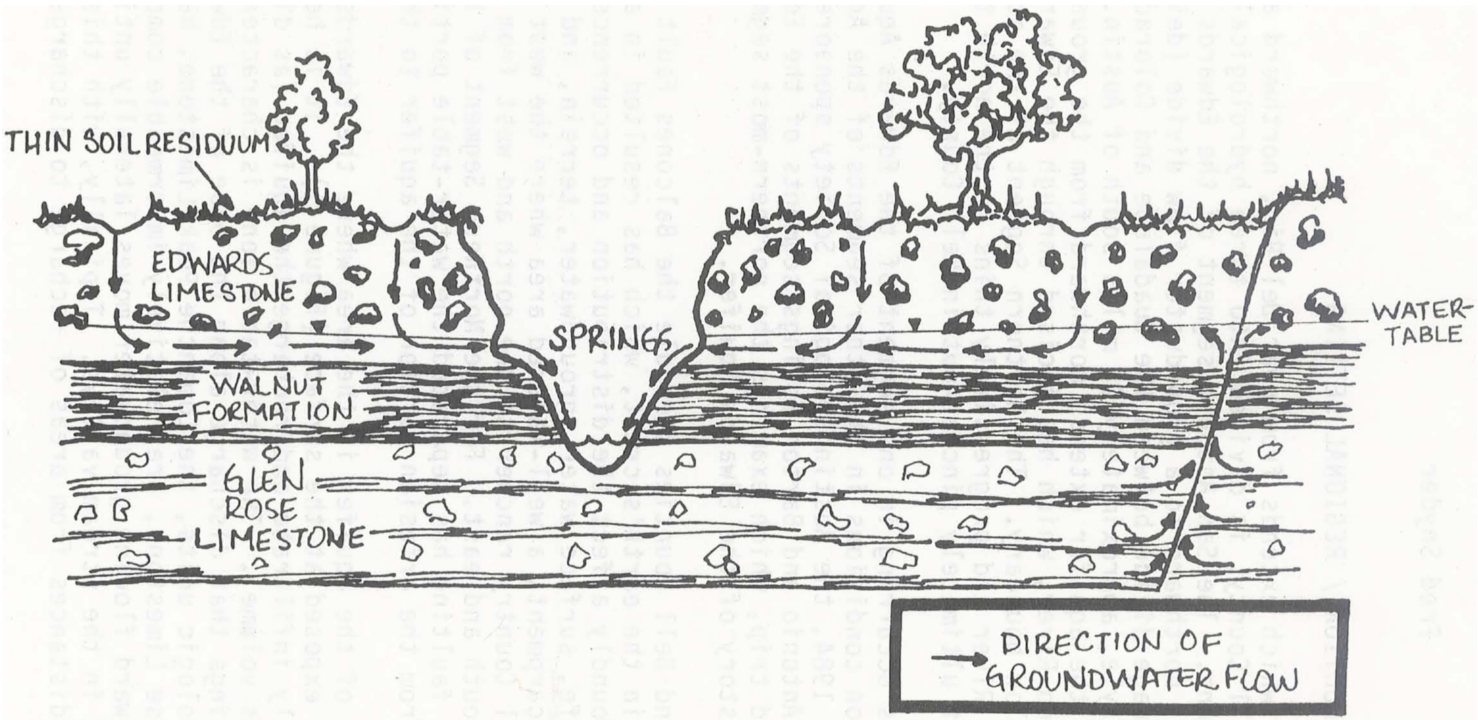


Figure 1.

Water-Table Zone of the Northern Edwards Aquifer reportedly continued to flow during the very dry conditions of the summer of 1984. This suggusts that the springs are receiving additional recharge, possibly from the underlying Trinity Aquifer. The Trinity Aquifer, which is under artesian head, may contribute sufficient recharge by upward leakage along nearly vertical faults and fractures to sustain spring flow even during drought conditions.

To the east the artesian zone of the Edwards Aquifer is overlain (from oldest to youngest) by the Del Rio Clay, Buda Limestone, Eagle-Ford Shale and Austin Chalk. In this area the full thickness of the Edwards Aquifer is present in the subsurface. The Artesian Zone is characterized by numerous springs, but in contrast to the water-table springs, these artesian springs seem to exhibit a greater rate of discharge. The artesian springs issue by upward flowing goundwater along nearly vertical faults and fractures in the younger formations overlying the Edwards Aquifer (Figure 2). Some of the springs in this area have reportedly never gone dry, including the drought period of the mid-1950s. Undoubtedly, some springflow is contributed by the Austin Chalk where since it is exposed at the surface. But this rock unit is typically characterized by local, low-flowing groundwater systems that cannot account for the relatively high and sustained springflow.

The presence of springs providing baseflow of streams in northern Travis and Williamson Counties are of considerable economic significance. Spring-fed streams, furnishing ample water supply, recreational possibilities, and mineral springs, have been commercially developed from time to time. Dissolution of limestone by water is responsible for the numerous caves enjoyed by spelunkers, some of which have been promoted for sightseers. The springs that feed the streams in the area insured both timber and good water so necessary to early settlers.

FIELD INVESTIGATIONS OF SELECTED SPRINGS

In September, 1985, field investigations of several selected springs (Figure 3) were conducted in which the specific conductance, PH, and temperature were measured (Table 1).

Specific conductance is an indication of the degree of mineralization of a water and may be used to estimate the concentration of dissolved solids in the water. Young groundwater is generally characterized by relatively low values of specific conductance, since during its short residence time within the limestone, only a limited amount of carbonate dissolution can occur resulting in groundwater relatively low in dissolved solids. On the other hand, older groundwater tends to become relatively more concentrated in dissolved solids, thus is characterized by higher specific conductance values.

Groundwater from the Edwards Aquifer generally has lower values of specific conductance as compared to groundwater from the underlying Trinity Aquifer. Specific conductance values of several selected springs were measured in an attempt to determine the origin of the spring waters. Values ranged from 444 micromhos to 816 micromhos. Most of the springs are probably a mixture of groundwater from both the Edwards and Trinity Aquifers, with the exception of some of the springs in the water-table zone which are characterized by relatively low specific conductance values suggesting origination solely from the Edwards Aquifer. The Edwards water, being

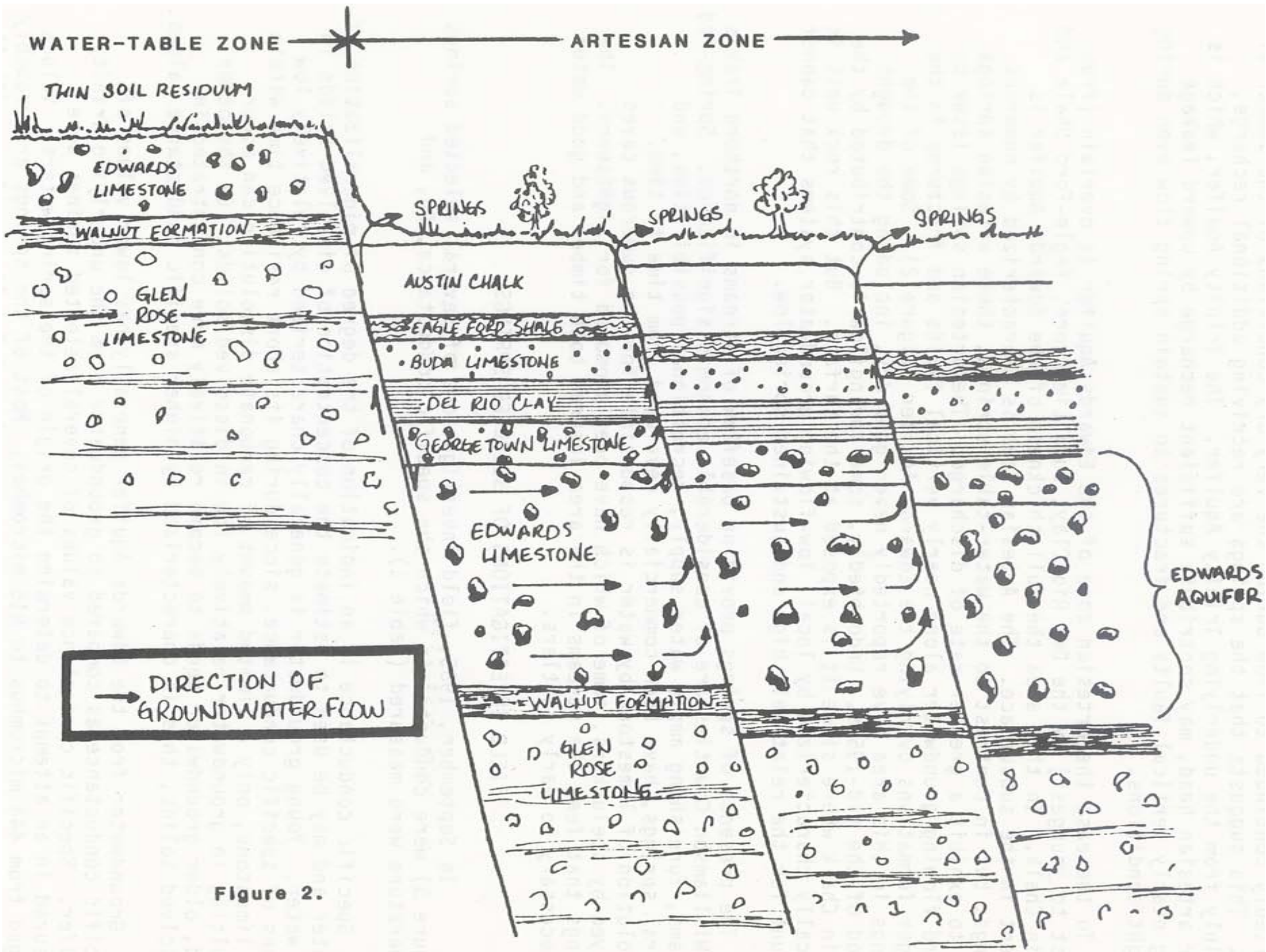


Figure 2.

Hydrogeologic Cross-Section of the Water Table and Artesian Zones of the Northern Edwards Aquifer Within the Balcones Fault Zone.

TABLE 1. VALUES OF WATER QUALITY PARAMETERS OF SELECTED SPRINGS (SEPTEMBER, 1985)

SPRINGS:	SPECIFIC CONDUCTANCE (umhos)	PH	TEMPERATURE (C)
GEORGETOWN SPRINGS:	633	7.05	22.0
BERRY SPRINGS:	609	6.95	22.0
PECAN SPRINGS:			
FISHER	584	7.44	
TANYARD	580	7.13	21.5
WARRICK	530	7.11	23.5
RUMSEY	576	7.13	21.8
POWER HOUSE SPRINGS:	618	7.31	21.5
TANGLEWOOD SPRINGS:	816	7.04	24.5
JESTER SPRINGS:	444	7.93	24.5
SCHLUMBERGER SPRINGS:	615	7.12	21.8

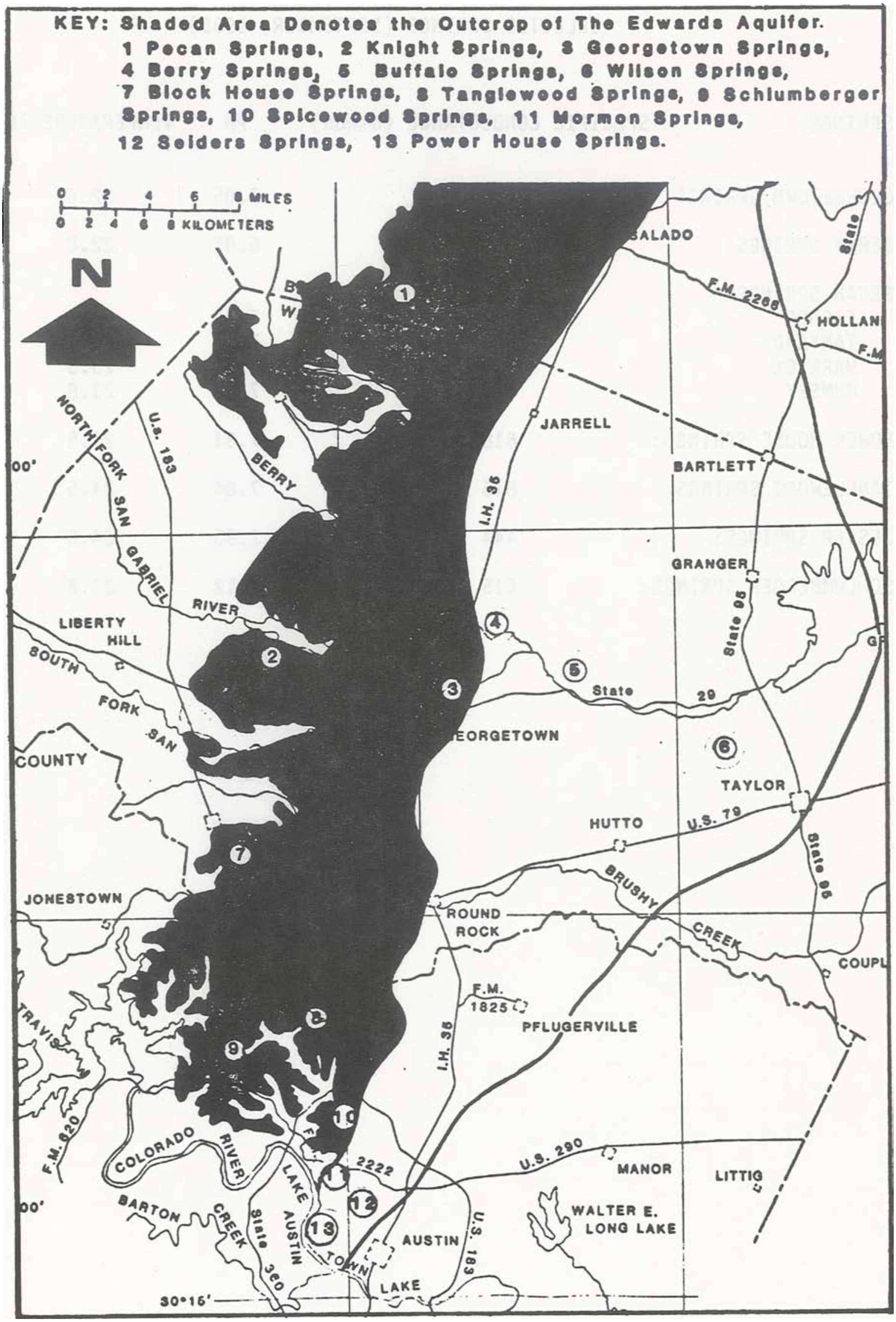


Figure 3. Locations of Selected Springs

relatively young and low in disolved solids, probably travels only a short distance from its recharge area to where it is discharged as spring flow. But groundwater flowing short distances through fractured and cavernous carbonate rocks, has little opportunity to have pollutant loading attenuated. Thus, over the water-table zone of the Northern Edwards Aquifer where groundwater flow distances are relatively short, water quality issues associated with development are most critical. The springs in Tanglewood Estates exhibit the highest value of specific conductance and are in an area presently undergoing intense development. Disturbance of the natural ground surface is resulting in highly increased erosion and sedimentation rates. The sediment-laden surface water infiltrates into the groundwater system; thus, the spring water becomes more highly concentrated in dissolved solids as reflected in elevated the specific conductance value.

The pH, like specific conductance, is a good indicator of general water quality. The pH of a solution is a measure of its hydrogen ion activity and is significant because it may affect taste, corrosion potential, and water treatment processes. The pH values measured of selected springs varied from 6.95 to 7.93. Most all of the values reflect the slightly basic (pH $>$ 7.0) character of the groundwater due to the prevalence of carbonates and bicarbonates, which tend to increase the PH.

The temperature of the spring waters varied from 21.5 degrees celsius to 24.5 degrees celsius. Spring water from the artesian zone tends to be relativey warm (22 degrees celsius) since it originates from deep below the surface where temperatures increase with depth. However, the springs in the water-table zone generally measured relatively cooler temperatures approaching the mean annual air temperature of this area. This may suggest that the water from the springs in the water-table zone originate from an intermediate depth that is not affected by a temperature gradient associated with increasing depth or by daily temperature fluctuations which may affect the more shallow depths. Some of the water-table springs are characterized by relatively high temperatures (24.5 degrees celsius), which may suggest that they originate from very shallow depths and probably flow along relatively short groundwater flow paths before discharging as springflow. It is interesting to note that the springs believed to be fed by water flowing only short distances as reflected in specific conductance values, are also the springs with the highest temperatures.

Spring discharge values of selected springs are given in table 2.

HISTORICAL ASPECT OF SPRINGS

Undoubtedly, the presence of springs were a major factor in the settlement of this area. Burned-rock midden and worked flint flakes found near several springs testify that prehistoric man valued this area of clear water as a place to live. Some springs in the area were a rest stop on the Chisolm cattle trail. Pioneer expeditions are known to have camped near springs in the area. Corn and flour mills built by early settlers utilized springs as a power source.

For additional examination of historical aspects of springs in this area, see Brune, 1981, and Scarbrough, 1973.

TABLE 2. DISCHARGE OF SELECTED SPRINGS

SPRINGS	DATE	DISCHARGE (cfs)
GEORGETOWN SPRINGS:	(1945)	3.5-5.0
	(July, 1975)	5.05
BERRY SPRINGS:	(March, 1964)	13
PECAN SPRINGS:	(June, 1975)	11
KNIGHT SPRINGS:	(July, 1940)	0.89
	(March, 1964)	0.66
	(July, 1975)	0.85
	(February, 1978)	0.78
WILSON SPRINGS:	(February, 1941)	0.1
	(May, 1975)	0.78
	(February, 1978)	0.46
BUFFALO SPRINGS:	(1975)	0.10
BLOCK HOUSE SPRINGS:	(July, 1975)	0.11
POWER HOUSE SPRINGS:	(December, 1895)	4.3
	(1897)	10
	(1899)	8
	(1970)	0.3
	(1973)	0.05
MORMON or TAYLOR SPRINGS:	(1904)	3
	(1918)	1.0
	(1973)	2.2
SEIDERS SPRINGS:		
upstream springs	(1978)	0.01
	(1979)	0.02
downstream springs	(1971)	0.34
	(1978)	0.04
	(1979)	0.06
SPICEWOOD SPRINGS:	(October, 1940)	0.0046
	(November, 1969)	0.05
	(July, 1974)	0.01
	(1979)	0

EDWARDS AQUIFER PROTECTION RULES, WILLIAMSON COUNTY

Steven P. Musick

On July 31, 1970 the Texas Water Quality Board, predecessor agency of the Texas Water Commission, adopted rules to protect the Edwards Aquifer in the San Antonio Region. The rules were designed to protect the aquifer through regulation of activities over the aquifer's recharge zone. The Edwards Aquifer is a carbonate aquifer with well developed karst features such as caves, solution channels, sinkholes, and large springs. These features contribute to the unique nature and also the unique susceptability of the aquifer to pollution from surface water sources. The Edwards Aquifer is the sole source supply of water for the San Antonio metropolitan area, with a population of over 1,000,000. Awareness of the vulnerability of their drinking water source prompted local government agencies to request State regulation to protect the aquifer. This same concern for groundwater protection also prompted the U.S. Congress to develop a program for the protection of sole source aquifers in the Safe Drinking Water Act of 1974 and the U.S. Environmental Protection Agency (EPA) to designate the Edwards Aquifer in the San Antonio region through this program as the nation's first federally protected Sole Source Aquifer.

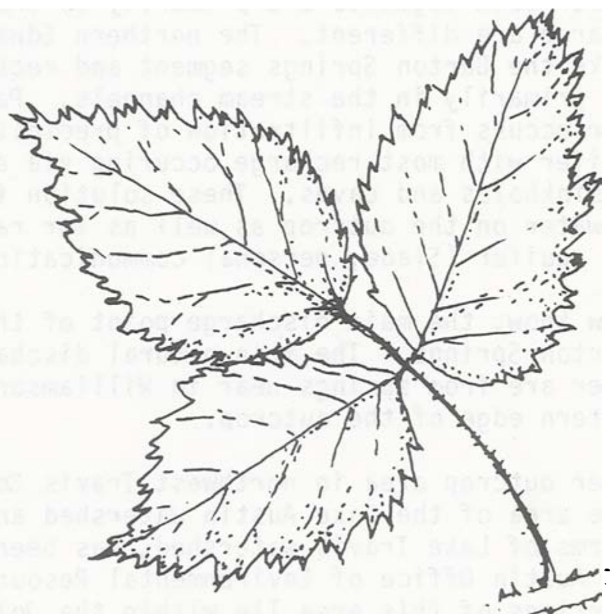
The City of Round Rock, concerned about its drinking water supply, requested the Texas Department of Water Resources (immediate predecessor to the Texas Water Commission) in the Spring of 1984 to adopt rules to protect the Edwards Aquifer in Williamson County. The Edwards Aquifer provides the sole source of water for the city of Round Rock, several communities, local industries, and private residences along and east of the IH 35 corridor in Williamson County. A large part of the public water supply for the City of Georgetown is also provided by the Edwards Aquifer. With the increased development of recent years has come dramatic increases in withdrawals of ground water from the Edwards Aquifer. Continued development will likely continue the increase in groundwater pumpage, possibly causing declines in water levels. Drought conditions during 1984 emphasized the susceptability of the aquifer to increased pumpage with many wells experiencing significant drawdown. Declining water levels could result in changes in the pattern of recharge to the aquifer. These concerns were important in the adoption of rules for Williamson County in April of 1985 to protect the recharge zone of the Edwards Aquifer.

The Williamson County rules were designed, based on the existing rules for the San Antonio Region, to protect the Edwards Aquifer through regulation of activities which may discharge pollutants to the surface waters over its recharge zone. There are six categories of activities which are regulated over the recharge zone: water pollution abatement, sewage collection systems, wastewater treatment and disposal systems, private sewage facilities, prohibited activities, and hazardous substance storage. The rules covering these activities are administered by the Texas Water Commission with the exception of private sewage facilities. The jurisdiction for this activity is delegated to the Commissioners Court of Williamson County. Compliance with the rules is achieved through submission of plans and specifications to the Commission's District 14 Office in Austin for review with approval from the Executive Director of the Commission. Wastewater discharges allowed under the aquifer protection rules must still apply for and receive a permit from the Texas Water Commission.

For activities on the recharge zone, the rules, in general: require a site specific geologic and technical report addressing prevention of pollution from surface water runoff for new developments; specify minimum standards for design and testing of sewage collection lines; prohibit new or increased wastewater discharges except irrigation; specify treatment levels for wastewater discharges for 10 miles upstream of the Recharge Zone; specify construction standards, density limitations, licensing requirements, and prohibited disposal methods for private sewage facilities; designate the County Commissioners Court of Williamson County as the licensing authority for private sewage facilities; prohibit certain activities such as feedlots, waste disposal wells, and solid waste landfills; and, require special construction standards, spill containment, and leak detection monitoring for storage of hazardous substances. The rules also provide procedures for appealing decisions of the Executive Director to the Texas Water Commission and requesting variances to the rules.

The Edwards Aquifer Protection Rules adopted for Williamson County will have a significant effect on development. Organized sewage treatment systems cannot increase current discharges on the recharge zone, nor will new discharges, i.e. new treatment plants, be allowed. New or increased discharges from wastewater treatment plants within 10 upstream miles of the Recharge Zone must meet the more stringent effluent discharge standards of 10 milligrmas per liter (mg/l) biochemical oxygen demand, 15 mg/l total suspended solids, and 2 mg/l ammonia nitrogen. For developments utilizing private sewage facilities such as septic tank systems, the density of such systems is limited to one unit per acre. In addition, residences served by private sewage facilities are required to connect to organized treatment systems when available. New sewage collection lines on the Recharge Zone are required to meet more stringent construction standards and exfiltration testing than are required elsewhere. Existing collection lines must be inspected for exfiltration. All collection lines must be evaluated every 5 years for leakage. Underground facilities storing hazardous substances are required to have double wall construction or approved equivalent construction. Above ground storage facilities are required to have spill containment area equal to 1.5 times the storage capacity of the facility.

The Recharge Zone is defined in the rules as that area specifically delineated on official maps in the offices of the Executive Director. The Recharge Zone for Williamson County is delineated on 12 U.S.G.S. 7.5 minute topographic base maps. The Recharge Zone consists primarily of the outcrop of the Edwards Limestone and the Georgetown Formation.



Dewberry
Rubus trivialis

ENVIRONMENTAL CONCERNS REGARDING THE NORTHERN EDWARDS AQUIFER

Laura De La Garza and Charles W. Sexton

INTRODUCTION

Over the past years the Barton Springs segment of the Edwards aquifer has received much attention however, the Edwards aquifer north of the Colorado River (northern Edwards aquifer) has been somewhat neglected. The geohydrology of these two segments are different in several respects. The Balcones fault zone is important in the formation of both aquifers, however in the Barton Springs segment the Balcones fault system is the western boundary of the recharge zone, whereas in the northern Edwards aquifer, the faults delineate the eastern boundary of the recharge zone.

Groundwater flow for both segments are primarily to the northeast, but the mechanisms of recharge are different. The northern Edwards does not have a contributing zone like the Barton Springs segment and recharge to the aquifer does not occur primarily in the stream channels. Part of the recharge to the northern aquifer occurs from infiltration of precipitation directly on the outcrop of the aquifer with most recharge occuring via solution cavities, i.e. stream channels, sinkholes and caves. These solution features allow for rapid infiltration of water on the outcrop as well as for rapid movement of groundwater within the aquifer (Slade, personal communication).

As most people now know, the main discharge point of the southern Edwards aquifer is from the Barton Springs. The main natural discharge points of the northern Edwards aquifer are from springs near in Williamson and Bell Counties, near the eastern edge of the outcrop.

The Edwards aquifer outcrop area in northwest Travis County, particularly the Bull Creek drainage area of the Lake Austin watershed and the Cypress Creek and Lime Creek arms of Lake Travis watershed, has been extensively studied by the City of Austin Office of Environmental Resource Management (OERM) (figure 1). Portions of this area lie within the Jollyville Plateau, which is nearly flat terrain where the Edwards limestone is exposed along Highway 620. This northwest area is hydrogeologically and biologically distinct from the main portion of the rest of the northern aquifer and will be further explained in the body of this paper. Drainageways have cut through the lower portion of the Edwards Limestone, the Walnut Formation (the confining layer of the aquifer), to the Glenn Rose Limestone. This process of downcutting has created a highly dissected terrain known as the Hill Country. What is of interest is the edge of the Jollyville Plateau where drainageways have cut into the resistant limestone creating steep canyon heads. The slope breaks which expose the contact between the base of the Edwards Limestone and the confining Walnut Formation are the points of discharge from the water-table aquifer. Springs are abundant in the canyon heads of Bull, Cypress, and Lime Creeks.

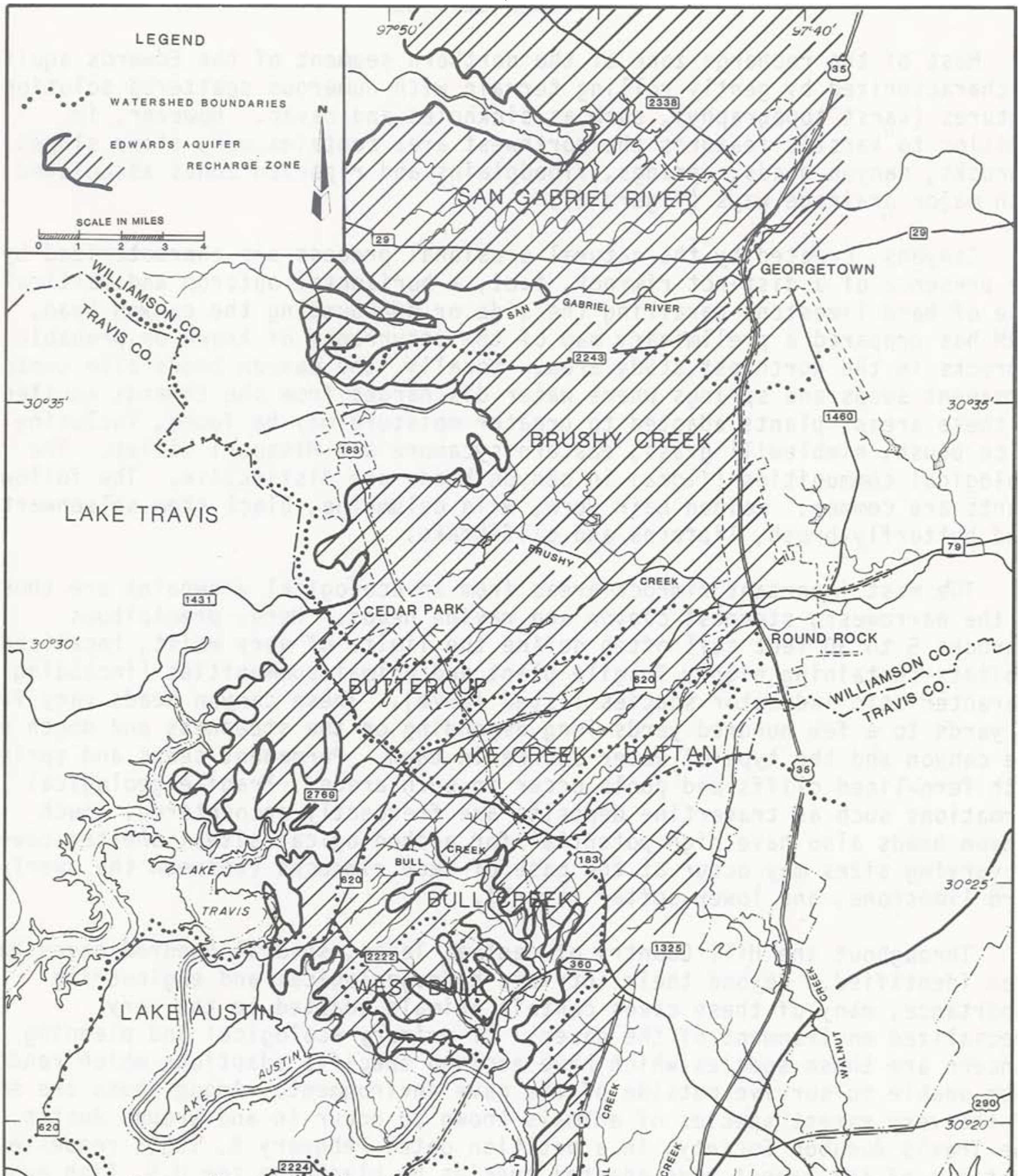

LEGEND
WATERSHED BOUNDARIES
EDWARDS AQUIFER RECHARGE ZONE
N
SCALE IN MILES
0 1 2 3 4
97°50'
97°40'
30°35'
30°30'
30°25'
30°20'
30°15'
SAN GABRIEL RIVER
GEORGETOWN
SAN GABRIEL RIVER
WILLIAMSON CO.
TRAVIS CO.
BRUSHY CREEK
LAKE TRAVIS
BRUSHY
CREEK
CEDAR PARK
ROUND ROCK
BUTTERCUP
LAKE CREEK
RATTAN
BULL CREEK
BULL CREEK
LAKE TRAVIS
WEST BULL
LAKE AUSTIN
LAKE AUSTIN
WALNUT CREEK
SHOAL CREEK
WALLER CREEK
WALTER E. LONG LAKE
BARTON CREEK
CREEK
BARTON
TOWN LAKE
LAMAR
COLORADO RIVER
HAYS CO.
35
2338
29
2243
1460
183
79
1431
620
2769
1325
2222
360
290
1
2224
71
696
973
LDLG Oct 85

Figure 1

PHYSICAL SETTING

Most of the recharge zone of the northern segment of the Edwards aquifer is characterized by gently rolling terrain with numerous scattered solution features (karst topography), such as sinkholes and caves. However, in addition to karstic features the northwest area contains many steep slopes, rimrocks, canyon heads, springs, floodplains and riparian zones associated with major drainage ways (figure 2).

Canyons, created by the natural erosional process are characterized by the presence of a distinct rimrock, i.e., a horizontal outcrop and vertical face of hard limestone paralling the side or surrounding the canyon head. OERM has prepared a preliminary map of the occurrence of known or probable rimrocks in the northwest study area. Locally, the canyon heads also contain permanent seeps and springs where water discharges from the Edwards aquifer. In these areas, plants adapted to greater moisture may be found, including spice brush, nimblewill grass, eastern sycamore and Missouri violet. The biological communities (flora) in canyon heads are distinctive. The following plants are common: maiden hair fern, wild columbine, black stem spleenwart, wand butterfly-brush, lipferns and cliffbrake.

The most important rimrock areas from an ecological viewpoint are those in the narrowest, steepest canyon and ravine heads. Here, precipitous rimrocks 5 to 30 feet tall often define the limits of very moist, localized habitats containing highly fragile plant and animal communities (including the characteristic indicator species listed above). These canyon heads vary from 25 yards to a few hundred yards long depending on the steepness and depth of the canyon and the type of water source in them. Permanent seeps and springs with fern-lined cliffs and pools occur in such areas. Fragile geological formations such as travertine deposits are frequently encountered. Such canyon heads also have high potential for archeological sites; shelter caves of varying sizes may occur at the base of such rimrocks (between the overlying hard limestone, and lower softer layers).

Throughout the Hill Country of central Texas, several hundred caves have been identified. Beyond their intrisic hydrogeological and engineering importance, many of these caves contain animals adapted to the very specialized environment of the caves. Of primary ecological and planning concern are those species which have evolved specific adaptions which render them unable to survive outside of the cave environment. Among these are some of the very rarest species of animals known to occur in and around Austin. The Travis Audubon Society, in a petition dated Feburary 8, 1985, requested that six of the rarest cave-adapted species be placed on the U.S. Fish and Wildlife Service's list of endangered species.

ENVIRONMENTAL CONCERNS

The major goal of the City of Austin is to maintain good water quality. The northern Edwards aquifer not only supplies drinking water for many people in northern Travis and Williamson Counties, but also contributes water from spring flow to Lake Travis and Lake Austin (the City's primary sources of water). The quality of water from springs, storm-water runoff and wastewater effluent that gathers in the creeks is directly related to the water quality of the lakes.

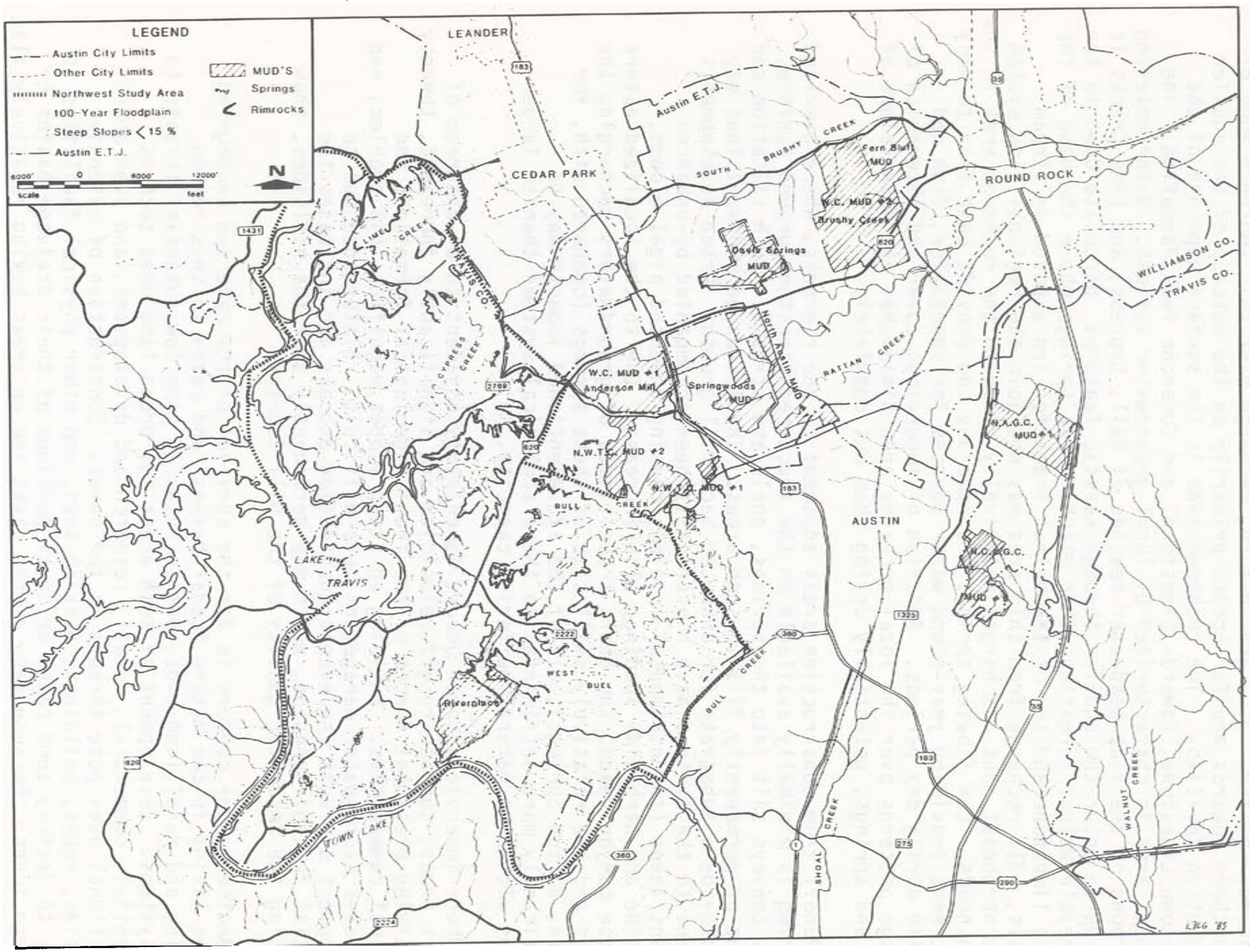

LEGEND
Austin City Limits
Other City Limits
Northwest Study Area
100-Year Floodplain
Steep Slopes < 15 %
Austin E.T.J.
MUD'S
Springs
Rimrocks
scale
feet
N
LEANDER
CEDAR PARK
ROUND ROCK
AUSTIN
Austin E.T.J.
SOUTH BRUSHY CREEK
Fern Bluff MUD
W.C. MUD #2 Brushy Creek
Davis Springs MUD
WILLIAMSON CO.
TRAVIS CO.
RATTAN CREEK
W.C. MUD #1 Anderson Mill
Springwoods MUD
North Austin MUD
N.W.T.C. MUD #2
N.W.T.C. MUD #1
N.A.G.C. MUD #1
N.C.M.G.C. MUD #3
LIME CREEK
TRAVIS CO.
CYPRESS CREEK
BULL CREEK
WEST BULL
LAKE TRAVIS
Riverplace
TOWN LAKE
SHOAL CREEK
WALNUT CREEK
183
1431
2769
620
2222
360
1325
35
275
290
2224
1
LBLG '85

Figure 2

Recharge in this region north of the Colorado River is not concentrated in the stream beds as is commonly the case over the Barton Springs segment of the Edwards aquifer. As stated before, recharge over this southern edge of the northern Edwards aquifer occurs primarily on the outcrop of the aquifer via solution cavities. The recharge zone is the surface exposure of the Georgetown Limestone, Edwards Limestone, and Comanche Peak Formation. The northwest area is characterized by local groundwater systems. Water entering the ground on the flat headwater reaches of Bull, Cypress, and Lime Creeks is believed to enter the aquifer through karstic features, percolate down to the impermeable Walnut formation, then discharge as springs where the base of the Edwards limestone and top of the Walnut Fromation are exposed in stream channels. All recharge from this area may not join the regional flow system to the northeast, but discharges relativelly close to the recharge area in the canyon heads. Low flowing springs are numerous and provide base flow to many area creeks providing year-round water sources for vegetation, fish and wildlife during dry periods. Addition of impervious cover and alteration of drainage patterns over the local recharge area diminishes the flow volume of seeps and springs, potentially drying them out completely.

Runoff from construction areas adjacent to the rimrocks, where overland filtering is minimally available on the fractured limestone ground surface, easily conveys silt into the springs, pools and streams. Such siltation can plug up or permanently fill in such areas. The increased sediment load may also provide a substrate for enhanced bacterial growth. Urban developments adjacent to the springs have historically been accompanied by enhanced nutrient loads (to detrimental levels), causing unwanted algal blooms. Pesticide and herbicide loadings also increase. Due to the localized nature of these canyon heads, the short travel times of groundwaters recharging the springs and the relatively small size of these springs (compared with, for example, Barton Springs), all of the aforementioned impacts may be significantly more detrimental to these ecological systems than to larger systems with more natural buffering capacity.

Where impervious cover occurs immediately adjacent to or upstream of rimrock areas, surface runoff velocities are significantly increased, thereby multiplying erosional forces of the fragile geological formations and botanical communities. Building on steep slopes magnifies this problem, and this makes storm-water management more difficult. Disturbance due to development disrupts the evapotranspiration process and increases the potential for soil erosion, which may permanently scar the hillsides, thus impacting the aesthetic quality of the Hill Country.

Another major concern is for the survival of the rare and endangered species living in the mature "cedar brakes" and caves in this region. Ranching and rural land uses, per se, usually pose low potential threats to cave systems. Development of such areas for urban land uses such as residential, commercial, retail, research and development, and even some recreational uses pose threats to the caves. Construction of extensive utilities, roads, buildings, parking lots, and other physical facilities is likely to destroy some caves or cover portions of their drainage basins or recharge zones. Because many of the caves are on areas having relatively flat Edwards limestone outcrops, the cave entrances occur on land not protected by existing prohibitions of development on steep slopes or floodplains. In other words, these caves occur on land which might otherwise be considered highly desireable (or necessary) for placement of structures. Inadvertent damage to caves by ill-trained or uninformed construction contractors is a distinct possibility. At present, for instance, compliance with existing City of Austin requirements for erosion and sedimentation controls measures is frequently inadequate. Actions are currently being taken to ensure higher compliance of the controls.

Portions of the norther Edwards aquifer contains prime habitats for rare and endangered birds, i.e., the Golden-cheeked Warbler and Black-capped Vireo. The Golden-cheeked Warbler is obligately dependent on old juniper-oak woodlands for nesting habitat with the amount of habitat available for the species seriously declining. The Black-capped Vireo is a small bird species which has been declining seriously in much of its breeding range. The primary center of distribution is now the Texas Hill Country.

PROTECTION STRATEGIES

1) Construction setbacks of a minimum of 150 feet from canyon heads and rimrocks. This setback would apply as well to temporary and permanent erosion control measures. Since rimrocks often grade away gradually in height to lesser stature as one procedes down-canyon, setbacks may be lessened where the rimrock is less than 5 feet high and no permanent surface water feature occurs in the adjacent canyon. Roads and utilities such as water and wastewater lines and transmission lines should be routed well around such canyon heads.

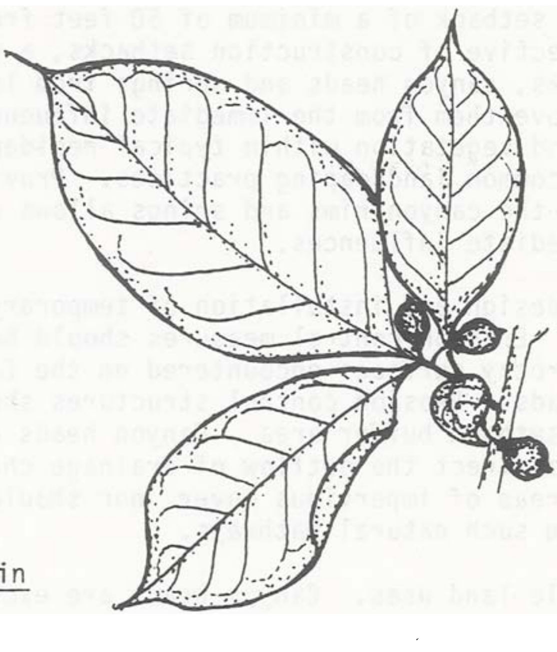
2) Lot-line setback of a minimum of 50 feet from canyon heads and rimrocks. Irrespective of construction setbacks, a primary mechanism avilable to protect rimrocks, canyon heads and springs from long-term urbanization impacts is to remove them from the immediate influence of residental lots. Impacts on soil and vegetation within typical residential lots is routinely pervasive due to common landscaping practices. Providing a setback from the most sensitive of the canyon rims and srings allows an ecological buffer outside these immediate influences.

3) Special design and installation of temporary and permanent erosion control measures. Erosion control measures should be appropriate for the highly irregular rocky surfaces encountered on the Edwards limestone adjacent to such canyon heads. Erosion control structures should not be placed within the construction setback buffer area. Canyon heads and ravines should not be used as targets to direct the outflow of drainage channels which collect water from the neraby areas of impervious cover, nor should surface flows be routed entirely away from such natural pathways.

4) Compatible land uses. Canyon heads are excellent areas near urban areas for small-scale nature interpretation facilitities. Steep canyon heads, with their sensitive habitats and diverse biological assemblages, are among the most appropriate areas to convey to the City of Austin's Nature Preserve System.

5) Ultimate protection of the biological diversity in Austin area caves depends on the physical protection of cave entrances, their local drainage basins, and, in some cases, the recharge zone for their subterraean waterbodies.

6) The Black-capped Vireo and Golden-cheeked Warbler are best protected by outright habitat preservation. Some warbler habitat is protected in the Barton Creek Greenbelt, Wild Basin Wilderness Park, the Travis Audubon Sanctuary, and in Lake Austin Municipal Park. Because of constraints placed on development on steep slopes enacted in various watershed ordinances during the past ten years, some Golden-cheeked Warbler habitat has also been protected on steep canyon slopes in certain developments west of Austin. Since known vireo sites west of Austin do not occur in floodplains or on steep slopes, there has been no previous protection of their habitat under existing ordinances. Habitat preservation may be accomplished in any for of permanent open space such as greenbelts, conservation easements, natural area parks or nature preserves. Vireo and warbler habitats should not be utilized for neighborhood parks or other heavy recreational use areas, but may be located next to such areas if appropriate physical protection or ecological buffering can be accomplished. These habitats should be preserved in the largest contigous blocks practical, rather than in isolated strips or islands of habitat surrounded by other land uses.



Spice wood
or
Spice bush
Lindera benzoin

REGULATION AND DEVELOPMENT OF THE
NORTHERN EDWARDS AQUIFER

Maureen McReynolds

INTRODUCTION

The area of the northern segment of the Edwards aquifer is within one of the most rapidly growing parts of Central Texas. Although precise data regarding growth rates for this area is not available, the following are growth rates for four of the cities which are at least partially in the recharge zone.

Table 1

Annual Growth rate estimates for the period 1980 - 1985

Georgetown	7.9%
Round Rock	16.7%
Cedar Park	8%
Leander	9.4%

(Source: Capital Area Planning Council)

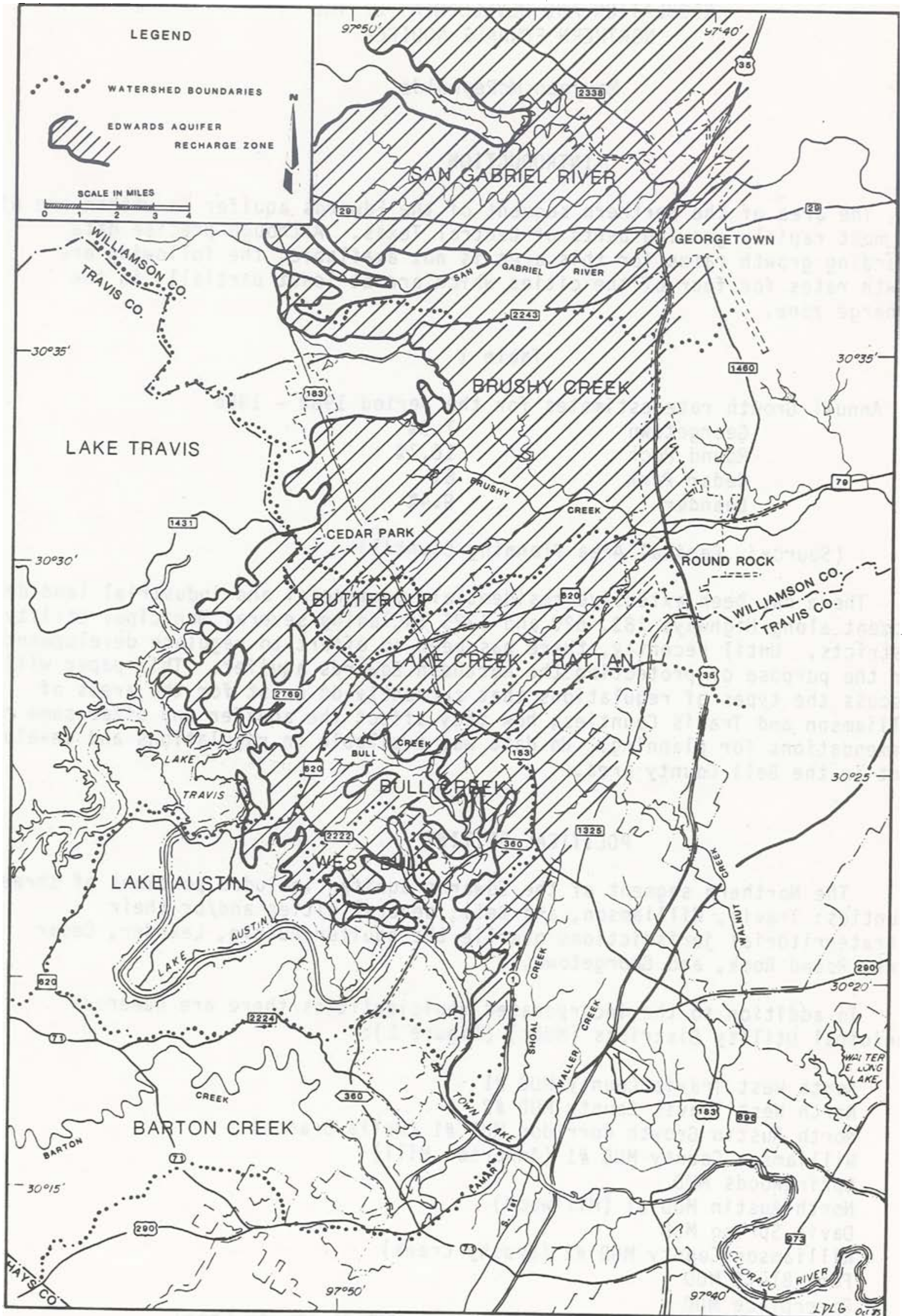
There has been extensive residential, commercial and industrial land development along Highways 183, 620 and 1325 including several Municipal Utility Districts. Until recently, there has been no effort to regulate development for the purpose of protecting the northern Edwards aquifer. This paper will discuss the types of regulations that currently do exist for the areas of Williamson and Travis Counties, how they affect the aquifer and offer some recommendations for planning. No data was available on regulations and development in the Bell County area.

POLITICAL SETTING

The Northern segment of the Edwards aquifer includes portions of three counties: Travis, Williamson, and Bell; several cities and/or their extraterritorial jurisdictions overlie the aquifer:Austin, Leander, Cedar Park, Round Rock, and Georgetown.

In addition to the incorporated municipalities there are numerous Municipal Utility Districts (MUDs) (Figure 1):

North West Travis County MUD #1
North West Travis County MUD #2
North Austin Growth Corridor MUD #1 (Wells Branch)
Williamson County MUD #1 (Anderson Mill)
Springwoods MUD
North Austin MUD #1 (Millwood)
Davis Spring MUD
Williamson County MUD #2 (Brushy Creek)
Fern Bluff MUD
Riverplace MUD
North Central Austin Growth Corridor MUD #1 (North Star)


LEGEND
WATERSHED BOUNDARIES
EDWARDS AQUIFER RECHARGE ZONE
SCALE IN MILES
0 1 2 3 4
N
97°50'
97°40'
30°35'
30°30'
30°25'
30°20'
30°15'
SAN GABRIEL RIVER
SAN GABRIEL RIVER
GEORGETOWN
WILLIAMSON CO.
TRAVIS CO.
BRUSHY CREEK
BRUSHY CREEK
LAKE TRAVIS
CEDAR PARK
ROUND ROCK
BUTTERCUP
LAKE CREEK
RATTAN
BULL CREEK
BULL CREEK
LAKE TRAVIS
WEST BULL
LAKE AUSTIN
LAKE AUSTIN
WALNUT CREEK
SHOAL CREEK
WALLER CREEK
WALTER E LONG LAKE
TOWN LAKE
LAMAR
S. 1st
BARTON CREEK
BARTON
CREEK
COLORADO RIVER
HAYS CO.
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2243
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183
79
1431
620
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LDLG Oct 85
Figure 1

A water pollution abatement plan must be approved prior to construction in a regulated development. The rule identifies regulated development as any residential subdivision or any public or private industrial, commercial, or multi-family construction, not located within the jurisdiction of an incorporated city or town exclusive of its ETJ. Residential subdivisions in which every lot is larger than five (5) acres and no more than one single-family residence per lot are not considered regulated developments.

The water pollution abatement plan must include a description of the nature and size of the development, the volume and character of the wastewater expected to be produced and the method of disposal, the character of stormwater runoff expected to occur, measures to be taken to prevent pollutants from entering significant recharge areas and any proposed methods for pluging wells, where applicable. For regulated developments consisting of more than 100 family units, or non-residential developments more than five (5) acres in size, the applicant must submit a geologic assessment which includes identification and location of any significant recharge areas in the development. (The rule defines significant recharge areas as sinkholes, caverns, faults and other geological features where rapid infiltration to the subsurface may occur.)

All owners of sewage collection systems on the recharge zone must meet special requirements. The major ones are summarized below:

1. Monolithic, caste-in-place concrete or precast fiberglass manholes with watertight rings and covers;
2. Compression or mechanical joints;
3. New and existing sewer lines to be tested, evaluated and certified by a Registered Professional Engineer and thereafter evaluated every five years;
4. New collection lines to have "stub outs" for the connection of anticipated private service laterals; private service laterals to be constructed sufficient to extend beyond the edge(s) of any street pavement under which they must pass;
5. All new gravity sewer pipe must meet the following requirements:
   (a) In place testing pulling a mandrel sized at 95% of the inside diameter (normally 92.5% is used);
   (b) Maximum allowable infiltration/exfiltration not greater than 50 gal. per inch of pipe diameter per mile per 24 hours (normally 200 gal. is acceptable);
   (c) Embedment materials to be of the highest class;
6. Prior to connecting a private service lateral into an organized sewage collection system, its conformance with the rules to be determined by a visual inspection and certified by a Registered Professional Engineer, Registered Sanitarian or appropriate city inspector;
7. Lines placed in areas subject to innundation and stream velocities which could cause erosion and scouring of backfill to be capped or encased with concrete;
8. Sewer lines that bridge caverns, sinkholes or solution channels to be constructed to maintain the structural integrity of the lines.

Sewer collection systems must operate in a manner so as not to cause pollution of the Edwards aquifer.

Each type of political subdivision has been designated some authority by the State of Texas which relates to water quality. Counties can adopt septic tank regulations. The regulations must be adopted by the Texas Water Commission (TWC) before they can be enforced. The County Health Department has a role in other health related problems, such as clean-up of pollution of a stream caused by a faulty septic tank or a chemical spill.

Municipalities can adopt and enforce subdivision regulations within their incorporated limits and extra-territorial jurisdiction (ETJ). Cities can also construct and operate sewage treatment plants which have been approved by the TWC.

Municipal Utility Districts are generally formed to provide a financing mechanism for construction of water, wastewater and fire protection facilities. Prior to issuance of a consent agreement for formation of a MUD within its ETJ, the City of Austin negotiates land development and fiscal plans with MUD representatives. A major goal of these negotiations is to minimize environmental impacts. If no agreement can be reached, the developer can, after meeting several conditions, request formation of the district through the TWC without the City's consent. Municipal Utility Districts which form outside of a city or its ETJ do not require such a consent agreement.

Water Control and Improvement Districts (WCID) are formed by the TWC under a different set of rules than MUDs. They can also provide water and sewer services. Currently, the Brushy Creek WCID is developing plans for a regional sewage treatment plant in the Brushy Creek watershed. The regional plant could serve all or part of several cities and MUDs.

Population projections for the area north of Austin and between Cedar Park and Round Rock were developed by consultants for the Brushy Creek WCID in March, 1985. The 1980 population density of the area was estimated to be 0.3 persons per acre (approximately 50,000). The population for 2010 is expected to be about 3 persons per acre or 290,000. with an ultimate build-out in 2035 of approximately 500,000 people.

REGULATIONS TO PROTECT THE AQUIFER

Rules of the Texas Water Commission

The most comprehensive set of regulations for protection of the Northern segment of the Edwards aquifer is the TWC (formerly Texas Water Devlopment Board) rule for Williamson County. The purpose of this subchapter is "to regulate activities with the potential for causing pollution of the Edwards aquifer. The activities addressed are those that pose direct threats to water quality."

The regulations address: land developments; sewage collection systems; wastewater treatment and disposal systems; private sewage facilities; and static hydrocarbon and hazardous substance storage facilities located within the recharge zone of the Edwards aquifer.

The importance of high standards for sewer lines in the Edwards aquifer is emphasized by instances of direct contamination of the aquifer. Barton Springs swimming pool in the Southern segment of the Edwards aquifer was closed several times because of high bacteria counts after rains in 1982. A major source of the bacteria was found to be broken sewer lines. (Bacteria counts also rise after rains as a natural result of stormwater runoff.) An outbreak of disease in Georgetown several years ago was traceable, at least in part, to contamination of water supplies in the Edwards aquifer from leaking sewer lines.

No new or increased discharges of treated wastewater will be permitted on the recharge zone. Land application of treated wastewater will be permitted on a case-by-case basis. All new or increased waste discharges for a distance of ten (10) miles upstream must, at a minimum, attain 10 Biochemical Oxygen Demand (BOD); 15 Total Suspended Solids (TSS); and 3 ammonia nitrogen (numbers represent parts per million). A list of existing and proposed sewage treatment facilities is shown in Table 2.

The Commissioners Court of Williamson County is the designated licensing authority for private on-site sewage facilities. Both a permit to construct a facility and a permit to operate it are required. Conditions for permit approval include:

1. Lot or tract must be large enough to permit the use of a private sewage facility without causing pollution, nuisance conditions or danger to public health.
2. Generally the minimum lot size must be one (1) acre.
3. No construction of a private sewage facility on steep slopes is permitted without proper construction techniques.
4. If the natural percolation rate is faster than one minute per inch or slower than sixty (60) minutes per inch an alternate site or alternate disposal method must be selected.
5. No components can be covered until an inspection has been made.

A license to operate a sewage disposal system may be revoked or suspended if the facility is not properly maintained or is causing pollution of the Edwards aquifer.

Prohibited activities include underground injection wells; new animal feedlots; and land disposal of industrial solid waste.

Facilities for underground storage of static hydrocarbon or hazardous substances must be of double-walled construction or an equivalent method. They must include leak-detection systems and spill-containment areas.

Facilities used for the above-ground storage of static hydrocarbons or hazardous substances must be constructed within controlled drainage areas that are sized to capture one and one-half times the storage capacity of the facility and that direct any spillage to a point convenient for the collection and recovery of the spillage.

The executive diretor of the Texas Water Commission intends to undertake further studies of the Comanche Peak Formation in order to determine if it should be included as part of the Edwards aquifer. Also, the TWC and the

TABLE 2

Sewage Treatment Plants located in the Northern Edwards aquifer

Name	Method of Disposal	Flow (MGD)	BOD (mg/l)	TSS (mg/l)	N (mg/l)	DO (mg/l)
Florence	irrigation	.25	20	20		
Lone Star Industries	retention	.05				
Jalarco, Inc.	irrigation	.05	20	20		
Williamson Co., MUD #1 Anderson Mill	discharge	.90	10	15		2
Williamson Co., MUD #2 Brushy Creek	discharge	.45	10	15		
Williamson Co., MUD #2 Brushy Creek North	discharge	.10	10	15		
Quantum Investments	irrigation	.02	20	20		
Block House Dev. Corp.	discharge	.10	10	15		
Williamson Co., MUD #3 Buttercup Creek	discharge	.25	25	40		2
Highland Resources Maconda Park	discharge	.60	10	15		2
Cedar Park #1	discharge	1.	10	15	3	4
Cedar Park #2	irrigation	.01	20			
Texas Tumbleweed	retention	.004				
Spicewood Dev. Balcones Village	irrigation	.181	20	20		
Leander	discharge (pending)	.75	10	15	3	5

Sewage Treatment Plants located in the Northern Edwards aquifer

Name	Method of Disposal	Flow (MGD)	BOD (mg/l)	TSS (mg/l)	N (mg/l)	DO (mg/l)
Bill Milburn (Anderson Mill West)	discharge (pending)	.10	10	15	2	4
Emile Jamail Davis Springs Branch	discharge (pending)	1.2	10	15		
Leander ISD	retention (pending)	.016				
Block House MUD	discharge (pending)	.5	5	5		1
NPC, Cedar Park MUD #1	irrigation (pending)	.115	10	15		
NPC, Williamson Co. MUD #7	irrigation (pending)	.1	10	15		
SCB Dev. Co. Logan Ranch	irrigation (pending)					
Spicewood Dev. Corp., STP #3	irrigation (pending)	.285	20	20		
Doyle Wilson The Parke	irrigation (pending)	1.27	10	15		

United States Geological Survey are preparing a project proposal that would study the Georgetown Formation in the Georgetown area to determine if it should be included as part of the aquifer.

Hazardous Materials Storage and Registration Ordinance

Another set of regulations that specifically addresses protection of the Edwards aquifer is the City of Austin's Hazardous Materials Storage and Registration Ordinance. This ordinance, which went into effect in June, 1985, applies within Austin's corporate limits and ETJ in the area of the Edwards aquifer recharge zone. This includes the recharge zone in the Lake Austin, Lake Travis, and Walnut Creek watersheds and portions of Lake Creek and Rattan Creek watersheds.

Hazardous materials stored at any facility in the regulated area must be registered with the City of Austin Fire Department. There are requirements for above-ground storage facilities as well as below-ground facilities. The purpose of the ordinance is protect the public health, life, resources, environment and property; to ensure fire protection, and to safeguard the health and lives of fire, police and emergency medical services personnel, by regulating the handling and storage of flammable or combustible liquids, solids or gases, organic or inorganic chemicals and fuels, and other hazardous materials.

Underground storage tanks have become a subject of national concern because of widespread leakage found in older tanks and groundwater pollution which has occurred as a result of the leakage.

Austin's requirements are similar to those of the TWC Williamson County Rules regarding hazardous materials and static hydrocarbon storage and use over the Edwards aquifer recharge zone. Existing underground storage tanks are to be tested for leaks with the frequency dependent on the age of the tanks (See Table 3).

Septic Tank Regulations

Septic tanks are regulated by the County Health Departments. The septic tank rules for the Edwards aquifer recharge zone in Williamson County have been described above. In Travis County, the septic tank rules are enforced by the Austin Travis County Health Department and have been adopted by the TWC.

The Travis County rules differ from those in Williamson County and in some areas are more stringent. For example, Travis County's percolation standards appear to be more stringent than those in the Williamson County TWC rules. Satisfactory rates are between 5 inches per 30 minutes and 20 inches per 30 minutes. Rates between 1 inch per 30 minutes and 5 inches per 30 minutes are considered marginal.

Geology and soils of Travis County are divided into three areas. Area II includes the areas of the Edwards and associated limestones. This area is considered marginal for septic tanks. Infiltrative capacity may be high, however effluent can travel along fractures with little or no cleaning action. The numerous springs in the area, the steep slopes, and the shallow,

TABLE 3

Frequency Requirement for Precision Tank Testing of Underground Tanks

Tank Age (as of June, 1985)	Test Frequency
newly installed to 5 years old	Not required
6 to 10 years old	Within 12 months of effective date of ordinance. Thereafter, every 2 years.
Over 10 years old	Annually beginning within 12 months after effective date of ordinanmce

rocky soils are also cited as posing severe limitations for septic tank systems.

Whereas, the Williamson County rules require a minimum lot size of one acre, in Travis County lot size depends on the number of bedrooms in the house, the physical features of the site and on the source of water supply. For a one (1) or two (2) bedroom house, the lot size where marginal conditions exist is 18,000 square feet; for a five (5) bedroom house it is 27,000 square feet. In computing minimum lot sizes, land in ravines, land with slopes greater than 30%, land below cliffs, and used for streets are not used. If an individual water well is used , the minimum lot size is one acre.

In marginal areas, evapo-transpiration systems are encouraged. For these systems, the minimum lot size is one-half acre.

There is a mandatory setback from water wells of 50 feet; from springs it is 75 feet.

Austin Watershed Ordinances

The portion of the Edwards aquifer recharge zone which outcrops in the Lake Austin and Lake Travis watersheds is regulated by the City's special watershed ordinances. In 1978, the Austin City Council adopted a Lake Austin subdivision development ordinance intended to protect the water quality of Lake Austin as a drinking water and recreational resource of the city, and to encourage innovative planning and design of urban development which responds to the unique and sensitive environments of the Lake Austin watershed. The ordinance has been amended several times with the most recent changes dated December, 1984.

In March, 1984, the City Council established interim standards for the Lake Travis watershed applying standards then in force in the Lake Austin watershed to the Lake Travis watershed.

The strategy of the ordinances is to minimize land disturbances from development activities and to control the volume, rate and quality of stormwater runoff originating from development. Although these watershed regulations are designed to protect surface water, they do have provisions that can affect the groundwater of the Edwards aquifer. The watershed ordinances apply both inside and outside of the City limits in the ETJ.

Major Provisions of the watershed ordinances are listed below:

1) Impervious cover is limited based on slope category. Impervious cover allowed can be transferred from steeper slopes to areas of slopes less than 15%, and to the 15-25% slope categories. (See Table 4)
2) Erosion control is required to comply with the City of Austin's Erosion and Sedimentation Control Manual. Restoration of vegetation is also required.
3) No impervious cover (except roads) is allowed on slopes over 35% gradient. Building foundations on slopes 15% gradient and over and on fill placed upon slopes 15% gradient and over must utilize design and construction practices certified by a Registered Professional Engineer.
4) Water quality detention-sedimentation basins are required when impervious cover is greater than 18% on slopes of 25% and under.

5) Natural drainage channels and overland flow to be utilized as much as possible.
6) Roadways are not to be constructed on slopes over 25% except where it is necessary to do so in order to provide access to an area with slope less than 25% and containing at least 5 lots.
7) Limitations are set for roadway clearing widths; for cut and fill; and for the length of time between roughcutting and final surfacing of roadways.
8) Roadway construction standards can be varied.
9) Cut and fill is limited to four feet.
10) Restrictions are placed on disposal of spoil from construction.
11) Sewer lines are not to be located in waterways except upon approval of a variance from the Planning Commission after considering an enviroment assessment evaluating the environmental impact of alternative sewer alignments.
12) Residential lots utilizing individual on-site systems must be at least one (1) acre in size.
13) Package treatment plants should have at least 8,000 square feet of irrigated land per living unit. No irrigation on slopes over 20% or in the 100-year flood plain. Package plants should have 100 days of storage capacity in the event of wet weather conditions. Permit requests from the state should be for 15 BOD/ 15 TSS or better quality.
14) Detention - sedimentation basins to release water through a filter medium if impervious cover exceeds 20% on slopes under 25%.
15) Maintenance requirements for detention - sedimentation basins are included.
16) A tree survey is required. The Planning Commission must approve removal of trees with a circumference of 60 inches or more as measured, 4 1/2 feet above the ground.
17) Variances are allowed when (a) property is deprived of privileges enjoyed by similarly situated and timed development; (b) departure of ordinance is minimal and of insignificant harmful environmental consequences; (c) need for variance not created by method of voluntary subdivision.
18) Variances must be reviewed by the Environmental Board. Affected persons can appeal to the City Council.
19) City may issue a notice to cease and desist if violations occur, and may take the violator before municipal court.

Northwest Area Plan

Subsequent to the adoption of the revised Lake Austin and Lake Travis Watershed Ordinance in March 1984, the citizens of Austin became concerned about the total amount of development possible in Northwest Austin, particularly for industrial and other non-residential uses. In July, 1984, the Austin City Council requested a study and report addressing land use planning and the provision of city services to territory now described as the Northwest Planning area. The northwest planning area is contained within the boundaries shown in Figure 2.

The objective of the Plan is to balance development with concern for the natural environment and the intensity of development with the ability to provide services to the area.

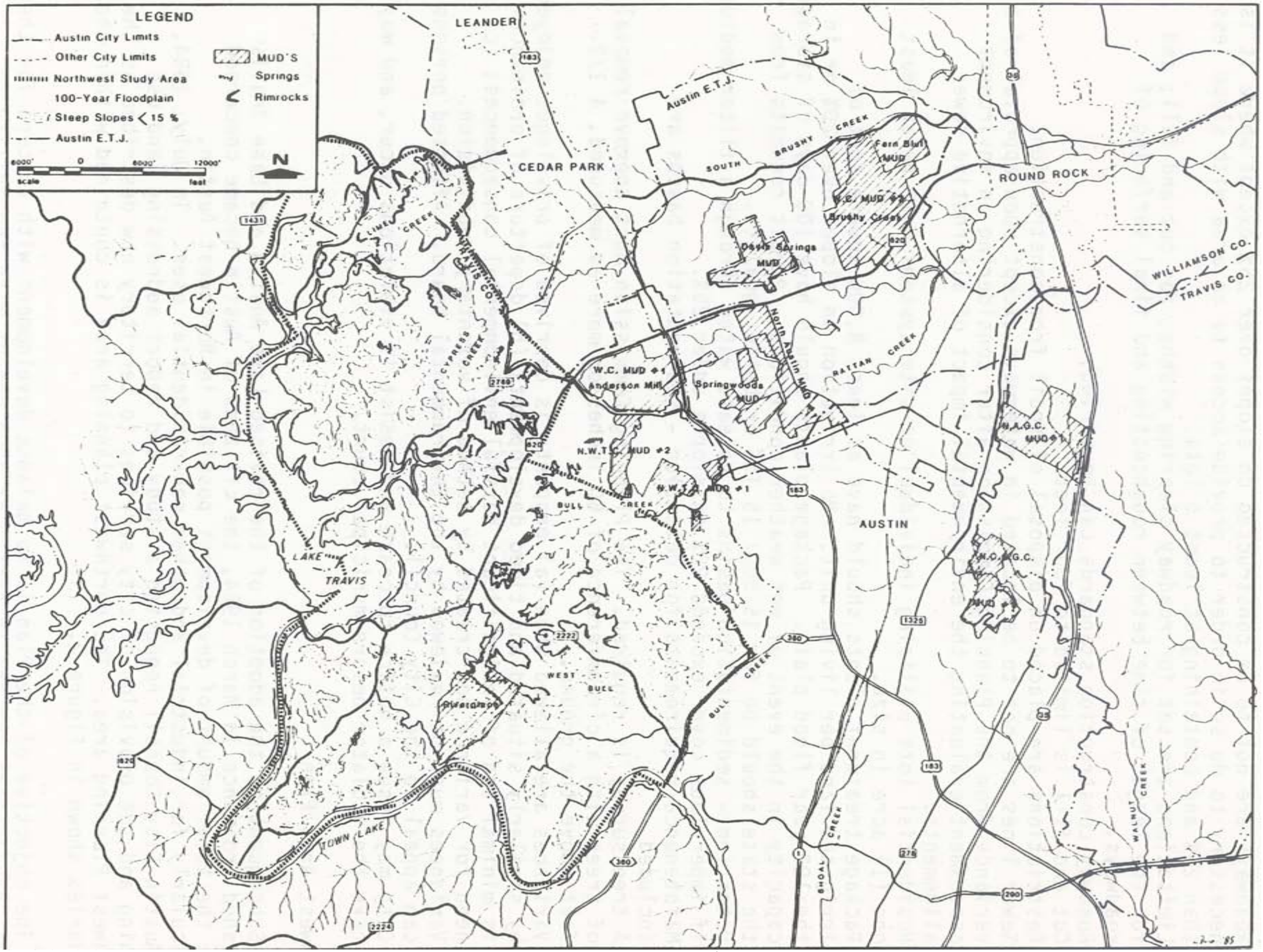

LEGEND
Austin City Limits
Other City Limits
Northwest Study Area
100-Year Floodplain
Steep Slopes < 15 %
Austin E.T.J.
MUD'S
Springs
Rimrocks
N
LEANDER
CEDAR PARK
ROUND ROCK
AUSTIN
Austin E.T.J.
SOUTH BRUSHY CREEK
Fern Bluff MUD
W.C. MUD #2 Brushy Creek
Oasis Springs MUD
WILLIAMSON CO.
TRAVIS CO.
W.C. MUD #1 Anderson Mill
Springwoods MUD
RATTAN CREEK
N.W.T.C. MUD #2
N.W.T.C. MUD #1
N.A.G.C. MUD #1
N.C.M.G.C. MUD #1
BULL CREEK
LIME CREEK
CYPRESS CREEK
TRAVIS CO.
LAKE TRAVIS
WEST BULL
BULL CREEK
TOWN LAKE
SHOAL CREEK
WALNUT CREEK

Figure 2

conversion formula. Non-residential uses are based on employment factors and allocated by floor-area rations. The reduced intensity of land use is correlated with available roadways and abilities to widen or add roadways.

The Northwest Plan will be adopted by the by the City Council as an ordinance. Controversy arose regarding the method for allocating where the limited non-residential use could be built and which porperties would be allowed how much square footage. The methodology has never been resolved. Currently, the City of Austin Department of Planning and Growth Management is developing amendments to the Northwest Plan to be reviewed by the City Council on October 15, 1985. One aspect of the proposed amendments will be to address biological and hydrogeological impacts more directly.

Waterway Development Ordinance

All development within the incorporated city limits of Austin that is to take place on land adjacent to or crossed by a waterway must obtain a waterway development permit. This requirement applies to virtually all development in the city. In the Lake Austin and Lake Travis watersheds, this permit requirement is satisfied by obtaining a site development permit covering the items listed above.

The portions of the Edwards aquifer in the Walnut, Lake, and Rattan Creek watersheds which are also within Austin's city limits are affected by the Waterway Development ordinance. This ordinance primarily addressed flood control, drainage and stormwater management. The two provisions which have a bearing on aquifer protection are: (1) the requirement for erosion control during construction and restoration following construction; and, (2) the protection of the natural and traditional character of the land and waterway to the greatest extent feasible.

Development can satisfy the first requirement by compliance with the City's Erosion Control manual. The natural and traditional character clause is generally interpreted to mean minimizing alterations to the natural drainage patterns; protection of springs; and provisions of non-development set-backs from stream channels. All of these factors can contribute to protection of the Edwards aquifer. The ordinance and its guidelines do not specifically require that land development plans follow these guidelines. However, many developers in north Austin have agreed to build filtration and detention ponds. This has occurred through negotiation with the Environmental Review division of the Office of Land Development Services.

RECOMMENDED ADDITIONAL PROTECTION STRATEGIES FOR THE EDWARD'S AQUIFER

Improved protection for the Edwards aquifer in Northwest Travis County could be achieved by amending the Northwest Area Plan (and/or the Lake Austin and Lake Travis Watershed Ordinances) to include mandatory setbacks from and prohibition of disruption to environmentally sensitive features such as springsa, caves, rimrocks and canyon heads. A minimum construction setback of 150 feet from canyon heads and ravines; and a lot-line setback of a minimum of 50 feet are recommended to reduce development impacts on these sensitive environmental features.

The goals of the Land Use Guidance Plan are listed below:

1) Ensure the compatibility between potential development and the existing natural environment. Assure the sensitivity of development to environmental features. This goal inherently involves the protection of the aesthetic character of the Hill Country. This would include efforts to prevent the scaring of slopes, and to preserve the character of the terrain.
2) Protect and improve the water quality of the regions creeks, lakes and aquifers in order to maintain a healthy water supply, prevent expensive treatment, and maintain recreational uses. This goal recognizes that Lake Travis will soon provide a substantial portion of the City's water supply, and that Lake Austin is already, and will continue to be, a major municipal water source. Also inherent in this goal is the stewardship of recreational resources of the Lakes and Hill Country. The recreational user base is very extenesive, regional and egalilterian. The lakes are frequently mentioned as an important element in the measure of Austin's "quality of life."
3) Enhance the relationship between the transportation system and adjacent land uses. Develop a balanced, safe and efficient surface transportation system which can adequately serve the area as it develops.
4) Provide utility services in the most efficient and equitable manner consistent with sound environmental and growth management policies. The efficient and equitable allocation of public resources should weigh the costs of investment in any one area against the opportutnties that may be lost for capital investments eleswhere to serve greater needs or more numerous users.
5) Provide for consistency and predictability in land development and the accompanying support services needed for growth in the area.

The provision of municipal services such as water, sewer and roadways is expensive in this area relative to flatter, less rocky areas of the city at lower elevations.

The Northwest Land Use Guidance Plan contains many policies that relate to the nature of development that would be permitted in the area. Several of these are more strigent than the watershed ordinance requirements; for example,no development on slopes over 15%; industrial uses prohibited; and other non-residential use limited. Residential density permitted would be calculated based on slope categories as follows:

Slopes	Dwelling Units Allowed / Acre
0-15%	2.5
15-25%	1.0
25-35%	0.5

The number of units permitted on 0-15% slopes is the sum of allowed dwelling units on a tract. Other housing types are allowed based on a

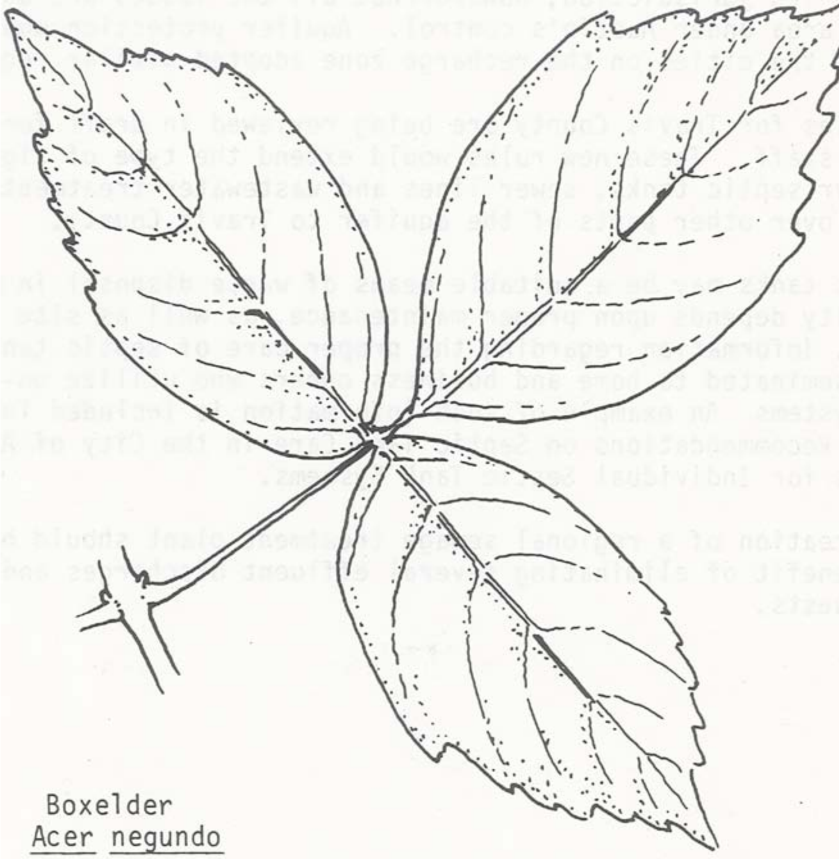
The City of Austin Environmental Board is currently reviewing a proposed Northern Edwards aquifer ordinance. This new ordinance would utilize techniques currently in practice in the Lower Watershed areas of the Barton Springs aquifer. Their recommendations may be included in a comprehensive watershed ordinance revision currently being drafted by Austin's Office of Land Development Services.

Currently the requirement for a water pollution abatement plan in the Texas Water Commission's Edwards aquifer rules for Williamson County does not apply inside the city limits of any city. Austin's current regulations address many of the issues required for the plan in the areas under its jurisdiction, however not all the issues are addressed in all of the area under Austin's control. Aquifer protection would be enhanced if the cities on the recharge zone adopted similar requirements.

TWC rules for Travis County are being reviewed in draft form by Commission staff. These new rules would extend the type of tighter controls ovr septic tanks, sewer lines and wastewater treatment facilities that apply over other parts of the aquifer to Travis County.

Septic tanks may be a suitable means of waste disposal in many areas. Their utility depends upon proper maintenance, as well as site selection and design. Information regarding the proper care of septic tanks should be widely disseminated to home and business owners who utilize on-site disposal systems An example of such information is included in the Health Department Recommendations on Septic Tank Care in the City of Austin Regulations for Individual Septic Tank Systems.

The creation of a regional sewage treatment plant should have the positive benefit of eliminating several effluent discharges and pending permit requests.



Boxelder
<u>Acer negundo</u>

ROAD LOG--EDWARDS AQUIFER, NORTHERN SEGMENT, TRAVIS AND WILLIAMSON COUNTIES, TEXAS

by

C. M. Woodruff, Jr., Fred Snyder, Laura De La Garza, Raymond M. Slade, Jr., Don G. Bebout, Ernest L. Lundelius, Jr., Tom S. Patty, and Sam Pole

MILEAGE

00.0 Set odometer to 0 at Sid Richardson Hall parking log (LBJ Library Complex).

Exit parking lot; turn left onto Red River Street.

00.2 Junction with East 26th Street; turn right. Get in left lane, cross under Interstate Highway 35 (IH-35), and prepare to enter access road.

00.4 Turn left onto access road.

01.0 Enter IH-35; proceed north.

02.2 We are crossing the Airport Terrace, the highest of the continuous Pleistocene surfaces formed by the Colorado River. The age may be roughly estimated as post-Kansan and (probably) pre-Wisconsinan, based on work by Ernie Lundelius and his students. They have found vertebrate bones in caves within the Edwards Limestone; these bones have been dated by their association with the red (terra rosa) soil that washed into the caves before the major streams had incised below the levels of the Edwards uplands (e.g., the Jollyville Plateau).

03.3 Cross U.S. Highway 290 overpass; we are traversing various members of the Austin Chalk.

04.2 Continue north past U.S. Highway 183 exit.

15.4 Exit 251; depart IH-35 for U.S. Highway 81. Proceed to Round Rock.

16.8 Cross Lake Creek.

17.1 Continue south past downtown Round Rock.

17.4 Cross Brushy Creek.

17.7 Intersection with U.S. Highway 79; turn right.

18.5 Turn right onto North Georgetown Street.

18.7 Cross Brushy Creek.

18.8 Turn right onto East Pecan Avenue.

19.0 STOP 1: VETERANS' PARK

Here, we will walk downstream along Brushy Creek and observe a sinkhole in the bed of Brushy Creek. The outcrop on the far side of the creek is Georgetown Limestone, so we are near the top of the Edwards aquifer. The sinkhole is a recharge feature only during dry periods (that is, depending on water levels within the aquifer). During wet periods, the water table intersects the creek level and no recharge occurs. Under those circumstances, the sinkhole may not even be visible owing to surface stream flow. At this site, most recharge will occur after rains that follow a dry period. Here, Raymond Slade will present a brief hydrologic overview of the northern segment of the aquifer (see Slade, this volume).

Turn around; proceed back to North Georgetown, and turn left there. Note, if sinkhole is not visible owing to water-table conditions, an alternate stop is the low-water crossing across Brushy Creek west of IH-35 near the old Chisholm Trail stage stop. There, one may observe the outcropping Edwards Limestone as well as the ruts worn in the stream bed by the wheels of stagecoaches and wagons crossing there.

19.5 Intersection with U.S. 79; turn left.

20.2 Junction with U.S. 81; proceed straight.

20.5 IH-35 access road; turn right.

20.6 Merge with IH-35; proceed north.

23.0 Cross Chandler Branch.

24.8 On left is Texas Crushed Stone quarry, which will be the fourth stop of this trip. On the right is Rabbit Hill, capped by Buda Limestone with slopes underlain by the recessive Del Rio Clay.

26.3 Exit from IH-35 onto U.S. 81; proceed north on access road.

26.9 Turn left beneath IH-35; proceed beneath overpass of southbound lane.

27.1 Turn right into Inner Space Caverns parking lot.

STOP 2--INNER SPACE CAVERNS

Inner Space Cavern was discovered in the spring of 1963 by a Texas Highway Department core-drilling crew, who were investigating the area for a proposed overpass for IH-35. During the drilling of several test holes, drill bits were lost, and this suggested that a major cave had been located. A 24-inch exploratory hole was subsequently drilled through which an individual was lowered to determine the extent of the cavity. It proved to be what we now know as Inner Space Caverns.

In November, 1963, permission was obtained by the Texas Speleological Society (TSS) to enter and explore the cave. The Texas grotto, a branch of the TSS, had primary responsibility for exploring and mapping the cave system. Spelunkers entered the cave on a rope tied to the front bumper of a Volkswagen "beetle." Approximately 7,000 ft of cave was surveyed and mapped (see fig. L-1). Today, Inner Space Caverns have been explored further and are known to consist of more than 4 miles of passageways.

Continued exploration indicated that Inner Space Caverns once had numerous openings to the surface. Many animals entered the caverns through these openings. Some were seeking refuge, some were brought in by predators, and some fell in accidentally. Local remains of these animals and associated plant debris provide information on paleo-environments and past fauna (see Lundelius, this volume).

Inner Space Caverns lies within the Edwards Limestone. It was formed by groundwater flowing along joints and other fractures. This flowing water, charged with carbonic acid (from carbon dioxide in the air, and especially, in the soil), was an effective solvent; and over time, the limestone readily dissolved. This process is still going on, and in this way, the aquifer system is continually enlarging its "plumbing." But in the air-filled chambers, some of this groundwater, saturated with calcium carbonate, allows the reprecipitation of aragonite in the form of diverse stalactites, stalagmites, columns, cave popcorn, cave ice, flowstone, cave coral, and cave drapery or bacon. Especially unusual cave formations found in Inner Space Caverns include soda straws and helictites. Soda straws hang from the ceiling as long hollow crystalline structures. Helictites are formations which do not grow primarily up or down. Instead, they are twig-like, extending laterally and showing apparent disregard for the law of gravity.

Chemical impurities in water seeping through the cave result in cave formations having a wide range of colors from white to yellow, brown, and red. In addition, clays and muddy debris have washed into the cave or have been left behind after the limestone dissolved. These materials commonly form stains on the exposed walls of the cave.

Inner Space Cavern is an important find. It had no surface access in recent time, so that when discovered it had

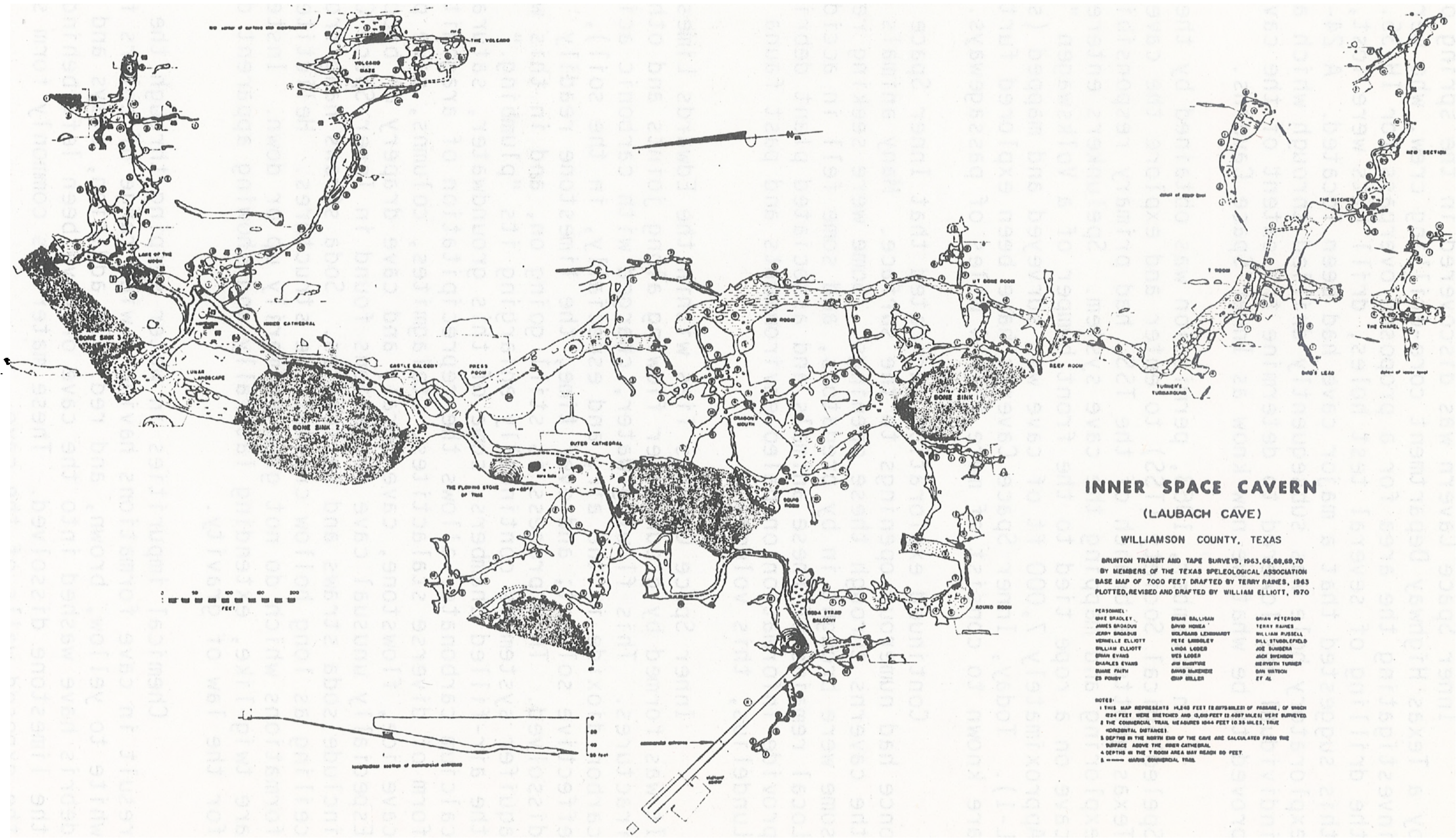


Figure L-1. Inner Space Cavern, plan view.

been spared abuse from people haphazardly entering the cave. In this way, the diverse cave formations were preserved--as were the fossils. This cave has now been systematically explored, and it was developed for its present commercial use by people familiar with caves. For these reasons, Inner Space Caverns provide a remarkable view into the aquifer's "plumbing," also, clues to how caves form and to the paleo-environments of Central Texas some 25,000 to 30,000 years ago are also preserved at this locality. The itinerary that follows focuses on the fossil bone localities within Inner Space Caverns. The tour through the cave will be led by Ernie Lundelius and Sam Pole.

CAVE ITINERARY

We enter the cave through an artificial entrance. Some of the natural passage in the first part of the cave has been enlarged for easier walking. In this first section, toes of two debris cones marking former openings into the cave can be seen (see figure L-2). Thus far, no bones have been found in these areas.

Cave Stop 1: The discovery drill holes can be seen in the ceiling of this large room. Both the small hole (one of the exploratory drill holes) and the large hole through which the initial explorers gained access to the cave are now accumulating travertine deposits. This attests to the speed with which travertine can sometimes accumulate.

Cave Stop 2: This is the passage leading to Bone sink 1 localities (see fig. L-2). All bone-producing areas along this passage are related to the former opening marked by the debris cone mapped as "Bone sink 1."

Cave Stop 3: We are now at the south side of the debris cone marked "Bone sink 2." We will walk around about one half of this debris cone looking at several localities that have produced fossil bones. No fossils have yet been found at the south side of the cone. Proceeding along the path and note the concrete retaining wall built to hold back loose material from the debris cone. The murals are by Michael Frary of the U.T. art department.

Cave Stop 4: Traversing the northeast side of the debris cone of Bone sink 2, where mammoth tusk, jaw, and other bones can be seen high up in the shaft. The exhibit at the end of the concrete wall contains specimens of species found in the cave. The slope to the north into the large basin is cemented at the top with a thin crust of travertine. Bones of camel and horse were cemented to the surface of this slope.

The excavations seen in the bottom of the basin produced

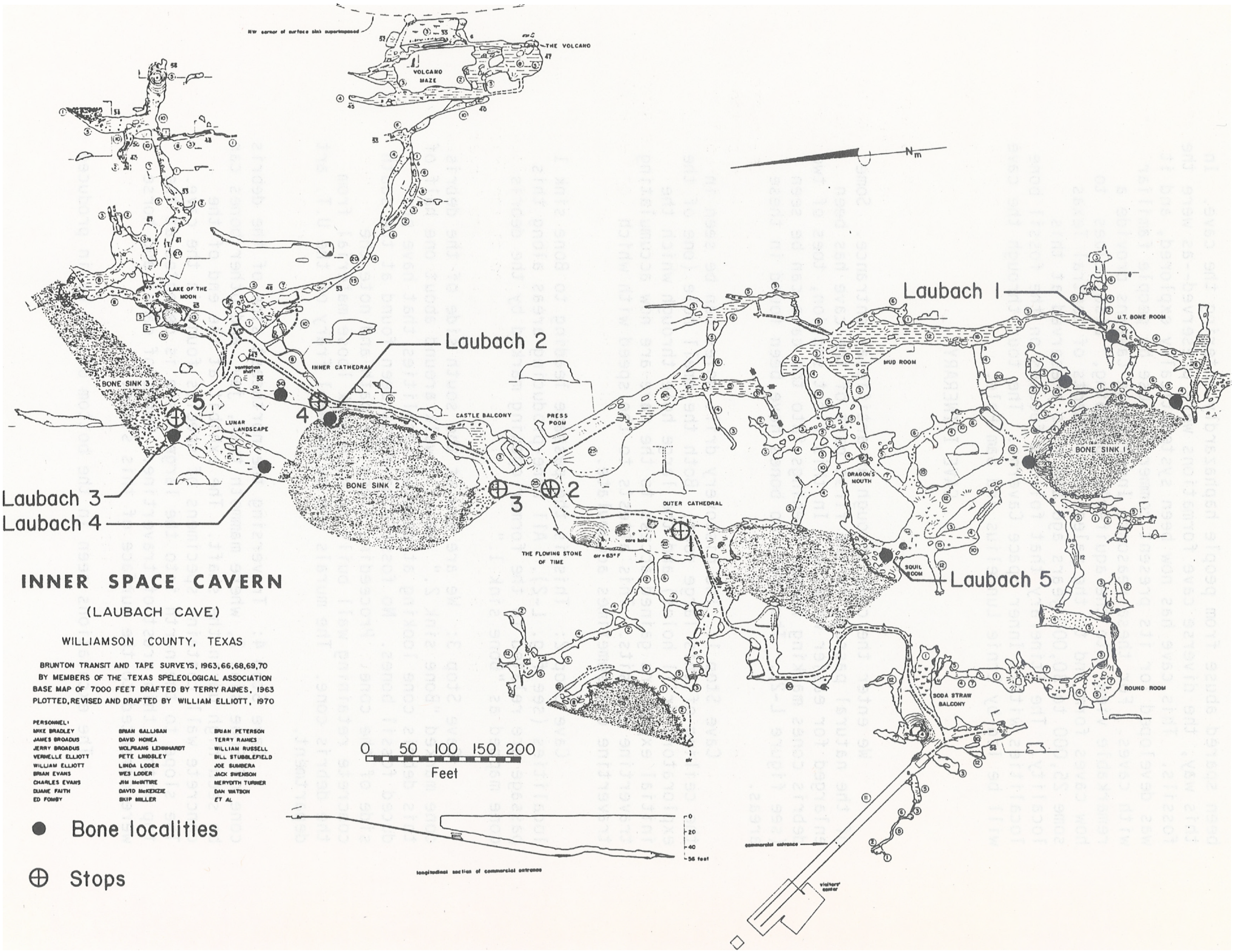


Figure L-2. Inner Space Cavern, bone localities.

little bone, the most noteworthy being the deciduous canine of the sabertoothed cat, Homotherium serum. They show the presence of several layers of travertine up to one inch in thickness separated by layers of loose, coarse-grained sand-sized particles of travertine and limestone.

Cave Stop 5: The debris cone labeled "Bone sink 3" is heavily cemented with travertine in contrast to the material in Bone sink 2. The bones that seemed to be unequivocally associated with this entrance were recovered from a deposit along the west wall of the cave. These were not extensive and have been totally removed. Some of the area that was occupied by them is now covered by the walk.

The area at the end of the walk labeled "Lunar Landscape" is very complicated. The presence of stalactites whose broad bases are suspended in the air indicate that subsidence has taken place in this area. The trench in this area has produced fossil bones, but the deposits suggest the possibility of mixing as a result of the subsidence and redeposition.

The area to the south of the Lunar Landscape is the north side of the debris cone of Bone sink 2. From excavations at the toe of the debris cone in this area, flint chips and charcoal resulting from human activities were recovered.

We will return to the entrance of the cave along the same route by which we entered. Continuing with the road log, we will now turn around and proceed back under IH-35.

27.3 Turn left onto access road on east side of IH-35.

28.2 Cross Georgetown Railroad tracks, the transportation route for the crushed limestone produced at the Texas Crushed Stone quarries. Now that shell is no longer dredged from the bays and estuaries, the Balcones Escarpment is the closest source of crushed aggregate for coastal cities.

29.2 Intersection with Texas State Highway 29; continue straight.

29.4 Courthouse Square, Georgetown; continue straight.

29.9 South Fork, San Gabriel River.

30.0 North Fork, San Gabriel River.

30.1 Turn right onto West Morrow Street.

30.4 Entrance to San Gabriel Park; continue on main road that skirts the north side of the park.

30.9 Park entrance; turn right.

STOP 3--SAN GABRIEL PARK

San Gabriel Park affords several views of the Edwards aquifer. The Georgetown Limestone crops out on the far side of the San Gabriel River. There are springs that issue from the alluvium (derived from the underlying Georgetown and Edwards Formations--probably via a fault). And there are large municipal water wells within the park.

The two wells located here in the park provide the municipal water supply for the City of Georgetown. These wells are developed in the Edwards aquifer. During the Summer of 1984, discharge from these wells averaged approximately 1.5 million gallons per day.

Georgetown Springs, also located in the park, discharge the Edwards aquifer. Based on two measurements, the flow of these springs has ranged from 3.5 cubic ft per second (cfs) to 5.2 cfs. This discharge is equally divided among three springs on the north bank of the San Gabriel River.

This will be our lunch stop. Here, Laura DeLaGarza will discuss the status of City of Austin plans that affect the northern segment of the aquifer. Also, Steve Musick of the Texas Water Commission will discuss State policies on this part of the aquifer. Fred Snyder will present data on springs flowing from the northern aquifer, and Ted Harringer will talk about well development within this area.

31.0 Turn around.

31.2 Turn left on Morrow Street, and proceed back to U.S. 81.

31.9 Junction with U.S. 81; turn left; proceed back through Georgetown.

32.8 Turn right (west) onto State Highway 29.

33.3 Cross South Fork, San Gabriel River.

33.6 Cross IH-35 overpass.

33.7 Turn left onto southbound access road.

34.0 Merge onto IH-35.

35.1 Cross South Fork, San Gabriel River again; Take Exit 259.

35.5 Intersection at Inner Space Caverns; proceed south on access road.

36.6 Entrance to Texas Crushed Stone; turn right.

STOP 4--TEXAS CRUSHED STONE COMPANY QUARRY

This quarry was opened around 1960 when the Texas Crushed Stone Company began phasing out operations at their quarry in northwest Austin (where Murchison Junior High School is now located--Stop 5 on this field trip). Over the past decade, stone production has averaged 10 million to 12 million tons per year, making it the largest limestone quarry in the country. Major commodities produced from this quarry include: concrete aggregate; asphaltic-mix aggregate; base material; rip rap; chemical stone; and agricultural stone. Texas Crushed Stone Company owns their own railroad line, and they design and build the rolling stock for the Georgetown Railroad. These rail cars are of state-of-the-art technology, designed for rapid loading and unloading and computerized weighing of the loaded hopper cars while the train is in motion. Unit trains convey this material to Houston. The Balcones Escarpment is the closest source to the Texas Gulf Coast for lime aggregate. After extraction of the stone, reclamation of this site is planned as a major corporate development site. Already, quarried parts of the tract are being back-filled with overburden, and in this way a major airport runway system is being constructed.

We will tour the quarry in the bus and will stop at a few sites away from working quarry faces to view the internal features of the Edwards Limestone. Especially notable are the small-scale porosity systems (in contrast to the large-scale porosity seen in Inner Space Caverns). For a discussion of the general geologic history of the Edwards Limestone in this area, see the paper by Bebout (this volume).

Turn around; proceed back to access road.

36.7 Turn right onto access road and continue south.

37.6 Intersection with Westinghouse Road; proceed south.

37.9 Enter southbound lane of IH-35.

42.1 Cross Brushy Creek and then exit (252-B) onto Ranch Road (RR) 620.

42.2 Bear right on RR 620; proceed west.

42.8 On right note flood-proofed lower story of commercial building along Brushy Creek.

47.0 Cross Davis Branch, Lake Creek; note the poorly defined drainage course. This is typical of tributaries to Brushy Creek across the Jollyville Plateau terrane.

Stream gradients are low, hence there has been little incision. In short, the drainage network is poorly developed. This is a major difference between the north aquifer segment and the Barton Springs segment of the aquifer. Owing to poorly integrated drainage, recharge might occur on the uplands away from the drainage courses as readily as within the waterways.

47.7 Cross Southern Pacific Railroad tracks; this is the "granite railroad," initially built along this route 100 years ago to transport granite from Marble Falls to Austin for construction of the State Capitol.

49.1 This low area is part an ill-defined tributary to Lake Creek; again note the poorly developed drainage.

49.8 Intersection with U.S. Highway 183; turn left. Note grassy swales along the northwest corner of this intersection (along the margins of the K-Mart parking lot). These man-made features are much employed to lessen the water-quality impacts of runoff from paved areas.

52.9 Turn right (southwest) onto Spicewood Springs Road.

53.5 ROLLING STOP--BREAKS OF JOLLYVILLE PLATEAU

This is not a suitable place to park and get out of the vehicles; instead this locality will be discussed at the next stop. We have just crossed from the Brushy Creek watershed and have entered that of Bull Creek (having gone from the Brazos to the Colorado drainage basin). The break in slope across this watershed is remarkable. The watershed marks the approximate edge of the Jollyville Plateau (and the contiguous recharge zone of the northern part of the Edwards aquifer). On the south side, deep dissection has cut entirely through the Edwards Limestone exposing the alternating beds of the Glen Rose Limestone below. The deep dissection has also provided drains for the water-table aquifer, and springs issue forth from the Edwards Limestone in many places--especially at the heads of draws. The evolution of this dramatic physiographic break is explored more fully by Woodruff (this volume).

Proceed down off Plateau uplands onto dissected terrain.

53.5 Near this locality, a spring is denoted on the USGS topographic map; no such feature was found during our preparation of this trip. The intensive construction (including cut-and-fill activities) has deranged not only surface drainage conditions, but the subsurface flow as well.

54.5 Here we are descending rapidly into the valley of Bull

Creek.

54.7 Cross tributary to Bull Creek.

54.8 Intersection of Old Lampasas Trail and Spicewood Springs Road; turn left. We will cross Bull Creek six times as we proceed along its incised valley.

54.9 Cross Bull Creek.

55.2 Cross Bull Creek again.

55.6 Note travertine from intermittent tributary/waterfall on left of road.

56.2 Cross Bull Creek.

56.7 Bull Creek.

56.8 On right, note house straddling Bull Creek; not an advisable use of a floodplain. Recall that the Balcones Escarpment is the locus of the largest flood-producing storms in the conterminous U.S. (Hoyt and Langbein, 1954). The actions of these extraordinary climatic events may be one reason that Bull Creek was able to incise so deeply beneath the surface of the Jollyville Plateau.

57.0 Cross Bull Creek again; not bluffs of Glen Rose Limestone at 12:00.

57.4 Bull Creek again.

57.7 And again.

58.2 Coming up on Loop 360; turn right before intersection and proceed under Loop.

58.3 Cross Bull Creek one last time before beginning ascent from valley.

58.6 Stop sign; turn right on Spicewood Springs Road, and continue climb back up to edge of outlying segment of the Jollyville Plateau.

59.4 Crest of ridge; now we are within Balcones Fault Zone; abrupt changes in slope probably correspond to drainage courses controlled by faults and other fractures.

59.6 Mesa Drive; proceed straight.

60.4 On left is Ceberry Street; at the intersection of Ceberry and Spicewood Springs Road is the site (according to

Brune, 1981) of THE Spicewood Springs.

60.6 Loop 1 (MOPAC) access road; turn right.

61.3 Turn right onto Far West Blvd.

61.4 We are entering an abandoned limestone quarry, formerly operated by Texas Crushed Stone. This is an excellent example of sequential multiple use of mineral lands.

61.6 Turn right onto Wood Hollow.

61.7 Turn right into parking lot along quarry face.

STOP 5--MURCHISON JUNIOR HIGH ABANDONED QUARRY

This abandoned quarry site affords a close-up view of porosity developed within the Edwards Limestone. Some of the discrete zones of solution (honeycombed intervals) provide an example of a major type of water-producing zone within the aquifer. This is a relict part of the aquifer, however; the pores are now filled with air, not water. This porosity may have formed shortly after the time of deposition of the Edwards (like the outcrop at Loop 360 and Bee Cave Road (Woodruff and Slade, 1984); or it may represent a more recent episode of solution development.

This area is an excellent example of multiple (sequential) land use. As mentioned previously (Stop 4), this locality was the main quarry for the Texas Crushed Stone Company before they opened up the site near Georgetown. When quarrying operations were discontinued around 1964, this area was reclaimed--first with the school and later with the commercial tracts that we see today. The prior quarry site for Texas Crushed Stone is where Highland Park Elementary is today.

At this stop we will sum up the day's work. Also, Mike Bentley will discuss aquifer tests conducted for the Edwards in east-central Travis County.

61.8 Leave parking lot on east side; turn right and then turn left onto Far West Boulevard.

62.0 Turn right onto access road; immediately enter Loop 1, southbound.

64.5 Exit Loop 1; West 35th Street.

64.8 Merge right beneath West 35th Street and circle up onto eastbound lane of West 35th.

65.4 Intersection with Jefferson Street; proceed straight.

65.5 Junction of 35th and 38th Streets; stay straight on 35th.

65.7 Cross Shoal Creek; Seider Springs issues forth from the Buda Limestone nearby.

66.0 Intersection with North Lamar Boulevard; continue straight.

66.3 Proceed straight across Guadalupe Street.

66.6 Junction with Speedway; turn right.

66.8 Bear left, remaining on Speedway.

67.0 Bear right, still on Speedway.

67.1 All-way stop; angle left onto San Jacinto Street.

67.2 Junction with Duval; proceed straight.

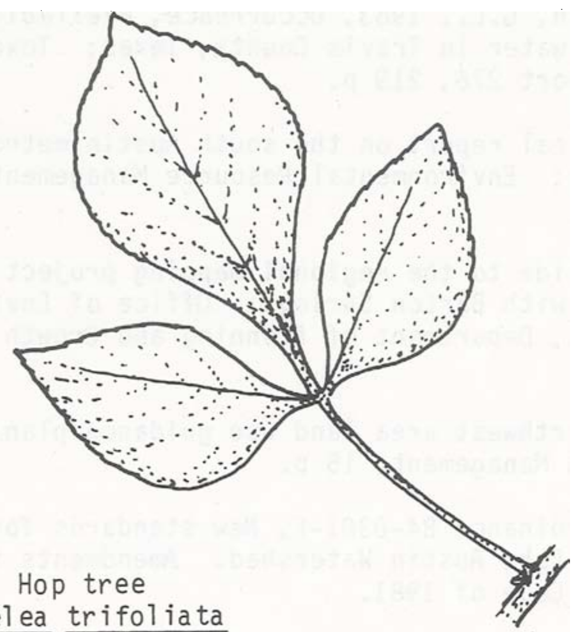
67.3 East 26th Street; turn left.

67.7 Cross East Campus Drive; continue straight.

67.8 Turn right on Red River Street.

68.0 Turn right into Sid Richardson Hall parking lot.

END OF TRIP.



Hop tree
Ptelea trifoliata

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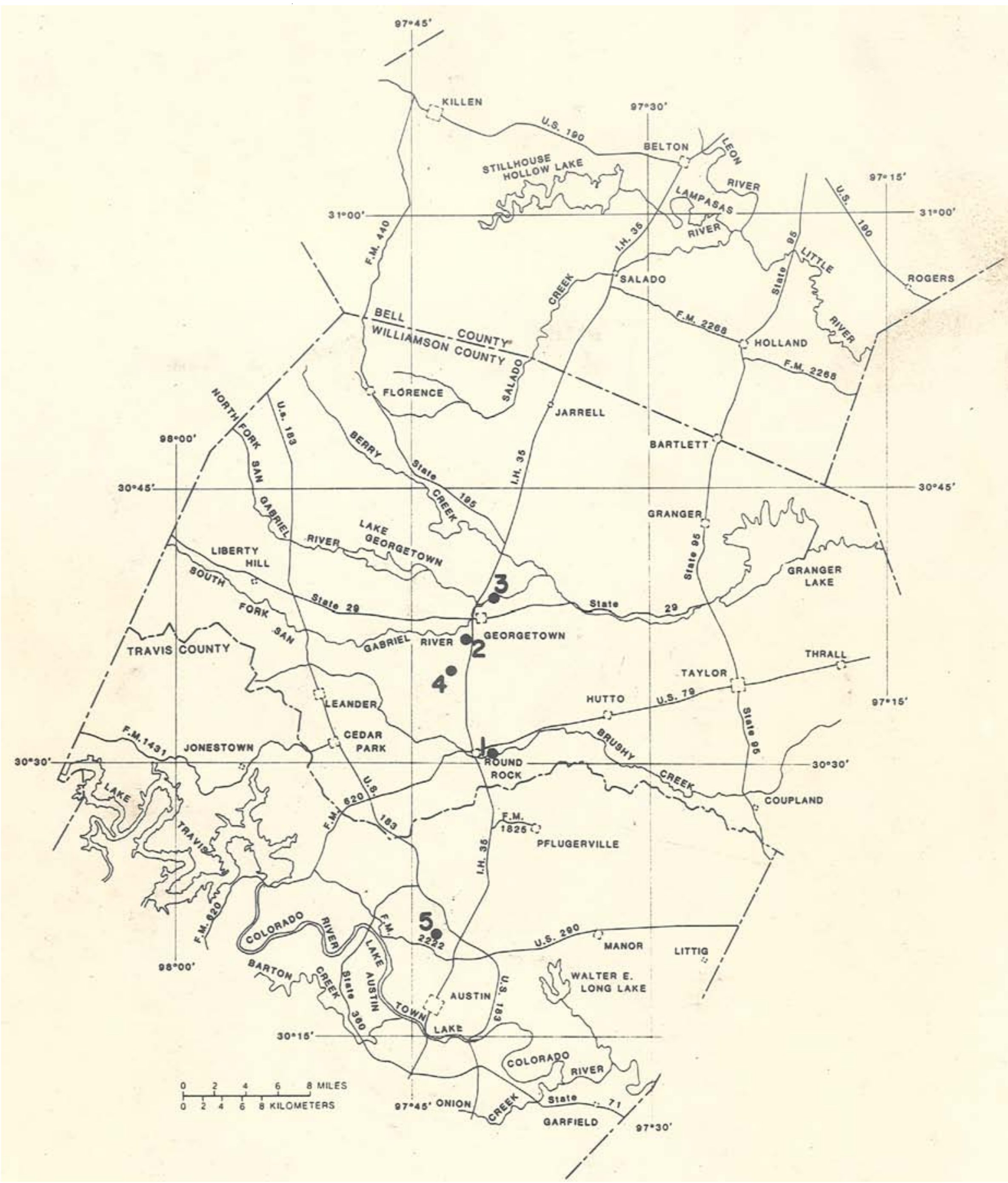

Location of field-trip stops