DETAILED HYDROGEOLOGIC MAPS OF THE COMAL AND SAN MARCOS RIVERS FOR ENDANGERED SPECIES HABITAT DEFINITION, TEXAS

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THESIS

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For my parents and my brother

Dan, Jean, and Andy Crowe

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The Edwards aquifer of Texas is a regionally-extensive carbonate aquifer, and Comal and San Marcos springs are its largest natural discharge points. They issue from faults in the confined portion of the aquifer to create Comal and San Marcos Rivers, which create habitat for a number of endangered species including the fountain darter *(etheostoma fonticola)*, Texas wild rice (*zinzania texana*), the San Marcos gambusia (*gambusia georgei*), and the San Marcos salamander (*eurycea nana*). Protection of the endangered species living in the spring systems provided the impetus for this study. Pumping from wells in the Edwards has been increasing over the past few decades, and if this trend continues, natural springs in the aquifer will eventually cease to flow. The species in the rivers are not only endangered because of low populations, but also by the possibility of a loss of spring discharge.

There are many different endangered species habitats present in the Comal and San Marcos systems, and this thesis presents maps and data on their characteristics. Hydrochemical, substrate, soil, vegetation, and flow information are included in these characteristics. Substrates have been separated into size classes to create maps of the river beds. Hydrochemical

parameters in the rivers were examined showing remarkable uniformity in their measurements along the entire lengths of both rivers, including a year-round nearly constant temperature. The soils surrounding each river were mapped and their hydrologic characteristics were examined. Vegetation in the rivers was also mapped, because of its importance to the habitats. The plants provide a structure that protects the endangered species from high flow velocities in the rivers, and they help stabilize the substrate. Flow characteristics, locations of seeps and springs, and velocity measurements, have been mapped for each river. Habitats are defined through the combination of vegetation, substrate, soil, hydrochemistry, and flow type for different areas of both rivers.

The flow velocities in the rivers are the most important characteristic, because it is the flow rate that controls the morphology of the entire river and the substrate that is present on the river bed. Through control of the substrate, the flow rate indirectly controls vegetation and habitat distributions in the rivers. Ranges of flow velocities necessary to maintain habitats in both rivers are estimated, because a change in the flow rate would alter the distribution of substrate on the river beds, and the current habitats would no longer exist. The Comal and San Marcos Rivers are unique because of their combinations of habitats, which is due primarily to the flow velocity variations in the rivers.

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Introduction

The Edwards aquifers are regionally-extensive carbonate aquifers located in central Texas (Figure 1). These aquifers can be identified: the Edwards-Trinity Plateau; the Balcones Fault Zone, and the Washita Prairie aquifers. The Edwards aquifer, as discussed in this study, refers to the Edwards Balcones Fault Zone aquifer between the groundwater divides near Brackettville, in Kinney County, and Kyle, in Hays County (Figs. 1 and 2). It is the sole source of water for nearly two million people, including the entire city of San Antonio and many of the surrounding rural areas. The Edwards is also one of the most productive aquifers in the United States; pumping of groundwater from its wells has increased steadily with growth in the region. Flow from the springs that discharge from the Edwards has decreased in proportion to the increasing withdrawal of water. If pumping from wells in the Edwards continues to increase, natural springs in the aquifer may eventually cease to flow.

The Edwards aquifer consists of 400 to 600 feet of thin to massively bedded limestone and dolomite. The lower confining unit of the aquifer is the upper member of the Glen Rose

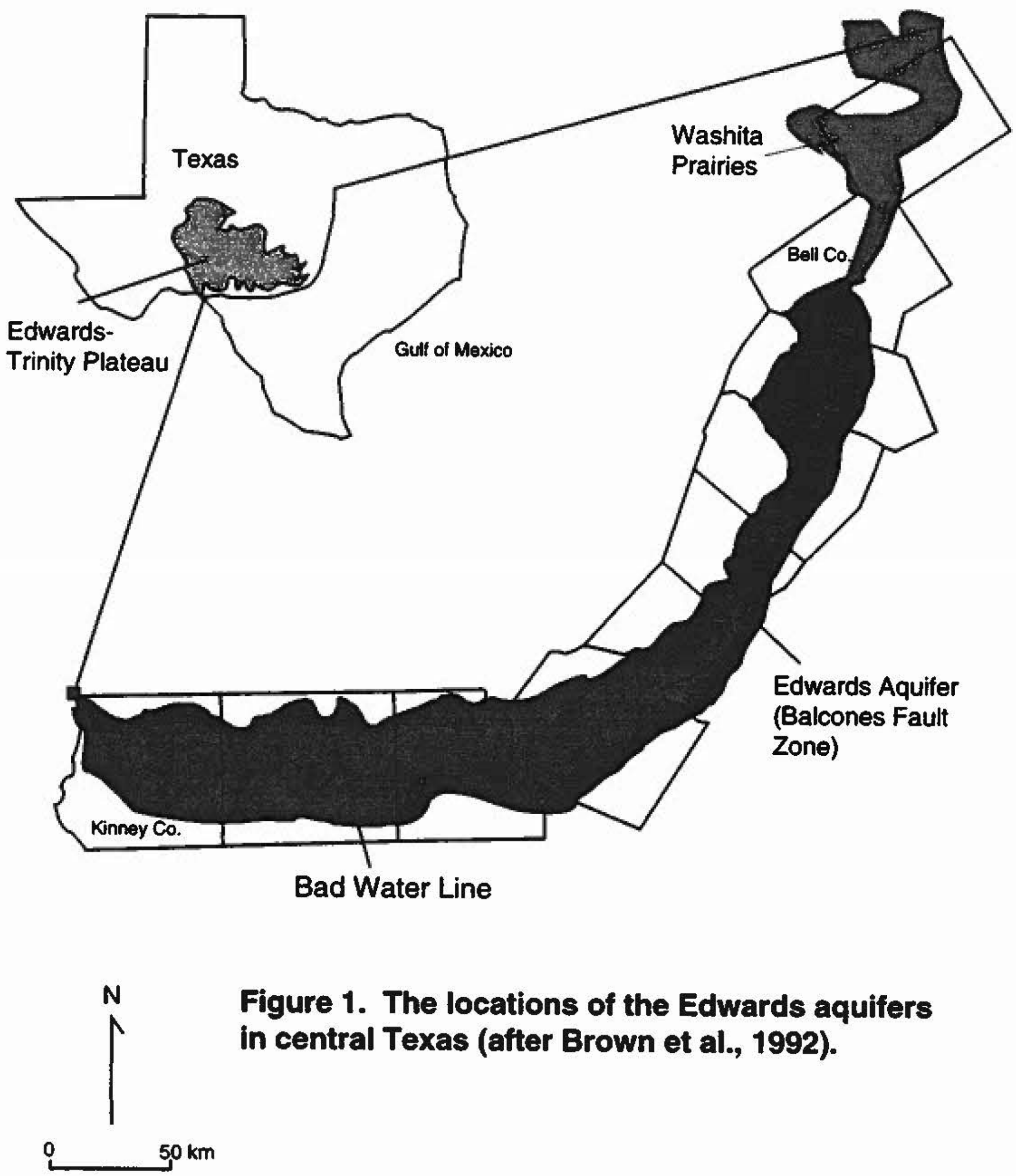


Figure 1. The locations of the Edwards aquifers in central Texas (after Brown et al., 1992).

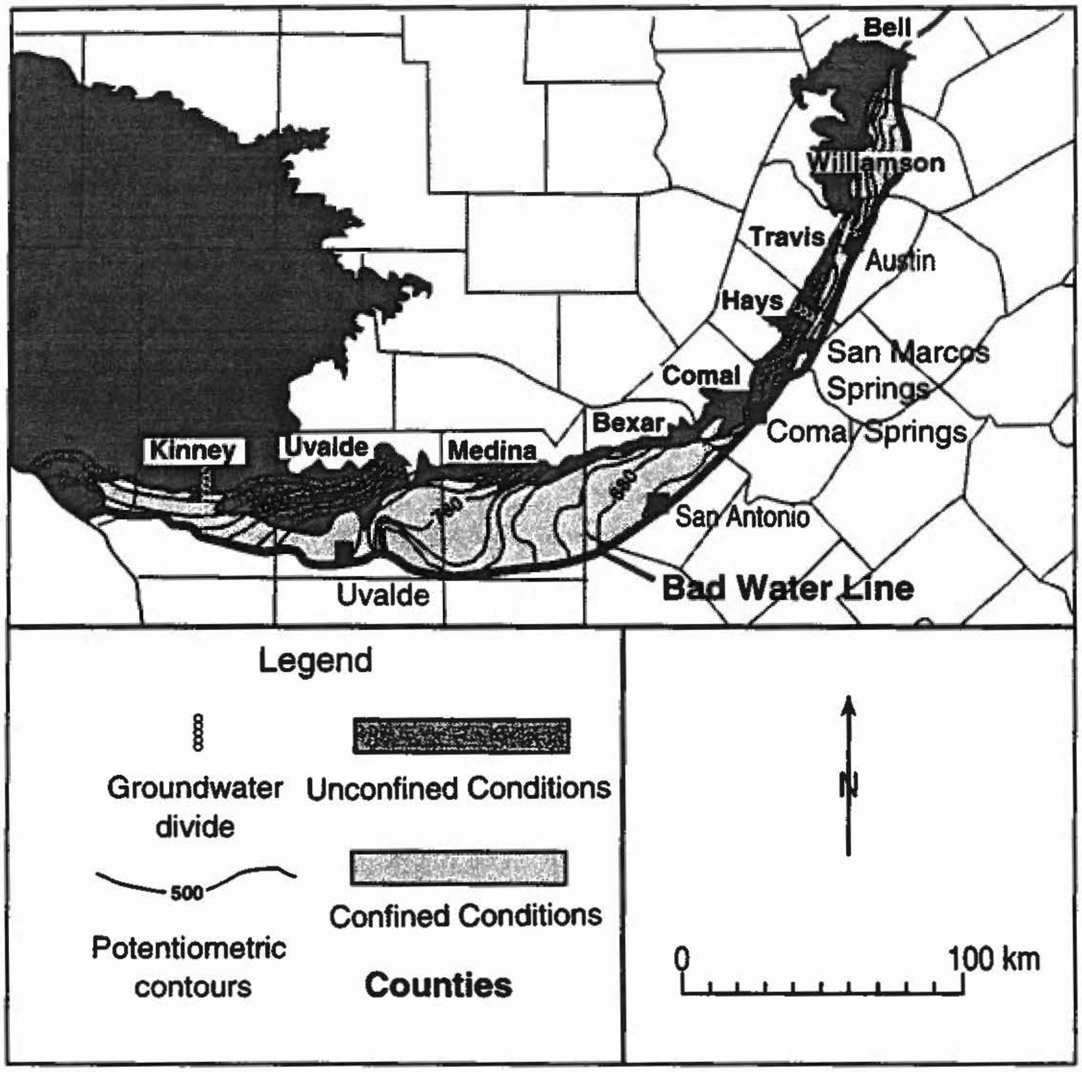


Figure 2. A map locating the confined and unconfined zones of the Edwards Balcones fault zone aquifer. The area south and east of the Bad Water Line is the Bad Water Zone. Counties and major cities are shown on the illustration for references to locations (after Oetting, in press).

Formation, and the upper confining unit is the Del Rio Clay, where present. The aquifer extends about 180 miles in length, and varies in width from about 5 to 40 miles (Figure 2). There are two regions in the Edwards, an unconfined zone and an artesian zone, which includes both freshwater and saline water portions (Figure 2). The saline water area is located south and east of the freshwater artesian zone, and it is known as the bad water zone. The bad water line marks the boundary between the freshwater and the saline water areas.

Comal and San Marcos springs flow from the confined freshwater portion of the aquifer. This is the part of the Balcones Fault Zone that is bounded by groundwater divides in Kinney County on the west and Hays County to the east. The up-dip limits of the surface outcrop of the Person Formation act as the boundary to the Balcones fault zone in the north and west, separating it from the Edwards plateau. In the far west, in Kinney and Uvalde Counties, the Edwards Plateau acts as the northern boundary. The bad-water line bounds the aquifer to the south and east.

Natural discharge from the aquifer occurs through spring flow at San Marcos, Comal, Hueco, San Antonio, San Pedro, and Leona Springs (Figure 3). The two largest spring systems in the Edwards aquifer are Comal Springs, at Landa Park in New Braunfels, Texas, and San Marcos Springs, at Aquarena Park in

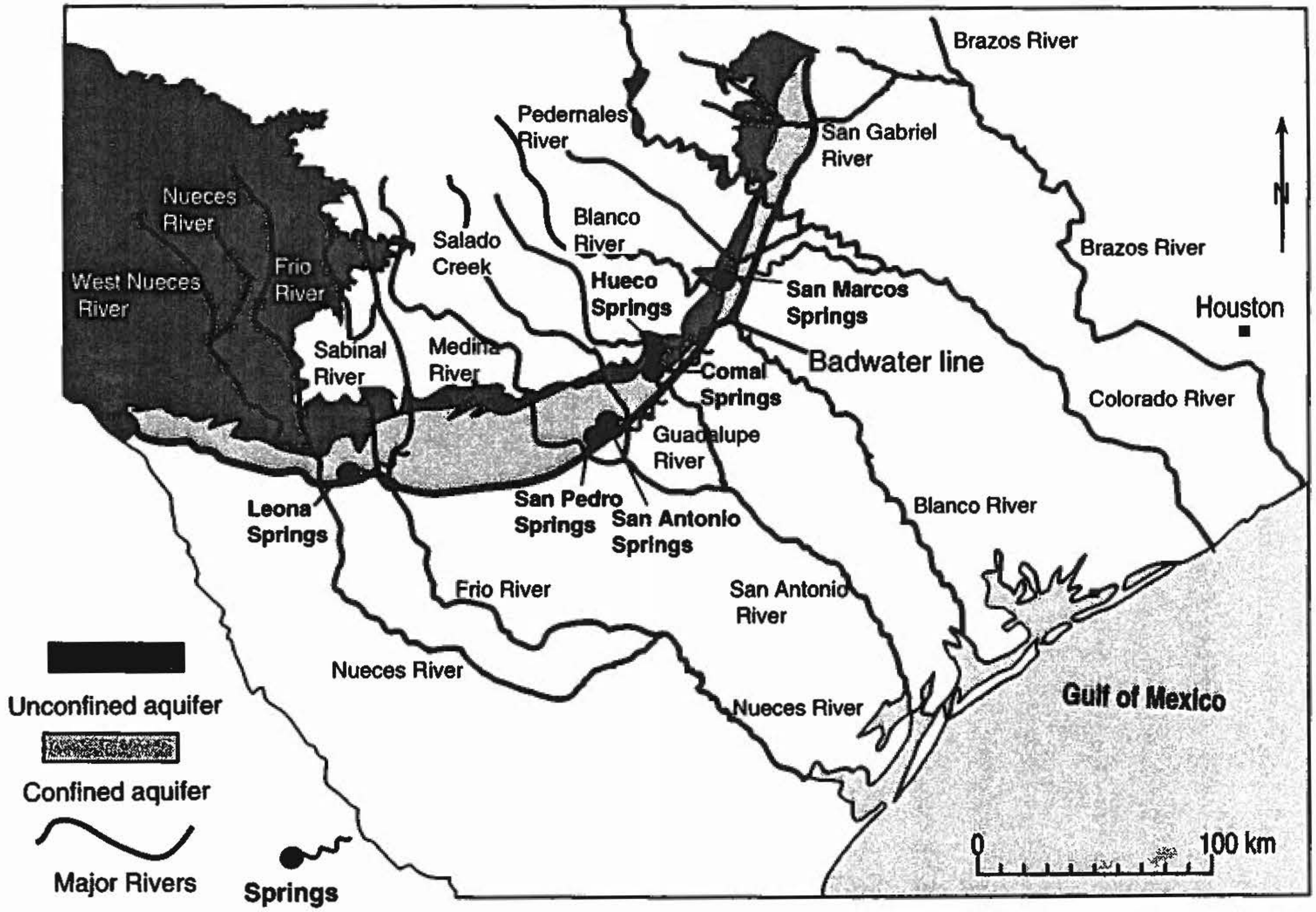


Figure 3. The locations of the major rivers crossing the Edwards aquifer and the springs discharging from the aquifer (after Oetting, in press).

San Marcos, Texas. While some of the other discharging springs now flow intermittently, San Marcos and Comal springs are yet perennial. These springs are the primary sources of the Comal and San Marcos Rivers, which provide important economic and recreational resources to the communities of New Braunfels and San Marcos. The springs also create habitat for a number of endangered species (Table 1), and contribute significant flow to the Guadalupe and Blanco Rivers, respectively.

TABLE 1. A list of the endangered species living in the Comal and San Marcos Rivers.

Common Name	**Latin Name**
<u>San Marcos River</u>	
San Marcos Gambusia	*Gambusia georgei*
Fountain Darter	*Etheostoma fonticola*
Texas Wild Rice	*Zinzania texana*
San Marcos Salamander	*Eurycea nana*
<u>Comal River</u>	
Fountain Darter	*Etheostoma fonticola*
Comal Springs Riffle Beetle*	*Heterelmis comalensis*

* The Riffle Beetle is currently under consideration for listing as an endangered species, but it has not yet been listed.

The endangered species listed in Table 1 have focused attention on the Comal and San Marcos spring systems. These species are endangered not only by their small populations, but by the increased possibility of a loss of spring flow. Increased pumpage of the Edwards has lowered aquifer levels, endangering spring flow, and in times of drought spring flow may diminish or cease. It has been projected that if pumping increases at its current rate, the springs will be dry by the year 2020 (Klemt et al., 1979 cited in Rothermel and Ogden, 1987).

Throughout the period of record, San Marcos springs have not ceased to flow, as shown on the historic stream flow hydrograph in Figure 4. A drought during the 1950's reduced San Marcos springs to their lowest discharge level of 48 cfs (1.3 m^3/s), and Comal springs ceased flowing completely (Fig. 5). Since that time both springs have experienced significant losses of flow twice, in 1984 and 1990 (Linam et al., 1993). Yearly cycles of spring discharge are apparent for both rivers in their stream flow hydrographs (Figs. 4 and 5). These cycles have increased over the past thirty to forty years, and decade droughts, like those of 1984 and 1990, have become more common. Pumping from the aquifer has also increased over the past few decades. The effects of this pumping trend are more evident in the Comal River hydrograph, because the period of record is longer for the Comal River than it is for the San Marcos

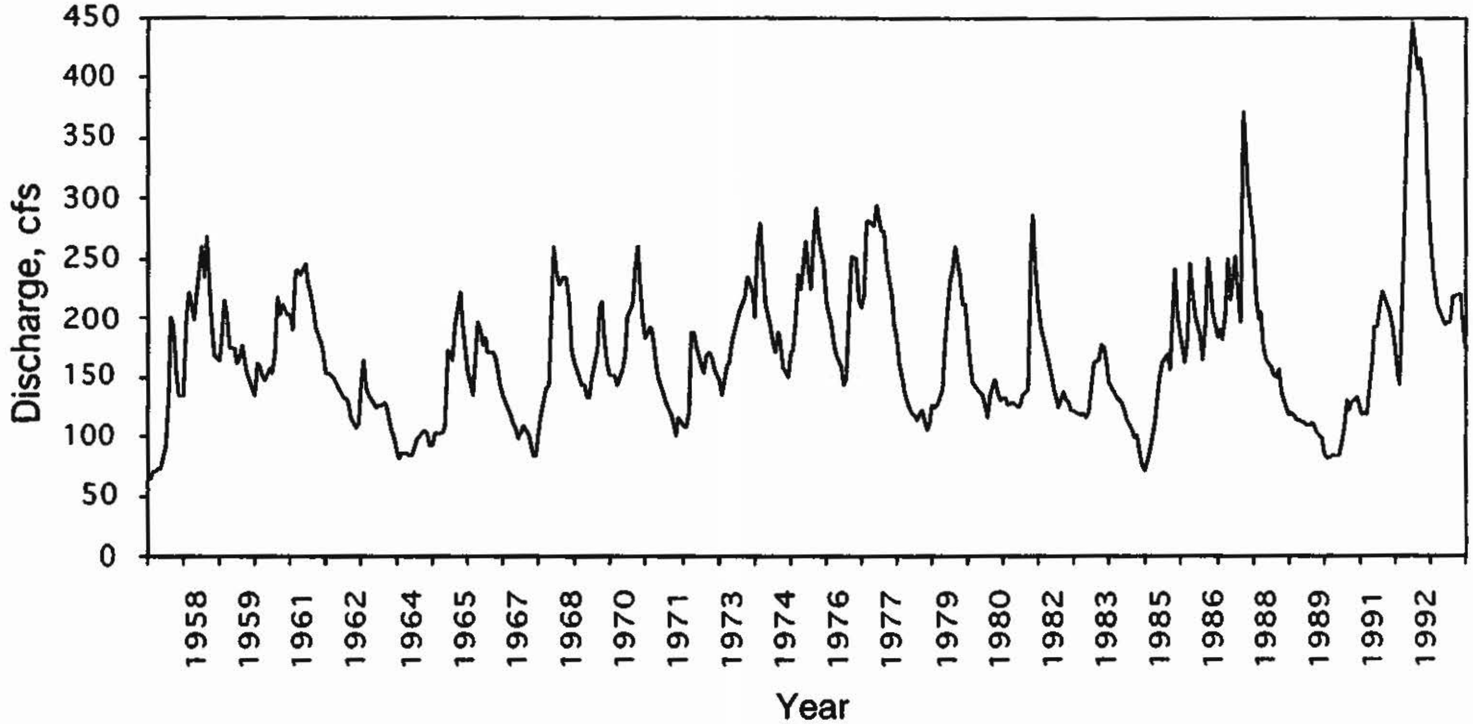


Figure 4. Stream flow hydrograph for the San Marcos River illustrating the period from 1957 to 1992 (after Buckner et al., 1992).

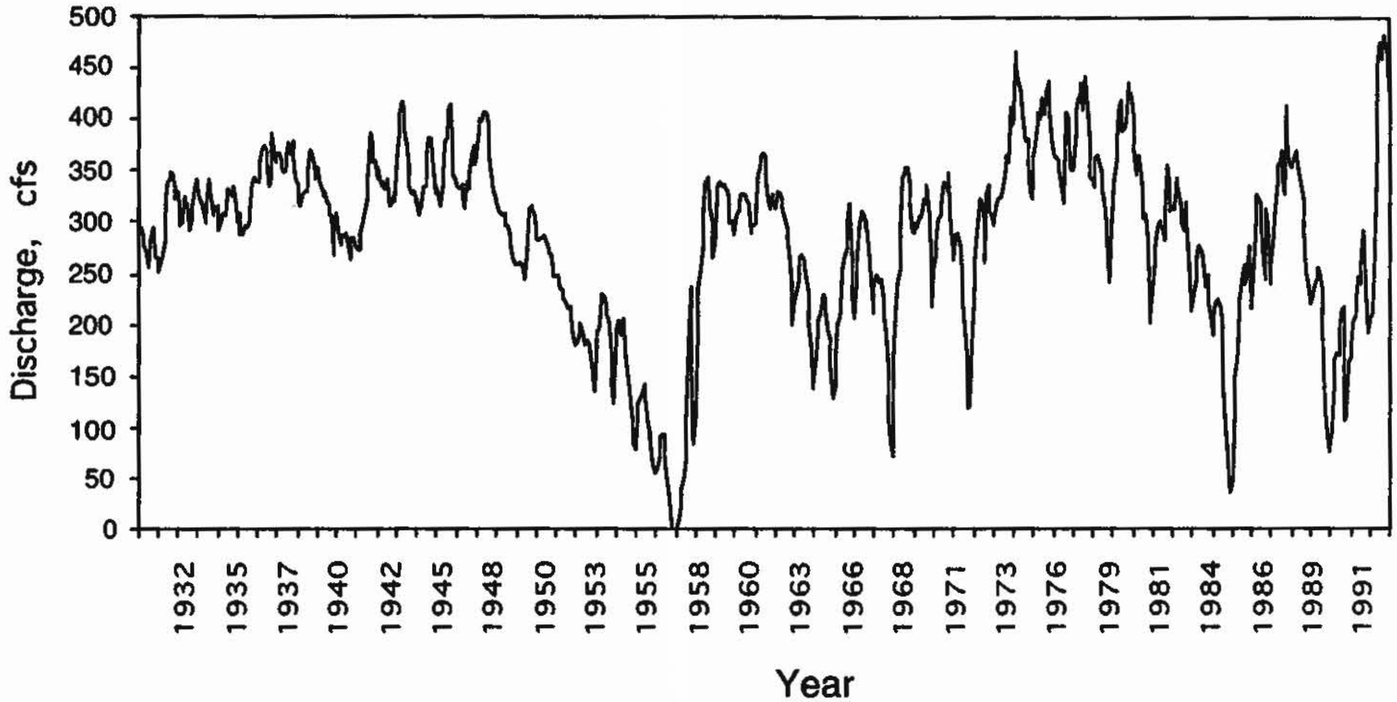


Figure 5. Stream flow hydrograph for the Comal River illustrating the period from 1930 to 1992 (after Buckner et al., 1992).

River.

The endangered species listed in Table 1 inhabit only the unique ecosystems created by San Marcos and Comal Springs and Rivers. There has been little previous documentation of the ecosystems in these rivers. Earlier maps of the systems were large scale and provided few details on hydrogeology. Far greater detail is necessary to completely characterize the Comal and San Marcos Rivers. Through a detailed examination of the rivers and springs, the habitats of the various endangered species in the rivers can be identified. There are many different habitats present in the systems, and the maps presented in this report illustrate the characteristics of the rivers and the habitats contained in them.

A complete description of the habitat area should include what is found in it and the flow that creates it. Hydrochemical, substrate, and vegetation distributions in the rivers, the soils around the rivers, and the flows in the rivers are also included in this description. Substrates range from mud and silt fines, through different sizes of gravel and cobbles, to areas of clean bedrock. Hydrochemical parameters describing both rivers include pH, temperature, alkalinity, specific conductance, fecal coliform, and nitrate, phosphate, and chloride concentrations. Water velocities are central to the delineation of the habitats, because they determine the vegetation and substrate distributions in the rivers. Consequently, flow characteristics, locations of spring orifices, stream discharge, and flow velocities are included in the mapping process. Flow levels necessary for the maintenance of the habitats are estimated.

This report examines the entire ecosystems created by the rivers, estimates their hydrologic requirements, and maps the details of the springs, their rivers, and the surrounding environments in order to assist in protection efforts. Because the springs are important as a supply of water to downstream users, as a habitat for endangered species, and as a recreation and economic resource, it is important to characterize them in order to either preserve the current spring systems or to plan for their future preservation or development. The habitat delineations in this report along with their flow velocity estimates help to identify those areas of both rivers where it is most important that flow velocity and discharge be maintained. With the detail provided by these maps, a more effective augmentation system for the maintenance of spring and river flow from external sources of water may be designed. With augmentation there would be minimal impact on the ecosystems present in the rivers in the event of a loss of spring flow.

Chapter 2:

Edwards Aquifer

Geologic and Depositional History

The rocks which form the Edwards aquifer were deposited in the Cretaceous Period. During the Early Cretaceous the Stuart City Barrier Reef was present along the border of the ancestral Gulf of Mexico (Figure 6). This reef separated the interior of Texas from the gulf, and as a result the interior region was a shallow marine sea having a very low dip towards the gulf. On the gulf side of the reef were open deep-marine waters. Deposition occurred throughout the Cretaceous on both sides of the reef, but it is in rocks from the landward side that most of the aquifer formed (Vauter and Yelderman, 1993). This depositional area is part of the large Comanche Shelf, which consisted of shallow water marine platforms surrounded by numerous relatively deep basins (Sharp, 1990). Figure 6 illustrates the locations of the largest of these features, which include the Maverick Basin, the San Marcos Platform, and the North Texas-Tyler Basin.

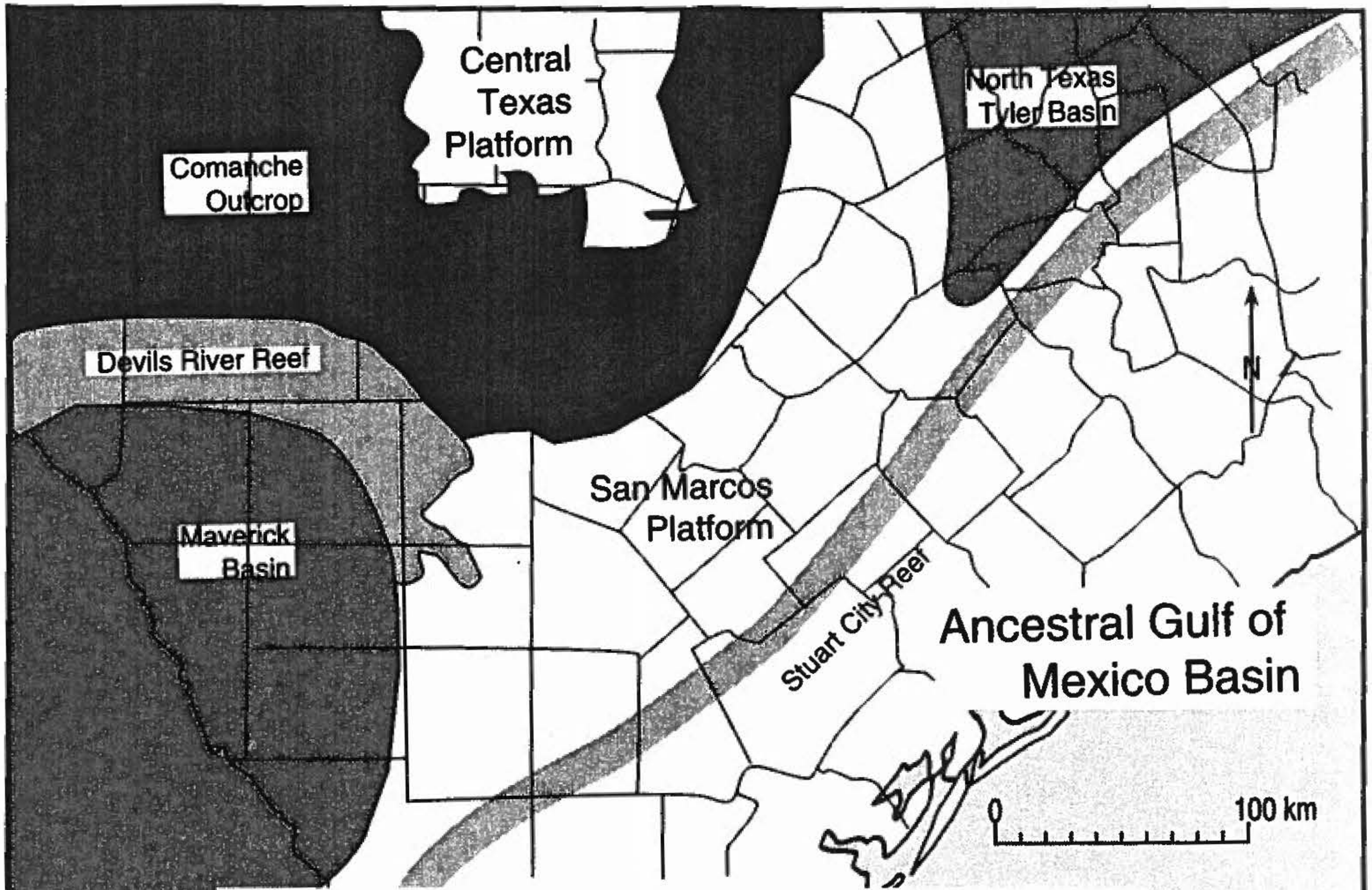


Figure 6. A map illustrating the topographic features that effected the depostion of the Edwards aquifer (after Rose, 1972).

Topographic and Stratigraphic Features

The basal confining unit of the Edwards aquifer system is the Glen Rose Formation, as shown in the stratigraphic column in Figure 7. The Glen Rose can be subdivided into upper and lower units: the lower unit consists of massive limestone and marl interbeds, where both fossils and sinkholes are common; the upper unit is composed of sandy limestone, marl, dolomite, and sand beds thinly interbedded with few fossils. On top of the Glen Rose, the formations that comprise the Edwards aquifer were deposited on the San Marcos and Central Texas Platforms. Marking the area of deposition are: the Maverick Basin, bounded by the Devils River reef trend; the North Texas-Tyler Basin, bounded by the Central Texas reef trend; the ancestral Gulf of Mexico, bounded by the Stuart City reef (Sharp, 1990).

The Edwards aquifer formed in the Edwards Group, which has been divided into the Person and Kainer formations (Figure 7). The Kainer Formation is the lower formation in the Edwards Group, and it has been subdivided into three members. The lowest is the Basal Nodular Member. Next is the Dolomitic Member, and included in it is the Kirschberg Evaporite unit (Maclay and Small, 1986; Rose, 1974). The uppermost member is the Grainstone Member.

Stratigraphically above the Kainer Formation is the Person Formation. The Person is subdivided into five members (Maclay

System	Series	Group	Formation	Member	Thickness (ft)	Lithology
Quat.			Alluvium		45	Gravel, sand, and silt
			Terrace Deposits		30	Coarse gravel, sand, and silt
Tertiary	Eocene	Claiborne	Reklaw		200	Sand, sandstone, and clay
			Carrizo Sand		200-800	Sandstone, medium to coarse
	Eocene Paleocene	Wicox Midway		Wills Point	500 - 1,000	Clay, siltstone, and sandstone with lignite
Cretaceous	Gulfian	Navarro			500	Upper; marl, sand, clay
		Taylor			300-500	Lower; chalky limestone, and marl
		Austin			200-350	Chalk, marl, and hard limestone
		Eagle Ford			50	Upper; flaggy limestone, shale Lower; siltstone, sandstone
	Comanchean	Washita	Buda Ls and Del Rio		100-200	Upper; dense, hard, nodular Limestone; lower, clay
			Georgetown Limestone		20-60	Dense argillaceous limestone with pyrite
		Edwards	Person	Marine and Cyclic	90-150	Limestone and dolomite chalky and recrystallized mix
				Leached and Collapsed	60-90	Recrystallized dolomite, limestone
				Regional Dense	20-30	Dense, argillaceous limestone
			Kainer	Grainstone	50-60	Limestone, hard, miliolid grainstone
				Dolomitic	150-200	Limestone, calcified dolomite, Kirshberg evaporites
				Basal Nodular	40-70	Limestone; hard, dense, nodular, mottled, and stylolitic
		Trinity	Glen Rose	Upper Member	300-400	Limestone, dolomite, shale, marl
				Lower Member	200-250	Massive limestone with marl beds
			Pearsall	Bexar	300	Limestone and shale
				Cow Creek Limestone		Limestone, dolomite, grainstone, packstone
				Pine Island Shale		Shale, argillaceous limestone
	Coahuilan	Nuevo Leon Durango	Sligo and Hosston		800-1,500	Limestone, shale, sandstone
Pre-Cret.						Slate, phyllite

Figure 7. Stratigraphic Column representative of the confined Edwards aquifer in the area of Comal and San Marcos Springs (after Maclay and Small, 1986).

and Small, 1986; Rose, 1974), with the Regional Dense Member as its lowest unit. This is a dark, argillaceous micrite layer that creates an easily recognized boundary between the Kainer and Person formations. On top of it are the Collapsed and Leached Members, comprised of recrystallized limestone and dolomite. The upper units are the Marine Member of limestone and dolomite and the Cyclic Member. All the Person Formation members are supratidal and intertidal in their origin (Maclay and Small, 1986; Sharp, 1990).

Before deposition of the Georgetown Formation, a period of erosion occurred in the Cretaceous, and approximately 30 meters of Edwards limestone was removed. This erosional period corresponds to a time when the Edwards Group was briefly exposed. It was upon the return to subaqueous conditions that the Georgetown Formation was deposited, completing the deposition of the rocks in which the Edwards aquifer later formed (Maclay, 1989). The Georgetown Formation overlies the Person Formation, and it is a limestone similar to others found in the Edwards Group. Subsequent to the Georgetown, the overlying siliciclastic units were deposited.

All of the rocks deposited in shallow marine waters on the Comanche Shelf, and where the depositional waters were deeper, a greater number of rock units stratigraphically formed. The Del Rio was the first of the siliciclastic units to form. It is a clay and shale layer with some dense limestone beds interspersed. Where the Del Rio completely covers the Edwards Group, it serves as a confining layer, creating the confined zone in the Edwards aquifer. Overlying the Del Rio Clay are a series of units that also help to confine the Edwards where they are present. These units include, in sequence overlying the Del Rio Clay, the Buda Limestone, the Eagle Ford Group, the Austin Group, the Taylor Group, and then the Navarro Group in the Cretaceous system. During the Tertiary, the overlying Midway, Wilcox, and Claiborne formations deposited. Quaternary alluvium and terrace deposits overlay the formations. In the Edwards Plateau, the Del Rio Clay is present only locally, and other overlying units are not present.

Structural Features

The major structural event of the Edwards occurred in the early Miocene (Vauter and Yelderman, 1993). This was the downwarping of the Gulf of Mexico basin causing the Edwards Group and overlying rocks to be deformed. The Edwards Plateau remained stable while the area just south of it was affected by the downwarping. A series of en echelon, down-to-the-coast, normal faults were created over several hundred meters, forming the Balcones fault zone. These faults trend northeast-southwest, which closely follows the strike of the buried

Ouachita fold belt (Sharp, 1990). The zone covers an area of 400 km, from Val Verde County to Bell County, and the throw of the faults have reached up to 900 meters (Small, 1986). Some of the faults have enough throw to completely off-set the aquifer; the Comal Springs Fault is an example of one of these large faults.

Geomorphology

Initial deposition of the Edwards Group created intergranular voids, skeletal grainstones, loosely packed burrows in biomicrites, shrinkage cracks, and breccias which all contributed to the primary porosity and permeability of the rocks (Maclay and Small, 1986). Karstification of the San Marcos and Central Texas Platforms occurred during the Early Cretaceous when areas of the platforms were exposed. Erosion of the Edwards limestones that occurred before deposition of the Georgetown Formation created an opportunity for intense karstification in the upper Person Formation, increasing its porosity and permeability. Meteoric waters circulating through these limestones during this period enhanced solution of the rocks, and pre-existing pore spaces and voids were increased in size (Dieke, 1990).

Another period of intense karstification occurred in the late Cenozoic, and it is continuing today in the Balcones fault zone (Sharp, 1990). Meteoric waters circulating through the faults and fractures have increased them through solution enhancement, and a series of caverns have resulted. Flow in the Balcones fault zone occurs very quickly through these caverns, and an almost channelized flow system has developed. The enlarged fractures have also aided in infiltration into the aquifer from overland flow and losing streams crossing the area (Sharp, 1990).

Hydrostratigraphy

The Edwards aquifer system has two distinct regions (Figure 2). First is the recharge zone for the Edwards which consists of all the areas where aquifer rocks crop out, and the aquifer is generally unconfined. Groundwater in this unconfined zone flows through beds that generally dip 4 meters per kilometer to the southeast (Abbott, 1975).

The confined or artesian zone is separated into a freshwater portion and a saline water portion. The freshwater artesian zone is the area from which Comal and San Marcos springs issue. The Del Rio Clay confines the limestones here. Groundwater flow is dominated by flow through the faults, and because the faults strike to the northeast, the overall direction of water movement is also to the northeast.

The saline water portion of the artesian zone is located south and east of the freshwater aquifer area, and it is known as the Bad Water Zone. Water in this zone is also confined by the Del Rio Clay; it has a very slow circulation rate, and residence times have been dated at over 20,000 years using Carbon-14 dating techniques (Pearson, 1973). The bad water line is the interface between freshwater and saline water, and it marks the location in the subsurface of a concentration of 1000 mg/l or more of dissolved solids.

Recharge

Recharge occurs through precipitation and losing streams where the Edwards rocks are exposed in the Balcones Fault Zone. All of the rivers that cross the aquifer are losing, with the exception of the Guadalupe River (Rothermel and Ogden, 1987). Infiltration from their channels while passing over porous and fractured Edwards limestone causes these streams to lose all or most of their base flow and much of their storm runoff. Infiltration losses account for 60% to 80% of the recharge to the Edwards aquifer in the San Antonio area; the remainder of the recharge is derived from direct infiltration on the interfluves (Rothermel and Ogden, 1987).

Some additional recharge may occur as cross-formational flow from the Glen Rose Formation (Rothermel and Ogden, 1987). Such flow occurs predominantly where the Glen Rose Formation is juxtaposed against the Edwards limestone in areas of the

Balcones fault zone. Annual recharge to the Edwards aquifer for the period 1934-1991 has been estimated along with the historical maximum and minimum amounts, and it is shown in Table 2 (Brown et al., 1992; Vauter and Yelderman, 1993).

TABLE 2. Maximum, minimum, and average annual amounts of recharge to the Edwards aquifer.

Recharge	acre-feet	hm^3
average annual (1934-1993)	682,000	840.91
maximum (1987)	2,003,600	2470.44
minimum (1956)	43,700	53.88

Cubic hectometer (hm^3) is the metric conversion for acre-feet, where 1.0 hm^3=811.03 acre-ft (Maclay and Small, 1986)

Storage

The total amount of water in storage in the Edwards aquifer has been estimated recently by Hovorka et al. (1993) to be 215 million acre-feet (265,095 hm^3). This estimate represents all of the water stored in the aquifer, both recoverable and unrecoverable. Storage is divided into 156.6 million acre-feet (193,087.8 hm^3) in the confined freshwater area and 58.5 million acre-feet (72,130.5 hm^3) in the unconfined area. To develop this estimate, Hovorka et al. (1993) first estimated the porosity throughout the aquifer. Through models using three-dimensional Stratigraphic Geocellular modeling software, the Edwards was divided into 196 layers; a complete description of the modeling process is described in Hovorka (1993). This model developed porosity estimates over the entire aquifer. High frequency cyclicity in the aquifer makes the vertical porosity distribution highly variable, and there are lateral gradational changes in the porosity across the aquifer. Porosity estimates range from 10% to 35%, with an average of 21.7% for the Edwards Group rocks.

Through a comparison of the high and low potentiometric surfaces of the aquifer as they were mapped during record low levels in 1984, and record high levels in 1992, Hovorka et al. (1993) estimated the specific retention. The difference in the amount of water in aquifer at these potentiometric levels estimates specific retention at 58% of the porosity. This amount represents the fraction of the total water in the unconfined area of the aquifer which is not recoverable. Previous estimates by Maclay and Small (1976) were that only 25%-50% of the pore spaces in the aquifer would drain by gravity. Allowing for the differences between the total amount of porosity and the amount of specific retention, Hovorka et al. (1993) calculated storativity at 2.6×10^{-4}. Maclay and Small (1986) previously estimated this amount as between 10^{-4} and 10^{-5}, assuming an average porosity of 20%. These two estimates closely agree.

Maclay and Small (1986) estimated an effective porosity for the full thickness of the aquifer to be about 2%, based on geophysical and laboratory data, and Maclay (1992) estimated the specific yield of the Edwards aquifer at 25 million acre-feet (30,825 hm^3).

The volume of the unconfined zone represents 30% to 40% of the total volume of the aquifer. Therefore, a large amount of water released from the aquifer comes from storage in this zone. Maclay (1992) estimated the amount of water stored in the unconfined zone to be 20%-25% of the total amount of stored water in the aquifer. The amount of water retained in the unconfined zone after a recharge event is strongly affected by the geologic structure of the aquifer. Because faults in the Balcones fault zone trend northeast-southwest, they can act as barriers to flow moving from the unconfined zone into the confined zone. This would allow a greater volume of water to remain in the unconfined zone for longer period of time and tend to direct flow subparallel to the strike of the faults (Figure 8).

The portion of the confined freshwater aquifer from which Barton Springs issue is hydraulically separated from the area of San Marcos and Comal springs by the groundwater divide in Kyle, Texas. This section is adjacent to the San Antonio region, and it is between the in Kyle divide and the groundwater divide

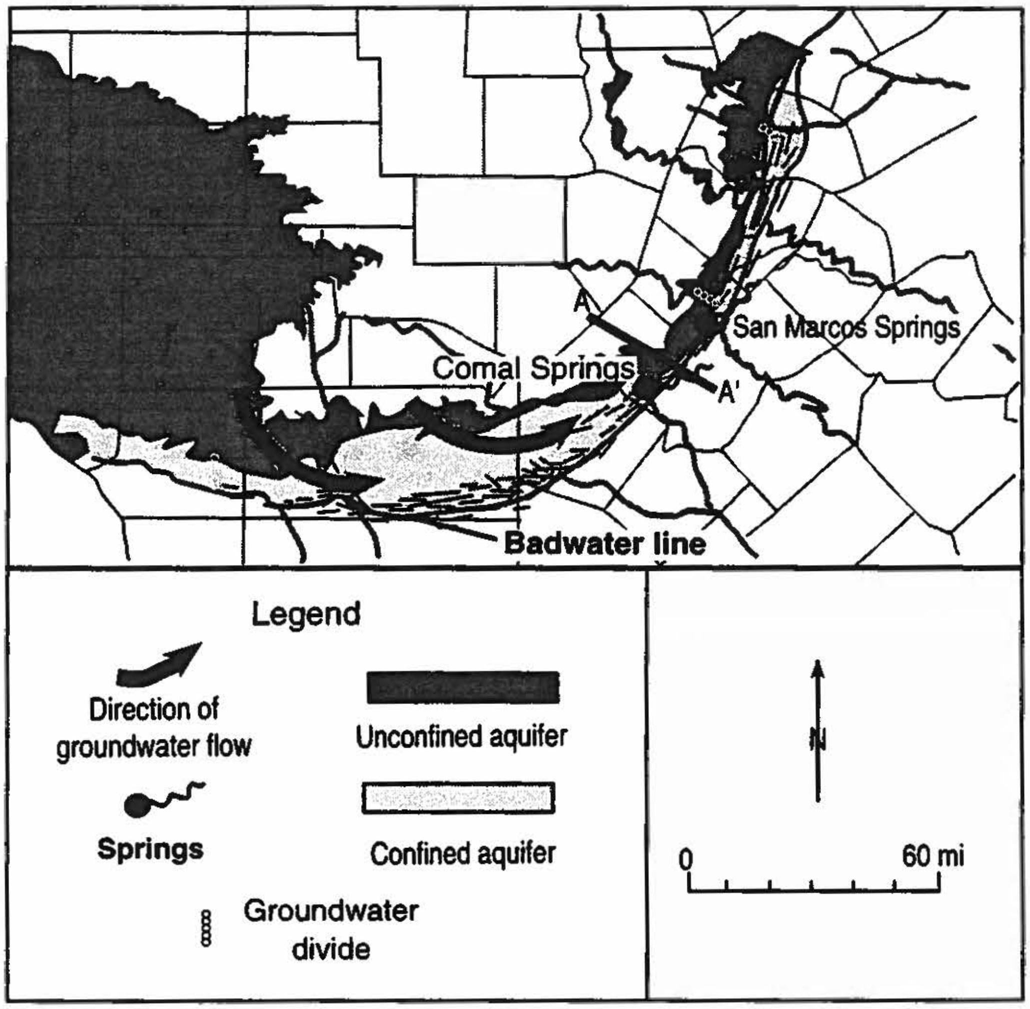


Figure 8. Generalized directions of groundwater flow in the Edwards aquifer (after Oetting, in press).

in northern Travis County (Baker et al., 1986).

Transmissivity

The Edwards aquifer does not have an uniform distribution of permeability, which makes an estimate of the aquifer's transmissivity difficult. Maclay and Small (1986) divided the aquifer into 21 subregions based on its geology, hydrology, and hydrochemistry. Transmissivity estimates for these subareas range from negligible amounts in some areas of the recharge zone to approximately 2 million ft^2/day for the most permeable subarea in the confined region. The highest transmissivities were in the confined freshwater region where there are low hydraulic gradients, large sustained spring flows, uniform water temperatures, and uniform water quality within a subarea. Faults in the Balcones fault zone provide master conduits for flow in those subareas, and these faults are responsible for the overall high transmissivity of the aquifer (Woodruff and Abbott, 1979). Transmissivities were not estimated for the saline water portion of the confined zone.

Groundwater Flow

Although the dip of the aquifer formations is towards the Gulf of Mexico, the regional direction of groundwater flow within the aquifer in the vicinity of Comal Springs and southwest of San

Marcos Springs is toward the northeast (Figure 8). Flow patterns through the aquifer are illustrated in the cross-section A-A', shown in Figure 9. Groundwater in the Balcones Fault Zone flows through faults to the northeast. The majority of the water travels in this direction, and it is discharged as spring flow.

Maclay and Small (1986) estimated an average linear groundwater velocity in the Balcones Fault Zone to be about 27 ft/day (8.23 m/day), while estimates of groundwater velocities made at individual well sites range from 2-31 ft/day (0.6-9.45 m/day). Faults provide important conduits for groundwater flow, and the main faults are discontinuous, high-angle, normal faults which display a net down-to-the-coast displacement (Clement, 1989; Woodruff and Abbott, 1979).

Although most individual faults exhibit less than 200 ft of throw, some offset the aquifer by as much as 900 ft (Small, 1986). The Edwards aquifer is vertically displaced for its entire thickness at places along major northeastward-striking normal faults. At these places, ground-water circulation is diverted northeastward. Flow along these faults is discharged as spring flow, and Comal and San Marcos springs both receive the majority of their flow through faults.

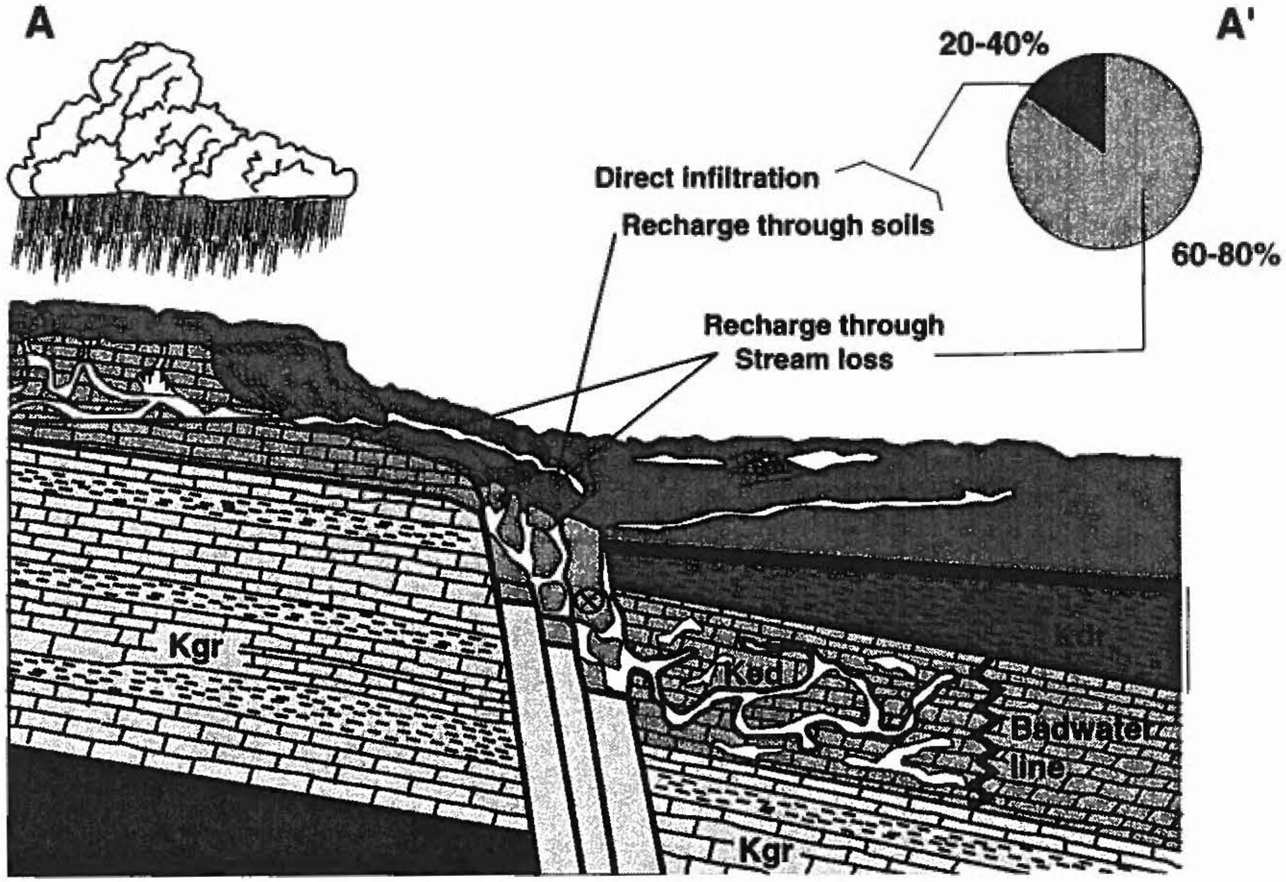


Figure 9. Cross-section A-A' illustrating flow through the Edwards aquifer (after Oetting, in press). Kdr is the Del Rio Formation; Ked is the Edwards Group, and Kgr is the Glen Rose Formation, as shown in Figure 7.

Chapter 3:

Methods

Much of the data presented in this report were compiled through an extensive literature survey relating to the Comal and San Marcos River systems. Most of the soil data came from the literature, as did the majority of the hydrochemical data. All of these data were then field checked. New data collected in the field for this report include substrate, vegetation, and channel velocity and discharge data. The field work consisted of mapping of vegetation and substrate in both the San Marcos and Comal Rivers. Water quality sampling, species sampling, and water column velocity data were collected on the Comal River. Field work on the Comal River was performed during the month of June, 1993, when flow in the river averaged 360 cfs (9.72 m^3/s). Field work on the San Marcos River was performed during September, 1993, when flow in the river averaged 220 cfs (5.9 m^3/s).

Field Mapping

Aerial imagery of both rivers was used for field mapping of the substrate and vegetation. This consisted of three-band false color composite imagery from a low altitude flight over the rivers by Utah State University during the fall, 1992. Substrate and vegetation information for each river was mapped directly onto the photos while in the field. Vegetation was identified visually. Information was gathered along the entire length of the river, rather than through cross-sections at intervals in the rivers. Observations were made by foot or by boat, depending on the characteristics of the reach in question.

The substrate was classified according to the modified Wentworth scale (Selley, 1982), which separates substrate by size into the series of classes shown in Table 3. This is a practical way to separate between mud, clay, granule, small gravel, and all the other size classes. Substrate was measured and identified visually for separation into these categories.

The modified Wentworth scale was used together with the Hjulstrom diagram to estimate flow limits for different classes of substrate. The Hjulstrom diagram (Figure 10) illustrates the flow velocities that cause erosion, transportation, or sedimentation to occur given different grain sizes of substrate. This diagram is an accepted method of estimating flow velocity ranges (Selley, 1982).

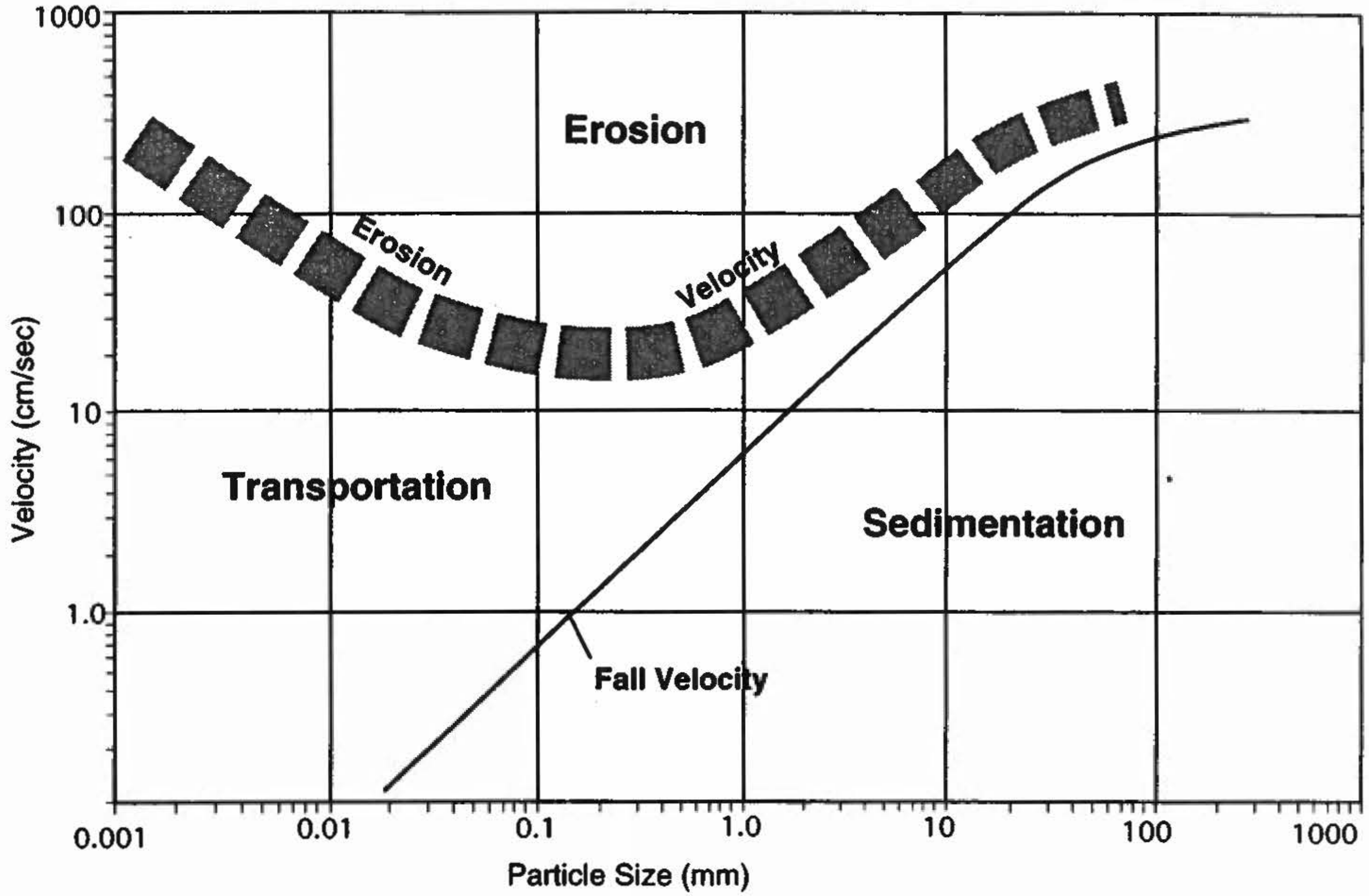


Figure 10. Hjulstrom diagram indicating the velocities at which material of different sizes are transported or eroded (Selley, 1982).

TABLE 3. Modified Wentworth classification scale.

Sediment Class	**Size (mm)**
Organics	miscellaneous
Clay	< 0.004
Silt	0.004 - 0.062
Sand	0.062 - 1.0
Coarse Sand	1.0 - 2.0
Granule	2.0 - 4.0
Small Gravel	4.0 - 8.0
Medium Gravel	8.0 - 16.0
Large Gravel	16.0 - 32.0
Rubble	32.0 - 64.0
Small Cobble	64.0 - 128.0
Large Cobble	128.0 - 256.0
Small Boulder	256.0 - 512.0
Medium Boulder	512.0 - 1024.0
Large Boulder	> 1024.0
Bedrock	solid

Water Quality Sampling

Sampling was performed on the Comal River where hydrochemical data were collected at random sites over the length of the river. A Hydrolab (Figure 11) was used to collect and to analyze the waters. It was used by placing the probe into the water, and after approximately twenty seconds, once the probe has equilibrated, hydrochemical measurements were directly reported by the Hydrolab. Dissolved oxygen, temperature, pH, and specific conductivity data were taken in this manner.

Flow column velocities were measured at each of the sites where the Hydrolab was used with a Marsh-McBirney flow meter (Figure 12), which is placed into the water column with the probe at the sampling depth, facing upstream. The screen on the meter then showed the flow velocity for that depth, and a measurement was taken once it had equilibrated. This meter was used to measure flow velocities at two tenths and eight tenths of the total column depth, where the river was at least two feet deep. Where the river was less than two feet deep, only the six tenths velocity was measured. At all of the sites an additional measurement was taken at a depth of 15 cm above the river bed, representing the velocity above the boundary layer of the river bed.

Figure 11. Hydrolab used for collecting hydrochemical data.

Figure 12. Marsh-McBirney flow meter used for measuring flow velocities in the water column.

Hydrochemical data were put into spreadsheet format, and statistical analyses were performed. All of the data were tested to determine whether they were log normally or normally distributed. The remaining statistical analyses were performed accordingly. Maximum and minimum values for each of the parameters were identified along with ranges, means, and standard deviations. The standard deviation provides an estimate of the amount of variance in the data points.

Species Sampling

Fish were collected and counted in the locations where measurements of hydrochemistry and flow had been made in order to determine where the fish, particularly the endangered fountain darter, prefer to live. A drop-net was built for this field investigation; it was 2 meters long, 1 meter wide, with an adjustable height (Figure 13). This net was dropped over areas of the Comal River, trapping the fish inside the net. A large mesh dip-net was then used to sweep the area 15 times, depleting it of fish. Fish of various species were counted and released. Where the flow in the river was too strong for the net to hold or the system was too deep for sampling, scuba teams performed visual observations of the area. Spring openings were also sampled for species, such as salamanders. Nets were placed around the largest spring openings in the Comal system

Figure 13. Sampling for the fountain darter on the Comal River during July, 1993.

for a period of 24 hours in order to capture any animal life leaving the spring orifice. Selected information from the July, 1993, sampling is included in this report.

While field mapping procedures were the same for both rivers, the San Marcos River was not sampled for the species of fish living in it. The two river systems are similar, and the fountain darter data from the Comal River are assumed to be true for the San Marcos.

All of the data collected in both rivers are discussed in the following chapters. The data were analyzed and correlated for the identification of habitats in the rivers. The data were also used to estimate the flow velocities in each river.

Chapter 4:

Comal River

The Comal River system is very complex. Ground water flow to Comal Springs is controlled by a series of en echelon, normal faults connected by smaller side faults, which have been enlarged by karstification. These faults influence the flow in two ways: first, they create zones of high permeability that are further enlarged by karstification, and second, they juxtapose permeable beds against non-permeable beds, creating flow barriers. The Comal Fault, which is the main conduit for flow to the springs, places the Edwards Formation against the Taylor Formation (Figure 14). This gives rise to a flow system that is both highly heterogeneous and anisotropic. Water flows to the springs from deep in the artesian part of the aquifer; this is primarily older water from the southwestern portion of the Edwards aquifer (Pearson, 1973).

Recharge to Comal Springs

It is generally accepted that Comal springs receives very little recharge locally (Ogden et al., 1985; Pearson, et al, 1975; Thompson and Hayes, 1979). Five groundwater traces

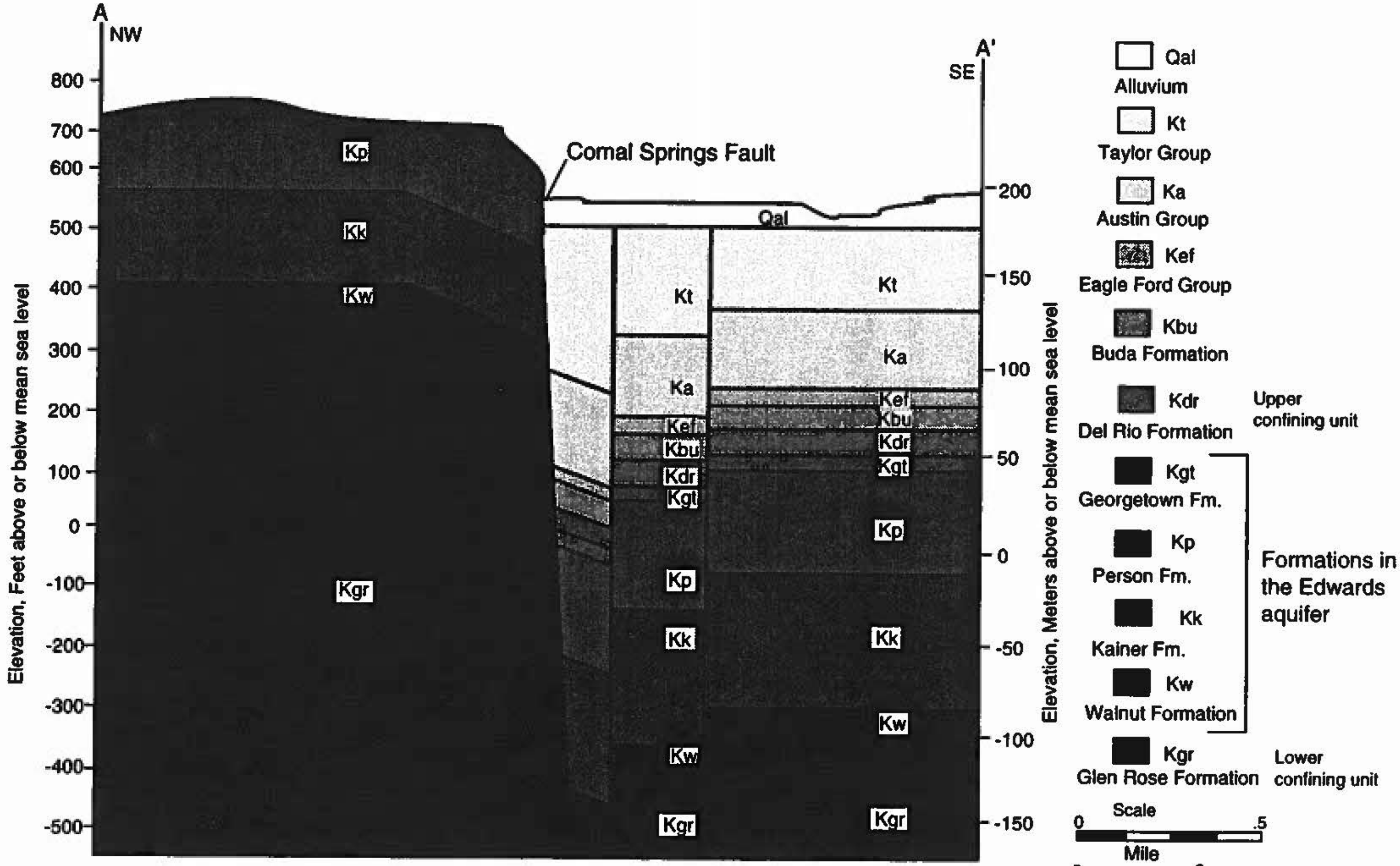


Figure 14. Geologic cross-section through Comal Springs locality (after Guyton and Assoc., 1979).

performed by Pearson et al. (1975) at Comal failed to show up in any of the spring orifices. However, Rothermel and Ogden (1987) have shown that there is some amount of local recharge into some of the Comal springs following large rain events. Hydrochemical parameters, including discharge, temperature, nitrate, and pH all increased slightly a few days after the rain. Specific conductivity, and sulfate and chloride concentrations decreased after the rain event. These shifts indicate a small component of local recharge.

Rothermel and Ogden (1987) hypothesized that the local recharge waters form a temporary 'wedge' of mounded groundwater with a steeper hydraulic gradient on top of the normal groundwater in storage in the Comal basin. This wedge of water then discharges through the spring openings before the pre-existing groundwater in storage. Formation of this recharge 'wedge' can be either to the northeast or to the southwest of the fault, and it would act in this same manner in either case. If it formed with a northwestern recharge wedge, it would do so where the Person Formation limestone crops out next to the Taylor marl (Rothermel and Ogden, 1987). Pearson's (1973) estimate of the age of the Comal waters may have overlooked the local recharge component, as Pearson sampled the waters during a dry period, with no additional sampling following storm events.

Individual spring orifices exhibit different amounts of response to rain events. Dyes injected into a well 1000 feet upgradient of the Comal River in Panther Canyon by Rettman in 1984, did not show up at the nearest spring orifice. The only traces of it that showed were in the spring discharge point furthest to the west of the injection point (Rothermel and Ogden, 1987). These dye traces indicate that the springs in the Comal system are not all hydraulically connected, and they do act independently of each other.

Description of Comal River

Water discharges from the Comal Fault at an elevation of 190 meters above sea level, in Comal County. The springs issue from the aquifer along the trace of the fault. Most flow into Landa Lake at the north end of the Comal River system (Figures 15 and 16). There are four springs large enough to have associated spring runs into Landa Lake. The largest of these has an average discharge of 21.7 cfs (0.6 m^3/s), while the smallest averages 1.0 cfs (0.3 m^3/s; Ogden, Spinelli, and Horton, 1985). Two other large springs contribute to Landa Lake, but they have not formed spring runs; these are marked on Figure 16 as the large springs. The bottom of the lake acts similar to a sieve with hundreds of small springs bubbling up into the lake. These springs add significantly to the amount of water in the system,

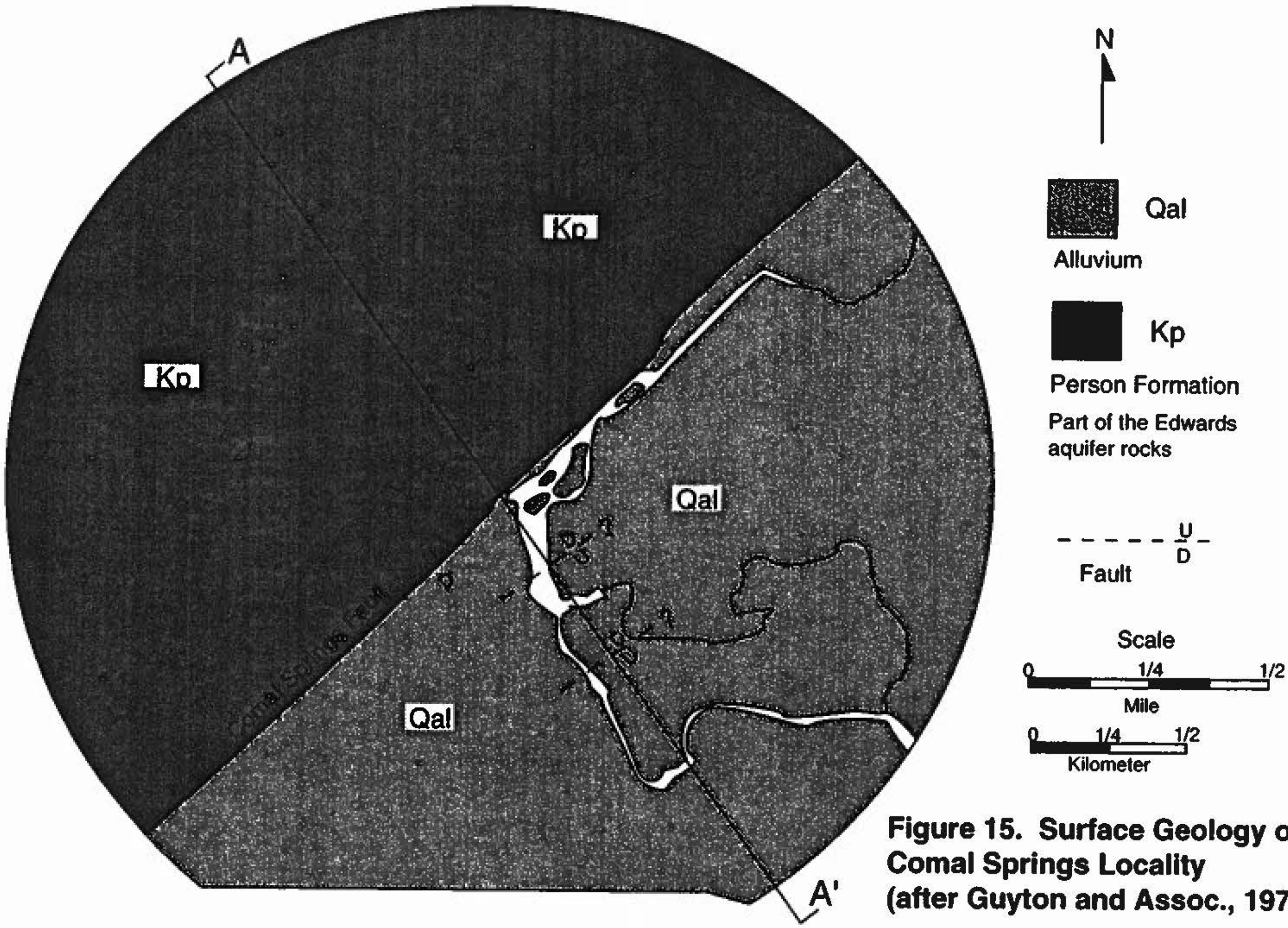


Figure 15. Surface Geology of Comal Springs Locality (after Guyton and Assoc., 1979).

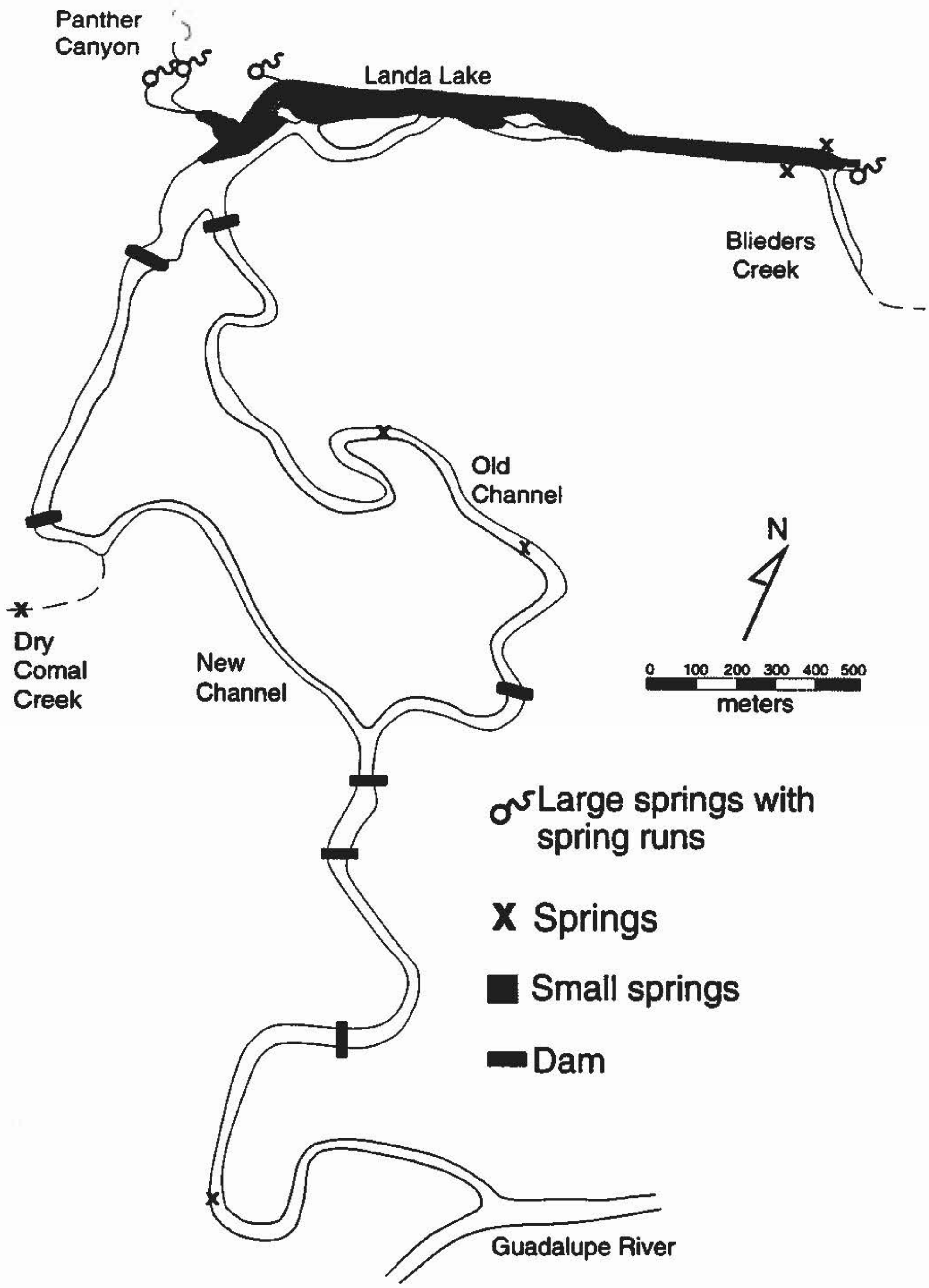


Figure 16. A map locating the large springs with spring runs, the springs, the small springs, and the dams in the Comal River system (after Brune, 1981).

and they are marked on Figure 16 as the shaded area. They cover the lake bed. The north edge of Landa Lake hosts groundwater seeps along its length. Together with the water from the large springs on the river, these waters produce the majority if not all of the flow in the Comal system. The lake is the headwater of the Comal River, which travels 1.6 km to its confluence with the Guadalupe River.

A few tributary creeks and spring runs lead into Landa Lake (Figure 16), from which the Comal River splits into the old channel and the new channel downstream. The old channel remains relatively unchanged from its natural state. While some of its flow is diverted to the water theme park located along its banks, The Schlitterbahn, this water is returned to the old channel downstream. The new channel is a man-made channel more uniform in width than the old channel. The new channel has a bedrock river-bed in areas, which is clean of any gravels. The river is the site of a number of parks and tubing locations. Both channels re-join and together travel to the confluence with the Guadalupe River (Figure 16).

The new channel is not the only alteration that has been made to the river. The Comal River has a number of control features on it, such as dams and tube chutes (Figure 17). These dams operate as overflow features, rather than as water release devices. They create areas along the river where flow is faster

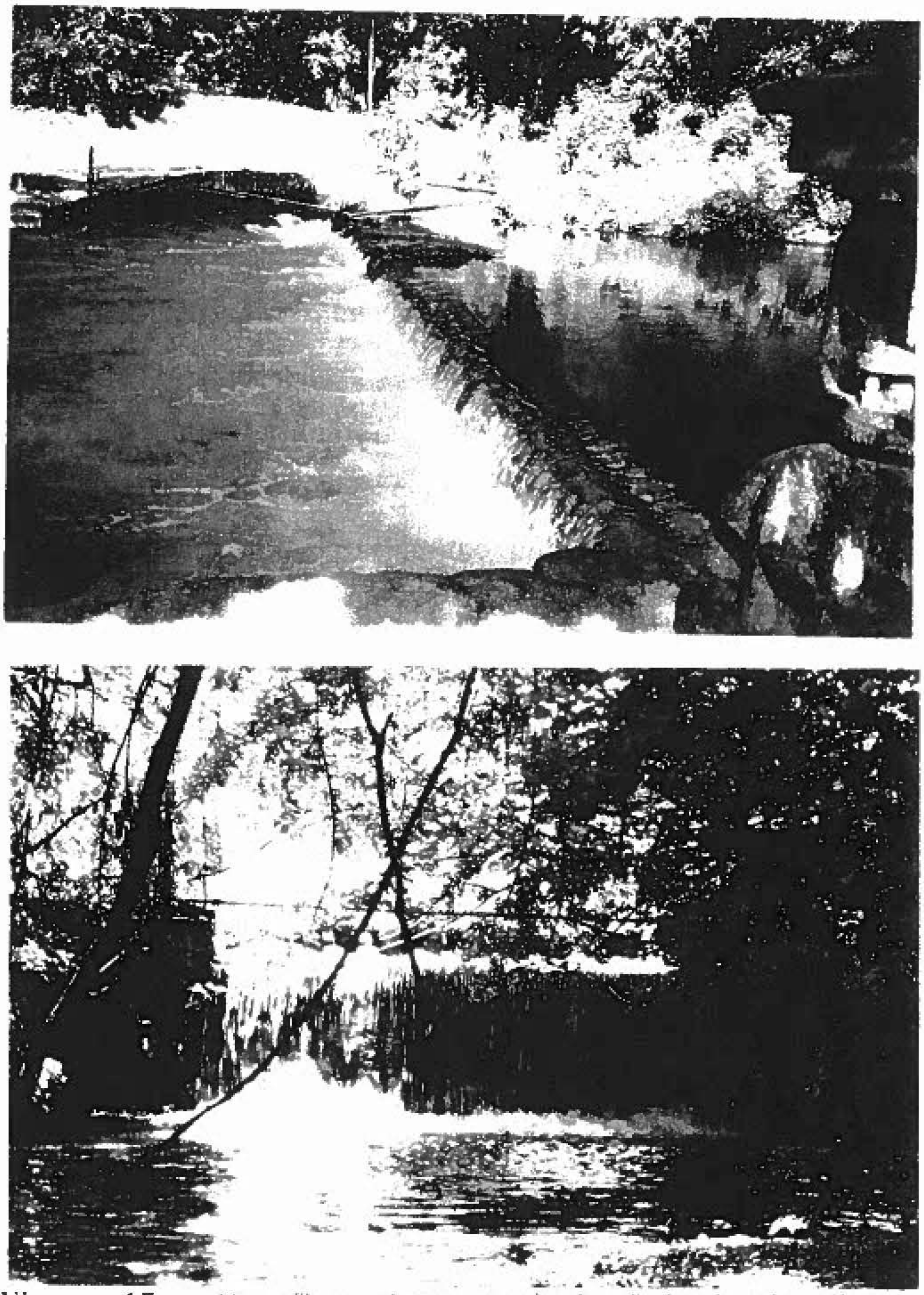


Figure 17. Overflow dams typical of both the San Marcos and Comal Rivers.

immediately following the dam until it naturally slows again downstream. The river is also the site of much recreational activity. Summer homes are located along its banks, as well as The Schlitterbahn water theme park. Its waters are used for recreation, particularly swimming and boating. It is heavily populated during summer months. The banks of the Comal have parks and a golf course on them.

The long-term average flow through the Comal River is 296 cfs (8.37 m^3/sec) as cited by Buckner et al. (1988). The river ceased to flow during the mid-1950's, when the area was in a long drought, and discharge also dropped drastically in 1984 and 1990 to 24 cfs (0.7m^3/s) and 46 cfs (1.2 m^3/s), respectively (Linam et al., 1993). The annual stream flow hydrograph for the river for the year 1987 is shown in Figure 18. The pattern of flow for this year is typical for the river. The flows become somewhat higher with spring storms that cause increased discharge from the aquifer and some storm run-off. The flow remains high for the duration of the summer months, and then decreases into the fall and winter. The Comal River is not a losing river.

Hydrochemistry

The hydrochemical data presented in Table 4 are a compilation from the literature, along with some new data. The

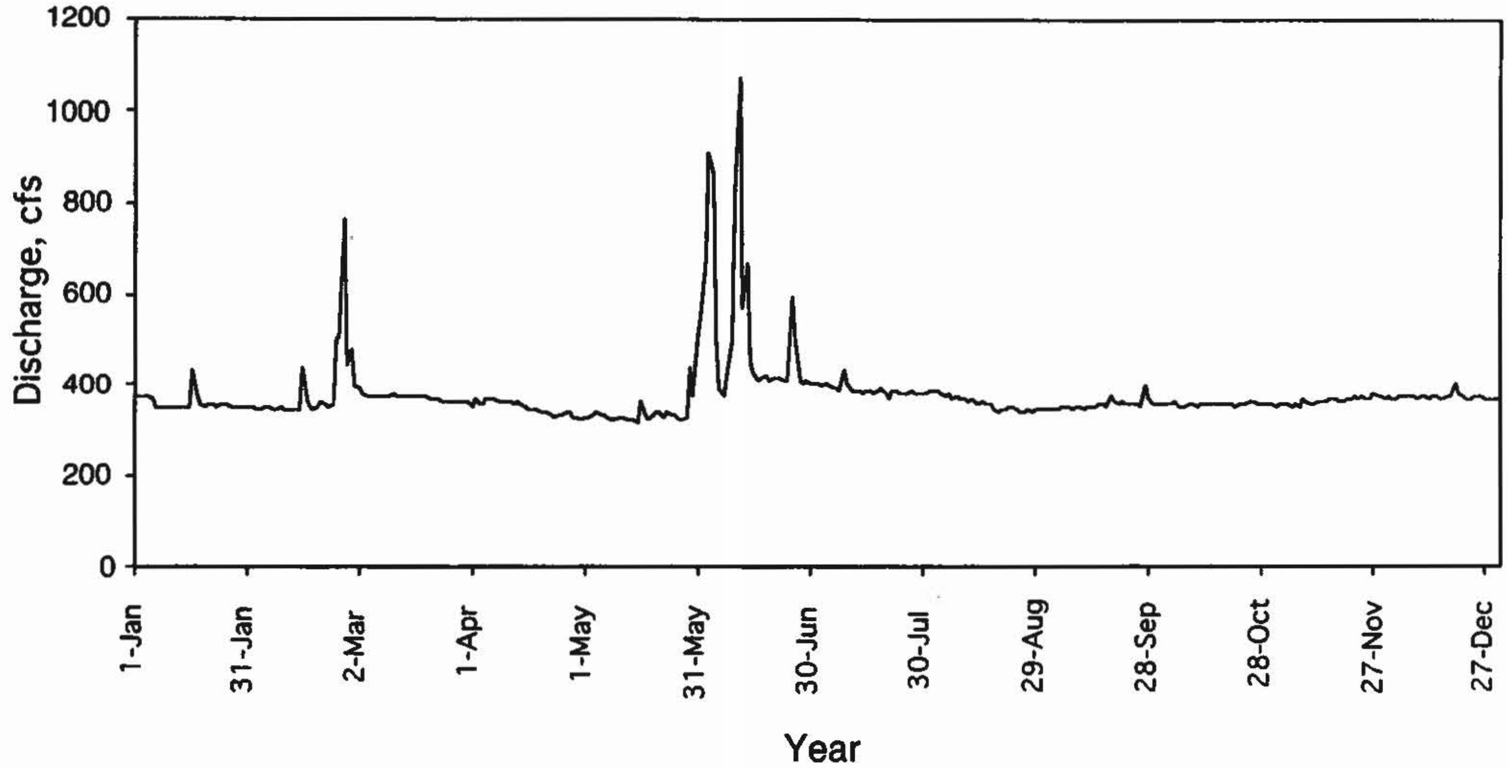


Figure 18. Annual stream flow hydrograph of the Comal River for 1987 (after Buckner et al., 1988).

TABLE 4. Maximum, minimum, range, and standard deviation for hydrochemical parameters in the Comal River.

	Maximum	Minimum	Range	Median	Standard Dev.
Temperature (C)	26.81	23.10	3.71	24.11	0.74
pH	8.29	6.80	1.49	7.14	0.14
Dissolved Oxygen (mg/l) *	10.27	1.00	9.27	4.85	0.20
Sp. Conductivity (umohs/cm)	768.00	485.00	283.00	529.81	63.77
Alkalinity (mg/l)	268.00	225.00	43.00	233.00	9.61
Nitrate (mg/l)	1.76	0.77	0.99	1.48	0.23
Nitrite (mg/l)	0.01	0.01	0.00	0.01	0.00
Kjeldahl-N (mg/l)	0.30	0.10	0.20	0.16	0.07
Chloride (mg/l)	33.00	15.00	18.00	17.91	4.66
Phosphate (mg/l)	0.12	0.01	0.11	0.05	0.04
Sulfate (mg/l)	27.00	13.60	13.40	22.10	5.07
Calcium (mg/l)	80.00	75.00	5.00	77.75	2.06
Magnesium (mg/l)	17.00	15.00	2.00	16.00	0.82
Bicarb. as HCO3 (mg/l)	279.00	188.00	92.00	235.28	34.87
Total Hardness (CaCO3 mg/l)	264.00	244.00	20.00	256.38	6.16
TDS (mg/l)	300.00	295.00	5.00	297.75	2.06
Fecal Coliform (#/100 ml) *	165.00	0.00	165.00	9.35	0.76
Total Organic Carbon (mg/l)	2.00	1.00	1.00	1.11	0.33
Ammonia (mg/l as NH3)	0.03	0.02	0.01	0.02	0.00
Potassium	1.90	0.70	1.20	1.30	0.85
Silica	12.00	11.00	1.00	11.50	0.71
Sodium	15.00	9.60	5.40	12.30	3.82
* indicates a log normal data distribution					

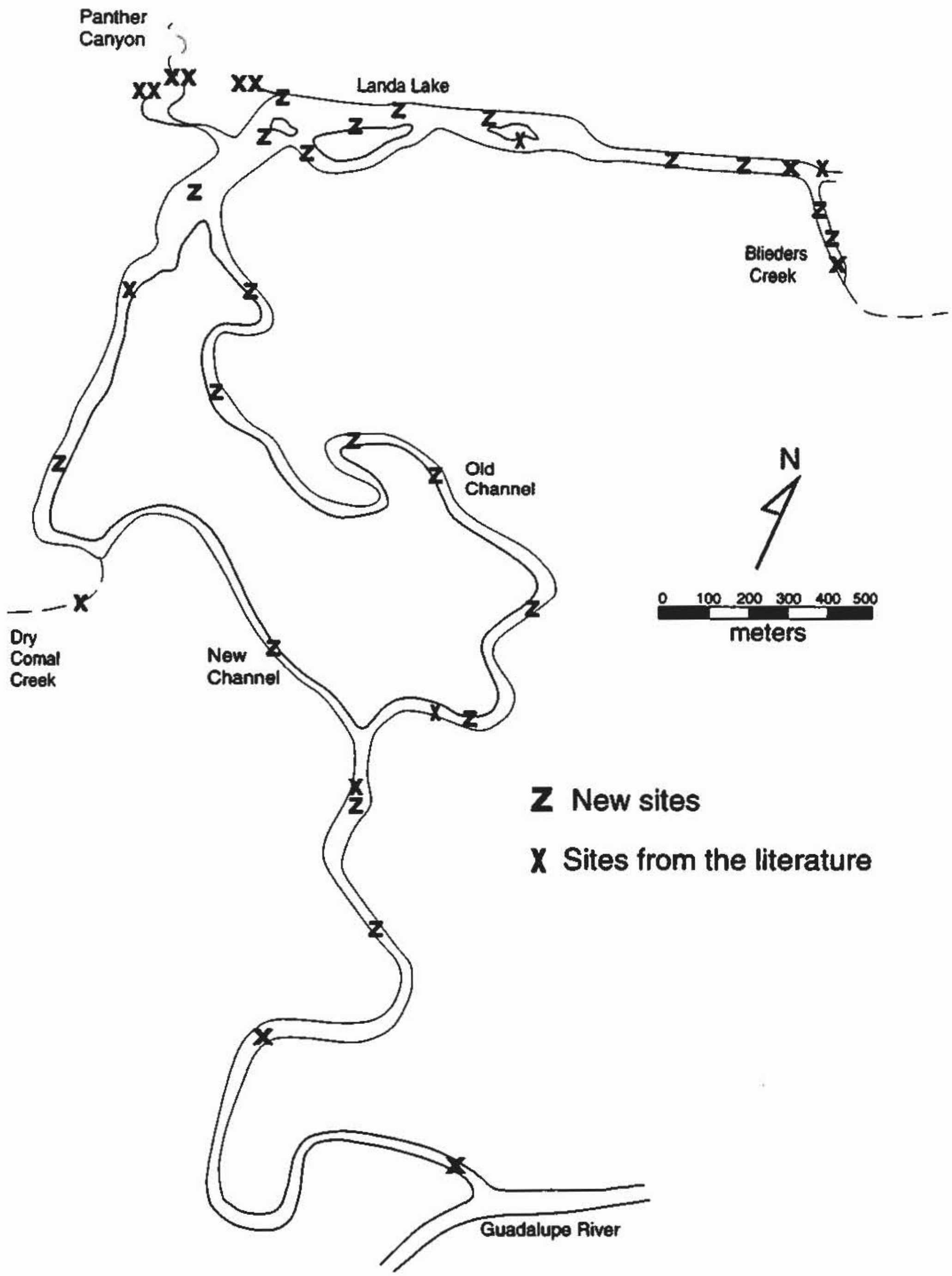


Figure 19. The location of sites where hydrochemical data were collected along the Comal River.

sites of the hydrochemical tests are shown on the location map for Comal River (Figure 19), illustrating that samples were taken along the entire length of the system. Data from this field work are included in Table 4; refer to Chapter Three (Methods) for the sampling techniques used. Table 4 lists the results of the analyses of the chemical data, while the complete listing of both the data from the literature and the new data are in Appendix A. The most consistently reported parameters were temperature, dissolved oxygen, pH, specific conductance, alkalinity, hardness, fecal coliform, and concentrations of nitrate, calcium, sodium, chloride, phosphate, and bicarbonate. The methods of analysis for each of the parameters are given in the referenced reports. In the case of the TDS values, Espey, Huston, and Assoc. (1975) sent the water samples to the Texas Department of Health laboratories. There TDS was evaluated using the standard EPA methods measurements by weight (Taras, et al., 1971).

The most notable aspect of this data is its uniformity; there is very little variation in the measurements. Ranges within the measurements are presented in Table 4 for each of the given parameters. Mean and standard deviation are shown for comparison. In most cases the datum range does not exceed two standard deviations of the measurements for that parameter, and for many of the parameters, it is less than that. For example, the temperature in the river shows a range of only 2.30 degrees. The overall river has a charge balance of 0.92.

The water is remarkably uniform in its hydrochemistry along the entire length of the river. Part of this is due to the large groundwater basin that supplies water to Comal springs and the deep flow system to the springs. While in storage water from different recharge areas mix before they discharge at the springs (Rothermel and Ogden, 1987). As a result the water has a very constant chemical composition. When there is local storm water recharge the hydrochemistry of the springs is altered only slightly; the waters are mixed and the local recharge component is so small that the changes in temperature, discharge, specific conductivity, and sulfate, nitrate, and chloride concentrations are small. There is a slight difference between the chemical composition of the spring water and the nearby Edwards well water. Wells within approximately 3 miles of Comal Springs measure slightly higher sulfate and chloride concentrations along with slightly lower calcium and magnesium concentrations. These differences indicate that there is almost no contact between the water discharging from Comal springs and the nearby aquifer area. The springs' hydrochemistry do not show the same values as the well waters (Rothermel and Ogden, 1987; Ogden et al., 1985).

Rothermel and Ogden (1987) did identify small seasonal shifts in the hydrochemistry of a few parameters. The dissolved oxygen measurements drop with drops in discharge, and higher sulfate values are found during the winter months. This is probably connected to the growing season. When there is no growth in the winter, plants are left to decay, and bacteria release sulfate from the decaying organic matter into the soils (Rothermel and Ogden, 1987). In addition, the months with lower spring flow, usually during the winter, showed lower calcium hardness values. Calcium precipitated out of the water into the previously saturated soil during the low flows, and when the discharge became high again in the spring and summer months, the calcium precipitates were dissolved into the waters (Rothermel and Ogden, 1987). These are the only significant variations in the hydrochemistry. The hydrochemical data might imply that the fountain darter and the Comal Springs riffle beetle require very specific water in which to live and to reproduce.

Some flow measurements through the water column were taken during sampling (location map, Figure 20); these data are presented Table 5. For those measurements taken in the water column, velocities at 15 cm, 0.8 of site depth, and 0.2 of site depth were measured. If the site was less than 2.0 feet deep, then only 15 cm and 0.6 of site depth were measured. These

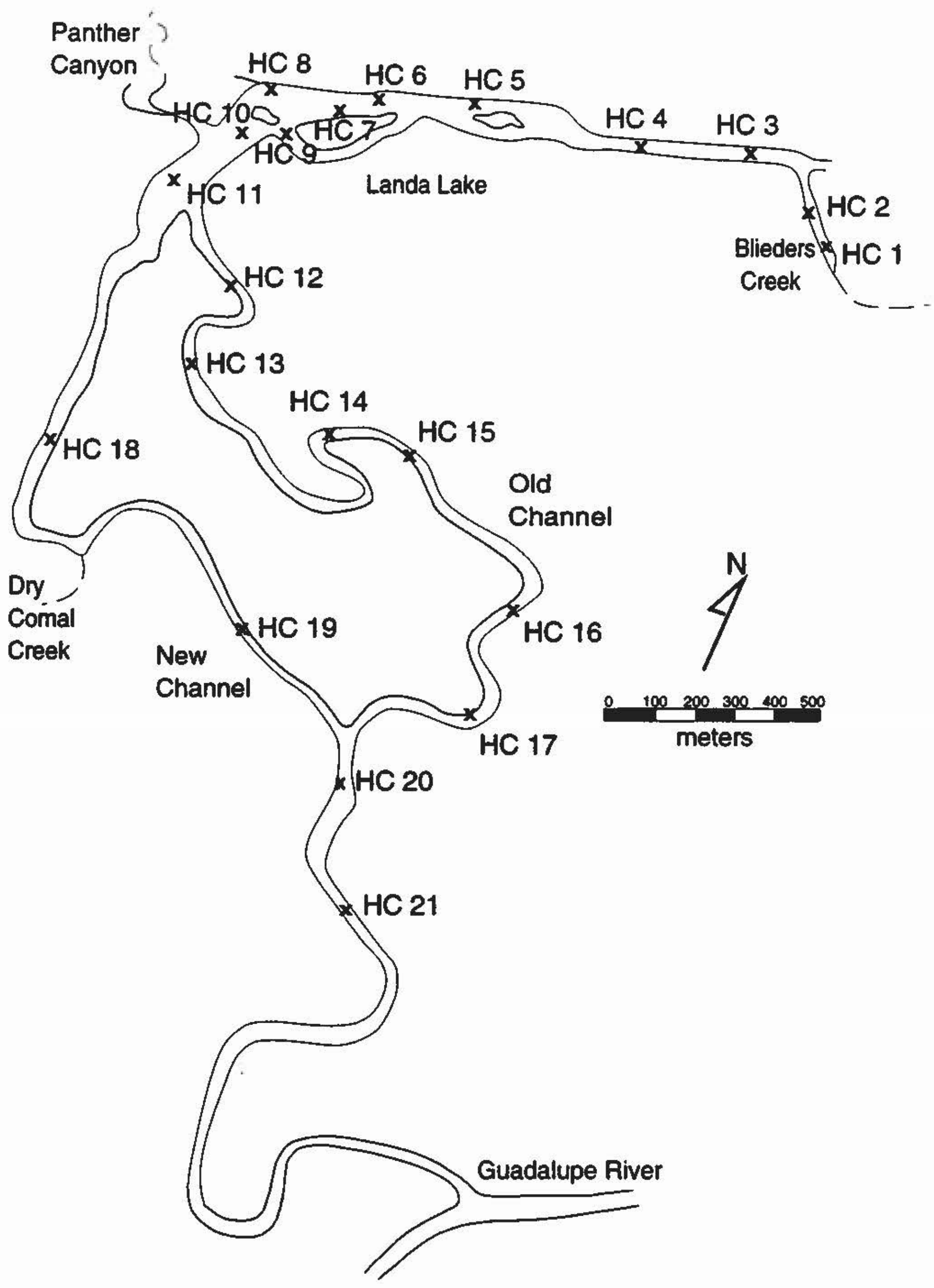


Figure 20. The location of sites where flow measurements were collected on the Comal River.

measurements were primarily taken where sampling was performed. As a result, some of the faster and deeper areas of the river are over-represented by edge velocity measurements.

TABLE 5. Measurements of flow velocities taken in the water column in the Comal River.

Site	Depth (ft)	15 cm Depth (ft/s)	0.8 Depth (ft/s)	0.2 Depth (ft/s)	0.6 Depth (ft/s)
HC 1	2.4	0.04	-0.06	-0.03	
HC 2	3.2	0.04	0.00	-0.01	
HC 3	2.0	0.06			0.03
HC 4	2.7	-0.04	-0.04	0.11	
HC 5	3.2	0.09	0.09	0.48	
HC 6	3.1	0.00	0.02	0.14	
HC 7	3.6	0.17	0.21	0.06	
HC 8	2.8	-0.03	-0.04	0.02	
HC 9	2.1	-0.03	-0.06	-0.01	
HC 10	4.2	-0.02	0.18	0.30	
HC 11	1.6	0.02	0.01	0.02	
HC 12	3.3	0.58	0.65	0.67	
HC 13	1.2	0.47			0.66
HC 14	3.5	0.04	0.05	0.30	
HC 15	4.7	-0.02	-0.03	-0.01	
HC 16	1.4	-0.04			-0.02
HC 17	1.3	0.55			0.59
HC 18	1.7	0.05			0.10
HC 19	2.4	-0.05	-0.07	-0.02	
HC 20	3.3	1.76	2.22	2.31	
HC 21	3.6	1.30	1.24	1.82	

Negative flows are encountered where water moves slightly back upstream. Often this occurred in areas where a small eddy formed in the flow.

Morphology

The morphology of the river is influenced by, although not entirely shaped by, the river's flow. These flow measurements show that the water moves at variable rates depending on its location in the Comal River system (refer to Figure 20). The three fastest spring runs are those clustered around Panther Canyon. These have a substrate of large gravel with some shear bedrock. Vegetation is almost non-existent in the immediate area of the springs. The spring run farthest to the west has plants growing in the run a distance from the spring opening; the other two spring runs have little to no vegetation in them. Flow is fast in all three of these spring runs. The fourth spring run, located close to Blieders Creek, has a very different appearance. It has slower moving water, muddier substrate, and vegetation in the spring run within a short distance from the spring opening. The depth of water averages around two to three feet in all four of the large spring runs, and all of them lead to Landa Lake.

Landa Lake is typical of slow to stagnant systems; it is full of vegetation, and the bottom is very muddy. It contains the deepest waters in the Comal system, and its flow velocities are rarely over 1 ft/sec (0.3 m/s). The lake has an elongated shape extending from the largest spring to the west to the largest spring to the east. There is input to the lake from springs along its length, most noticeably from springs and seeps along the north bank. These springs extend the east-west length of the lake, contributing to the lake's extent. Numerous small springs bubble up from the lake bottom, and they are visible where they create a ripple on the surface of the lake. Where three of the largest springs with spring runs are clustered in the area of Panther Canyon, the widest portion of the lake is found. Figure 16 shows the locations of the largest springs with spring runs, the other large springs, and the areas where small springs are numerous.

The old channel closely resembles its natural state. It has a meandering shape, and the flow in areas of the channel respond to this shape. There are a number of overflow dams on the old channel (Figure 17), and flow is altered with each one. Water pools on the immediate upstream side of the dam. Then flow is very high on the immediate downstream side of the dam, and it slows with distance downstream away from the dam. The new channel is man-made, with a uniform width and straight channel length. Measurements HC 20 and HC 21 show the highest velocities, and both of these come from the lower portion of the river, after the new and old channels have re-joined. These faster flows correspond to the area where the river has its greatest flow velocities, and the substrate is predominantly large gravel and bedrock. There is also a lack of vegetation in these areas. The only plants in this length of the channel grow along the bank's edge.

The lower river has a meandering shape, with one large bend. Towards the confluence with the Guadalupe River and near the end of the Comal River, there is a significant backwater effect on the Comal. The river's velocity drops significantly while turbidity and river depth greatly increase due to water from the Guadalupe River filling the Comal channel. All of the flow in the Comal River discharges into the Guadalupe at the point of confluence of the two rivers.

Soils

The soils immediately surrounding the river are important as contributors to the substrate found in the river bed. Soil data were taken from the Soil Conservation Services report on New Braunfels, and a map of the river showing the different soil types is given in Figure 21 with a key in Figure 22. Properties of these soils are taken from Batte (1984) and shown in Table 6. Water capacity is defined as the ability of the soil to hold water available to the plants. It is the difference between

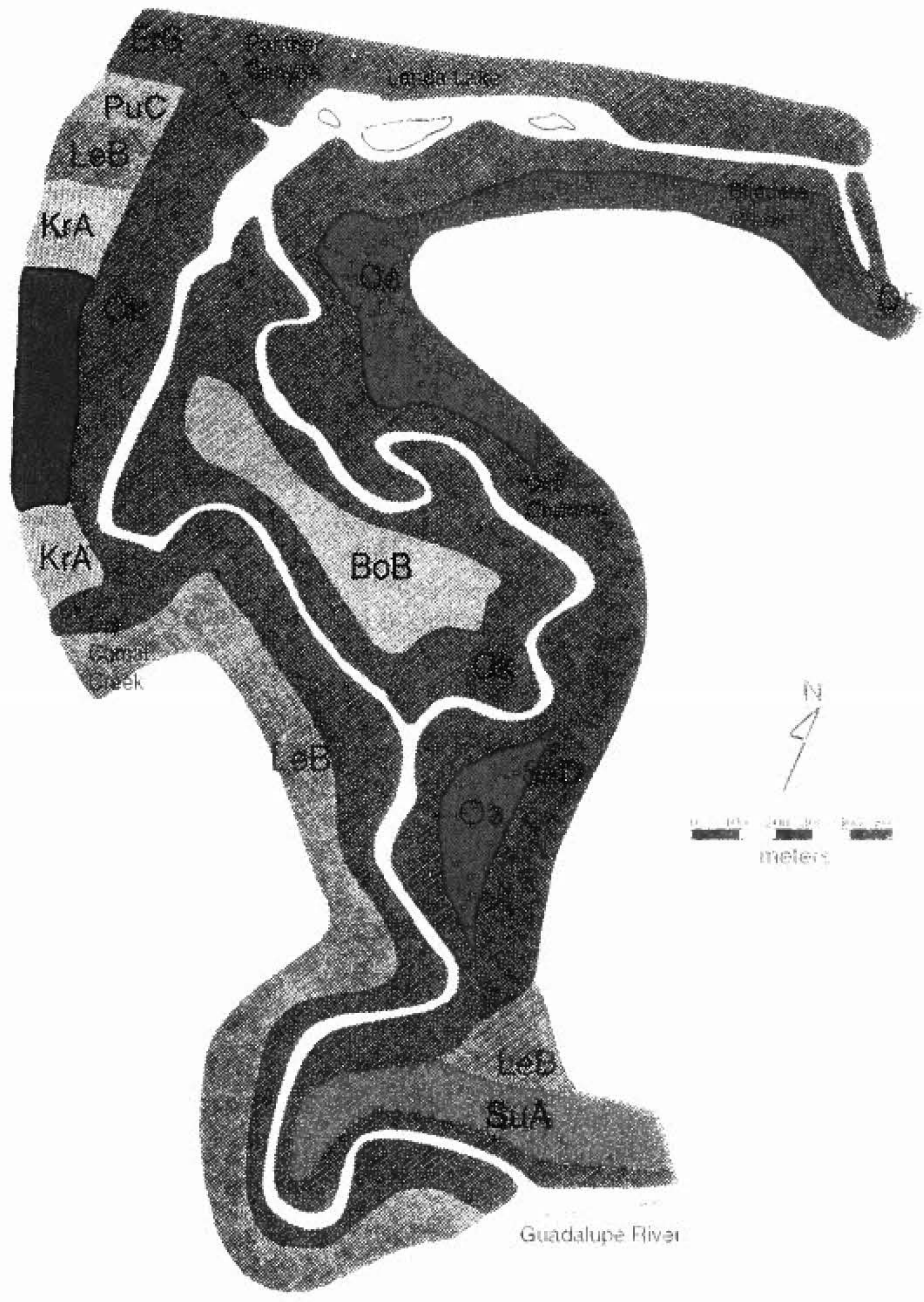


Figure 21. A map of the soil distribution around the Comal River (after Batte, 1984)

BoB : Boerne Fine Sandy Loam; Depth of 0-16 in (0-41 cm).
k = 2.0 - 6.0 in/hr (0.001-0.004 cm/s); Θ = 0.10 - 0 015

ErG . Eckrant-Rock clayey soils; Depth of 0-10 in (0-25 cm).
k = 0.2 - 0.6 in/hr (0.0001-0 0004 cm/s); Θ = 0.05 - 0.12

KrA : Krum Clay; Depth of 0-16 in (0-41 cm);
k = 0 2 - 0 6 in/hr (0.0001-0 0004 cm/s); Θ = 0.15 0.20

LeA . Lewisville Silty Clay: Depth of 0 - 17 in (0-43 cm);
k = 0.6 - 2.0 in/hr (0.0004-0.001 cm/s); Θ = 0.16 - 0.20

LeB: Lewisville SIlty Clay: Depth of 17 - 36 in (43-91 cm).
k = 0.6 - 2.0 in/hr (0.0004-0.001 cm/s); Θ = 0.14 - 0.18

Oa : Oakalla Silty Clay. Depth of 0 - 80 in (0-203 cm):
k = 0 6 - 2 0 in/hr (0 0004-0.001 cm/s) Θ = 0.12 - 0 19

Ok : Oakalla Soils; Depth of 0 - 80 in (0-203 cm);
k = 0.6 - 2.0 in/hr (0.0004-0.001 cm/s): Q = 0.12 - 0 19

Or : Orit Soils Depth of 0 - 20 in (0-51 cm),
k = 6.0 - 20 0 in/hr (0 004-0.014 cm/s): Θ = 0.03 - 0 08

PuC : Purves Clay; Depth of 0 - 10 in (0-25 cm).
k = 0.2 - 0.6 in/hr (0 0001-0.0004 cm/s); Θ = 0 12 - 0 18

SeD . Seawillow Clay Loam: Depth of 26 - 48 in (66-122 cm)
k = 0.6 - 2 0 in/hr (0.0004-0.0014 cm/s): Θ = 0.12 - 0 18

SuA : Sunev Silty Clay Loam: Depth of 0 - 15 in (0-38 cm):
k = 0.6 - 2.0 in/hr (0 0004-0.0014 cm/s); Θ = 0.11 - 0.16

Figure 22. Legend describing the soils around the Comal River k=hydraulic conductivity; Θ=water capacity (after Batte. 1984).

TABLE 6. Properties of the soils around the Comal River.

Soil Type	Depth inches cm	% Clay	k (av.) (cm/s)	Soil pH	Shrink /Swell	Water Cap. (in/in)
KrA	0-16 0-41	35-55	$2.8x10^{-4}$	7.4-8.4	high	.15-.20
LeA	0-17 0-43	28-45	$2.8x10^{-4}$	7.9-8.4	high	.16-.20
LeB	17-36 43-91	30-45	$8.4x10^{-4}$	7.9-8.4	high	.14-.18
Or	0-20 0-51	--	$7.1x10^{-3}$	7.9-8.4	low	.03-.08
Oa	0-80 0-203	25-43	$8.4x10^{-4}$	7.9-8.4	mod	.12-.19
Ok	0-80 0-203	25-43	$8.4x10^{-4}$	7.9-8.4	mod	.12-.19
SeD	26-48 66-122	--	$8.4x10^{-4}$	7.9-8.4	low	.12-.18
SuA	0-15 0-38	20-40	$8.4x10^{-4}$	7.9-8.4	low	.11-.16
ErG	0-10 0-25	35-60	$2.8x10^{-4}$	6.6-8.4	mod	.05-.12
PuC	0-10 0-25	35-55	$2.8x10^{-4}$	7.9-8.4	high	.12-.18
BoB	0-65 0-41	12-23	$2.8x10^{-4}$	7.9-8.4	low	.10-.15

the amount of water in the soil at field moisture capacity and the amount of water in the soil at wilting point for the plants; it is expressed as the inches of water stored per inch of soil (Batte, 1984).

The soils are silty and clayey loams that are typically found on stream terraces and in flood plains, as would be expected in the area around the Comal River. These clays and silts probably contribute to some of the muddy substrate found often throughout the river. The soils show a permeability ranging from $8.4x10^{-4}$ cm/sec to $7.1x10^{-3}$ cm/sec, which may limit local recharge. The soils range up to 60% calcium carbonate content, with most near 60%, and the clays are calcareous throughout (Batte, 1984).

On the southern side of Landa Lake is a layer of alluvium with a thickness of 8 meters overlaying the dense, marly Taylor Formation (Guyton and Assoc., 1979). Water may collect and store in the alluvium rather than infiltrating into the Taylor marl. However, the layer is thin and limited in its thickness, so its storage capacity is probably not great.

Vegetation

A number of different types of vegetation were identified in the Comal system, but some species are much more common than others (Figure 23). The vegetation map illustrates the dominant plants in each area of the river system. Because only the dominant plants could be represented in the illustration, small individual patches of a plant may not be fully represented. Photos of the most important plants living in the Comal River system are shown in Figure 24. The presence and abundance of different species of vegetation is linked to the time of year, and the vegetation map presented is relevant for the summer. In general the same species are present throughout the year, but in varying abundance.

Chara is found only in the Blieders Creek area where it is dominant. Similarly filamentous algae are dominant in an area of the old channel. While it is mixed with other plants elsewhere in the river, it is not dominant in these other areas. *Ludwigia*, *Potamogeton*, *Vallisneria*, and *Cabomba* grow in varying proportions throughout the spring runs and the river, with the exception of the new channel. Different vegetation species are often mixed together, each one patchy in its coverage of the area.

Most of the old channel and Landa Lake are full of different plant species, but the new channel and the portion of the channel after the old and new channels re-join have only a small amount of vegetation present along one side. *Potomageton* grows in combination with riccia in a narrow band

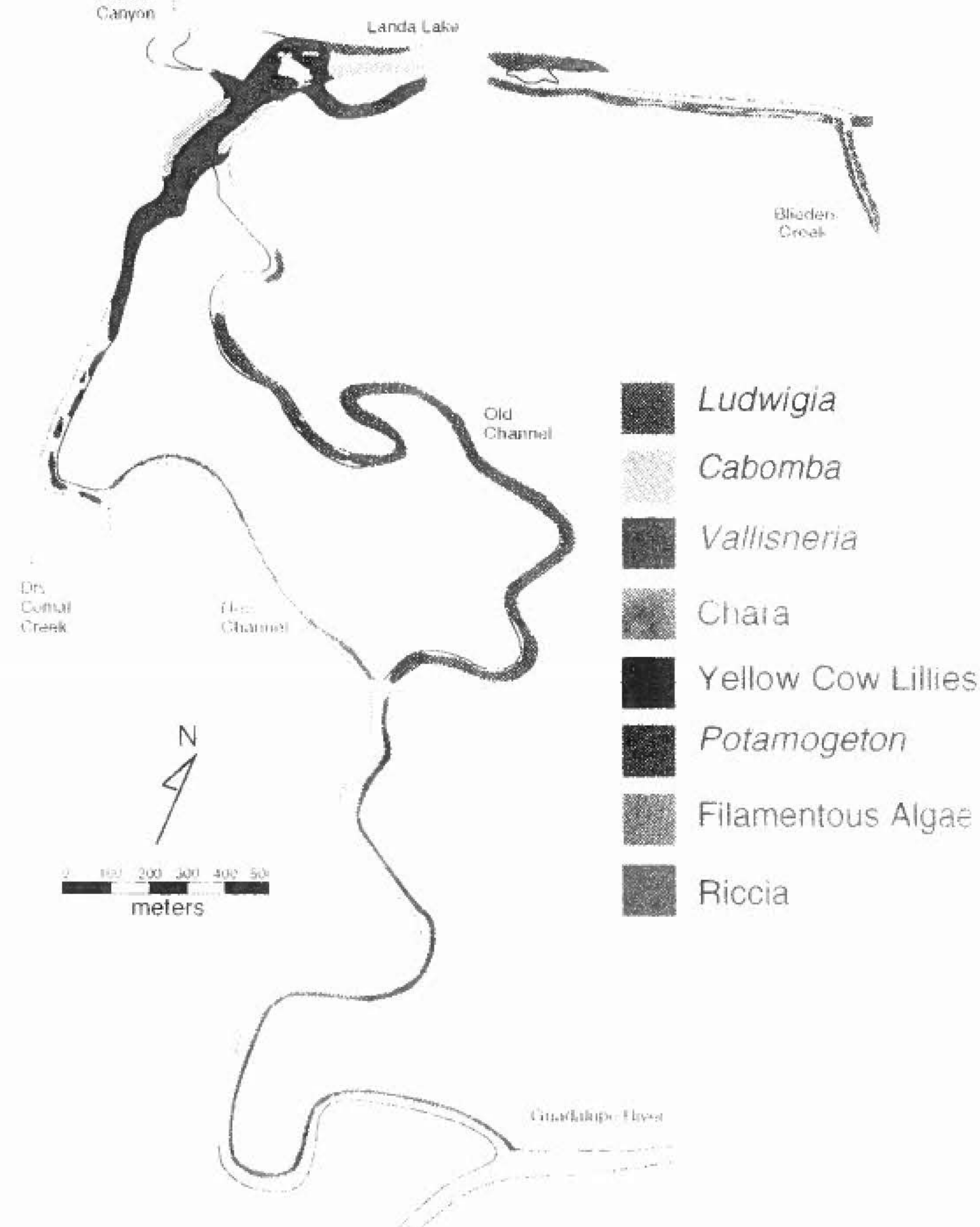
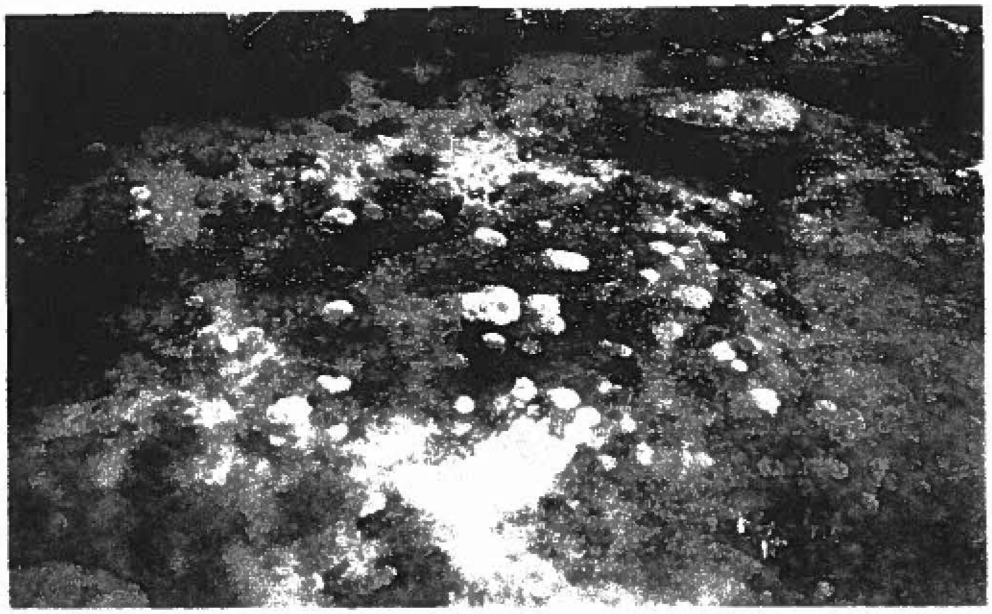


Figure 23. Map of the vegetation in the Comal River during June, 1993.



(a) *Cabomba*
(b) *Ludwigia*

Figure 24. Comal River vegetation (a) Cabomba; (b) Ludwigia; (c) Chara; (d) Yellow Cow Lillies; (e) Vallisneria; (f) Riccia

(c) Chara

(d) Yellow Cow Lillies

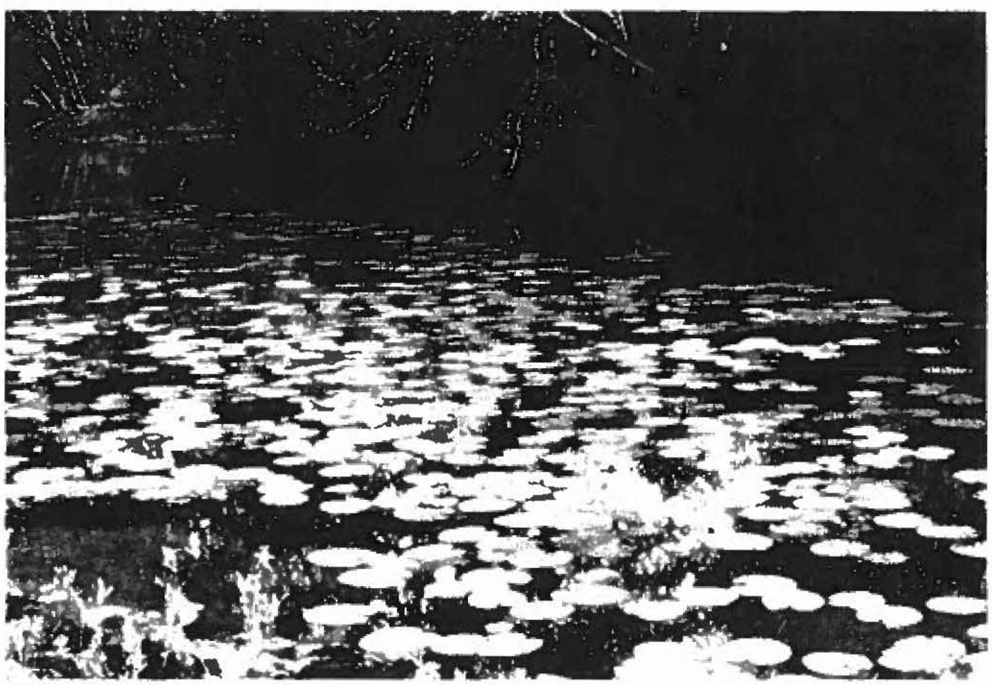
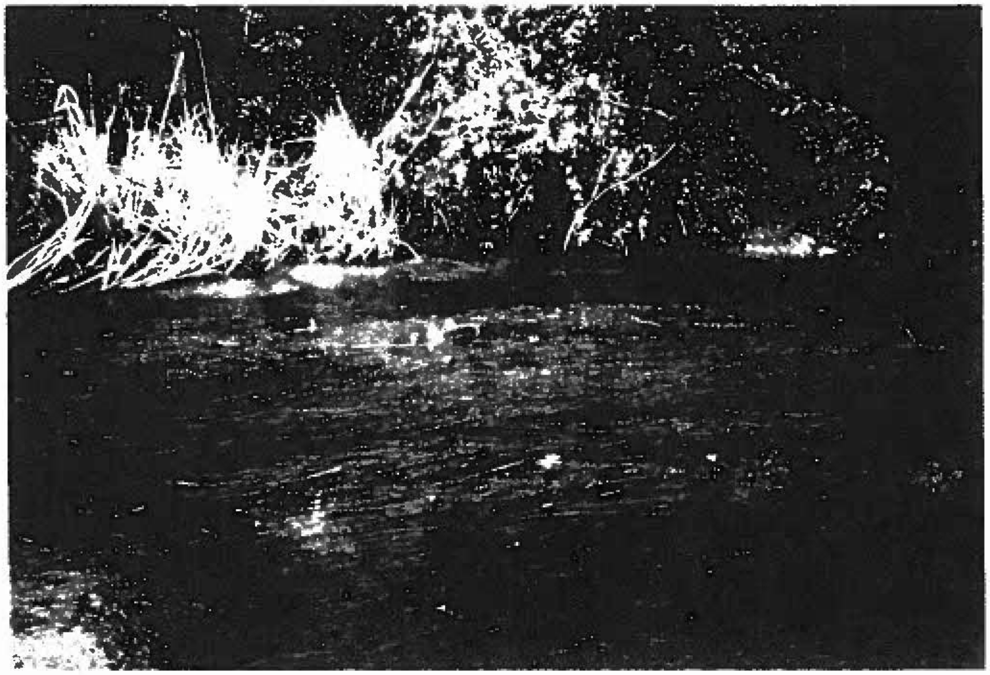


Figure 24. Continued.



(e) *Vallisneria*

(f) Riccia

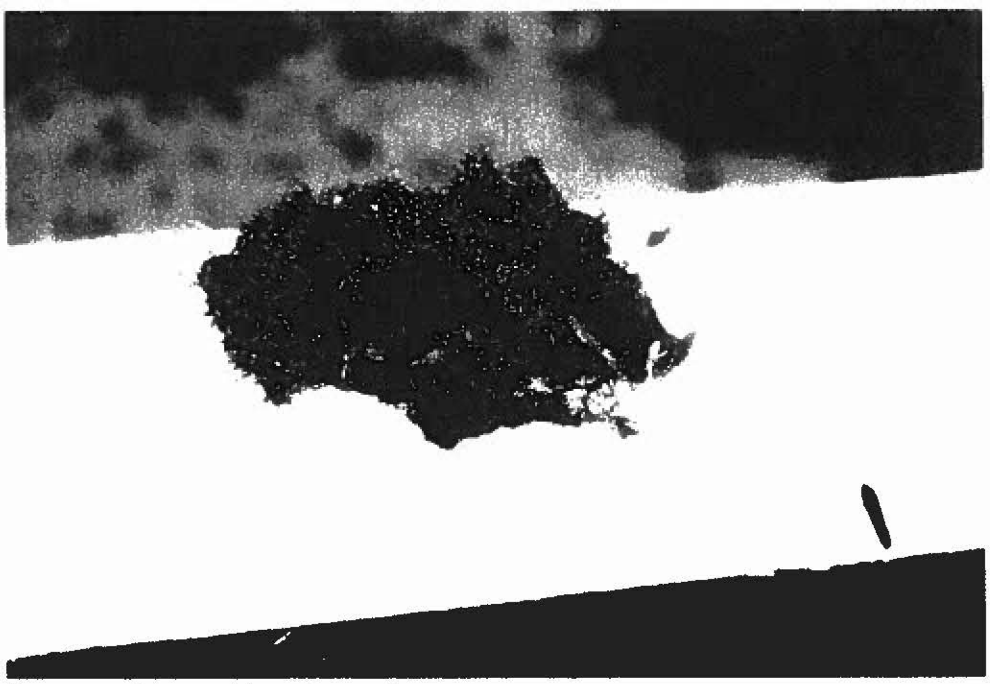


Figure 24. Continued.

down the side of the new channel, creating a distinct edge habitat. An edge habitat is possible where the bank of a river having a high flow creates enough of a boundary edge effect to slow the water immediately adjacent to it. Flow rates in the lower channel are very fast and the bedrock substrate allows for little plant growth anywhere but along the inside channel banks.

Throughout the Comal River, the dominance of different plant species correlates with the flow velocities in the system. Vegetation is able to grow only where the flow is not so swift that it prevents the plants from establishing roots. In very slow moving to stagnant waters, vegetation proliferates and fills the channel. Vegetation in turn influences the substrate present in the river, and it provides habitat for the fish. In areas of high flows, plants can provide shelter from high flow velocities for fountain darters. Riccia and filamentous algae provide some of the best plant structures for the darters, because they grow in thick mats. Riccia and filamentous algae are common in combination with other plants in many areas of the river, providing a plant combination with structure for the darters to inhabit (Hardy, 1994).

Landa Lake is predominantly a stagnant flow system, and as such it should be filled with vegetation. It does not have 100% plant cover however, because of the presence of the rams horn snail in the Comal system. This species of snail has been introduced to the system, and it is capable of clearing an area of plants. The snail eats the plant's stems and leaves. It has already cleared areas of the lake of almost all plant life. The affects of this snail species are currently limited to the lake, and they have not de-vegetated any channel areas.

Substrate

Substrates mapped in the Comal River are shown in Figure 25. The system has very little sand in it; the fines are mostly silts and clays. In the Comal River, mud is a mix of clay and silt. Different sizes of gravel, ranging from granule to large gravel and cobble, predominate throughout the system. Where vegetation is present and the stream velocity is low, mud is likely to accumulate. In open areas of substrate where there is no vegetation, gravel accumulates. In the new channel flow is around 2 ft/sec (0.6 m/s), and shear bedrock is the most common substrate with a few pockets of poorly-sorted gravel. In some cases an odd combination of substrates is present, for example, cobble and small gravel. In these areas, the larger substrate, usually cobbles or boulders, originated from the bank areas, and it has not been transported to that location by the river. Gravel and bedrock substrates are controlled by the flow in the river.

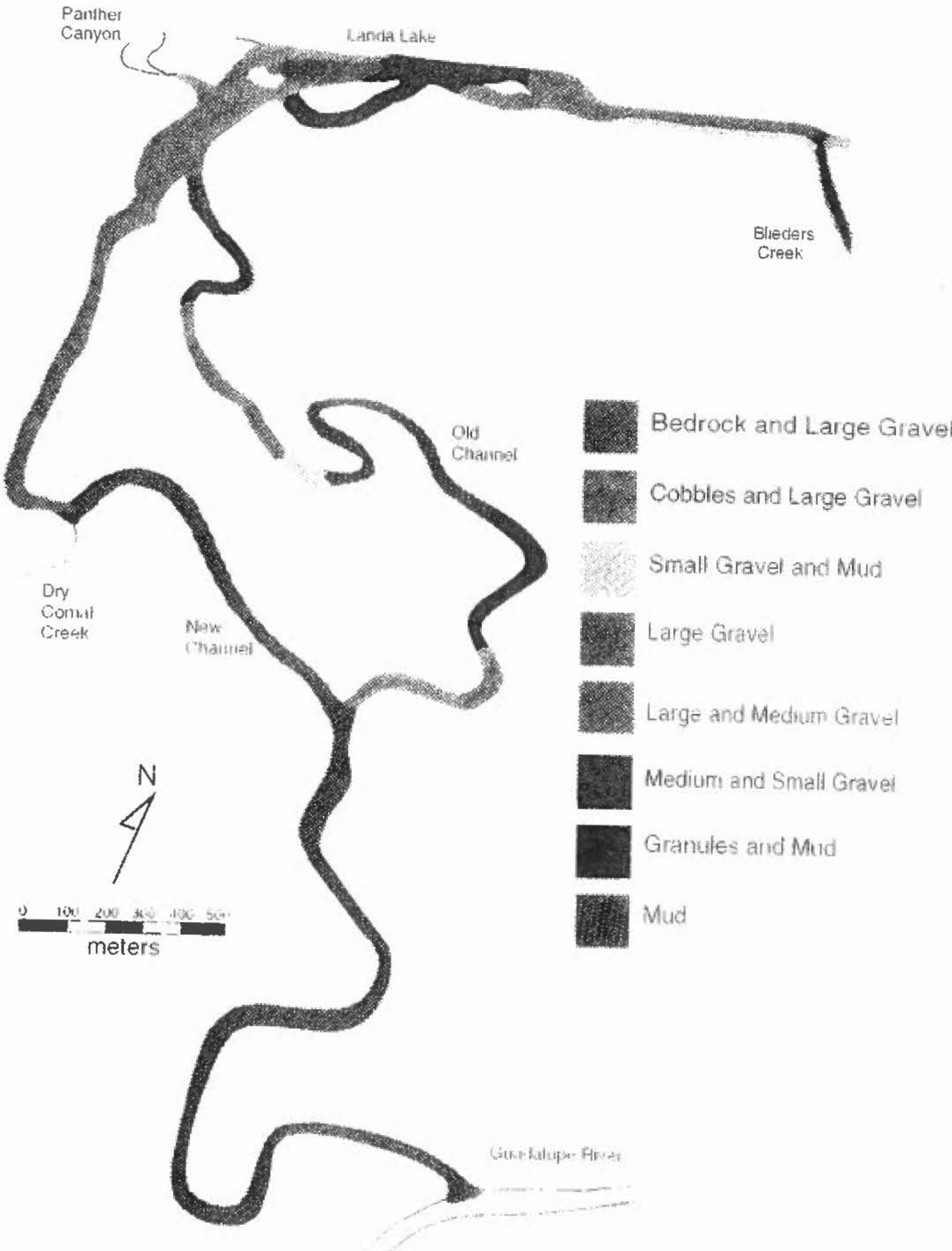


Figure 25. Map of the substrate in the Comal River during June, 1993.

Where the flow is high, scouring of the channel bottom occurs, leaving only bedrock. There are often isolated areas of scoured channel found after an overflow dam (refer to Figure 17), where a plunge pool has formed. A natural progression from large gravel sizes down to small gravel and some fines occurs in the downstream direction from a dam feature as the flow velocity decreases with distance. This is similar to the vegetation patterns following these dams.

In areas of lower flow velocities, fine gravel and, in a few cases, sand accumulates. In the slow flowing areas of the river fines form the substrate, encouraging the growth of vegetation. Once vegetation takes root, it helps stabilize the channel bottom, and mud accumulates. Generally where the vegetation is thick, soft organic mud covers the channel bottom; examples of this are in the old channel where filamentous algae fills the river, and in the areas of Landa Lake filled with *Ludwigia* and *Cabomba*. The substrate plays an important part in determining the vegetation and thus the habitat of an area.

Chapter 5:

Discussion: The Comal River

Habitats

Habitats have been defined for the length of the Comal River system, and they are presented in Table 7 with a corresponding location map in Figure 26. All information gathered on the river system was taken into account in their definitions. Habitats are a unique combination of vegetation, substrate, chemistry, and flow type. The hydrochemical parameters are less important to the identification of habitats, because they are quite uniform throughout the river and the habitats.

The two dominant types of vegetation and substrate were identified for each habitat. During field mapping, it became apparent that this would be sufficient for a description of the river, and that the majority of the river did not have more than two different plants or substrates. Where vegetation was present the approximate percentage of coverage in the river has been noted in the habitat definitions. In the old channel,

TABLE 7. Descriptions of the habitats found in the Comal River system.

Habitat	Vegetation 1	Vegetation 2	Substrate 1	Substrate 2	Flow Type	# F. Darters	% Veg. Cover (approx.)
1	Chara	Y. Cow Lilly	Mud	Granules	Pool	20	100
2	None	None	Cobbles	Gravels	Pool	2	0
3	*Potamogeton*	Riccia	Mud	None	Slow Run	7	100
4	*Ludwigia*	*Cabomba*	Med. Gravel	Small Gravel	Slow Run	3	90
5	None	None	Large Gravel	Sand	Slow Run	1	0
6	*Ludwigia*	*Potamogeton*	Cobbles	Large Gravel	Pool	12	60
7	*Vallisneria*	*Ludwigia*	Cobbles	Large Gravel	Pool	5	90
8	*Vallisneria*	*Potamogeton*	Med. Gravel	Small Gravel	Pool	6	100
9	*Vallisneria*	*Cabomba*	Mud	None	Pool	6	50
10	*Vallisneria*	*Ludwigia*	Cobbles	L.-Med. Gravel	Deep Fast Run	10	20 - 50
11	None	None	Bedrock	Large Gravel	Slow Run	0	0

TABLE 7. Continued.

Habitat	Vegetation 1	Vegetation 2	Substrate 1	Substrate 2	Flow Type	F. Darters	% Veg. Cover (approx.)
12	*Vallisneria*	*Potamogeton*	Cobbles	L.-Med. Gravel	Riffle	3	40
13	F. Algae	*Potamogeton*	Mud	None	Slow Deep Run	9	100
14	*Ludwigia*	*Potamogeton*	Cobbles	Gravels	Slow Shallow Run	2	50
15	*Potamogeton*	Riccia	Mud	Small Gravel	Deep Fast Run	7	100
16	None	None	Bedrock	Large Gravel	Deep Fast Run	0	0
17	None	None	Large Gravel	Sand	Pool	1	0
18	None	None	Large Gravel	Cobble	Fast Run (springs)	1	0

Vegetation 1 is the dominant plant in the area
Vegetation 2 is the subdominant plant in the area
Substrate 1 is the dominant type of substrate in the area
Substrate 2 is the subdominant type of substrate in the area
Flow types are defined in Table 8
F. Darter is the average number of fountain darters found in one cell in the habitat area
% Veg. Cover is the approximate amount of plant cover in that area of the river

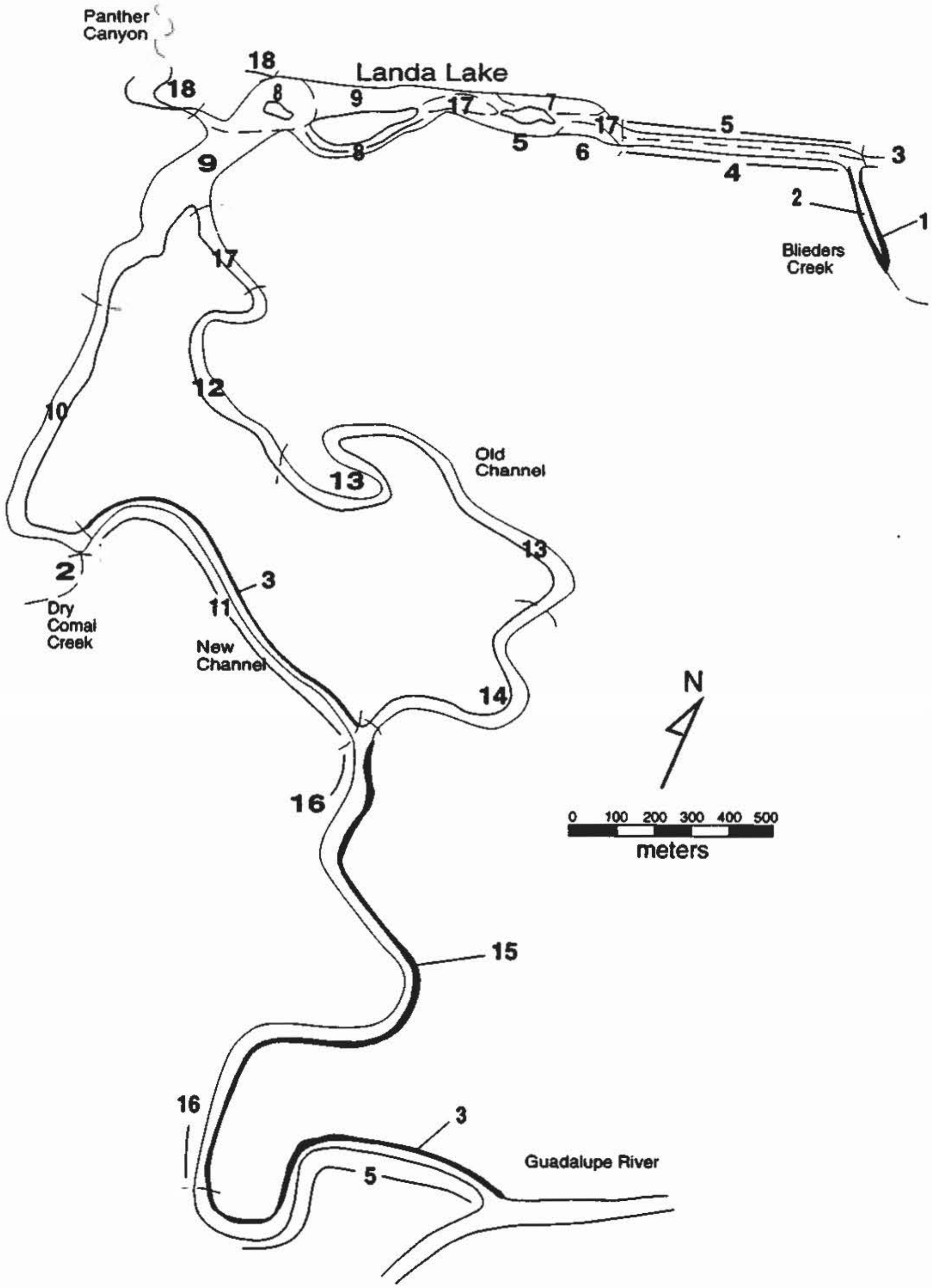


Figure 26. A map illustrating the distribution of habitats in the Comal River.

TABLE 8. A summary of the different flow types

Flow Type	Description
Backwater	Almost stagnant water from a different
	source
Backwater Pond	Backwater that fills an area and is
	stagnant
Pool	Stagnant water
Deep Pool	Pool at least 4 feet deep
Plunge Pool	Pool that develops after a dam
Run	Water moving 1-2 ft/sec on its surface
Slow Run	Water moving less than 1 ft/sec on its
	surface
Fast Run	Water moving at least 2 ft/sec on its
	surface without turbulence
Deep Slow Run	Slow run at least 4 feet deep
Shallow Slow Run	Slow run under 2 feet deep
Deep Fast Run	Fast run at least 4 feet deep
Riffle	Water moving fast enough to create
	turbulence on its surface

vegetation often filled between 70%-100% of the river, and in the new channel, it either created a well vegetated edge habitat, or it was not present at all. The dominant plant and substrate types are listed first (as number 1) for each habitat, with the sub-dominant listed second. Flow types are listed as run, riffle, slow run, fast run, deep slow run, deep fast run, shallow slow run, plunge pool, deep pool, backwater, or backwater pond. These terms refer to the surface velocity of the river in these areas. A summary of the flow types and their brief descriptions are given in Table 8.

Seventeen (17) different habitats were identified, and a few of these occur in several locations in the Comal River system. In some cases an area of the system has more than one habitat present; for example, part of the new channel has an edge habitat of #3 and a channel habitat of #11. There are numerous habitats in Landa Lake, corresponding to the patchy distribution of plant species. Typical numbers of fountain darters for one sampling area (a 2 meter by 1 meter area, refer to Chapter Three [Methods] for sampling techniques) in each habitat type are given in Table 7.

Fountain Darters

Most of the darters live in the vegetated areas. Fountain darters appear to prefer some plants over others, and the structure provided by riccia and filamentous algae provide the darters with protection from both predators and high flow rates. As a result, darters are much more common in habitats that include some filamentous algae or riccia in their vegetation.

Scuba teams observed many fountain darters living in the open substrate areas of the river. Throughout the Comal system, the fountain darter lives in areas where flow velocities are low. This includes most of the system, because where flow velocities are high, darters are able to live in the shelter provided by large substrate material. Substrates such as gravel provide the darters with protection from floods and high flow velocities in the river channel. Darters were also seen where the substrate is dominantly large slabs of bedrock, because they were able to find shelter in depressions in the rocks and just behind slabs of bedrock, as in habitats #10 or #16. Low flow velocities are also found in the boundary layer present along the river bed. The boundary layer appeared to provide an area of stagnant water along the river bottom, and, as a result, darters were seen within three inches of the bottom throughout the Comal system (Hardy, 1994). This is the case for habitat #16, in the high flow velocities of the new channel.

More fountain darters are found in areas of the river with low flow velocities, however, because they are able to live in the water column as well as in the boundary layer in these areas. Where this is combined with a structure provided by vegetation, optimum fountain darter habitat is found; habitats of low flow velocity and either riccia or filamentous algae. Photos of some of the darter habitats are shown in Figure 27. This includes habitat #1 in Blieders Creek and habitat #6 in Landa Lake. Generally the substrate in these areas is very muddy.

Comal Springs Riffle Beetle

Sampling for the Comal Springs riffle beetle was not conducted during the fountain darter sampling, because it was not then under consideration for listing as an endangered species when the sampling began. It has been found only in the spring runs that are clustered near Panther Canyon in the Comal system (McKinney and Sharp, 1994). Using this as a guide for its habitat preferences, the riffle beetle appears to inhabit areas of gravel substrate, swift flow rate, and little to no vegetation. The riffle beetle could find these habitat characteristics in habitat #18 in the spring runs.

Flow Velocity Requirements

The amount of water necessary for the maintenance of

(a) Blieders Creek
(b) Landa Lake

Figure 27. Fountain darter habitats on the Comal River (a) Bleiders Creek; (b) Landa Lake; note that small springs are visible on the surface of the lake

each of the habitats in the system has been estimated through the combined use of the modified Wentworth scale and the Hjulstrom diagram (Figure 28). Through examination of the substrates found in each habitat and the upper and lower flow limits for those substrates, the upper and lower water velocity limits were estimated for each habitat, and they are given in Table 9. For each of the habitats, the smaller of the two substrates given was used in the calculations. This would be the substrate most susceptible in the event of alterations to the water velocity.

Flow velocity limits are very important, because a catastrophic loss of habitat could occur under drastically different velocities. A drop in the spring flow discharge could result in habitat loss if it resulted in lower flow velocities. Fine substrates would begin to settle into habitats where they are not now present. The impact of this would probably be great in habitat #18, the spring runs, where there is little vegetation and the substrate tends to be predominantly cobble. Other habitats in the system, including #16 in the new channel, would also be effected by lower flow rates. Medium gravel would begin to settle if the flow velocity dropped below 2.5 ft/s (0.75 m/s), and it is not present in these habitats under normal flows. A drop in the depth of water could also occur under reduced spring

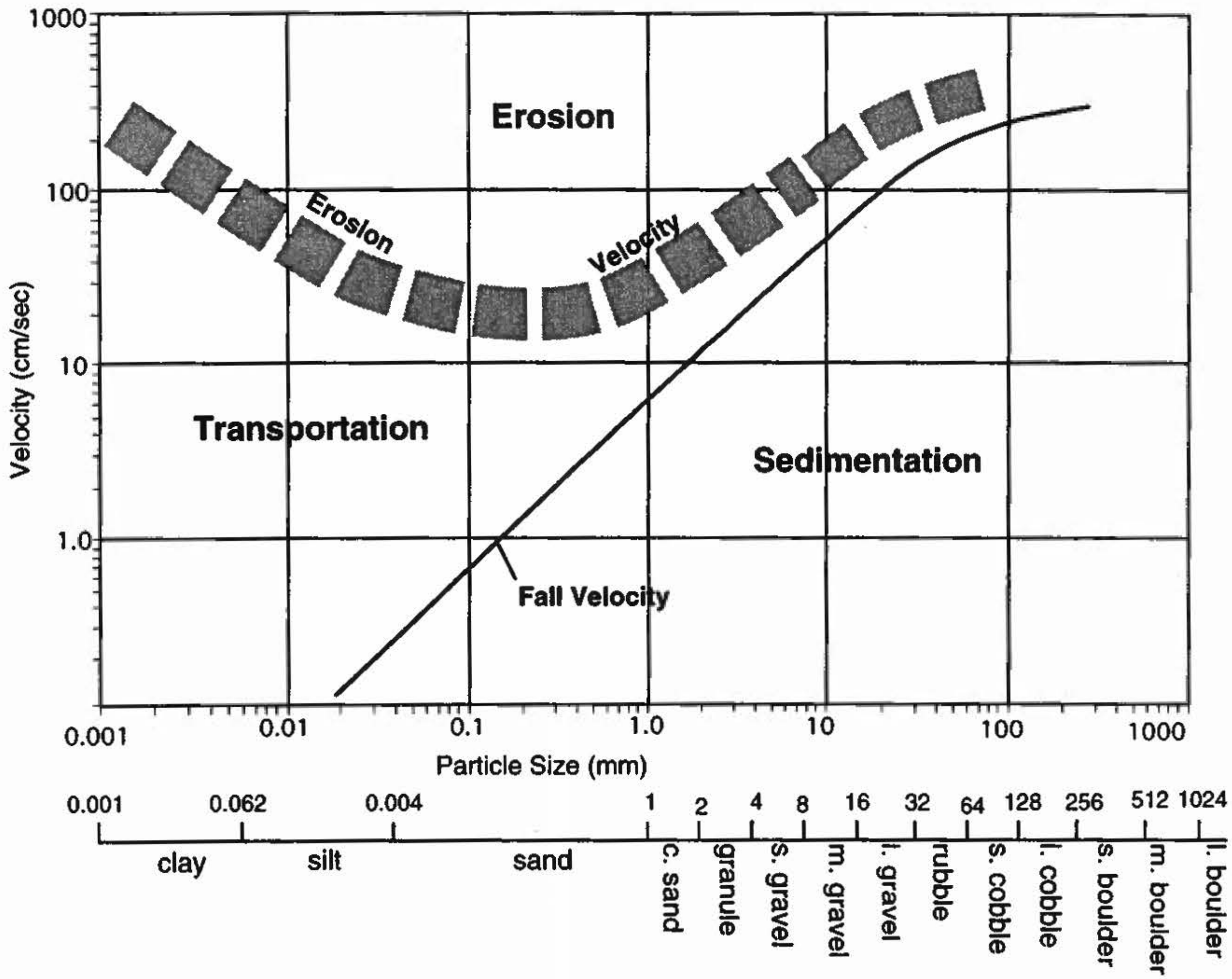


Figure 28. Hjulstrom diagram with modified Wentworth scale. This illustrates the different flow rates at which sediments are transported, eroded, or settled.

TABLE 9. Flow velocities for habitats in the Comal River.

Habitat	Substrate 1	Substrate 2	Lower Flow Velocity	Upper Flow Velocity
1	Mud	Granule	0.0000 ft/s 0.0000 m/s	0.0003 ft/s 9×10^{-5} m/s
2, 14	Cobbles	Gravel	0.8333 ft/s 0.2500 m/s	4.0000 ft/s 1.2000 m/s
3, 9, 13	Mud	None	0.0000 ft/s 0.0000 m/s	0.0003 ft/s 9×10^{-5} m/s
4, 8	Medium Gravel	Small Gravel	0.8333 ft/s 0.2500 m/s	1.0000 ft/s 0.3000 m/s
5, 17	Large Gravel	Sand	0.0003 ft/s 9×10^{-5} m/s	0.2000 ft/s 0.0600 m/s
6, 7	Cobbles	Large Gravel	2.5000 ft/s 0.7500 m/s	4.0000 ft/s 1.2000 m/s
10, 12	Cobbles	Large - Med. Gravel	1.0000 ft/s 0.3000 m/s	2.5000 ft/s 0.7500 m/s
11	Bedrock	Large Gravel	2.5000 ft/s 0.7500 m/s	4.0000 ft/s 1.2000 m/s
15	Mud	Small Gravel	0.0000 ft/s 0.0000 m/s	0.0003 ft/s 9×10^{-5} m/s
16	Bedrock	Large Gravel	2.5000 ft/s 0.7500 m/s	4.0000 ft/s 1.2000 m/s
18	Cobbles	None	6.6667 ft/s 2.0000 m/s	10.000 ft/s 3.0000 m/s

discharge, causing vegetation to become emerged.

An added complication under lower flow velocities in the Comal system is the rams horn snail. The snail feeds on the vegetation in the lake and river; it is capable of clearing an entire area of plants. A loss of flow in the Comal system may cause the snail to proliferate, and it would eat most of the vegetation in the system. A proliferation of the rams horn snail would therefore have a devastating effect on fountain darter habitats, especially in Landa Lake, where the snail has already had some impact. Habitats #9, #7, #17, and #6 are all depleted in vegetation, and all are located in the lake. With a greater snail population, the habitats in Landa Lake that are already partially de-vegetated could become void of all plants, and areas of both channels may begin to show a loss of vegetation. Habitat #13 in the old channel is now well vegetated with 100% plant cover, and it may lose a lot of its plant life to snails. These well vegetated habitats host some of the highest populations of fountain darters, and the vegetation is an important component of these habitats.

When the flow is high enough, some of the snails are washed downstream, keeping the population in the river under control. However, lower flow rates allow the snail population to rise, and the snails can eat through the stems and leaves of enough plants to destroy the existing habitat. The only current estimate of flow necessary to control the snail population is that of the U.S. Fish and Wildlife Service, which estimates a flow rate of 200 cfs.

Similarly destructive results would be found in the Comal River if the flow velocity became too high, although sustained higher flow velocities are not likely. Above the upper flow velocity limit for each habitat, scouring of the substrate is likely. This would remove mud from the substrates, and the entire river could become void of mud or organic matter under a higher flow velocity. The plants each appear to prefer different substrates for growth. If the substrates change, the distribution of vegetation will change accordingly.

Most of the plants grow in the muddy substrates, and mud will erode at flow velocities greater than 0.0003 ft/s (9×10^{-5} m/s). In many of these areas, the mud is very thick, so any initial erosion would have little impact on the habitats. But if the flow velocity remains at a level that will erode mud, all of the mud may eventually be scoured. Habitats with a primarily mud substrate include #9 in Landa Lake and #13 in the old channel. One of the other common substrates in the Comal system is a small gravel, and with a flow velocity greater than 1 ft/s (0.3 m/s), small gravel will begin to erode downstream. Habitat #15, the edge habitat in the new channel, has a substrate of mud and small gravel, and it could be altered under a higher flow velocity. Because of these potential alterations, increasing the flow velocities through the river to try to wash the rams horn snail downstream is not a feasible option for dealing with the problems the snail causes. The Comal River is unique because of its combination of habitats, which is created by flow velocity variations in the river. While increased flows endanger the habitat distribution in the river, the more immediate threat is the loss of spring flow into the system.

Annual Flow Requirements

The U.S. Fish and Wildlife Service has estimated that the average annual discharge into the Comal River that is necessary for the preservation of the current river system is 200 cfs (5.7 m^3/s). This assumes that until discharge in the river drops below this value, there is little to no alteration in the habitats or their distribution. Discharge averaging in the range of 250 cfs to 200 cfs should result in similar habitat characteristics and distributions in the river. There is a second requirement provided by the Fish and Wildlife Service of 155.6 cfs (4.4 m^3/s) annual average discharge into the river if the rams horn snail population can be controlled by means other than high flow velocities. This lower discharge requirement indicates that in the event that the amount of water in the river drops below 200 cfs, much of the habitat alteration would be due primarily to the snail.

If the annual discharge dropped to 150 cfs (4.3 m^3/s) for a prolonged time, the effects of the snail would be immediately noticeable. The snail population would increase, and the vegetation in those areas effected by the snails at normal flows could be non-existent. In addition, the habitats near these that have a substantial amount of vegetation under normal flows would likely also be devastated, especially in Landa Lake and the old channel. Habitats #9, #8, # 7, #6, #4, #13, and #14 would lose their vegetation component. The snail would also begin to spread into areas where it is not currently a problem, but only if the flow velocity is low enough for the snail to proliferate. Edge habitats along the new channel, habitats #15 and #3, would begin to be effected. Although the fountain darter lives throughout the river system, its optimum habitats correspond to those that would be devastated by the snails. As a result the darter population would suffer and diminish, but it would not necessarily be destroyed. The riffle beetle would probably not be effected very much, because its favored habitats are those with gravel substrate and little vegetation.

While a drop to 150 cfs (4.3 m^3/s) annual discharge would allow the snail population to increase, it would probably not cause much of a reduction in the flow velocities through the river. In those areas where vegetation had aided in slowing river flow rates the snail may have eaten enough plants that the flow velocities would increase. The erosion of mud and other fine substrates from existing habitats would begin with the higher flow velocities. If the discharge remained at 150 cfs for a prolonged time, much of the fine substrate could be washed out of the habitats. The resulting Comal system would be lacking in vegetation, and the river channel would be more predominantly gravel.

If the annual average discharge drops to 100 cfs (2.7 m^3/s) for a prolonged time, the hydrochemistry in the river may alter slightly. The river's temperature would raise to near its present upper limit (Espey, Huston and Assoc., 1975). There would probably be almost no vegetation remaining in the river because of the snails. Without vegetation the seasonal oxygen trends discussed in Chapter Four would change. The vegetation cycle with decomposition was the cause of the oxygen trend, and as a result, the trend may become very small. Other chemical parameters should not show very much of a shift, and the overall hydrochemistry would not be altered much.

With the loss of spring discharge, the velocity in the river would probably begin to slow, and many of the runs would become slow runs or even pools. This change would be most visible following overflow dams on the river, such as in habitat

#12. The water would slow faster after the dam, and the length of the riffle would be shorter. However, with the flow velocities lowering, mud may begin to settle onto the river bed again. The lake and river would see an increased amount of fines, but little plant life.

Upon a drop to 50 cfs (1.4 m^3/s) annual discharge for a prolonged period, the hydrochemistry of the river system would begin to effect the remaining life. The temperature in the river would likely increase, and the daily temperature variations could become very high (Espey, Huston and Assoc., 1975). The fountain darter is believed to be sensitive to the river's temperature, and this may be too high for the remaining darter population to survive and to reproduce. The riffle beetle may also begin to be adversely effected. Mud and other fines may begin to accumulate in its habitats, thereby putting stress on the species. Gravel would settle into the new channel, and mud would settle elsewhere.

Because maintenance of the substrate, vegetation, and soil input in a habitat depend on relatively invariant flow velocities, any alteration to the flow rate would affect all of the components of the habitats. The fountain darter and riffle beetle each have a preference for certain vegetation, flow velocity, and substrate combinations, and their existing habitats would be devastated by a shift in flow velocity. Under a great enough flow alteration, the species may suffer or die out. In the interest of maintaining the existence of the species dependent on the flow of the Comal River system, flow augmentation should occur to maintain the flow rates in these habitats.

Chapter 6:

San Marcos River

The San Marcos River has its headwaters in Hays County along the San Marcos Fault (Figure 29). Outcrops of the Person, Georgetown, Eagle Ford, Del Rio, and Buda formations surround the river, and the San Marcos Fault places the Austin and Taylor formations against the Person, Georgetown, and Del Rio formations (Figure 30; Maclay and Small, 1986). The majority of the flow in the San Marcos system originates from springs along this fault. In addition, approximately 30% of the flow in the river comes from local recharge. Because of this local component of recharge, the water in the San Marcos is on the average younger than that in the Comal (Puente, 1976). Water enters the system through over a hundred small and large springs in Spring Lake, a man-made lake at the head of the river (Figure 31). Water flows from the lake through the San Marcos River to its confluence with the Blanco River. There are 15 large springs which average 135.3 cfs (3.7 m^3/s) total discharge (Ogden, Spinelli, and Horton, 1985). Although there are numerous small seeps and springs in the Spring Lake, only the largest springs have been measured. These large springs are also clearly visible

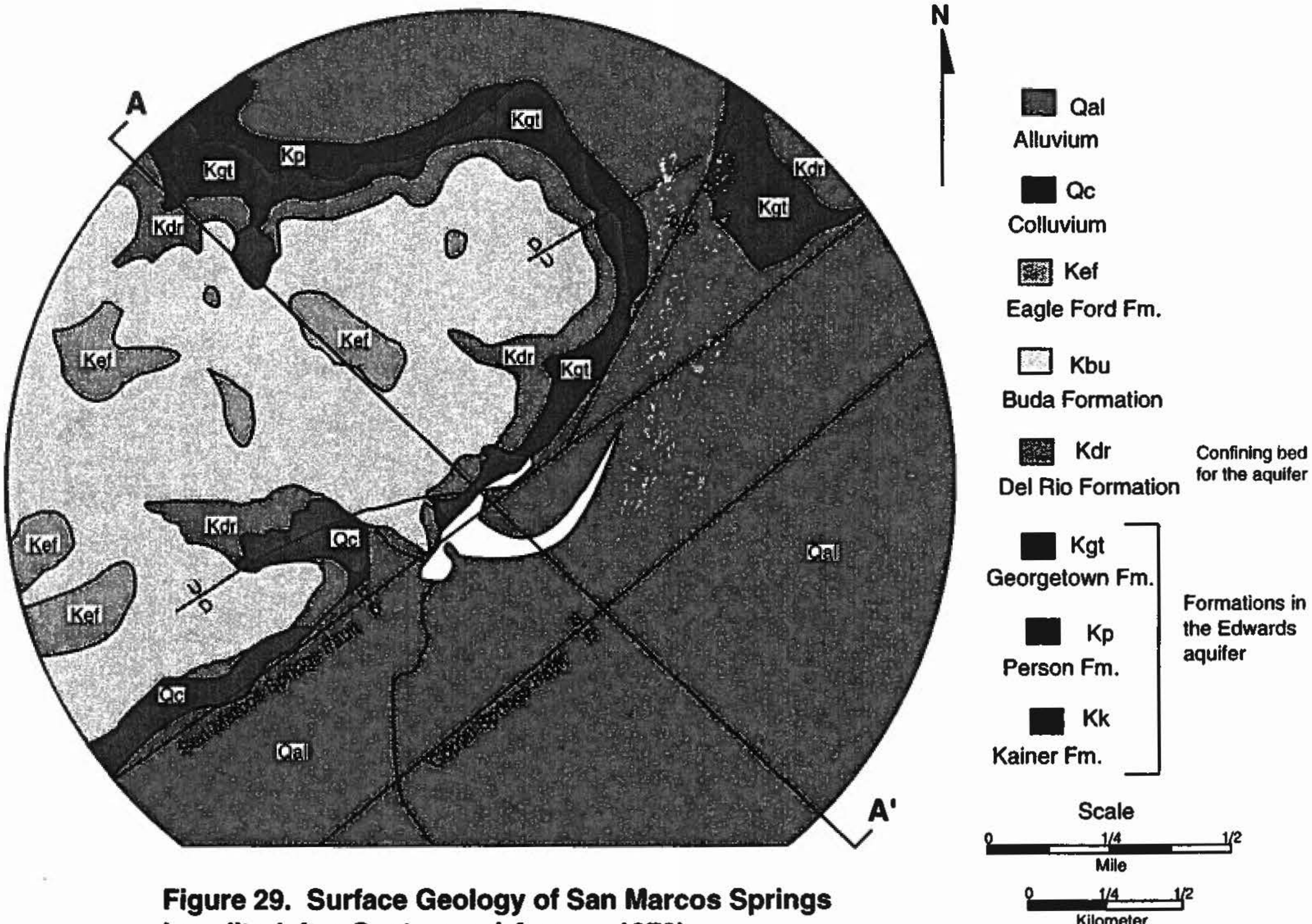


Figure 29. Surface Geology of San Marcos Springs Locality (after Guyton and Assoc., 1979).

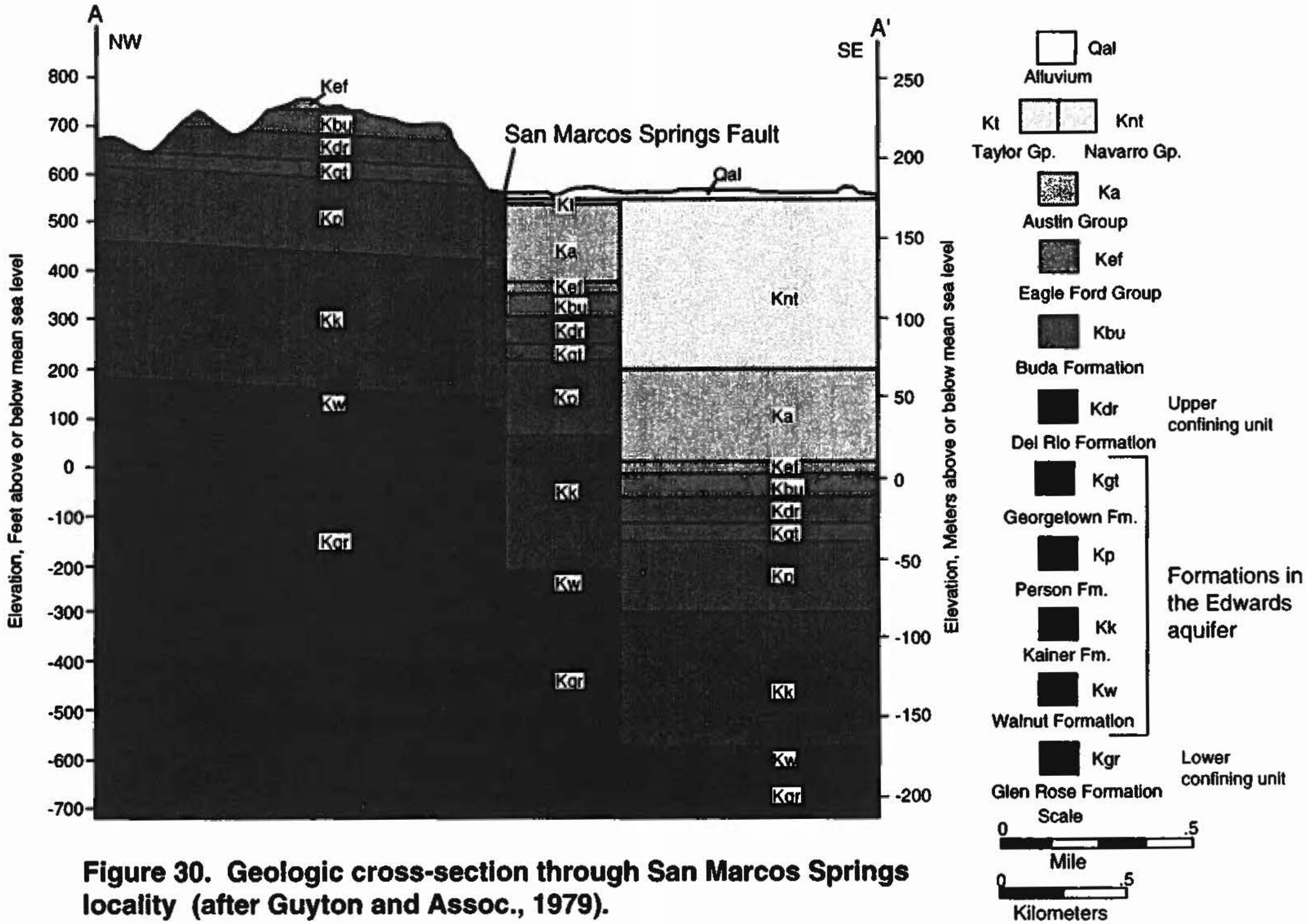


Figure 30. Geologic cross-section through San Marcos Springs locality (after Guyton and Assoc., 1979).

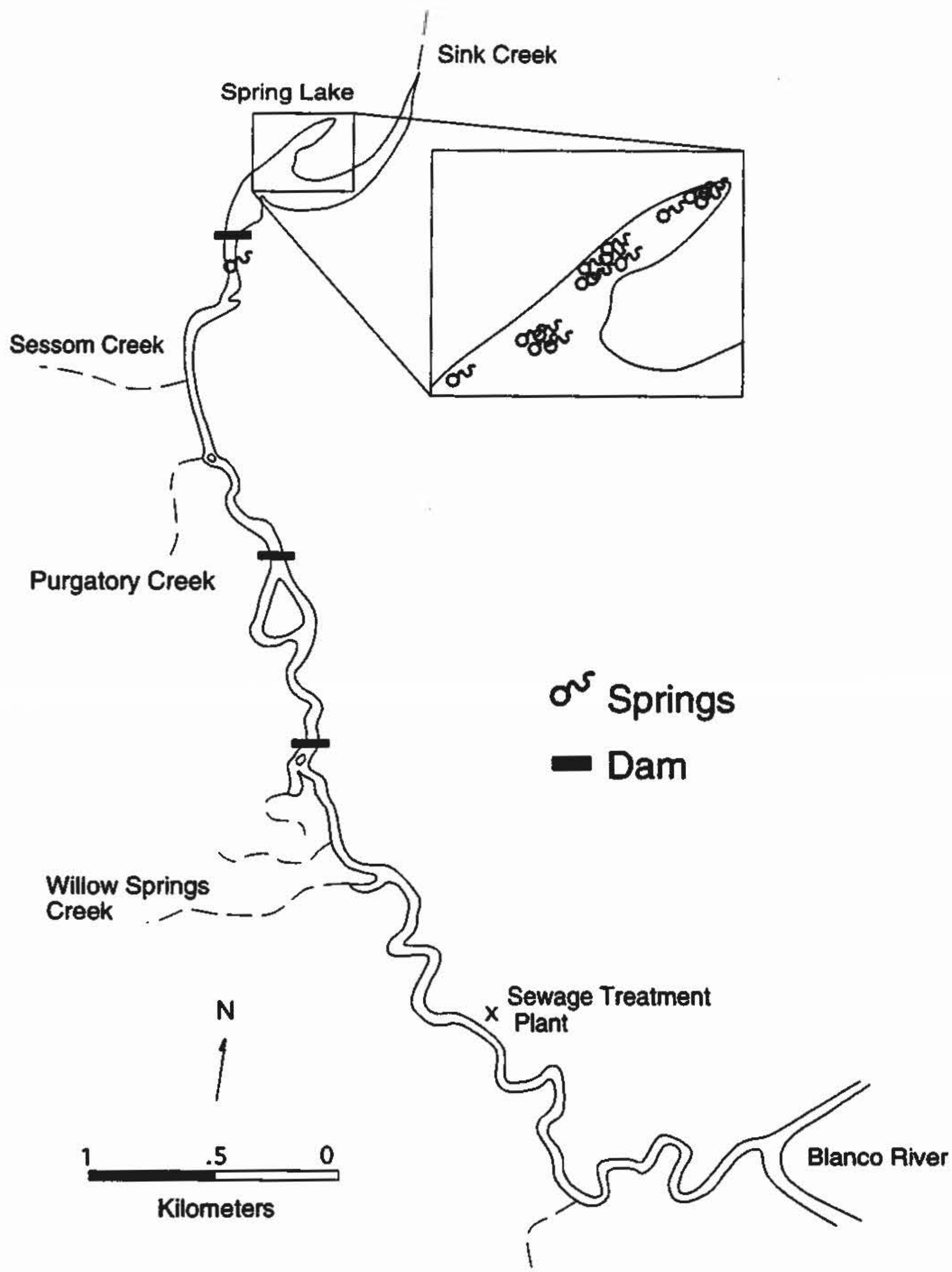


Figure 31. A map locating the springs and the dams on the San Marcos River system (after Espey, Huston, and Assoc., 1975).

when looking down from the surface of the lake. Like the Comal River, the San Marcos River is not a losing river.

Description of the San Marcos River

Compared with the Comal River, the San Marcos has had fewer alterations, but they are similar. Spring Lake was created by a dam, which was originally used to generate power along the river. Now the dam controls flow into the river, and the lake has an amusement park, Aquarena Springs, built around it. Aquarena Springs does not take and return water, but it does redirect some of the spring flow. Also in contrast to the Comal, the San Marcos River has not been split, but a number of small overflow dams are present on the river, as well as a sewage treatment plant on its downstream section. The San Marcos River also is the setting of many parks and tubing operations, similar to the Comal River. It is a popular recreation spot during summers. Southwest Texas University is located in San Marcos, and it also has a park on the river.

The long-term average flow through the San Marcos is 168 cfs (4.74 m^3/sec) as cited by Buckner et al. (1988). Unlike the Comal, the San Marcos has never ceased flowing in historical times. It reached its historical low flow of 48 cfs (1.3 m^3/s) during the 1950's drought. The yearly stream flow hydrograph for 1987, is shown in Figure 32, and it illustrates the seasonal

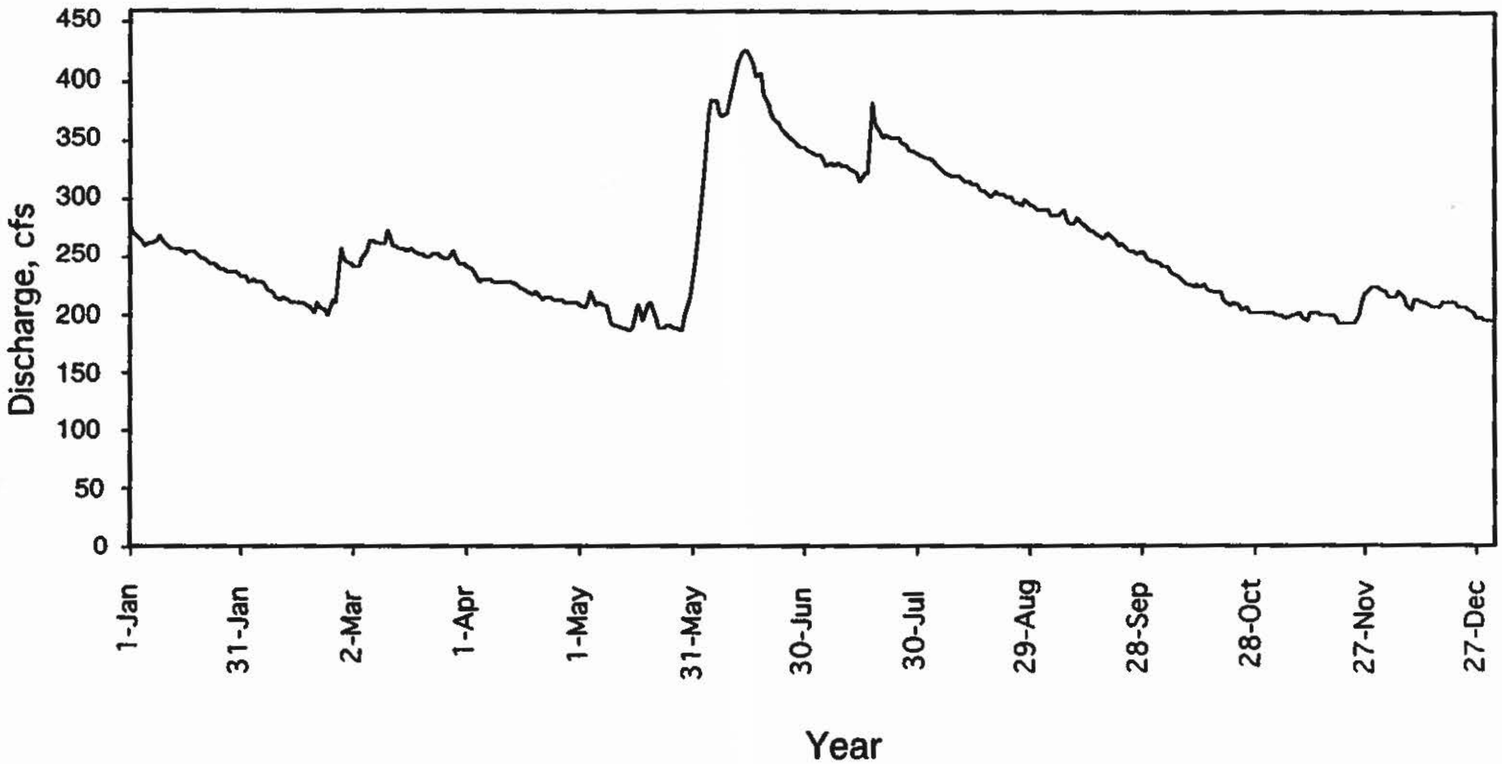


Figure 32. Annual stream flow hydrograph for the San Marcos River for 1987 (after Buckner et al., 1987).

distribution of flow. Spring storms increase flow in the river during the late spring and summer months. Local recharge has enough significance in San Marcos to help maintain higher flows over the summer, and then flows decrease during the fall and winter months.

Hydrochemistry

The hydrochemical data presented in Table 10 are a compilation of the literature. The analyses of the data are given in Table 10, and the individual data measurements are in Appendix B. Sites of the hydrochemical tests are given on the location map for the San Marcos (Figure 33). Methods of analysis of the different parameters are given in the referenced reports, and, as is the case for the Comal hydrochemical data, standard EPA methods of analysis were followed. All of the data were tested to determine whether they were log normally or normally distributed, and the statistical analyses were made accordingly. These data are similar to the data for the Comal River. The most consistently reported parameters were temperature, dissolved oxygen, pH, specific conductance, alkalinity, hardness, fecal coliform, and nitrate, calcium, magnesium, chloride, phosphate, and bicarbonate concentrations. These data again show very little variation, suggesting remarkable uniformity through the river system. Because the

TABLE 10. Maximum, minimum, range, and standard deviation for hydrochemical parameters in the San Marcos River.

	Maximum	Minimum	Range	Median	Standard Dev.
Temperature (C)	24.20	21.50	2.70	22.71	1.00
pH	8.40	6.85	1.55	7.34	0.38
Dissolved Oxygen (mg/l) *	7.50	3.80	3.70	5.89	0.11
Sp. Conductivity (umohs/cm)	700.00	410.00	290.00	516.50	68.60
Alkalinity (mg/l)	258.00	232.00	26.00	246.63	10.47
Nitrate (mg/l)	1.77	1.23	0.54	1.50	0.15
Chloride (mg/l)	29.50	18.00	11.50	21.34	3.02
Phosphate (mg/l) *	1.57	0.01	1.56	0.05	0.60
Sulfate (mg/l)	25.40	13.60	11.80	19.50	3.78
Calcium (mg/l)	88.00	78.00	10.00	84.00	3.93
Magnesium (mg/l)	17.00	16.00	1.00	16.63	0.52
Bicarb. as HCO3 (mg/l)	315.00	244.00	71.00	280.62	28.62
Total Hardness (CaCO3 mg/l)	300.00	150.00	150.00	264.65	36.42
TDS (mg/l)	327.00	303.00	24.00	316.63	10.82
Fecal Coliform (#/100 ml) *	11000.00	0.00	11000.00	203.00	1.27
Sodium	11.00	10.00	1.00	10.13	0.35
Total Organic Carbon (mg/l) *	14.00	1.00	13.00	3.74	0.81
Ammonia (mg/l as NH3)	0.10	0.10	0.00	0.10	0.00
Silica	13.00	9.00	4.00	11.00	2.83
* indicates a log normal data distribution					

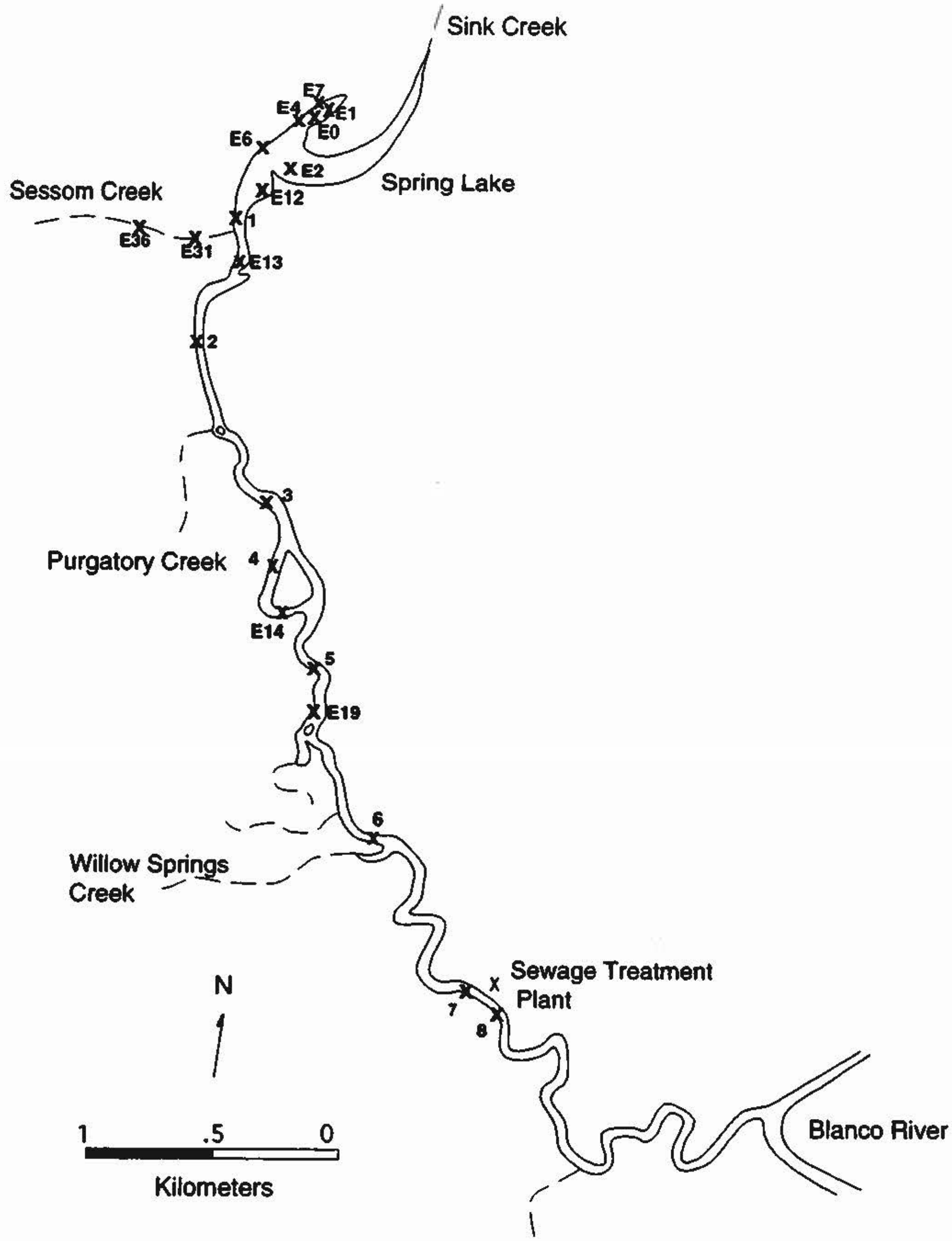


Figure 33. The locations of sites where hydrochemical data were collected along the San Marcos River.

majority of the flow comes from springs which discharge from the same fault in the Edwards aquifer, their hydrochemical composition remains very constant throughout the year.

Temperature in the river varies only 2.7 degrees, and most of the hydrochemical parameters measure within a range of two standard deviations or less. Local flow contributions to the San Marcos River cause the standard deviations of the San Marcos hydrochemical parameters to be slightly larger than for the Comal River. The flow to San Marcos Springs originates from the aquifer a distance from the spring orifices. Edwards' wells in the vicinity of the springs show a slightly higher sulfate, sodium, and chloride values with slightly lower calcium and magnesium values than the spring waters, indicating that there is no immediate contact between the spring waters and the surrounding aquifer waters (Rothermel and Ogden, 1987; Ogden et al., 1985).

Spring flow provides the majority of the water in the river. Because of this, the river reflects the constant nature of the spring waters, and a constant hydrochemical composition is maintained over the length of the San Marcos. This implies that the species present, the fountain darter, the San Marcos salamander, the San Marcos gambusia, and the Texas wild rice, may require very specific water in which to live and to reproduce.

Soils

The soils around the San Marcos River contribute to the substrate in the river. Soil data were taken from the Soil Conservation Services report on San Marcos, and a map of the San Marcos River illustrating the different soil types is given in Figure 34, with a legend in Figure 35. Soil properties are taken from Batte (1984) and presented in Table 11. Water capacity is measured as the difference between the amount of soil water at field moisture capacity and the amount at wilting point. It is the ability of the soil to hold water available to the plants, and it is expressed as the inches of water stored per inch of soil (Batte, 1984).

The soils present in the San Marcos area are very similar to those found around the Comal River; again, they are predominantly silty and clayey loams found on stream terraces and flood plains. The clays are calcareous, and the soils have a calcium carbonate content of up to 60%.

Permeability for the clays ranges between 4.2×10^{-5} cm/sec and 8.4×10^{-4} cm/sec (Batte, 1984), and the clays allow for little infiltration. The Orif soil has a permeability much higher than the other soil types at 7.1×10^{-3} cm/sec, and it is high enough to allow infiltration, which may aid the local recharge to the

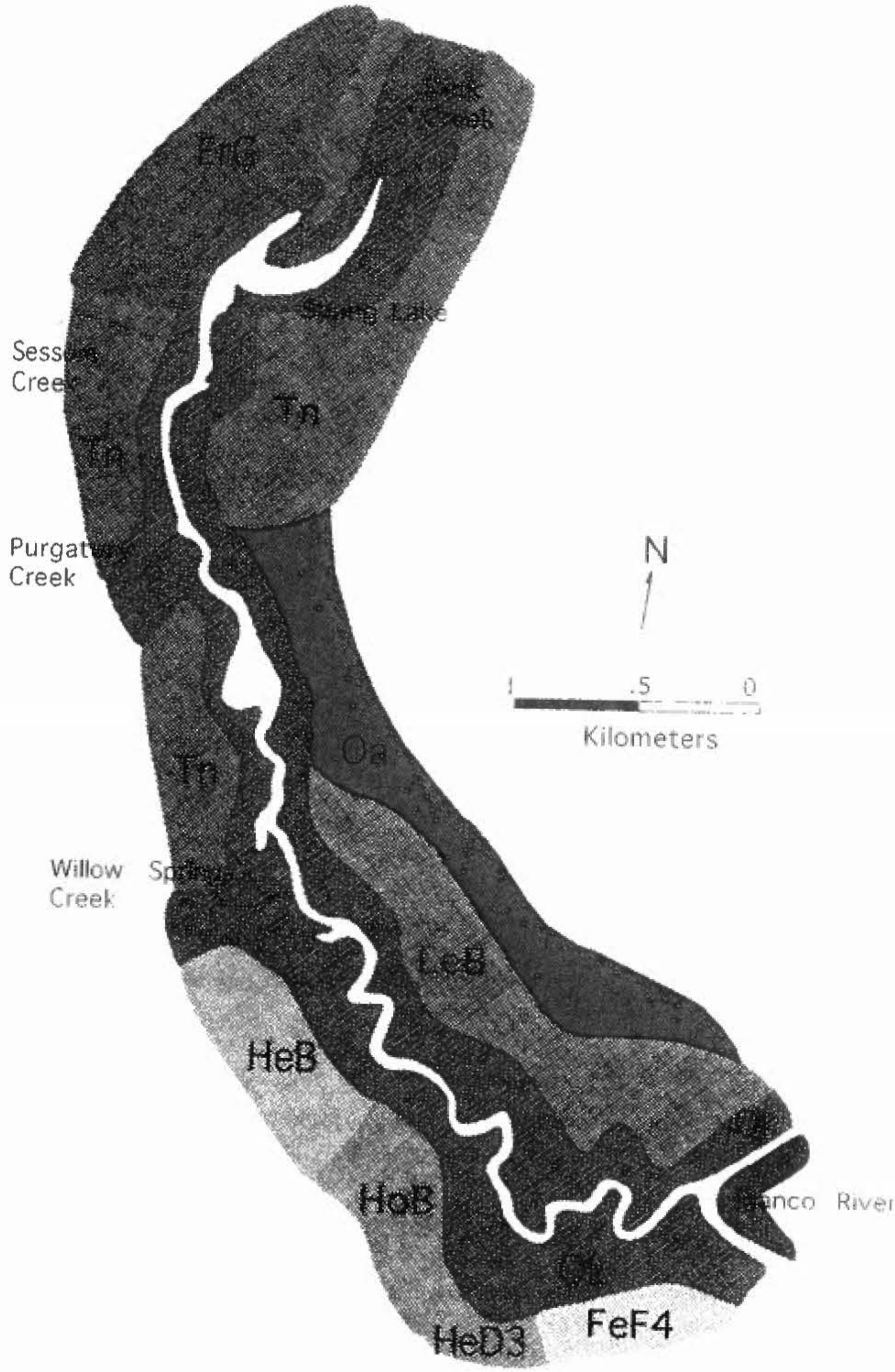


Figure 34. A map of the soil distribution around the San Marcos River (after Batte, 1984)

ErG : Eckrant-Rock clayey soils; Depth of 0-10 in (0-25 cm);
k = 0.2 - 0.6 in/hr (0.0001-0.0004 cm/s); Θ = 0.05 - 0.12

FeF4: Ferris Clay; Depth of 0 - 60 in (0-152 cm);
k < 0.06 in/hr (4.2×10^{-5} cm/s); Θ = 0.12 - 0.20

HeB : Heiden Clay; Depth of 0-22 in (0-56 cm);
k < 0.06 in/hr (4.2×10^{-5} cm/s); Θ = 0.15 - 0.20

HeD3: Heiden Clay; Depth of 22-88 in (56-224 cm);
k < 0.06 in/hr (4.2×10^{-5} cm/s); Θ = 0.12 - 0.20

HoB : Houston Black Clay; Depth of 0-25 in (0-64 cm);
k < 0.06 in/hr (4.2×10^{-5} cm/s); Θ = 0.15 - 0.20

LeB : Lewisville Silty Clay; Depth of 17 - 36 in (43-91 cm);
k = 0.6 - 2.0 in/hr (0.0004-0.001 cm/s); Θ = 0.14 - 0.18

Oa : Oakalla Silty Clay; Depth of 0 - 80 in (0-203 cm);
k = 0.6 - 2.0 in/hr (0.0004-0.001 cm/s); Θ = 0.12 - 0.19

Ok : Oakalla Soils; Depth of 0 - 80 in (0-203 cm);
k = 0.6 - 2.0 in/hr (0.0004-0.001 cm/s); Θ = 0.12 - 0.19

Or : Orif Soils; Depth of 0 - 20 in (0-51 cm);
k = 6.0 - 20.0 in/hr (0.004-0.014 cm/s); Θ = 0.03 - 0.08

Tn : Tinn Clay; Depth of 0 - 25 in (0-64 cm);
k = 0.06 - 0.2 in/hr (4.2×10^{-5}-0.0001 cm/s); Θ = 0.15 - 0.20

Figure 35. Legend describing the soils around the San Marcos k=hydraulic conductivity; Θ=water capacity (after Batte, 1984).

TABLE 11. Properties of the soils around the San Marcos River.

Soil Type	**Depth inches cm**	**% Clay**	**k (av.) (cm/s)**	**Soil pH**	**Shrink /Swell**	**Water Cap. (in/in)**
Ok	0-80 0-203	25-43	2.8×10^{-4}	7.9-8.4	mod	.12-.19
Tn	0-25 0-64	35-60	2.8×10^{-4}	7.4-8.4	high	.15-.20
Oa	0-80 0-203	25-43	8.4×10^{-4}	7.9-8.4	mod	.12-.19
HeB	0-22 0-56	40-60	4.2×10^{-5}	7.9-8.4	v. high	.15-.20
HoB	0-25 0-64	40-60	4.2×10^{-5}	7.4-8.4	v. high	.15-.20
FeF4	0-60 0-152	40-60	4.2×10^{-5}	7.9-8.4	v. high	.15-.18
HeD3	22-80 56-224	40-60	4.2×10^{-5}	7.9-8.4	v. high	.12-.20
ErG	0-10 0-25	35-60	2.8×10^{-4}	6.6-8.4	mod	.05-.12
LeB	17-36 43-91	30-45	8.4×10^{-4}	7.9-8.4	high	.14-.18
Or	0-20 0-51	- -	7.1×10^{-3}	7.9-8.4	low	.03-.08

system. This horizon covers a larger area in the San Marcos system than it does in the Comal system. Alluvium present on the southern side of the San Marcos system has a thickness of 18 meters (Espey, Huston, and Assoc., 1975), and the layer of alluvium is much thicker here than it was on the Comal River. Consequently, it could have a significant water storage capacity, also aiding in local baseflow to the river.

Vegetation

The San Marcos River hosts numerous plant species, including many of those found in the Comal River. A map illustrating the vegetation in the river is shown in Figure 36, and photos of some of the additional plant species are in Figure 37. The growth and abundance of the different plant species are dependent on the time of year, similar to those on the Comal River, and the map presented here is for the summer season. The most notable addition in the San Marcos is the endangered Texas wild rice, which grows only in the San Marcos River. Its distribution is shown in Figure 36. There have been fewer man-made alterations to the San Marcos River than to the Comal. As a result, vegetation in the San Marcos tends to be more extensive in the areas where it is present; it is not as patchy as on the Comal River.

Spring Lake is largely a mix of *Cabomba*, *Hydrilla*, and *Microphyllia*, except where the springs bubble up out of the

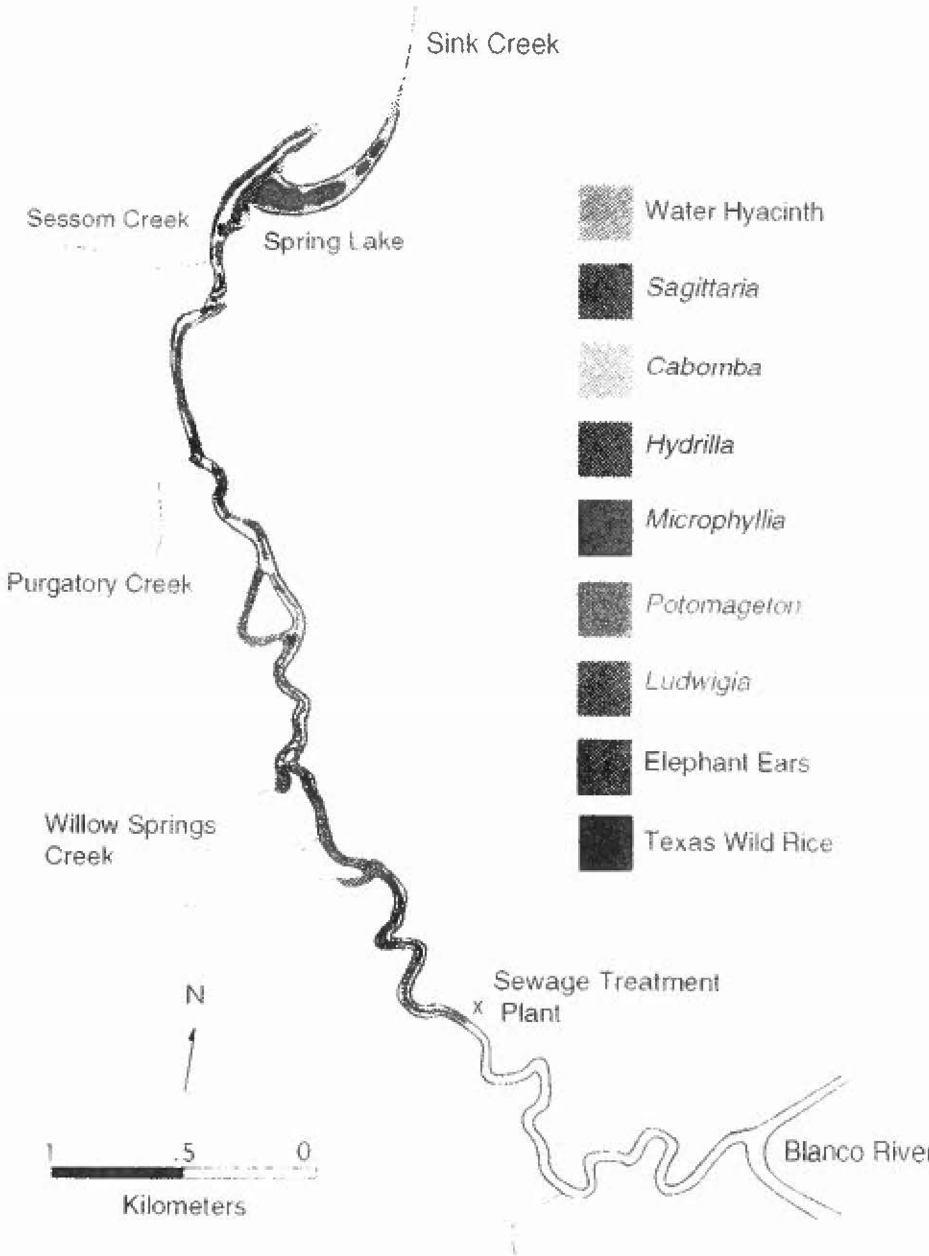
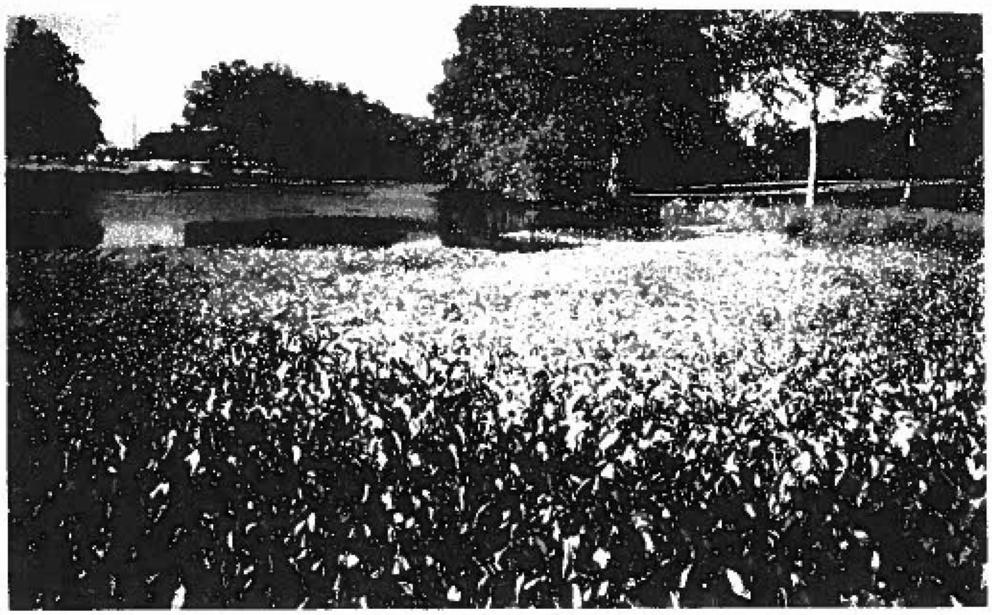


Figure 36. Map of the vegetation in the San Marcos River during September, 1993.



(a) *Hydrilla*
(b) Elephant Ears

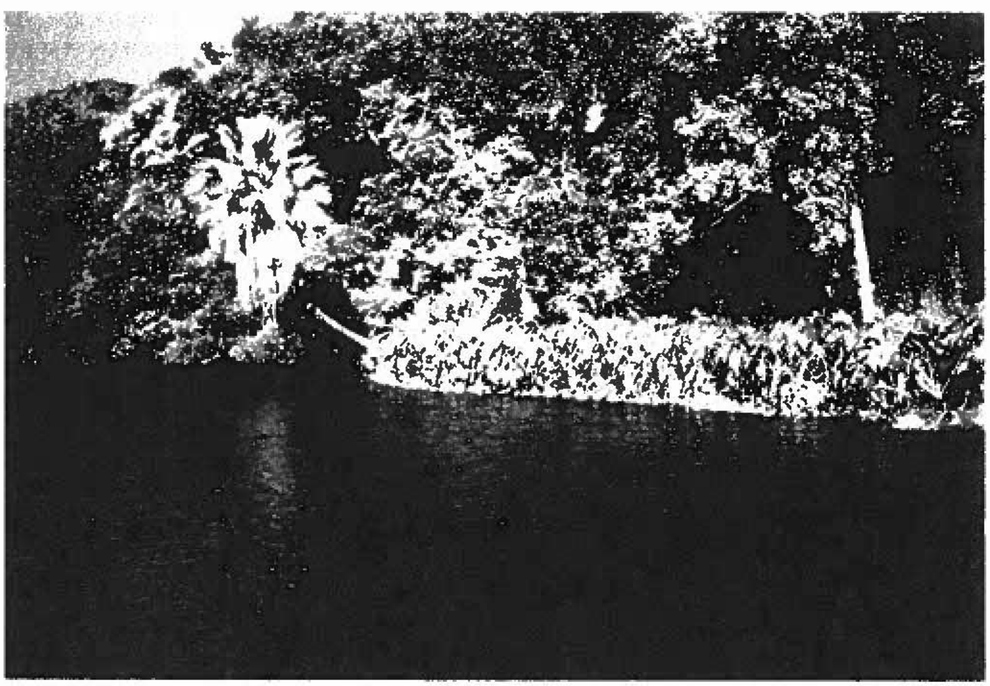
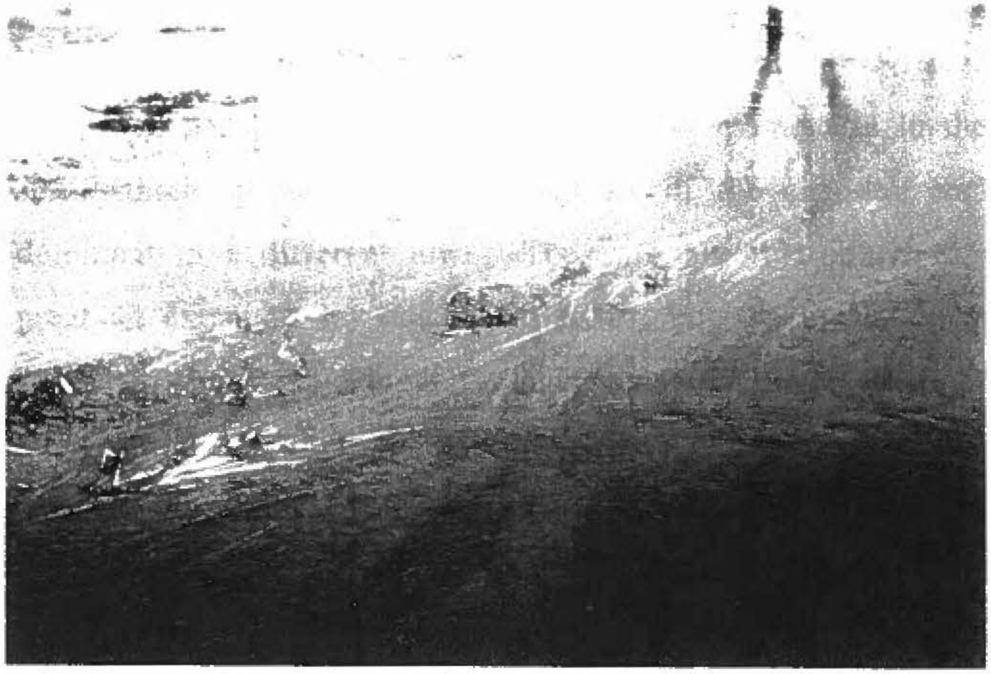


Figure 37. San Marcos River vegetation (a) Hydrilla; (b) Elephant Ears; (c) Texas Wild Rice; (d) Microphyllia



(c) Texas Wild Rice

(d) *Microphyllia*

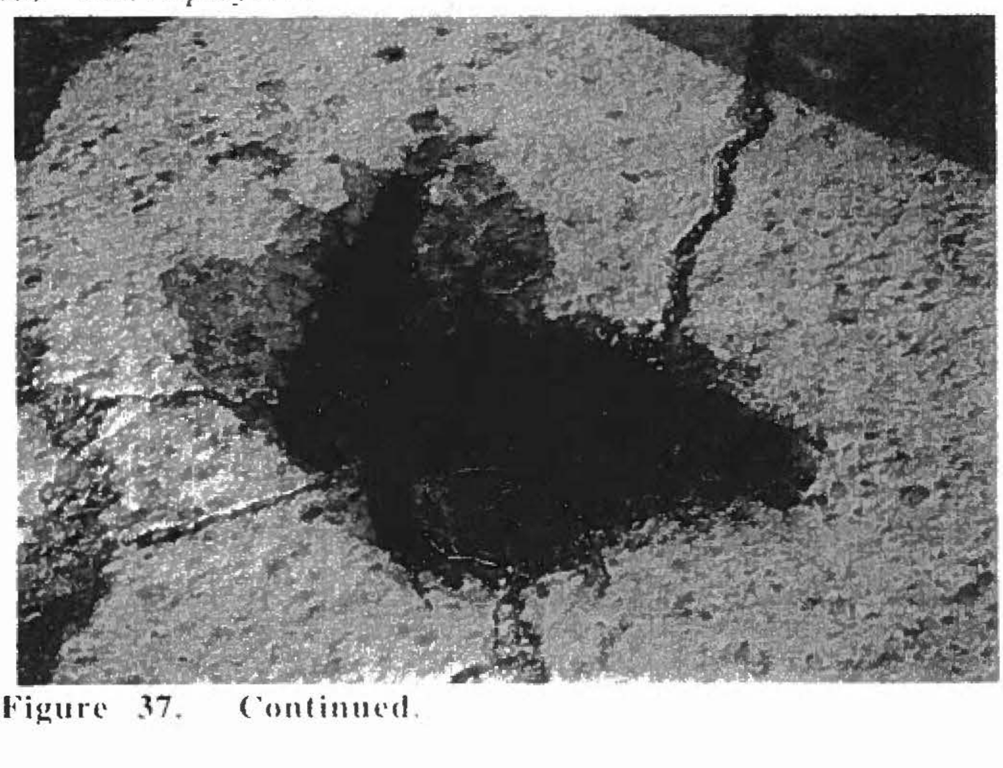


Figure 37. Continued.

fault. There the lake bottom is void of vegetation. Vegetation in the channel consists primarily of *Potomageton*, *Sagittaria*, and *Hydrilla*, and it is not as extensive in its coverage as in the lake. These three species cover the majority of the channel, each one dominant in a different area. They are not intermixed to as great an extent as on the Comal River, but the plants do co-exist in some of the same areas. Plants generally cover about 50% of the river channel. Elephant ears grow along the banks of the channel for almost its entire length; it is an introduced plant that has become a major part of the river system.

Depending on the flow and substrate present, species of vegetation grow in different areas of the river. Plants only grow where the flow in the river has not washed away all of the substrate and is not too fast for the plants to take root. Many plants favor areas of the river that are sandy or muddy, and because the river is predominantly gravel, these plants do not cover the river's extent. Texas wild rice grows in a variety of areas, but it appears to favor those areas with a gravel substrate.

Areas that are without any vegetation cover correspond to high flows due to overflow dams or the dam on Spring Lake. These dams are of the same type as those on the Comal River (refer to Figure 17). The exception to this is the section of river past the sewage treatment plant. Sewage effluent flows into the river at this point, and there are only a few patches of elephant ears growing along the river below the plant. This is also near the confluence of the San Marcos River with the Blanco River. As a result, backwater effects due to the Blanco River are seen here; the river becomes deeper, slower, and more turbid.

Substrate

The substrate distribution in the San Marcos River is shown in Figure 38. The patterns are similar to the Comal River substrate (refer to Figure 25). For example, both the Comal and San Marcos Rivers have large clast substrates where the flow velocity is high and fine substrates in low velocity areas. The most notable difference between the two systems is that the Comal system has more combinations of different substrate types than the San Marcos system. This corresponds to the fact that the San Marcos has been less altered than the Comal, so that the San Marcos channel maintains a more uniform and faster flow along its length. Consequently, the San Marcos River has greater uniformity in its substrates. This is similar to the distribution of vegetation in the river. Commonly, the flow in the channel is around 1 ft/sec (0.3 m/s), and the corresponding substrate is a mix of mostly poorly-sorted gravel with some sand. Where cobbles or boulders are found in the river, they are usually from a source on the bank.

Figure 38. Map of the substrate in the San Marcos River during September, 1993.

The portions of the channel where mud accumulates along with the granules and sand are where the flow velocity is slower than along the main run of the channel. In some areas, such as the portion of the channel between Sessom Creek and Purgatory Creek (refer to Figure 38), the difference between the two different flow regimes (between the main run in the center of the channel and the slower water closer to the bank) is visible on the water surface. In comparison to the Comal River there is very little mud present in the river channel and a great deal more sand. The area past the sewage treatment plant presents an exception to these generalities. The combination of increased water from the Blanco River and the sewage effluent causes the flow velocity to drop dramatically, and the only substrate present for a length of the river is a thick mud. Only after a distance of approximately 60 meters downstream of the plant are small gravel again part of the substrate.

Chapter 7:

Discussion: The San Marcos River

Habitats

Habitat definitions, prepared over the length of the San Marcos River system, are presented in Table 12 with a corresponding location map in Figure 39. Definitions of habitats were made using the same method as that for the Comal system, with all of the information gathered on the river system taken into account. Habitats are defined through the combination of vegetation, substrate, hydrochemistry, and flow type information. Hydrochemical parameters are less important to the differentiation of habitats, because they are uniform throughout the river and therefore throughout the habitats. There are more habitats defined for the San Marcos River than for the Comal River, but in many cases habitats are very similar to each other.

From the field mapping, it became apparent that two substrate types and three types of vegetation would be sufficient for each habitat definition, because most of the river could be described well using this system. Three plant species were identified rather than just two to help account for the

TABLE 12. Descriptions of the habitats found in the San Marcos River system.

Habitat	Vegetation 1	Vegetation 2	Vegetation 3	Substrate 1	Substrate 2	Flow Type	% Veg. Cover (approx.)
1	*Caboamba*	*Microphyllia*	Elephant Ear	Mud	None	Backwater Pool	100
2	*Hydrilla*	*Sagitaria*	*Caboamba*	Mud	None	Slow Run	100
3	None	None	None	Cobbles	Large Gravel	Pool (Springs)	0
4	*Potamogeton*	*Ludwigia*	Elephant Ear	Large Gravel	Med. Gravel	Riffle	30
5	*Potamogeton*	*Hydrilla*	None	Gravels	Sand	Fast Run	50
6	*Potamogeton*	Wild Rice	Elephant Ear	Gravels	Sand	Fast Run	50
7	*Hydrilla*	None	None	Mud	None	Pool	100
8	*Potamogeton*	*Sagitaria*	None	Gravels	Sand	Fast Run	60
9	*Potamogeton*	Hyacinth	None	Gravels	Sand	Fast Run	30
10	Wild Rice	None	None	Gravels	Sand	Run	80
11	Wild Rice	*Ludwigia*	*Sagitaria*	Mud	None	Very Slow Run	80
12	*Hydrilla*	Wild Rice	Elephant Ear	Mud	Small Gravel	Slow Run	100
13	*Hydrilla*	Wild Rice	Elephant Ear	Gravels	Sand	Slow Run	50
14	None	None	None	Cobbles	Large Gravel	Plunge Pool	0
15	*Hydrilla*	Wild Rice	None	Large Gravel	Med. Gravel	Deep Pool	100

TABLE 12. Continued.

Habitat	Vegetation 1	Vegetation 2	Vegetation 3	Substrate 1	Substrate 2	Flow Type	% Veg. Cover (approx.)
16	*Hydrilla*	Wild Rice	None	Gravels	Sand	Run	15
17	*Hydrilla*	*Potamogeton*	Elephant Ear	Mud	None	Slow Run	100
18	*Hydrilla*	Wild Rice	Elephant Ear	Med. Gravel	Sand	Fast Run	30
19	*Hydrilla*	Elephant Ear	None	Small Gravel	Sand	Run	20
20	*Hydrilla*	*Potamogeton*	*Sagitaria*	Gravels	Sand	Run	80
21	*Hydrilla*	*Potamogeton*	*Sagitaria*	Gravels	Sand	Slow Run	90
22	None	None	None	Mud	None	Slow Run	0
23	None	None	None	Mud	Small Gravel	Fast Run	0
24	*Hydrilla*	Wild Rice	*Potamogeton*	Gravels	Sand	Run	80
25	*Hydrilla*	Wild Rice	Elephant Ear	Large Gravels	Med. Gravel	Run	80
26	None	None	None	Mud	Small Gravel	Slow Run	0
27	Elephant Ear	None	None	Mud	Small Gravel	Slow Run	5

Vegetation 1 is the dominant plant in the area
Vegetation 2 is the subdominant plant in the area
Substrate 1 is the dominant type of substrate in the area
Substrate 2 is the subdominant type of substrate in the area
Flow types are defined in Table 8
F. Darter is the average number of fountain darters found in one cell in the habitat area
% Veg. Cover is the approximate amount of plant cover in that area of the river

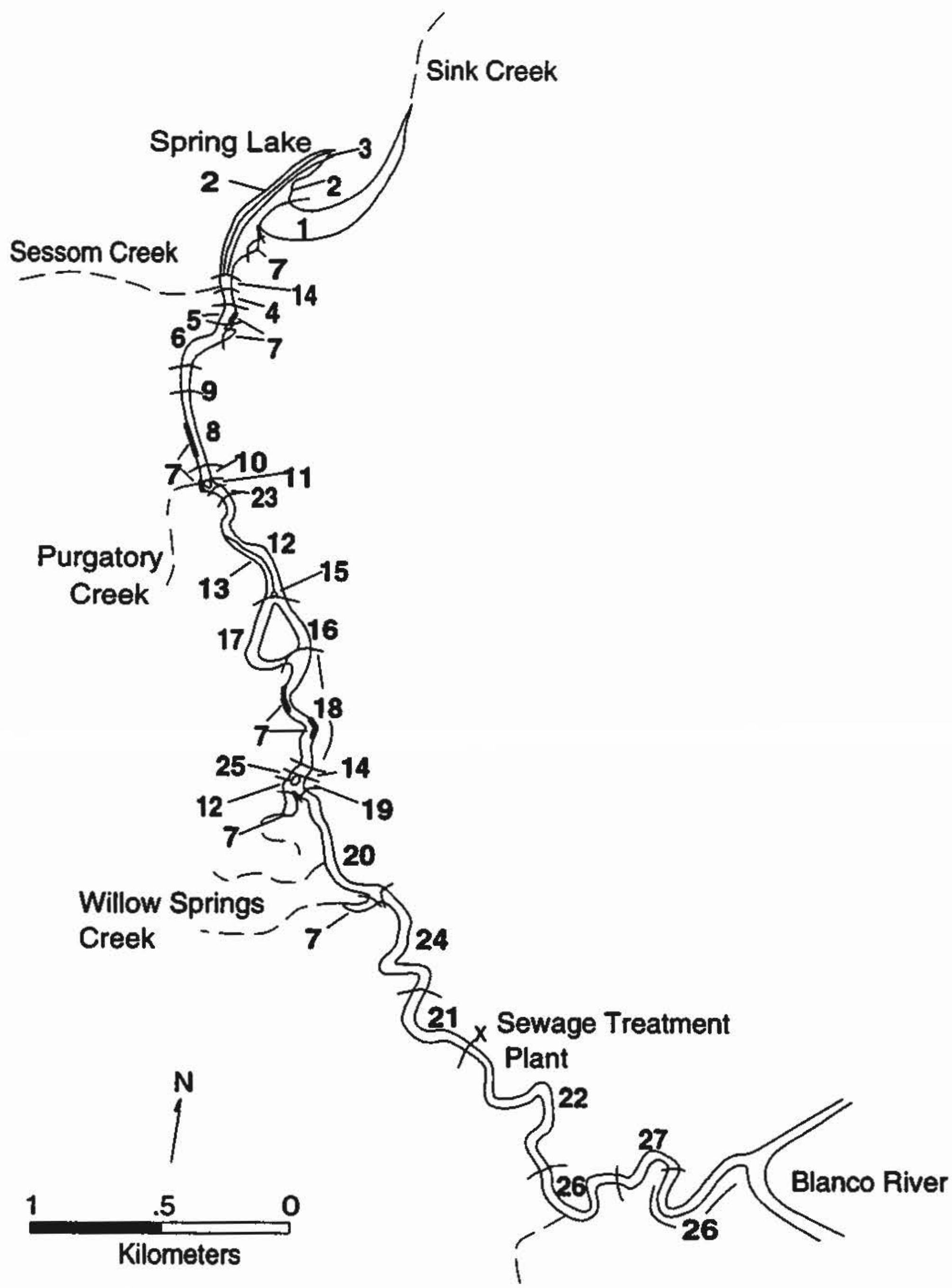


Figure 39. A map illustrating the distribution of habitats in the San Marcos River.

presence of elephant ears along the river's banks. An approximate percentage of vegetation cover was listed for the habitats, because in many cases vegetation did not fill the channel. Flow types are listed for each habitat, and these are same terms as those used to describe the Comal River (Table 8).

Some of the habitats are repeated along the course of the river, and in many areas more than one habitat is found. Often there is a distinct edge habitat in addition to a main channel habitat, especially around bends in the channel; for example, habitat #7 is found within an area dominated by habitat #18. This is due to the velocity distribution in the river as it bends. Where two flow regimes are found along the same length of the channel, the channel is split into two habitats. This is the case with habitats #12 and #13. Where the major springs bubble up from the fault line in Spring Lake, a different habitat is encountered than in the rest of the lake (habitat #3 rather than habitats #2 or #1). There is a change from habitat #21 to habitat #22 at the point in the river where the sewage treatment plant is located.

Texas Wild Rice

Texas wild rice is found only in the San Marcos River. It grows predominantly in areas of gravel substrate with rather swift flow, usually a run. The rice is most common in habitats

#10, #11, #12, and #24, although it is found to a lesser abundance in other areas. The wild rice has a limited depth range for growth; it must have water that is deep enough for it to extend, but not so deep that the plant cannot get sunlight. The optimum depth has been estimated by Poole (1992) to be between 0.2 meters (0.66 ft) and 3 meters (9.84 ft). These depths allow the plant an optimum amount of sunlight and carbon dioxide.

The rice grows in many places along the main part of the San Marcos River until the point of discharge of the sewage treatment plant. The distribution of the wild rice was shown on the San Marcos Vegetation Map in Figure 36. A good example of wild rice habitat is the area of the park on the campus of Southwest Texas University. These habitats are generally about four to six feet deep, and the wild rice grows up to the water surface; optimum habitat for the wild rice is shown in Figure 40.

Fountain Darter

There was no sampling for the fountain darter in the San Marcos River, but the habitat information found on the Comal River is assumed to apply to the San Marcos as well. The fountain darter favors those areas with low flow and a high percentage of vegetation cover; an example of this habitat is the upper part of Spring Lake, habitat #1. The fountain darter also

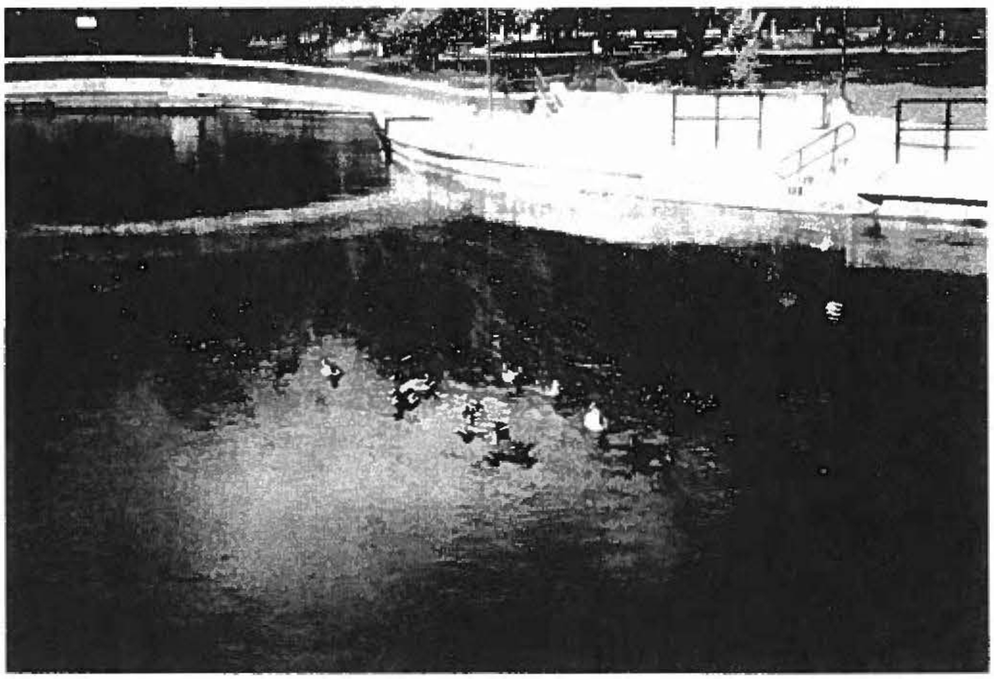


Figure 40. Texas Wild Rice habitat on the San Marcos River in the park at South West Texas State University.

inhabits areas of the river with gravel and sand substrates, where the river bed has created a boundary layer protecting the darters from high flow rates in the main channel. In areas with vegetation and a gravel river bed, the darter is also protected from floods (McKinney and Sharp, 1994). This combination of substrate, flow velocity, and vegetation is found in many places throughout the San Marcos River, which should result in a good fountain darter population in the system. The darter may also inhabit other areas, although it does not appear to prefer them. As a result, darter habitat includes Spring Lake and the length of the river until the sewage treatment plant.

San Marcos Gambusia

The San Marcos gambusia is native to the San Marcos River, and is also an endangered species. It is difficult to define a favored habitat for this fish, however, because this particular species of gambusia has not been seen in the last decade. Although it may be extinct, it remains on the endangered species list. The last sightings and studies of the San Marcos gambusia identified its area of habitat within the river. Unlike the fountain darter, the gambusia lived in only a limited area. It was found immediately upstream and downstream of the Interstate Highway 35 bridge over the river (McCoig, et al., 1986). It preferred a shallow water habitat where water temperatures remained rather constant, the substrate was a thick mud, and there was a lack of dense vegetation (McKinney and Sharp, 1994). There are only a few, limited area, habitats that meet the San Marcos gambusia's requirements. These include habitats #17, #11, and #7.

Constant population growth in the central Texas area and traffic on IH 35 has caused an increase in road runoff in the area under the bridge, and this is believed to be one of the reasons for the loss of the San Marcos gambusia. It has been discovered that the San Marcos gambusia has been inter-breeding with the hardier *gambusia affinis*, which also inhabits the San Marcos river. The resulting hybrid gambusia is more resistant to minor habitat alterations, and it has been successful in competition with the San Marcos gambusia for river habitat. Both *gambusia affinis* and the new gambusia are found throughout the river system, and neither is listed as endangered.

San Marcos Salamander

The habitat of the San Marcos salamander was well defined by Nelson (1993), so no sampling was performed for this species. The salamander has only been found around the springs in the Spring Lake area, where it is believed to live near the orifices of the springs themselves. It also lives in habitats #3 and #8 in the river, where there are similar habitat characteristics to the springs area of the lake. It prefers a predominantly small gravel and sand substrate. The river bed should also have some larger limestone boulders on it, although not as the predominate substrates. The salamander uses the large boulders as protection from predators. It also prefers habitats with vegetation cover, and a variety of different plant types are acceptable. The salamander has not been found in any of the stagnant areas of either the lake or the river; flowing water appears to be a habitat requirement as well (Nelson, 1993). All of the salamander's habitats needs are met in a number of habitats, including #3, #8, #6, #9, and #18.

Flow Velocity Requirements

The amount of water necessary for the maintenance of each of the habitats has been estimated using the same method as on the Comal River, through the combined use of the modified Wentworth scale and the Hjulstrom diagram (refer to Figure 28). Through examination of the substrates found in each habitat and the upper and lower flow velocity limits for those substrates, the upper and lower velocity limits were estimated for each habitat, and they are given in Table 13. For each of the habitats, the smaller of the two substrates given was used in the calculations, because that would be the one most susceptible in the event of alterations to the water velocity.

TABLE 13. Flow velocities for habitats in the San Marcos River.

Habitat	Substrate 1	Substrate 2	Lower Flow Velocity	Upper Flow Velocity
1, 2, 7, 11, 17, 22	Mud	None	0.0000 ft/s 0.0000 m/s	0.0003 ft/s $9 x 10^{-5}$ m/s
3, 14	Cobbles	Large Gravel	2.5000 ft/s 0.7500 ms	4.0000 ft/s 1.2000 m/s
4, 15, 25	Large Gravel	Medium Gravel	1.0000 ft/s 0.3000 m/s	2.5000 ft/s 0.7500 m/s
5, 6, 8, 9, 10, 13, 16, 20, 21, 24	Poorly-Sorted Gravel	Sand	0.0003 ft/s $9 x 10^{-5}$ m/s	0.2000 ft/s 0.0600 m/s
12, 23, 26, 27	Mud	Small Gravel	0.0000 ft/s 0.0000 m/s	0.0003 ft/s $9 x 10^{-5}$ m/s
18	Medium Gravel	Sand	0.0003 ft/s $9 x 10^{-5}$ m/s	0.2000 ft/s 0.0600 m/s
19	Small Gravel	Sand	0.0003 ft/s $9 x 10^{-5}$ m/s	0.2000 ft/s 0.0600 m/s

The flow velocity limits are very important, because a catastrophic loss of habitat could occur under drastically different velocities. Below the lower limit for each habitat, sedimentation of smaller substrates is likely, and with increased sedimentation, the existing habitats would be altered into different habitats. The most abundant substrate combination in the river is that of poorly-sorted gravel and sand, which occurs in 10 of the 27 different habitats. Under a flow velocity lower than 0.0003 ft/s ($9x10^{-5}$ m/s), mud and silt would begin to settle in these areas, and the existing substrates which aid in the growth of the wild rice would be destroyed. Similar results would be found if the velocity in the river becomes too high. Above a 0.2 ft/s (0.6 m/s) flow velocity limit for these habitats, scouring of the sand is likely. This situation would remove sand from its current habitat, along with the finer substrates in all the other habitats. The entire river could become void of any sand or mud under a higher flow velocity. The greater danger to the flow velocities in the river is a loss of spring discharge rather than prolonged higher spring discharge. Therefore while the impact of long-term high flow velocities may be determined, they are unlikely.

A change in the flow velocity in the river could occur if the amount of spring flow into the San Marcos system changed. Because the fountain darter has a preference for certain vegetation, flow velocity, and substrate combinations, their existing habitats would be devastated by a shift in flow velocity. Similar to the Comal system, while the darters are in many areas of the river, they prefer areas with low flow velocities and mud substrates. Therefore, if the flow velocity became greater than 1 ft/s (0.3 m/s) and the small gravel as well as the mud began to erode from these areas, the darter population would be adversely effected. The loss of substrate could also cause a reduction in plant life, and the habitat would then be completely altered.

The San Marcos salamander would also be hurt by a change in the flow velocity from the springs. If the flow became too great, the salamander would be swept downstream away from the spring openings. Yet the salamander requires flowing water for its habitat, indicating that a loss of spring flow discharge resulting in too low a flow velocity would be as great of a problem. A flow velocity below 0.0003 ft/s ($9x10^{-5}$ m/s) would increase deposition of silt and mud in salamander habitats (habitats #3, #8, #6, #9, #18), rendering them unsuitable. Under a large enough flow alteration, the species may not be able to adjust, and they may suffer or die off.

The Texas wild rice is of importance, and it grows in many different habitats over the length of the river. Habitats with a rather high flow velocities and a substrate of poorly sorted gravel with sand are where the wild rice appears to proliferate best. Texas wild rice is also found in other habitats, including habitats #10, #11, #24, #13, and #18, but it grows most often in the habitats with a gravel and sand substrate. This type of substrate has a flow velocity range of 0.0003 ft/s ($9x10^{-5}$ m/s) to 0.2 ft/s (0.06 m/s) before either muds are deposited or sand is eroded. Therefore any alteration in the flow velocity in the river beyond this range could cause damage to the wild rice population. An alteration in the flow rate may also alter the depth of the water in the river, preventing the wild rice from obtaining both sunlight and carbon dioxide. This would be equally damaging to the plant as a change in its substrate.

The rams horn snail lives in the San Marcos River as well as in the Comal River. While it has not become a problem in San Marcos, it has the potential to do so if it proliferates. If the flow velocities in the river decrease resulting in an increase in the snail population, the snail could destroy the vegetation in the San Marcos, including feeding on the wild rice.

Annual Flow Requirements

The U.S. Fish and Wildlife Service has estimated an annual average discharge requirement into the San Marcos river to be 100 cfs (2.7 m^3/s). This requirement assumes that the rams horn snail will not become a problem in the lake or the river. This assumes that any discharge in excess of 100 cfs will maintain similar habitats and habitat distributions to those currently in the river, and there will be no adverse effects to the river until the discharge drops below 100 cfs for a prolonged period of time.

If the average annual discharge fell to 75 cfs (2.14 m^3/s), altered hydrochemical parameters would begin to effect the system. Espey, Huston and Assoc. (1975) used a QUAL-I stream quality model developed by W.A. White of the Texas Water Development Board to model the effects of lowered spring discharge on the temperature of the San Marcos River. Their model was calibrated with river temperatures recorded in July, 1971, and 22.6 degrees C was taken as the background spring temperature. With a spring discharge of 75 cfs (2.14 m^3/s), the water temperature would rise to 26.8 degrees C, and this may be too high for the survival of the endangered species in the river, especially during summer. Other hydrochemical parameters would likely also shift as the percentage of water in the system from the Edwards aquifer becomes less and local recharge becomes proportionately more important. With reduced discharge into the springs from the aquifer, the amount of water in the system would become less, reducing both the depth of water and the water's flow velocity.

Under conditions of reduced spring discharge, the river would become more shallow, and some of the plants could become emerged. Many plant species, such as *Microphyllia, Sagittaria, Cabomba*, and *Vallisneria*, would probably adjust to the new water depth without dying out. The wild rice requires a certain depth for its optimum habitat. Consequently, it would suffer from a decline in spring flow. Some clusters of the wild rice would be stressed and some may die out. As a result, the rice would cover less area in the river. The lowering of flow velocities in the system would also hurt the wild rice. Most of the river is a run under normal flow conditions, and the water may slow to make it a slow run for most of its length. This would effect the swift flowing portion of the river channel, noticeably habitats #6, #8, #9, #11, and many more downstream in the river. Sand and mud would begin to accumulate to a greater degree in the areas where the substrate is currently poorly-sorted gravel and sand. This shift would further limit the area of optimum habitat for the wild rice.

The accumulation of fines would encourage the growth of plants that commonly grow in muddy substrates. These plants would expand into the newly formed, slow flowing areas of the river channel, possibly creating 100% plant cover. This would create increased competition for habitat area for the wild rice, and the rice would have its habitat further limited. The salamander would also suffer under these flow circumstances. It prefers gravel substrates and flowing water, and its habitat would become a slow run with a larger component of mud substrate. Its habitat could be completely destroyed by a loss of flow. The fountain darter, however, would probably benefit from the lower flow velocities. Its habitat area would increase, because it favors areas of low flow and dense vegetation. The increase in river temperature would negatively impact the darter, preventing the creation of optimum habitat. The darter may do well, but the other endangered species populations could begin to decrease.

If the average discharge dropped to 50 cfs (1.4 m^3/s) for a prolonged period of time, the river could become unsuitable for all of the endangered species. The plants in the San Marcos system, other than the wild rice, would grow and expand to cover most of the river channel. The hydrochemistry of the river would shift more, and seasonal trends would become more pronounced. Annual oxygen shifts would become larger with an increased amount of vegetation in the system. The river's flow velocity would slow, and chemical parameters, such as temperature, would be altered. According to Espey, Huston, and Assoc. (1975), the water would raise to 27.5 degree C, much higher than under normal flow conditions.

The only endangered species that would not have already suffered greatly under reduced discharges was the fountain darter, and the higher temperatures would effect its population.

The darter would be less likely to survive and to reproduce in the warmer river water (Espey, Huston, and Assoc., 1975). It is adapted to habitats having a constant temperature of approximately 23 degrees C, and it would probably begin to die out along with the remaining wild rice and salamanders. Habitats for both of these species were reduced under 75 cfs, and with the discharge at 50 cfs, their habitat devastation may become complete. The depth of the river will probably become too shallow for the wild rice to survive in, and the substrate will also be too muddy. The San Marcos gambusia, assuming that they are not already extinct, would also likely die out. Their habitat requirements include thermal consistency of water and sparse vegetation cover. This has been altered under the low flows. While Spring Lake would remain relatively unchanged, the river would become shallow with dense vegetation coverage and a predominantly mud substrate.

The San Marcos River is unique because of its combination of habitats, which is due in part to the flow velocities in the river. A drop in the amount of flow and, therefore, the flow rate in the channel is a serious threat to the river. A drop in flow rate would change the substrate in the channel and thus the habitats in the system. For this reason the flow velocity is critical to the maintenance of the present habitats. The plants in the San Marcos River each appear to prefer different substrates for growth. If the substrates change due to alterations in the river's flow velocity, the distribution of vegetation will change accordingly. The endangered species may not be able to survive in a new combination of habitat characteristics as well as they do with the present river channel. There is tolerance for some drop in flow rate as shown previously, but only to the point of accumulation of fines and raising of the water temperature.

Chapter 8:

Conclusions

This report identifies and defines, in detail, the hydrogeologic characteristics of the habitats in the Comal and San Marcos River systems. The habitats were defined and mapped, the identification of the most important habitats in terms of the endangered species living in the river systems has also been made.

A great threat to the habitats in the Comal and San Marcos Rivers is the potential diminution of flow by droughts and increased pumping of the Edwards aquifer. The likelihood of lowered spring flows due to pumping has increased dramatically in the past few decades. There are now "decade" level droughts in the Comal and San Marcos Rivers where the springs do not cease to flow completely, but the discharge is very low. An extended loss of flow in the rivers would have damaging effects on the ecosystems currently present. The substrate on the river beds would be redistributed under lower flows, and the lower flow velocities would cause the amount of fine substrates in the rivers would increase. Over a prolonged period of low flow, the morphology of the natural portions on the river channels may be altered. Their general shape could be changed due to increased sedimentation of point bars in the river under lower flows, altering the shape of the river bed. Because the plants grow preferentially in the fine substrates, an alteration could induce a change in both the plant species and the percentage of plant cover in the rivers. As a result, the area covered by the current habitats may shrink or it may disappear altogether, and new habitats with different characteristics would form.

Another effect of prolonged lowered flows would be an increase in the population of the rams horn snail on both rivers. The snail population is not yet a problem in the San Marcos River; in the Comal River it is controlled by periods of high flow velocity. The snails eat the stems and leaves of aquatic vegetation, and in this way they are able to virtually eliminate plants from areas of the lakes and rivers. By eliminating the vegetation component of the habitats, the snails can have a devastating effect on the rivers. In areas where plants help stabilize sediment and slow river flow, drastic alterations to the current system could occur.

There are also hydrochemical parameters in both the San Marcos and Comal Rivers that might change under lower flows. With less water flowing through the rivers and the water in the rivers remaining for a longer period of time, the temperature of the waters could be altered. In a climate such as that of Texas, the water in the systems would increase in temperature, especially during the summer months. As discussed in Chapter Seven, Espey, Huston and Assoc. (1975) modeled the effects that lowered spring flow would have on the San Marcos system. The same effects can be assumed to occur in the Comal system, because the two systems are similar. Using the QUAL-I stream quality model developed by the Texas Water Development Board, they found that under a discharge of 100 cfs (2.7 m^3/s), the temperature reached 26 degrees C; if the discharge dropped to 75 cfs (2.1 m^3/s), the temperature raised to 26.8 degrees C; under 50 cfs (1.4 m^3/s), the temperature reached 27.5 degrees C, and with 25 cfs (0.7 m^3/s), 29 degrees C was reached. The year-round nearly constant temperature of the rivers is one of their unique features. This may be important in their role as hosts to their endangered species.

Other parameters in the hydrochemical nature of the rivers would be altered under lowered spring flow discharge, because the percentage of water in the systems that originates from regional flow in the Edwards aquifer would be less. In Comal there is only a limited amount of local recharge following storms, but at San Marcos 30% of the normal flow is from local sources. Therefore, the impact that surface water input has to the rivers would be greater in the San Marcos River.

Hydrochemistry may begin to fluctuate more in response to storms in the Comal and, especially, the San Marcos watersheds. Seasonal trends in hydrochemical parameters could become more pronounced, effecting everything in the systems. The difference in winter and summer flows could become greater, causing larger seasonal variations in temperature. Other seasonal trends, such as oxygen and sulfate, would not be affected to a large degree.

With lowered spring flows, the potential damage of accidental pollution in the area becomes greater. There would be less water to help dilute any spills, and reduced river velocities would allow pollution to remain concentrated in the rivers for a longer period of time. While pollution is detrimental to the river systems under any flow conditions, its potential hazard increases as flow is reduced. It is because of the potential for dire consequences in the event of a loss of spring discharge that the species in the systems are endangered. With the exception of the San Marcos gambusia, the populations of the endangered species are not decreasing. It is the increasing potential for their habitats' alteration and possible destruction that causes the fountain darter, salamander, and wild rice to be endangered.

In 1991, the Sierra Club brought suit against the U.S. Fish and Wildlife Service contending that not enough was being done to safeguard the endangered species in the Comal and San Marcos Rivers from a loss of flow. As a result of this lawsuit, the state of Texas is now required to maintain the flow in the rivers at levels set by the Fish and Wildlife Service. The suggested discharge requirement on the San Marcos River is 100 cfs (2.7 m^3/s) yearly, and for the Comal River it is 200 cfs (5.7 m^3/s) yearly. This latter discharge requirement drops to 155.6 cfs (4.2 m^3/s) if the rams horn snail population can be controlled.

The implication of these minimum flow requirements is great in the city of San Antonio, because San Antonio is the largest user of the Edwards aquifer. There are numerous rural areas and farmers that also rely on wells in the Edwards, but the city of San Antonio makes up the largest proportion of the use. The amount of water pumped from the Edwards for municipal use in Bexar County (mainly San Antonio) in 1988 was 258,000 acre-feet (318.11 hm^3). In contrast, the pumpage for rural usage was only 44,600 acre-feet (54.99 hm^3) in 1988 (Krier and Smith, 1992). Municipalities used 85% of the total amount of water pumped from the Edwards in one year in one county. As a result of this, San Antonio is examining different courses of action that would maintain spring flow at Comal and San Marcos. San Antonio and the surrounding areas are experiencing rapid growth, and although limiting growth in the area would slow the pumping trend from the aquifer, it may not be considered a politically feasible option. The current plan for San Antonio in the event of a drought does not reduce pumping until the Edwards aquifer is at 625 feet above mean sea level, and Comal springs issue from orifices that are within a few feet of 623 feet above mean sea level (Maclay, 1992).

Currently, San Antonio is totally reliant on the Edwards aquifer for its water. It has been estimated in Krier and Smith (1992) that pumping from the Edwards aquifer must be reduced to 250,000 acre-feet per year to maintain spring flow at Comal Springs in the event of a large drought. Therefore an option for reducing pumping in San Antonio is to begin greater utilization of surface-water sources and possibly other aquifers. This would reduce pumping from the Edwards aquifer and the likelihood of a loss of spring discharge. The possibility of maintaining spring flow through artificial augmentation in times of low flows is a third alternative that the city of San Antonio, through the Edwards Underground Water District, is investigating.

When discharge from Comal and San Marcos springs lowers below the minimum flow requirements, augmentation of the water in the systems would provide a replacement for the lost Edwards waters. The habitat characterizations in this report are useful in the augmentation process for identifying the areas of each system that are the most important for maintenance of flow velocity and for those areas where augmentation would be of the most use. In the Comal system, augmentation of the flow would best be done in Landa Lake. Blieders Creek can be supplied by backing water into it from the lake, and both the old and new channels flow from the lake. By putting more water into Landa Lake in times of low flow, the majority of the system would be preserved.

In the San Marcos system, augmentation would be best carried out by adding to the water either in Spring Lake or in local recharge. Increased local recharge can augment the flow in the San Marcos River, which already has a significant local flow component. Spring Lake is the head of the channel and its flow supplies the channel. By putting more water into Spring Lake in times of low spring discharge, the system would maintain higher flow velocities.

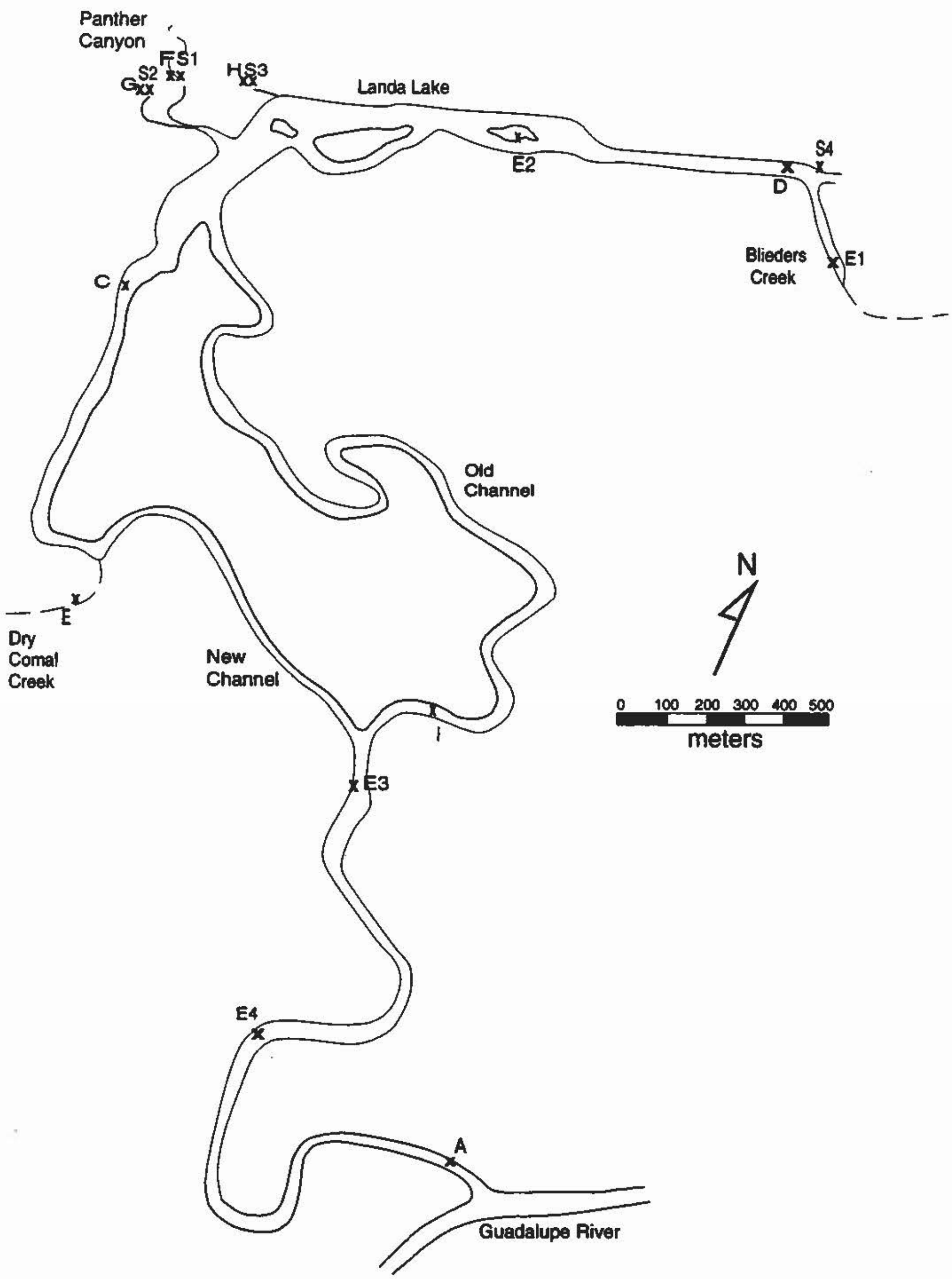
Based on the habitats defined for each of the species, maintenance of spring orifice flow does not appear to be necessary for the survival of the species in either the San Marcos or the Comal River. To provide water to the systems through the spring orifices would be the most natural way to augment, but it is not absolutely necessary. Provided that the hydrochemistry of the augmentation waters closely match the Edwards waters already in the systems, augmentation could be a viable solution to the spring flow problems. It would maintain the current river systems without any alteration to the habitats, and it could protect the rivers from minor droughts.

Appendix A:

The following tables list the hydrochemical data taken on the Comal River. Table A-1 is a complete list of the hydrochemical data that was collected during the field work on the river. Table A-2 lists the hydrochemical data taken from the existing literature on the Comal River. All of the data from both tables were summarized in Table 4, which was presented in Chapter 4. Figure A is a location map of the sites where data were collected along the Comal River.

TABLE A-1. Hydrochemical data from sampling on the Comal River.

Sampling Site	pH	Dissolved Oxygen (mg/l)	Temperature (C)	Specific Conductivity (umohs)
HC1	7.41	8.63	26.81	530
HC 2	7.22	5.30	24.87	549
HC 3	7.27	3.93	23.77	563
HC 4	7.29	4.28	24.03	560
HC 5	7.26	4.94	24.17	559
HC 6	7.38	5.69	24.21	560
HC 7	7.26	5.62	23.85	556
HC 8	7.31	6.11	24.10	557
HC 9	7.40	7.06	25.10	557
HC 10	7.36	6.42	23.70	556
HC 11	7.39	8.53	25.30	555
HC 12	7.69	7.29	25.35	543
HC 13	7.72	8.21	25.63	560
HC 14	7.85	8.83	25.73	555
HC 15	7.81	10.27	25.28	568
HC 16	8.29	8.94	26.40	563
HC 17	7.98	7.17	26.60	552
HC 18	7.19	7.38	24.83	545
HC 19	7.50	7.42	26.06	529
HC 20	7.49	7.37	23.68	547
HC 21	7.60	7.25	25.06	540
Maximum	8.29	10.27	26.81	568.00
Minimum	7.19	3.93	23.68	529.00
Range	1.10	6.34	3.13	39.00
Mean	7.50	6.79	24.96	552.48
Standard Dev.	0.29	1.64	0.99	10.38
Locations of sampling sites are shown in Figure 20				



Appendix A. Map of sites where sampling for hydrochemical data was performed on the Comal River system.

TABLE A-2. Hydrochemical data on the Comal River.

	Temp. (C)	D.O. (mg/l)	pH	Sp. Conductance (umohs/cm)	Alkalinity (mg/l)	Nitrate (mg/l)	Chloride (mg/l)	Phosphate (mg/l)	Fecal Coliform (#/ 100 ml)	Sulfate (mg/l)	Calcium (mg/l)
E1	24.5*	1.0*		485.0	226.0	1.5	15.0			25.0	75.0
E2	24.7*	2.5*		490.0	230.0	1.5	15.0			23.0	80.0
E3	24.8*	3.0*		490.0	226.0	1.5	15.0			27.0	78.0
E4	25.0*	6.0*		485.0	225.0	1.5	15.0			24.0	78.0
S1	23.4	5.3	7.1	485.0		1.3	23.3	0.09	2.0	18.0	
S2	23.4	4.5	7.2	490.0		1.1	22.6	0.12	32.0	17.4	
S3	23.3	4.8	7.1	490.0		1.4	21.9	0.09	2.0	18.5	
S4	23.8	5.1	7.1	490.0		1.2	24.6	0.10	0.0	19.1	
S5 *	23.1	5.2	7.2	499.0	234.0	1.6	16.9		0.8	14.0	
S6 *	23.2	4.8	7.2	496.0	234.0	1.6	16.7		5.6	13.6	
S7 *	23.2	4.9	7.2	499.0	234.0	1.6	16.9		6.7	13.7	
S8 *	23.4	4.6	7.2	497.0	231.0	1.5	18.0		2.6	14.8	
A	24.7	8.0	7.2	557.0	233.0	1.6	15.0	0.02	85.0	26.0	
B	24.6	8.1	7.2	558.0	230.0	1.6	15.0	0.02	50.0	26.0	
C	24.3	7.2	7.1	555.0	232.0	1.6	15.0	0.01	55.0	26.0	
D	24.8	5.9	7.0	557.0	229.0	1.6	16.0	0.02	10.0	26.0	
E	25.4	6.4	7.2	768.0	268.0	0.8	33.0	0.04	165.0	26.0	
F	23.8	5.7	7.2	553.0	229.0	1.6	16.3	0.10	0.0	26.0	
G	23.8	4.7	6.9	555.0	229.0	1.7	15.0	0.01		26.0	
H	23.9	5.5	6.8	554.0	234.0	1.8	15.0	0.01		27.0	
I	25.2	6.6	7.4	573.0	237.0	1.4	15.0	0.01	95.0	27.0	
M1											
M2											
E1, E2, . .	Espey, Huston, and Assoc., 1975: from June 6, 1974										
S1, S2, . .	Ogden, Spinelli, and Horton, 1985				* values reported are bottom measurements						
A, B, . . .	Ottmers, 1987										
S5-S8	Rothermel and Ogden, 1987: Mean values reported using the same sampling sites as Ogden et al, 1985										
M1,M2	McKinney and Sharp, 1994										

Magnesium (mg/l)	Bicarbonate as HCO3 (mg/l)	Total Hardness as CaCO3 (mg/l)	TDS (mg/l)	Nitrite (mg/l)	Ammonia (mg/l NH3)	Kjel-N (mg/l as N)	TOC (mg/l)	Sodium	Potassium (mg/l)	Silica
17.0	278.0		295.0							
15.0	279.0		298.0							
16.0	280.0		300.0							
16.0	278.0		298.0							
	230.0	264.0								
	190.0	252.0								
	188.0	260.0								
	196.0	244.0								
	234.0	261.0								
	234.0	257.0								
	234.0	256.0								
	231.0	257.0								
				0.01	0.02	0.2	1			
				0.01	0.02	0.1	1			
				0.01	0.02	0.2	1			
				0.01	0.02	0.1	1			
				0.01	0.02	0.3	2			
				0.01	0.02	0.1	1			
				0.01	0.02	0.1	1			
				0.01	0.02	0.1	1			
				0.01	0.03	0.2	1			
								15.0	1.9	12.0
								9.6	0.7	11.0

Appendix B:

Appendix B is a complete list of the hydrochemical data taken on the San Marcos River. For the San Marcos River, the hydrochemical data from the existing literature are presented. These data were summarized in Table 10, which was presented in Chapter 6. Figure B is the location map of the sites where data were collected on the river. Further hydrochemical data were not collected during field work on this river.

TABLE B. Hydrochemical data from the San Marcos River.

	Temp.	D. O.	pH	Sp. Conductance	Alkalinity	Nitrate	Chloride	Phosphate	Fecal Coliform	Sulfate
	(C)	(mg/l)		(umohs/cm)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(#/100 ml)	(mg/l)
E0	21.6	4.6	7.2	480.0		1.4	22.9	0.09	2.0	17.4
E1	21.5	4.3	7.2	430.0		1.3	21.8	0.09	0.0	20.2
E2	22.3	5.7	7.2	445.0		1.5	23.0	0.09	0.0	21.7
E4	21.5	3.8	7.2	468.0		1.5	24.5	0.12	6.0	19.1
E6	22.3	5.4	6.9	540.0		1.8	29.5	0.09	0.0	14.4
E7	21.5	4.1	7.1	485.0		1.2	22.1	0.10	36.0	17.4
E12	23.0		7.3	610.0		1.6	21.6	0.20	2500.0	13.6
E13	23.0		7.3	600.0		1.5	22.8	0.09	140.0	14.0
E14	21.5		7.5	410.0		1.3	21.0	0.09	4000.0	14.0
E19	21.5		7.6	425.0		1.8	21.0	0.09	220.0	15.8
E31	23.5		7.3	522.0		1.4	23.0	0.09	11000.0	16.9
E36	24.0		8.4	700.0		1.8	25.5	1.57	400.0	25.4
1		7.0		550.0	257.0	1.5	19.0	0.01		22.0
2		6.8		525.0	256.0	1.6	18.0	0.01		21.0
3	23.0	7.0		545.0	258.0	1.5	18.0	0.01		22.0
4	23.2	7.5		520.0	240.0	1.6	18.0	0.01		22.0
5	23.5	7.4		510.0	241.0	1.5	18.0	0.01		23.0
6	23.7	6.8		520.0	236.0	1.5	18.0	0.01		22.0
7	24.0	7.0		510.0	232.0	1.5	19.0	0.01		24.0
8	24.2	7.2		535.0	253.0	1.4	20.0	0.12		24.0
S1										
S2										
	1, 2, . . .	Espey, Huston, and Assoc., 1975: June 6, 1974 measurements								
	E0, E1, . .	Ogden, Spinelli, and Horton, 1985				vaules given are bottom measurements				
	S1,S2	McKinney and Sharp, 1994								

Calcium (mg/l)	Magnesium (mg/l)	Sodium (mg/l)	Bicarbonate as HCO3 (mg/l)	Total Hardness as CaCO3 (mg/l)	TDS (mg/l)	Sodium (mg/l)	TOC (mg/l)	Ammonia (mg/l as NH3)	Silica
			252.0	296.0					
			248.0	276.0					
			244.0	296.0					
			248.0	256.0					
				246.0					
			248.0	280.0					
				300.0					
				216.0					
				248.0					
				214.0					
				150.0					
				290.0					
88.0	17.0	10.0	314.0	290.0	327.0				
87.0	17.0	10.0	312.0	287.0	325.0				
88.0	17.0	10.0	315.0	290.0	327.0				
81.0	16.0	10.0	293.0	270.0	308.0				
82.0	17.0	10.0	294.0	274.0	311.0				
81.0	16.0	10.0	288.0	267.0	305.0				
78.0	17.0	10.0	283.0	265.0	303.0				
87.0	16.0	11.0	309.0	282.0	327.0				
						11.0	14.0	0.1	13.0
						10.0	1.0	0.1	9.0

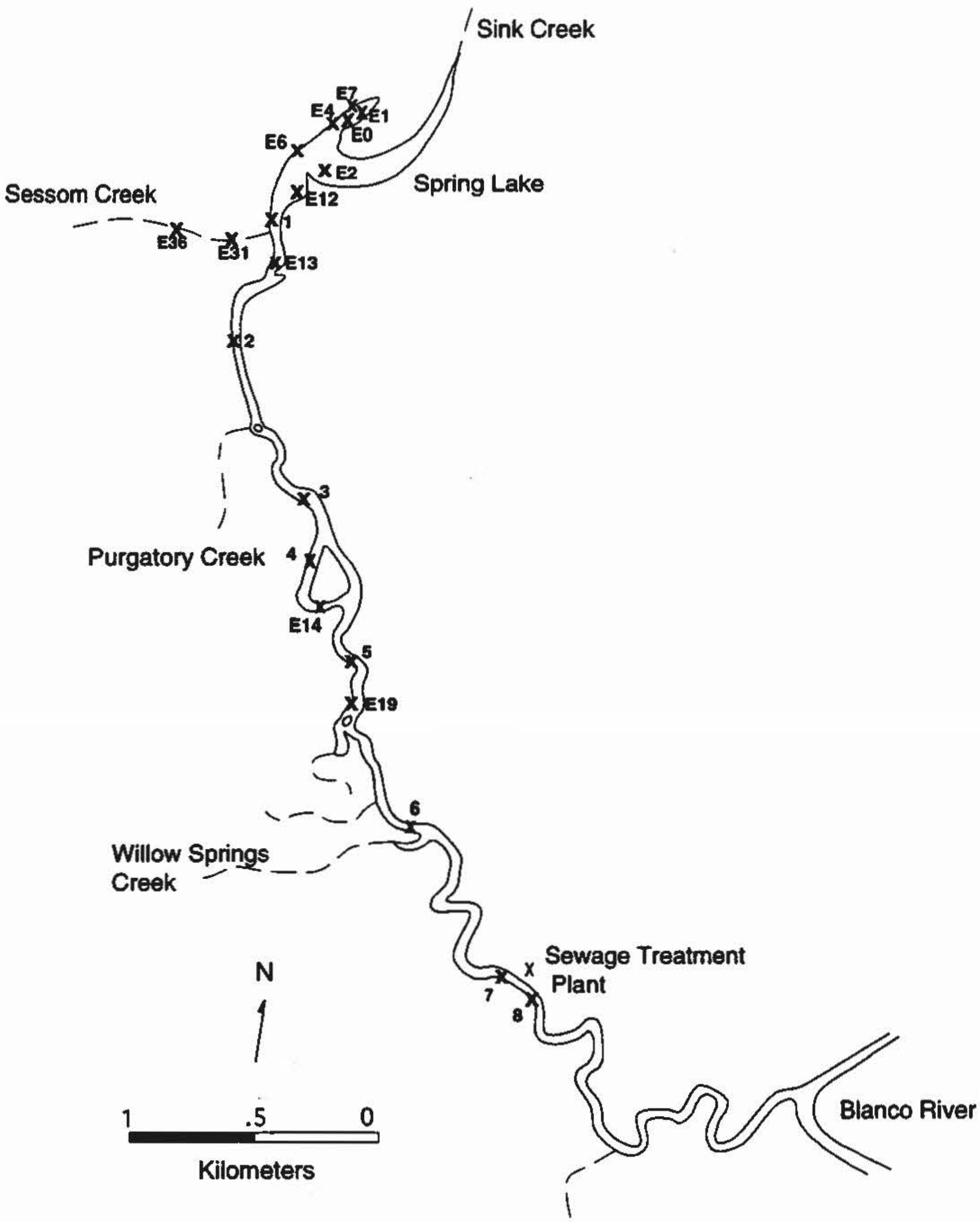


Figure B. A map of the sites on the San Marcos River where hydrochemical data were collected.

Bibliography

Abbott, Patrick L.,1975, On the hydrology of the Edwards limestone, south-central Texas: Journal of Hydrology, v. 24, p. 251-269.

Baker, E.T., Jr., Slade, R.M., Jr., Dorsey, M.E., and Ruiz, L.M., 1986, Geohydrology of the Edwards aquifer in the Austin area, Texas: Texas Water Development Board Report 293, 215 p.

Batte, Charles D., 1984, Soil Survey of Comal and Hays Counties, Texas: U. S. Department of Agriculture Report.

Brown, D. S., Petri, B. L., Nalley, G. M., 1992. Compilation of hydrologic data for the Edwards aquifer, San Antonio area, Texas, 1991, with 1934-1991 summary: Edwards Underground Water District Bulletin 51, 169 p.

Brune, Gunnar, 1981, Springs of Texas: Fort Worth, Gunnar Brune, pp. 129-131.

Buckner, H.D., Shelby, W.J., and Davidson, H.J., 1988, Water resources data, Texas: water year 1987: U.S. Geologic Survey Water-Data Report TX 87-3.

___________, 1989, Water resources data, Texas: water year 1988: U.S. Geologic Survey Water-Data Report TX 88-3.

_____________, 1992, Water resources data, Texas: water year 1991: U.S. Geologic Survey Water-Data Report TX 91-3.

Clement, T. J.,1989, Hydrochemical facies in the badwater zone of the Edwards aquifer, central Texas [Masters Thesis]: Austin, Texas, University of Texas, 102 p.

Deike, Ruth G., 1990, Dolomite dissolution rates and possible holocene dedolomitization of water-bearing units in the Edwards aquifer, south-central Texas - A summary, *in* E.S. Simpson and J.M. Sharp, Jr., eds., International Association of Hydrogeologists, Selected Papers from the 28th International Geological Congress: Heise, Hannover, v. 1, p. 67-82.

Espey, Huston, and Assoc., 1975, Investigation of flow requirements from Comal and San Marcos Springs to maintain associated aquatic ecosystems, Guadalupe River Basin: Texas Water Development Board Report.

Guyton, William F., and Assoc., 1979, Geohydrology of Comal, San Marcos, and Hueco Springs: Texas Department of Water Resources, Report 234, 85 p.

Hardy, Thomas, 1994, Unpublished field notes from January.

Hovorka, S.D., Ruppel, S.C., Dutton, A.R., and Yeh, Joseph, 1993, Edwards aquifer storage assessment, Kinney County to Hays County, Texas: University of Texas Bureau of Economic Geology Contract Report for the Edwards Underground Water District No. 93-04-F0, 101 p.

Klemt, W. B., Knowles, T. R., Elder, G. R., and Sieh, T. W.,1979, Ground-water resources and model applications for the Edwards (Balcones Fault zone) aquifer in the San Antonio region, Texas: Texas Department of Water Resources Report 239, 94 p.

Krier, Senator Cyndi Taylor, and Smith, Representative Terral, Co-chairs, 1992, Special committee on the Edwards aquifer. Committee report to the 72nd Legislature, Texas.

Linam, Gordon W., Mayes, Kevin B., and Saunders, Kenneth S., 1993, Habitat utilization and population size estimate of fountain darters, *Etheostoma fonticola*, in the Comal River, Texas: The Texas Journal of Science, v. 45, No. 4, p. 341-348.

Maclay, Robert W., 1992, Edwards aquifer in the San Antonio region; a very productive water distribution system needing a mangement strategy: South Texas Geological Society Bulletin, pp. 11-25.

Maclay, R.W., and Small, T. A., 1976, Progress report on geology of the Edwards aquifer, San Antonio area, Texas, and preliminary interpretation of borehole geophysical and laboratory data on carbonate rocks: U. S. Geologic Survey Open-file report 76-62, 65 p.

Maclay, R.W., and Small, T. A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio Area, Texas: Texas Water Development Board Report 296, 121 p.

Maclay, Robert W., 1989, Edwards aquifer in the San Antonio Region; its hydrogeology and management: Bulletin of the South Texas Geological Society, Vol. 4, 11 p.

McCoig, Gary M., Cradit Jon A., and Fox II, Lloyd, 1986, Property ownership, water rights, and recreational use of the San Marcos River: U.S. Fish and Wildlife Service, 62 p.

McKinney, Daene C., and Sharp, John M., Jr., 1993, Springflow augmentation of Comal Springs and San Marcos Springs, Texas Phase I: Feasibility study for the Texas Water Development Board, 27 p.

Oetting, Gregg, and Banner, Jay, 1994. Unpublished report.

Ogden, A. E., Spinelli, A. J., and Horton, J., 1985, Hydrologic and hydrochemical data for the Edwards aquifer in Hays and Comal Counties: Edwards Aquifer Research and Data Center R1-85, 102 p.

Ottmers, Donald D., 1987, Hydrology, field measurements, and water chemistry: Texas Water Commission IS 87-08, 36 p.

Pearson, F.J., Jr., 1973, The evalusation and application of C^{14} dating of groundwater: USGS Open-File Final Report. Army Research Office Proj. ARO-O No. 5830-EN.

Pearson, F. J., Jr., P. L. Rettman and T. A. Wyerman, 1975, Environmental tritium in the Edwards aquifer, central Texas, 1963-71: U.S. Geological Survey open-file report 74-362, 36 p.

Poole, J.M., 1992, Conservation of the upper San Marcos River ecosystem: performance report prepared under Section 6 of Endangered Species Act: Texas Parks and Wildlife Department, 6 p.

Puente, Celso, 1975, Relation of precipitation to annual ground-water recharge in the Edwards aquifer, San Antonio Area, Texas: USGS Open-File Report 75-298, 31 p.

Puente, Celso, 1976, Statistical analysis of water-level, springflow, and streamflow data for the Edwards aquifer in south-central Texas: Edwards Underground Water District Bulletin, 58 p.

Reeves, R. D., and Ozuna, G. B., 1986, Compilation of hydrologic data for the Edwards aquifer, San Antonio area, Texas for 1983-84, with 1934-84 summary: Edwards Underground Water District Bulletin, p. 43-44.

Rose, P. R., 1972, Edwards Group, surface and subsurface, central Texas: University of Texas Bureau of Economic Geology Report of Investigations 74

Rose, Peter R., 1974, Edwards Group, surface and subsurface, central Texas: University of Texas Bureau of Economic Geology Report of Investigations No. 74, 198 p.

Rothermel, Samuel R., and Ogden, Albert E., 1987, Hydrochemical investigation of the Comal and Hueco Spring systems, Comal County, Texas: Edwards Aquifer Research and Data Center R1- 87, 182 p.

Selley, R., 1982, An introduction to sedimentology, 2nd edition: New York, Academic Press, Inc., 415 p.

Sharp, J.M., Jr., 1990, Stratigraphic, geomorphic and structural controls of the Edwards aquifer, Texas, U.S.A.: *in* E.S. Simpson and J.M. Sharp, Jr., eds., International Association of Hydrogeologists, Selected Papers from the 28th International Geological Congress: Heise, Hannover, v. 1, p. 67-82.

Small, T. A., 1986, Hydrologic sections of the Edwards aquifer and its confining units in the San Antonio area, Texas: U.S. Geological Survey Water Resources Investigations Report 85-4259, 52 p.

Taras, Michael J., Greenburg, Arnold E., Hoak, R.D., and Rand, M.C., eds., 1971, Standard methods for the examination of water and wastewater, 13th edition: Washington, D.C., American Public Health Association.

Texas Water Resources, 1993, Legislature agrees on compromise to manage Edwards aquifer. Vol. 19, No. 3, *in* Vauter, Brian, and Yelderman, Joe C., Jr.,eds., The hydrogeology of the Balcones fault zone Edwards aquifer: San Antonio region. Assoc. of Engineering Geologists Annual Meeting guidebook. 87 p.

Thompson, G. M., and J. M. Hayes, 1979, Trichlorofluoromethane in groundwater - a possible tracer and indicator of groundwater age: Water Resources Research, Vol. 15, No. 3, 8 p.

Vauter, Brian, and Yelderman, Joe C., Jr., 1993, The hydrogeology of the Balcones fault zone Edwards aquifer: San Antonio region: Assoc. of Engineering Geologists Annual Meeting guidebook, 87 p.

Woodruff, C. M., and Abbott, P. L., 1979, Drainage-basin evolution and aquifer development in a karstic limestone terrain, South-Central Texas, U.S.A.: Earth Surface Processes, Vol. 4, No. 4, p. 319-334.

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