

EVALUATION OF AUGMENTATION METHODOLOGIES IN SUPPORT OF IN-SITU REFUGIA AT COMAL AND SAN MARCOS SPRINGS, TEXAS



Prepared for the
Edwards Aquifer Authority



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Prepared by



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A. INTRODUCTION

In the summer of 1956, Comal Springs and Landa Lake stopped flowing. Between June and August 1956, lake levels in Landa Lake declined 6 feet. The flow rate at San Marcos Springs decreased to 46 cfs. In 1966, 1971, 1984, 1989, and 1990 additional dry periods occurred such that some of the springs at Comal Springs went dry or had the potential to go dry. In 1991 the Sierra Club filed suit against the U.S. Fish and Wildlife Service arguing that the habitat of endangered species at the springs was threatened. In 1993, the U.S. Fish and Wildlife Service (USFWS) defined the take and jeopardy discharge values for both springs as a result of a February 1, 1993 Judgment (amended on May 26, 1993) in the case of *Sierra Club vs. Secretary of the Interior* (No. MO-91-CA-069, U.S. Dist. Ct., W.D. Texas). The court ordered the USFWS to make certain determinations relative to minimum spring flows and aquifer levels necessary for the endangered and threatened species associated with the Edwards Aquifer. The purpose of these determinations was to provide guidance to Federal agencies and pumpers from the aquifer to assist them in taking appropriate actions to ensure their activities do not take or jeopardize listed species or result in adverse modification or destruction of critical habitat. The spring flows and aquifer levels were to be based on best available information and the USFWS's best professional judgment (USFWS 1996). Since then the Edwards Aquifer Authority (Authority) and its predecessor agency, the Edwards Underground Water District, have been working toward developing strategies to maintain flow during drought conditions. The original research on spring augmentation focused on the concept that large volumes of water could be imported to the two springs to meet the USFWS's flow requirements. The work was conducted by the University of Texas, Center for Research in Water Resources (CRWR) in 1995. The basic concept, at that time, was that large volumes of water (200 cfs) would need to be imported to meet the take and jeopardy levels set by USFWS. Several of the strategies were determined to be very expensive (1 billion dollars or more, even in 1990's dollars). A summary of these strategies and their estimated costs (in mid 1990 dollars) is provided below.

The CRWR study (McKinney and Sharp, 1995) of the feasibility of springflow augmentation evaluated the following options for enhancing springflow at Comal and San Marcos Springs: injection wells, infiltration galleries, regionally-enhanced surface recharge, locally-enhanced recharge, direct addition of water to the springs, and aquifer baffles. The source of the

augmentation water in this study was generally considered to come from a production wellfield in western Bexar County.

To implement an injection well strategy, the study assumed that augmentation water could be obtained from Edwards Aquifer production wells in western Bexar County, and would be imported and injected by a series of injection wells near the springs. Surface water was also a consideration for injection, though it was noted that Edwards-source water would offer better compatibility from a water chemistry perspective. The study notes constraints of lower head levels during periods of droughts and uncertainty associated with achieving safe yield, some uncertainty surrounding the environmental effects of constructing the injection wells, the need to acquire easements for the construction of a pipeline, a complex permitting environment, and that a direct addition strategy is preferable. The total initial capital cost for this option, providing a total of 300 cfs, is approximately \$200,000,000. Annual maintenance and operations costs are estimated at approximately \$14,600,000.

The infiltration gallery option described a means of localized delivery of external source water, which allowed the water to infiltrate slowly into the subsurface above the spring lakes at Comal Springs and San Marcos Springs. This option recommended sourcing the water from the Edwards (western Bexar County), the construction of a pipeline to Comal Springs, and the construction of a smaller pipeline to San Marcos Springs. The study noted the constraints of unknown hydrogeological efficiency of the galleries, construction impacts to the environment, and a complex permitting environment. Costs for this option were not estimated, though the essential costs for developing production wells and delivering to the spring sites are the same as the injection well strategy.

Recharge enhancement was considered by the CRWR on both a regional scale and a local scale. As the report noted, the potential yield of these projects was nominal in comparison to the needed augmentation volumes, and thus is discussed primarily as a supplemental means of augmenting flow and generally keeping head levels in the aquifer higher. Cost estimates for these projects were not available to the CRWR, though some estimates of cost were prepared by HDR, Inc. and were prepared as part of the Region L Water Plan.

The direct addition alternative evaluated by the CRWR proposes the construction of a discharge manifold system to supply regulated and site-specific flow to the orifices. The study assumed

the same source of this water, including the same means of delivery from western Bexar County to the inlet of the manifold system. The study noted the constraints of certain environmental effects to the spring ecosystem. The majority of cost associated with this project lay in the development of source water and delivery to the manifold system. The manifold system itself was estimated to cost approximately \$645,000 and an additional \$1,100 per discharge point.

The final strategy explored by the CRWR study was the construction of aquifer baffles. The purpose of these structures was to isolate the spring systems from the regional flow of the aquifer, thereby making them theoretically more drought tolerant. The strategy was envisioned in connection with the production and delivery scenario assumed in the previous alternatives. The report noted the considerable unknown constraint of impact to the subsurface physical and biological conditions at the spring sites. The cost of this alternative was estimated at \$234,000,000 and approximately \$14,000,000 on an annual basis (excluding the interest costs). The report noted that this option “should be viewed as a measure of last resort” in the event that no other alternative is available.

Since the 1995 study, several important changes have occurred with regard to the management of the aquifer. The primary change has been that the Edwards Aquifer Authority was created and has become a functional agency with the authority to regulate groundwater pumpage to minimize the future impact of droughts. A groundwater management program was developed that would reduce the frequency and duration of severe drought, though not completely eliminating the potential for low flow conditions at the springs. The Authority's drought management plan requires groundwater pumpers to reduce pumpage by certain percentages as water levels decline and hit threshold elevations at designated index wells or specified threshold spring flows at Comal Springs and San Marcos Springs. In addition, substantially more information has been gathered since the USFWS proposed the take and jeopardy values for each species and some would argue that those levels are unnecessarily conservative. We now have a much better understanding of the detailed hydrogeology and hydrology of the springs, the locations of the most critical habitats within the spring complexes, and the flow rates needed to sustain the species. The issues of what constitutes minimum required flows needs to be reevaluated.

The objective of this study was to investigate updated options that would complement the objectives of the regional pumpage reduction programs. In essence, the results of this project would maintain viable habitat long enough for the rains to return. To accomplish this goal augmentation strategies would need to be "custom designed" for each spring. This required a more detailed evaluation of:

- The hydrogeology of the Comal Springs and San Marcos Springs areas, including a better understanding of how the springs and associated lakes changed under different flow regimes
- The distribution of the endangered species in the springs and lakes
- The different strategies that either added water to the springs to help prevent rapid decreases of flow over time or focused the available flow to the most critical areas so as to maintain suitable conditions.

This document addresses three areas:

1. The hydrogeology and hydrology of Comal and San Marcos Springs,
2. The location of the highest quality habitat in the spring complexes, and,
3. The use of additional waters to supplement the natural flows at the springs.

This report does not offer a single final answer, but does prioritize recommendations as to how the Authority might proceed toward a possible solution.

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B. HYDROGEOLOGY of the Eastern Edwards Aquifer

Groundwater in the eastern part of the Edwards aquifer (Comal and Hays Counties) flows from the southwest to the northeast in a series of fault blocks associated with the Balcones Fault Zone. The fault blocks to the east are buried to great depths and flow is under confined conditions. The fault blocks to the northwest are at land surface and may receive local recharge and therefore may be under unconfined conditions.

Groundwater discharges from these fault blocks as springs. The first spring complex, going from west to east, is Comal Springs and is located along the Comal Springs Fault. Previous researchers have considered these springs to be artesian, that is, groundwater is rising from depth in the fault block and discharges at the surface because of artesian pressure. As water levels in the aquifer rise and fall, spring flow closely tracks the local and regional water levels. Most of the spring flow comes from the regional groundwater, presumably extending all the way to Uvalde County. Only part of the groundwater flow in this part of the aquifer discharges at Comal Springs, the rest passes beneath Comal Springs and flows onto San Marcos Springs.

San Marcos Springs is the next set of springs to the east. They differ from Comal Springs in several ways. San Marcos Springs flow rates usually are less than those of Comal Springs because most of the regional flow is considered to be discharged at Comal Springs. San Marcos Springs receives water from the up-thrown block west of the San Marcos Springs Fault. In this up-thrown fault block, the Edwards is exposed at land surface and therefore the aquifer is in the recharge zone and unconfined. San Marcos Springs are also at the end of this part of the Edwards groundwater flow-system. To the north, groundwater in the Edwards flows from north to south toward San Marcos Springs. All the groundwater in this part of the aquifer has to discharge at San Marcos. There is no underflow beneath San Marcos Springs flowing on to some undetermined point of discharge as has been postulated for Comal Springs.

Comal Springs stopped flowing and San Marcos Springs flow declined to 46 cfs during the summer of 1956, which is considered the drought of record for the region. The purpose of this study and report was to evaluate if there were strategies that could be employed, primarily at the local level, to maximize flow at these two springs during drought periods such that the low-flow and no-flow conditions would not occur again. To develop appropriate strategies for these springs, it is important to understand as much as possible about how the springs work. That is, to

understand the plumbing, where the water goes in and where it comes out, and to determine whether there are any cross connections.

The following sections describe the detailed geology and hydrogeology of both Comal and San Marcos Springs to provide a basis for evaluating augmentation options. Specific work for both Comal and San Marcos Springs conducted for this study included:

- Review local geologic interpretation at Comal and San Marcos Springs to see if there was new information, particularly geophysical logs, to update older interpretations.
- Construct and evaluate potentiometric surface as to how groundwater flow may be controlled by regional structures.
- Identify major producers in the immediate area of both springs.
- Review how the springs work.
- Locate springs orifices.
- Develop the history of spring flow during periods of drought.

B.1 HYDROGEOLOGY AND HYDROLOGY OF COMAL SPRINGS

B.1.1 Geologic Setting

The geologic formations occurring within the study area are comprised of rocks of Cretaceous (about 100 million years old) and Quaternary (less than one million years old) age. The strata in the vicinity of Comal Springs has developed from the accumulation of thick sequences of marine sediments deposited during Cretaceous times. Major tectonic uplifting of the Edwards Plateau occurred along the Balcones Fault Zone (BFZ) during Miocene times, which resulted in accelerated erosion and similar exposures and topography of present day. A relatively thin veneer (25 - 40 feet) of Quaternary age alluvial deposits lies above the Cretaceous erosional surface down-dip of the Comal Springs Fault. The boundary between the Edwards Plateau and Gulf Coastal Plain physiographic provinces (Carr, 1967) occurs within the study area along the trace of the Comal Springs Fault. The BFZ is comprised mostly of normal “down-to-the-coast” faults with some down-to-the-northwest faults occurring in the immediate vicinity down-dip of the Balcones Escarpment. The Comal Springs occur at multiple orifices along the Comal Springs Fault.

B.1.2 Stratigraphy

The stratigraphy of the Edwards Aquifer and its confining units was determined in this investigation by the analysis of surface geology, borehole geophysical logs, and drillers' logs from wells constructed in the vicinity of Comal Springs. This investigation identified more than 100 borehole geophysical logs from wells in the region. The majority of logs were generated by the oil and gas industry and contributed greatly to the understanding of the regional stratigraphic model. Wells constructed by the Edwards Underground Water District (EUWD) in an investigation to refine the location of the Edwards Aquifer freshwater/ saline-water interface (“bad water line”) (Poteet and others, 1992) have been used to in determine both the hydrostratigraphy of the aquifer and the variations in the quality of water within the study area. A cross-section of the Comal Springs area is shown in Plate 1.

The geological formations that comprise the Edwards Aquifer in the vicinity of Comal Springs are approximately 500 feet in total thickness. These formations include the Georgetown Formation, Person Formation, and Kainer Formation. These formations have been subdivided into eight hydrogeologic units (Units I through VIII) by Maclay and Small (1976). The

stratigraphic, lithologic, and hydrologic characteristics of the rocks in the Comal Springs area are summarized in Table B-1. The Edwards Aquifer is bounded below by the Glen Rose Formation (upper member) and above by the Del Rio Clay. Only the formations occurring within the Edwards Aquifer are described in detail for the purposes of this report.

The Edwards Group ranges from 440 - 530 feet thick and is comprised of the Kainer and Person Formations. The Kainer Formation is approximately 310 feet thick in the vicinity of Comal Springs. The lithology of the Kainer Formation ranges from mudstone to miliolid grainstone to crystalline limestone. The Kainer is subdivided into four informal members that include (from bottom up) basal nodular member, dolomitic member, Kirschberg evaporite member, and grainstone member. The basal nodular member (Unit VIII) is a tan to brown, marly, nodular limestone of about 50 – 60 feet in thickness. This is the lowermost unit of the Edwards Group and effectively functions as the lower confining unit for the Edwards Aquifer in the study area. Analysis of borehole geophysical data indicates that the water quality within the basal nodular member is slightly to moderately saline in the areas down dip of the Comal Springs Fault.

The dolomitic member (Unit VII) is a dense, crystalline limestone with interbedded grainstone and burrowed mudstone. The dolomitic member is approximately 120 feet thick and easily identified on the combined display of the neutron and density porosity logs by numerous “crossovers” between the plots. Analysis of borehole geophysical data indicates that the water quality within the dolomitic member is slightly to moderately saline in the vicinity of Comal Springs.

The Kirschberg evaporite member (Unit VI) overlies the dolomitic member and is about 60 feet in thickness. This hydrogeologic unit consists of crystalline limestone interbedded with mudstone containing chert lenses. Collapse features are common. The resulting secondary porosity makes this the most prolific of the aquifer units within the Kainer Formation.

The grainstone member (Unit V) overlies the Kirschberg evaporite as the uppermost unit of the Kainer Formation. The grainstone member is approximately 60 feet in thickness. It is composed of thick sequences of dense, tightly-cemented, *miliolid* grainstone. Primary matrix porosity as measured on geophysical logs is some of the lowest in the Edwards Aquifer. Secondary fracture porosity accounts for the bulk of effective porosity in this aquifer unit.

System	Hydrogeologic subdivision		Group, formation, or member			Hydrologic function	Thickness	Lithology	Water-bearing properties
Quaternary	Local aquifers		Quaternary Aluvium, Quaternary Terrece Deposits and Leona Formation, undifferentiated.			AQ	25-40	Fine calcareous silt, sand, interbedded with calcareous gravel grading down into coarse chert gravel and clay.	Yields small to large quantities of fresh to slightly saline water, locally
Upper Cretaceous	Upper confining unit		Navarro and Taylor Groups, undivided			CU	600	Blue-gray compact shaly clay and clayey marl	Yields small quantities of slightly saline to moderately saline water. Relatively impermeable.
			Austin Group			AQ	225-350	Massive, chalky to marly, fossiliferous mudstone and chalk, grading downward into interbedded limestone and shale	Yields small to moderate quantities of fresh to slightly saline water in upper part.
			Eagle Ford Group			CU	30-50	Dark gray to brown, flaggy, sandy shale and argillaceous limestone	Yields very small to small quantities of slightly to moderately saline water
			Buda Limestone			AQ	40-50	Buff to light grey, dense mudstone, hard, massive.	Yields small to moderate quantities of fresh to slightly-saline water
			Del Rio Clay			CU	40-50	Blue-green to yellow-brown fossiliferous clay	Not known to yield water
Lower Cretaceous	I	Edwards Aquifer	Georgetown Formation			CU	25-30	Gray to light tan marly limestone	Yields small quantities of fresh to moderately-saline water in study area.
	II		Person Formation	Cyclic and marine members, undivided	AQ	70-75	Mudstone to packstone; <i>miliolid</i> grainstone	Yields moderate to large quantities of fresh to moderately-saline water in study area.	
	III			Leached and collapsed members, undivided	AQ	60-65	Crystalline limestone; <i>miliolid</i> grainstone; chert	Yields moderate to large quantities of fresh to moderately-saline water in study area.	
	IV			Regional dense member	CU	20-24	Dense, argillaceous mudstone	Not known to yield water;	
	V		Kainer Formation	Grainstone member	AQ	50-60	<i>Miliolid</i> grainstone; mudstone to wackestone, chert.	Yields moderate to large quantities of fresh to moderately-saline water in study area.	
	VI			Kirschberg evaporite member	AQ	50-60	Highly altered crystalline limestone; chalky mudstone; chert	Yields moderate to large quantities of fresh to moderately-saline water in study area.	
	VII			Dolomitic member	AQ	110-120	Mudstone to grainstone; crystalline limestone; chert	Yields moderate to large quantities of slightly-saline to moderately saline water in study area	
	VIII	Basal Nodular member		CU	50-60	Shaly, nodular limestone; crystalline limestone; chert	Yields small quantities of water slightly-saline to moderately-saline water in study area		
	Lower confining unit		Upper member of the Glen Rose Formation			CU	350-500	Yellowish tan, thinly bedded limestone and marl.	Yields small quantities of slightly-saline to moderately-saline water in study area.

Table B-1. Table showing a summary of the lithologic and hydrologic properties of the hydrogeologic subdivisions of the Edwards Aquifer and upper/ lower confining units in the vicinity of the Comal Springs and San Marcos Springs, Comal and Hays Counties, Texas

[Hydrogeologic subdivisions, groups, formations, members, thickness, lithology, and water-bearing properties modified from Small and Hanson (1994), Hanson and Small (1995), BEG (1979), BEG (1982), DeCook (1960), and George (1952)]

The Person Formation of Rose (1972) is about 160 feet thick in the vicinity of Comal Springs. The composition of the Person Formation ranges from crystalline limestone to grainstone to mudstone and is comprised of three informal hydrogeologic units: the regional dense member; the leached and collapsed members, undivided; and the cyclic and marine members, undivided.

The lowest hydrogeologic unit within the Person Formation is the regional dense member (RDM) (Unit IV). This unit effectively functions as a confining unit between the upper and lower portions of the Edwards Aquifer (except in areas where extensive fracturing and faulting facilitate vertical flowpaths). The RDM is approximately 20 feet thick. The RDM is composed of a dense argillaceous mudstone and is easily identified in outcrop and on a variety of geophysical porosity logs. The nature of this unit makes it a distinctive horizon that can be easily mapped throughout the region.

Overlying the RDM is the leached and collapsed members, undivided (Unit III). This sequence of interbedded mudstone and grainstone intervals has formed a highly transmissive aquifer unit. The nature of this unit results from groundwater leaching of primary evaporites. The resulting voids weaken the rock matrix to the point that extensive collapse breccias form.

The cyclic and marine members, undivided (Rose, 1972) (Unit II) is the uppermost unit of the Edwards Group. This sequence is composed of mudstone to fossiliferous packstone and is approximately 75 feet thick.

The uppermost unit of the Edwards Aquifer is the Georgetown Formation (Unit I). This marly limestone is approximately 30 feet thick in the area of Comal Springs and is readily identified by the presence of the fossil brachiopod *Waconella wacoensis*. The Georgetown is identified in geophysical logs in the area but is rarely seen in outcrop with thin, very weathered exposures. In the subsurface, the Georgetown is effectively a confining unit and yields little water from wells. It is a readily mapped horizon in areas where the lower Del Rio Clay is exposed.

B.1.3 Comal Springs Surface Geology

In the Comal Springs area, the local surface geology on the up-thrown block of the Comal Springs Fault is generally described by an exposure of Person Formation (Units II and III). Unit I has been completely eroded away in the near vicinity but is visible in a small exposure about 1.5 miles to the west in a road cut on Loop 337. Unit IV may be just below the surface in the deepest portions of Panther Canyon. On the down-thrown side of the Comal Springs Fault, the

geologic substrate is comprised of the Navarro Group overlain by various alluvial deposits of Leona Formation gravel and clay; and Quaternary-age terrace to recent alluvium in a veneer of varying thickness of approximately 25-40 feet. The thickest areas of this veneer are in the vicinity of Landa Lake and the Comal River.

B.1.4 Regional Structure

The study area occurs at the physiographic boundary between the Gulf Coastal Plain and the Edwards Plateau provinces. The boundary between these two areas is generally the Balcones Fault Zone (BFZ). The BFZ is comprised of numerous, generally parallel, normal faults. Some of these faults have displacements greater than 1,000 feet. The majority of the faults are down to the southeast toward the Gulf of Mexico. Some faults, particularly those in the immediate front of the BFZ, are down to the northwest. The BFZ delineates the front of the Edwards Plateau that uplifted thick sequences of Cretaceous sediments during Miocene times.

Locally, BFZ faults have resulted in a net displacement of as much as 750 feet across the Comal Springs Fault in the vicinity of Comal Springs. In the study area, a number of monitor wells have been constructed during several investigations by the U.S. Geological Survey and the Edwards Underground Water District (now Edwards Aquifer Authority). These wells are shown in the cross-section on Plate 1. Additionally, the San Antonio City Public Service Board constructed several wells in the 1950s in an effort to provide a cooling water supply for the Comal Electrical Power Generating Station (EPGS) located nearby. All of these wells were logged with various borehole geophysical methods and have provided a wealth of information on local structure/stratigraphy. This investigation identified as many as nine significant faults (including the Comal Springs Fault) between wells 68-23-316 and 68-23-616. The cross-section in Plate 1 uses nine wells in the Comal Springs area to identify significant structure. Of particular interest is that the net throw of the down-thrown block down-dip of Comal Springs is down-to-the-coast, but within that block there are seven faults of lesser displacement that are up-to-the-coast. The effect is that a graben has formed in the front of the Comal Springs Fault comprised of several en-echelon faults. It is possible that this fault configuration exerts significant control on groundwater flowpaths, hydrostratigraphy, and water quality in the area. A previous examination of borehole video logs from the monitoring wells in the Comal Springs transect indicates that there are perhaps hundreds of small displacement faults distributed across the area. The use of geophysical logs only captures the magnitude of the more significant faults.

B.1.5 Assessment of Edwards Aquifer Water Quality from Geophysical Logs

The assessment of the site hydrogeology focused upon an examination of borehole geophysical logs both at the regional and local level. The regional examination of these data was intended to develop a stratigraphic conceptual model appropriate to each major spring site at Comal Springs and San Marcos Springs. At the local level, the examination of borehole geophysical logs identified significant geologic structures occurring within and between wells, differentiated the informal members of the Edwards Aquifer, and identified variations in the total dissolved solids (TDS) content of groundwater.

In respect to the examination of aquifer water quality, the methods of Schultz, (1992, 1993, and 1994) were used to assess total dissolved solids (TDS) content of groundwater. In the Comal Springs area, it was particularly helpful to have relatively large amounts of measured water quality data both from total well discharge and from discrete sampling at selected depths. This measured data provided a “calibration” to electrical resistivity and formation porosity measurements taken from the geophysical logs. Thus, the assessment of aquifer water quality could estimate TDS to an accuracy of +/- 5%. In general, the cross-section of Comal Springs in Plate I indicates the presence of groundwater having a TDS content either greater or less than 1,000 mg/L TDS content (that value being the defining criteria between fresh water and slightly saline water).

Horizontal and vertical changes in groundwater quality in different zones in the wells at the Comal Springs area were determined by analyzing a combination of data collected during the investigation by Poteet and others (1992) and geophysical log interpretation using the methods described in Schultz (1992, 1993, and 1994). These field water quality data included field Specific Conductance (S.C.) measurements and laboratory TDS measurements taken on samples collected at discrete depths from wells in that investigation. More specifically, the quality of groundwater within the aquifer matrix (as determined on borehole geophysical logs) was determined by comparing the calculated Specific Conductance value to measured S.C. and TDS values determined from actual field samples and applying the derived algorithm to other zones of interest. Thus, a reasonably accurate estimation of TDS was derived using this procedure. The technique to estimate groundwater TDS content requires an understanding of groundwater resistivity and total porosity within the aquifer matrix.

Utilizing the equations:

$$R_{wa} = R_t/F \quad (1)$$

where

R_{wa} = apparent electrical resistivity of formation water (in Ohm-Meters);

F = the formation factor (computed from porosity sensitive logs or estimated from porosity values from nearby wells) (dimensionless); and

R_t = total electrical resistivity of the formation beyond the invaded zone (in Ohm-Meters)

and

$$F = 1/\phi^m \quad (2)$$

where

ϕ = porosity (the fraction of the total volume occupied by pores and voids) (in percent);
and

m = cementation factor (a cementation factor of 2 is a common value for Edwards Group carbonates) (dimensionless).

Combining equations (1) and (2) gives

$$R_{wa} = R_t \phi^2 \quad (3)$$

where R_t is obtained from the most appropriate deep investigation resistivity curve available on the log being analyzed.

Specific Conductance at 25 °C (C_a) (in microSiemens per centimeter) is derived from R_{wa} by the equation:

$$C_a = 10,000 / R_{wa} \quad (4)$$

where R_{wa} is in Ohm-Meters at 25 °C (77 °F)

R_{wa} measurements are taken at formation temperature. The measurements need to be corrected to 25 °C (77 °F) by the Arps formula (Schlumberger (1969) and Jorgensen (1989)).

$$R_{wa}(77^\circ\text{F}) = R_{wa} ((\text{BHT} + 7) / 84) \quad (5)$$

where BHT is the formation temperature at the depth of measurement. Formation temperatures in the study area have been estimated by adding the mean annual surface temperature and a value of 1.5 °F per hundred feet of depth (Woodruff (1985)). A mean annual surface temperature (within the study area) of 68°F is assumed (Carr, 1967). C_a was compared to measured TDS samples from the investigation by Poteet and others (1992) to establish an empirical relationship. This dimensionless value (in the range of 0.55 to 0.67) is applied as a coefficient to C_a values to determine estimated TDS. Schultz (1992) determined that the correlation between measured and calculated TDS values agreed +/- 5% using this method.

Greater detail on actual calculations made in determining TDS content in the Comal Springs Transect can be found in Poteet and others (1992) and Schultz (1993). Additionally, a sample calculation for determining TDS content of formation waters can be found in Schultz (1993), page 41 and Schultz (1992) page 21.

The colored shading in the cross-section of Comal Springs in Plate 1 indicates the presence of groundwater having a TDS content either greater or less than 1,000 mg/L (that value being the defining criteria between fresh water and slightly brackish water).

All of the wells on the down-thrown side of Comal Springs demonstrated the presence of “bad” water in the lower half to one-third of the Edwards Group. Note that the “bad water line” is not a

sharp defining boundary, but has been interpreted to be a stratified boundary with inter-fingering fresh and saline waters (as shown in the cross-section). It is interesting to note that Unit IV (regional dense member) is not an absolute or particularly strong control on changes in water quality within the aquifer. It likely affects vertical transmissivity, but functions as a vertical boundary between fresh and slightly saline water in only one of the fault blocks near the front of Comal Springs.

Water quality within selected units of the upper confining unit above the Edwards were also examined. Borehole geophysical logs (performed in the open borehole before casing installation) indicate that fresh Edwards Aquifer groundwater may move upward along the Comal Springs Fault and associated faults and infiltrate the more permeable overlying formations (Austin Group and Buda Limestone). The resistivity curves of selected wells located down-dip from the Comal Springs Fault (to the east) show this freshening effect becomes less prominent: farther from the fault.

- 68-23-304 (Comal Plant #3 and closest to the Comal Springs Fault) - The high resistivity values in the Austin Chalk and the Buda Limestone suggest that these formations are charged with waters with TDS values near 250 mg/L.
- 68-23-602 (Comal Plant #2-intermediate distance) - The resistivity in the Austin Chalk is approximately 20% of the resistivity of the same interval in Comal Plant #3, which indicates that the TDS value is about 5 times as high (1,250 mg/L). In the same well, the Buda Limestone is approximately 20% as resistive indicating that the TDS value of groundwater in the Buda Limestone is in the range of 1,250 mg/L to 1,300 mg/L.
- 68-23-6-- (Comal Plant #1-farthest to the east) - The resistivity in the Austin Chalk in this well is about 35 ohm-m compared to a resistivity of 360 ohm-m in Comal Plant #3 indicating that the TDS value in the Austin Chalk in Comal Plant #1 is approximately 2,600 mg/L TDS. Additionally, the resistivity in the Buda Limestone is 13% of the value of the same interval in Comal Plant #3 which indicates that the TDS content of groundwater in the Buda Limestone in Comal Plant #1 is approximately 1,900 mg/L.

B.1.6 Summary

B.1.6.1 Geologic Setting of Comal Springs

- The Comal Springs Fault is the major structural feature in the area with 750 ft of displacement.
- On the down-thrown side the entire section of Edwards is present. On the up-thrown side, only Edwards Units II - IV are present.
- The down-thrown block may be a small graben which has focused groundwater flow in the down-thrown side.
- The thickness of the freshwater section decreases to the east.
- Fresh water is observed as shallow as the Austin Group and Buda Limestone near the Comal Springs Fault.

B.1.7 General Potentiometric Maps for Comal Springs Region, January 2002

A potentiometric surface map was constructed for the time period of January 2002 to describe the general movement of groundwater in the Edwards in the Comal Springs area. This map was integrated with the USGS geologic map of this area to indicate where fault control may impact groundwater movement and the general direction of groundwater flow. This map helps indicate the sources of flow at Comal Springs, and the degree to which Comal Springs may be considered as a separate hydrologic system from San Marcos Springs. A potentiometric surface map of this area for the January 1951 time period was previously prepared by George et al (1952).

The Edwards Aquifer Authority collects three times per year synoptic water level data for the Edwards Aquifer from the western extent of the Authority's jurisdiction in Uvalde County to its eastern extent in Hays County. Data points in Comal County have been used to generate a general potentiometric surface map for the Comal Springs area for January 2002 (Plate 2). These data are collected from wells which are unused or infrequently pumped to minimize the effect of drawdown in the water level measurements. The potentiometric contours on this map overlay the hydrogeologic subdivisions of the Edwards Aquifer (USGS, 1994). As can be seen on this map, the area is heavily faulted. The faults strike in a northeast-southwest direction. The principal faults in the area are the Comal Springs Fault, the Hueco Springs Fault, and the Bat

Cave Fault. At least two of these faults, the Comal Springs Fault and Hueco Springs Fault, appear to exert some control over groundwater flow.

B.1.8 Comal Springs Fault

Groundwater in the Edwards on the up-thrown block of the Comal Springs Fault principally flows to the east. Estimated potentiometric surface contours for January 2002 are presented in Plate 2. The gradient steepens into a potentiometric trough beginning approximately 10 miles west of Landa Lake, indicating groundwater discharge at Comal Springs. To the northeast of Comal Springs, the contours indicate flow towards San Marcos. Groundwater in the up-thrown block, therefore, continues beneath the Guadalupe River and toward the San Marcos area.

The potentiometric surface in the down-thrown block of the Comal Springs Fault (confined section) initially at the Bexar-Comal County line is at a slightly lower elevation than heads in the unconfined section. However, in the New Braunfels area, heads in down-thrown block are more than ten feet higher than heads in wells immediately across the fault. The Comal Springs Fault in the New Braunfels area appears to exert important structural control preventing the movement of water from the down-thrown block to the up-thrown block.

The degree to which the fault acts as a barrier to flow southwest of New Braunfels is less clear. The similarity of water levels in the up-thrown and down-thrown blocks four miles southwest of New Braunfels (as measured in wells 68-23-504 and 68-23-502, respectively, for several time periods) suggests that there may be flow between the fault blocks. There are few water level data available for the Edwards on the down-thrown block of the Comal Springs Fault. The number of residential and observation wells in the down-thrown block has likely been restricted by the depth and expense of construction. The resolution of potentiometric contours developed from these data are similarly limited. Additional water level data are needed in this area to better define the potentiometric surface in the down-thrown block and also be able to better understand whether and where the Comal Springs Fault may be acting as an impermeable barrier.

New Braunfels Utilities (NBU) currently produces from the Edwards from several wells on the up-thrown and down-thrown blocks, but these have not been used as part of the monitoring well network. Because these wells are not pumped regularly in the winter, wells NBU4, NBU5, and NBU6 might be included in the network of wells being used for the synoptic water level program to add more data in this area. NBU5 is located on the down-thrown block and NBU4 is located

on the up-thrown block. NBU6 is located very near the fault, but the driller's log is consistent with up-thrown block geology. Comparative water level measurements would likely reveal whether NBU6 is completed in the up-thrown or down-thrown blocks. By adding these wells to the Authority water level measurement network the hydrologic nature of the Comal Springs fault in the New Braunfels area could be better defined.

Down-gradient (northeast) from Comal Springs, no fresh water wells are completed in the down-thrown block of the Edwards Aquifer. Well 68-16-602 is located in the down-thrown block but contains saline water. This lack of any fresh water wells may indicate that no fresh water flows past Comal Springs in the down-thrown block. That is, Comal Springs may be the end of fresh water flow in the down-thrown block. The installation of additional monitoring wells should be considered to better understand these flow paths. A monitoring well downgradient of Comal Springs in the downthrown block would be very beneficial.

B.1.9 Hueco Springs Fault

The Hueco Springs Fault may be another important fault controlling flow in the Edwards. Water level measurements from the up-thrown block of the Hueco Springs Fault indicate a predominately eastward flow in the Edwards toward San Marcos Springs. Water levels in this fault block are characteristically higher than in the fault block between the Hueco Springs Fault and the Comal Springs Fault (Plate 2). January 2002 water levels on the down-thrown block of Hueco Springs Fault are significantly lower than those on the up-thrown block, suggesting fault control. Water levels in wells 68-15-912, 68-15-903, and 68-15-907, which are on the down-thrown block near Hueco Springs, are 639 ft, 639 ft, and 639 ft respectively. The water levels in these wells are consistently lower than the elevation of the Hueco Springs orifices (652 ft and 658 ft for the west and east orifices, respectively), indicating that spring discharge is from the up-thrown block and the fault is acting as a hydrologic barrier. Similar observations on a more limited data set also led to this inference by earlier investigators (Guyton and Associates, 1958).

Synoptic water level data for the Edwards in the up-thrown block of the Hueco Springs Fault are sparse, and some of these data may not actually reflect Edwards water levels in this area. Two wells reported to be completed in the Edwards (68-23-104 and 68-15-807) are deeper than would normally be expected for the known thickness of the Edwards on the portions of the outcrop over

which these wells are constructed. These wells may be partially completed in the Upper Glen Rose and may reflect Glen Rose water levels.

B.1.10 Location and Amount of Groundwater Produced in Area Around Springs

Local groundwater withdrawal has obvious implications for management strategies. Local pumpage reduces discharge at Comal Springs and may become a significant percentage of spring discharge during droughts.

The Edwards Aquifer is the principal source for groundwater in the Comal Springs area. The Edwards is exposed at land surface over much of the up-thrown block of the Comal Springs Fault, whereas on the down-thrown side the Edwards is not encountered until approximately 650 ft below land surface. Water wells with good production are present on both sides of the fault block, but depths to the Edwards have clearly limited the number of private wells on the down-thrown block.

Most public supply wells are located on the down-thrown block of the Comal Springs Fault in New Braunfels, and these are operated by NBU. NBU Well 5 is completed in the Edwards in the extremely productive fault zone. The depth and aqueous chemistry of NBU Wells 2 and 3 suggests a source in the Quaternary alluvium but it is assumed the source of the water is originally from the Edwards. NBU Well 4 and possibly NBU Well 6 are completed on the up-thrown block. These wells typically produce 2,000 to 4,000 gpm each. Total capacity for the NBU wells is about 13,000 gpm. In 2002 NBU wells produced a total of 2,600 ac-ft, for an average flow of 3.59 cfs. NBU pumpage averages about 10 cfs in the summer months. NBU has an Edwards Aquifer water right for 7,271 ac-ft/yr (or an average flow of 10.0 cfs) (Appendix 7).

Public water supply wells on the up-thrown block have historically been constructed and operated by NBU, the City of Garden Ridge, the City of Marion, the Balcones Woods development, the Hunter Oaks development, Country Hills Water Supply, and the City of Seguin. There are several residential, farm, and small community wells in the Edwards on the up-thrown block. The Preiss Heights area northwest of New Braunfels has several small residential wells drilled into the Edwards.

A small number of wells in the immediate vicinity of Hueco Springs all produce from the down-thrown block of the Hueco Springs Fault. Wells on the up-thrown block of the Hueco Springs Fault typically intercept the lower section of the Edwards, and some appear to draw from both the Edwards and the Glen Rose Formation.

B.1.11 Hydrogeologic Conditions at Comal Springs

The Edwards Aquifer Authority maintains two monitoring wells, the LCRA well (state well 68-23-304, also known as Comal Plant #3) and the Landa Park well (state well 68-23-302) in the northwest corner of Landa Park. The location of the two wells is indicated in Plate 2. The LCRA well is located on the down-thrown block of the Comal Springs Fault just west of Fredericksburg Rd. This well has a steel surface casing to 650 ft, above an open-hole completion to a total depth of 965 ft. The Landa Park well is located on the up-thrown block in Panther Canyon just west of Landa Park Dr., with an open-hole completion to a total depth of 320 ft. The two wells are separated by a horizontal distance of approximately 900 ft. Water level data from these wells are available on a daily basis as well as on a fifteen-minute basis.

Daily water level measurements for the Landa Park well relative to the LCRA well for the 1984-1992 interval and the 1999-2002 interval are plotted on Figure B-1. The 1984-1992 water levels are hand measurements collected by Oliver Haas and Bill Tepe of NBU. The 1999-2002 water levels are based on pressure transducer data maintained by the Authority. These measurements demonstrate a linear relationship, with approximately three feet of water rise in the LCRA well for every foot of water rise in Landa Park well. The head difference between the two wells increases such that at a Landa Park well water level elevation of 628 ft, the water level of the LCRA well is 643 ft, for a head difference of 15 ft. Below a Landa Park level of 622 ft, the relative water levels appear to trend more closely such that at a Landa Park well water level would approach the LCRA water level. At a Landa Park well water level of 619 ft., the LCRA water level would be expected to be about 620 ft. A time series plot of these data (Figure B-2) illustrates a similar but more pronounced water level fluctuations in the LCRA well relative to the Landa Park well.

The LCRA well consistently maintains a significantly higher water level elevation relative to the Landa Park well over a very short lateral distance between the two wells (Figure B-1). This head difference increases with rising water levels. This suggests that the Comal Springs Fault (in the

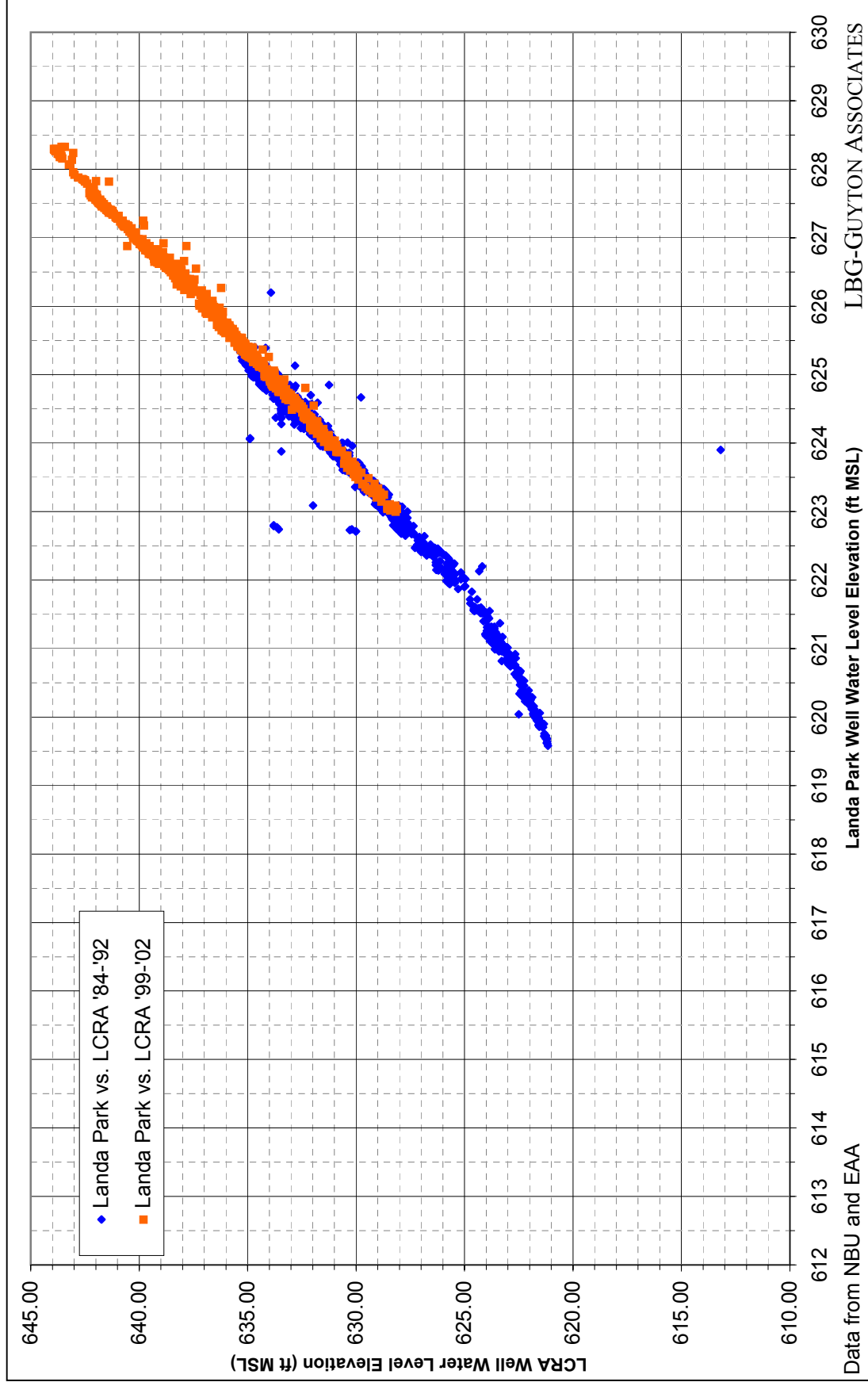


FIGURE B-1 LANDA PARK WELL VS. LCRA WELL WATER LEVELS

Data from NBU and EAA

LBG-GUYTON ASSOCIATES

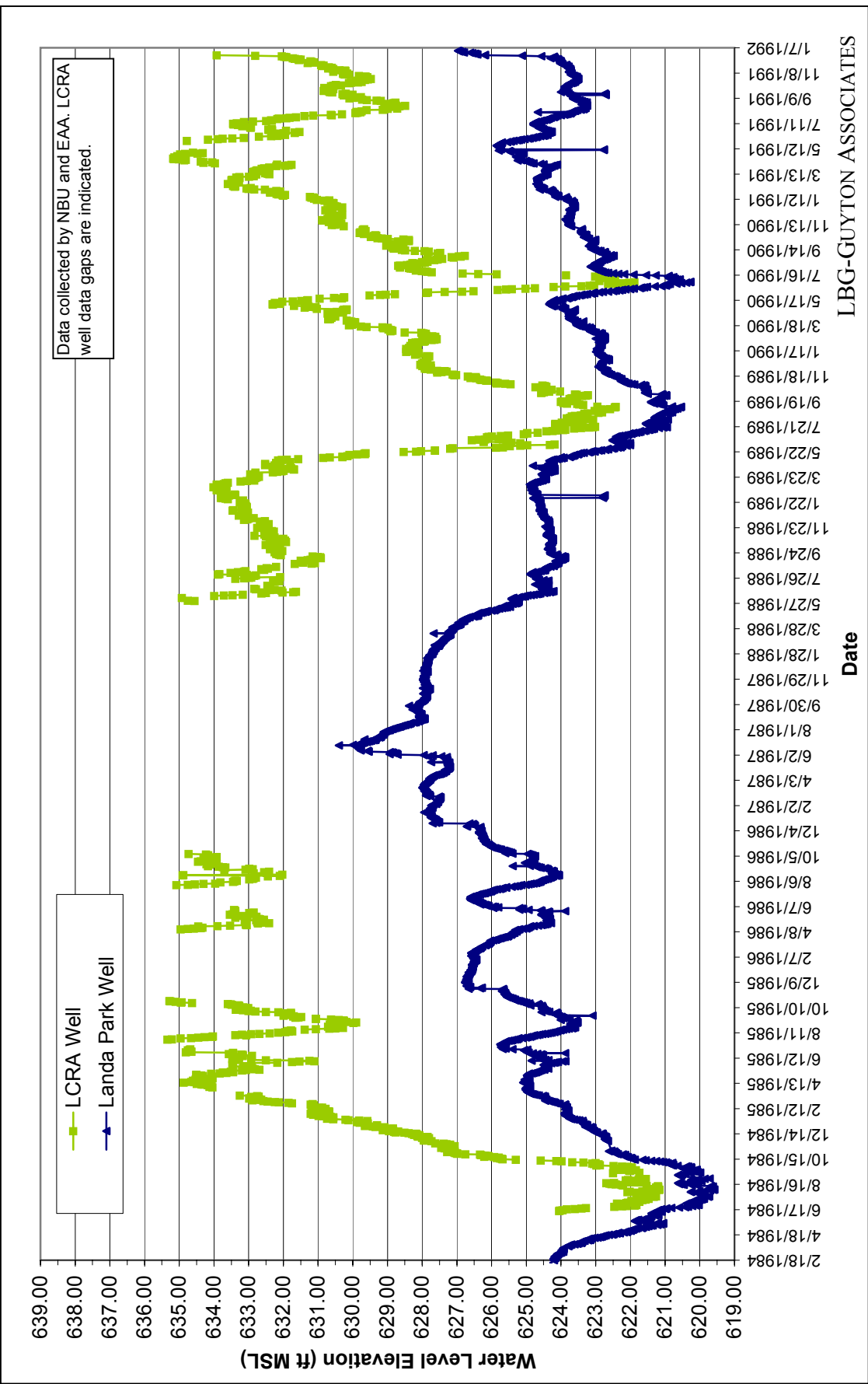


FIGURE B-2 TIME SERIES PLOT 1984-1991 FOR THE LCRA AND LANDA PARK WELLS

Comal Springs area) exercises significant control over groundwater flow between the up-thrown and down-thrown fault blocks, i.e., groundwater flow in the up-thrown block is separate from groundwater flow in the down-thrown block.

B.1.11.1 15-minute Measurements

Continuous water level data for the LCRA well indicate rapid fluctuations of 0.2 to 0.4 ft on the 15-minute monitoring interval. Figure B-3 illustrates these fluctuations in the LCRA well for the period of May 31 - June 6, 2003. NBU has reviewed operational data for the public supply wells in the area and has confirmed that their wells pump over short (i.g., 20-30 minutes) but frequent cycles. Short-term pumping cycles of high capacity NBU Well 5 in the down-thrown block are considered the most likely cause of these short-term water level fluctuations in the LCRA well. These short-term variations also indicate a confined aquifer response. NBU 5 can produce up to 4200 gpm and is approximately 1,000 ft from the LCRA well.

In contrast, rapid water level fluctuations are not seen in the continuous 15-minute data for the Landa Park well in the up-thrown block (Figure B-3). Water level changes are smaller and do not correlate with the NBU pumping cycles. The daily trends are also much smoother. The Landa Park well water level data indicate that the up-thrown block is under unconfined conditions and is not hydrologically connected to the down-thrown block.

The 15-minute water level data from the Landa Park well also indicate that the up-thrown block can be recharged. The Landa Park well water level data exhibit short-term rapid rises after heavy rains. Figure B-4 illustrates a recharge event as compared to total daily precipitation for New Braunfels during the period of May 31 - June 6, 2003. Note that the Landa Park well level appears little affected by the precipitation of June 2 - 5, 2003. There is a dramatic response to the more intense precipitation on June 6, however. This suggests storms that probably produce runoff in Panther Canyon cause this response in the Landa Park well. Water levels rose and fell rapidly after the storm event of June 6, 2003. The new water level after the event was about 0.2 ft higher than the previous water level. The rapid increase of water levels indicates local recharge from flow down Panther Canyon. The overall higher water levels following this event may indicate a small amount of regional recharge. NBU personnel report that Panther Canyon often flows after intense storms, but rapidly infiltrates before it reaches Landa Lake.

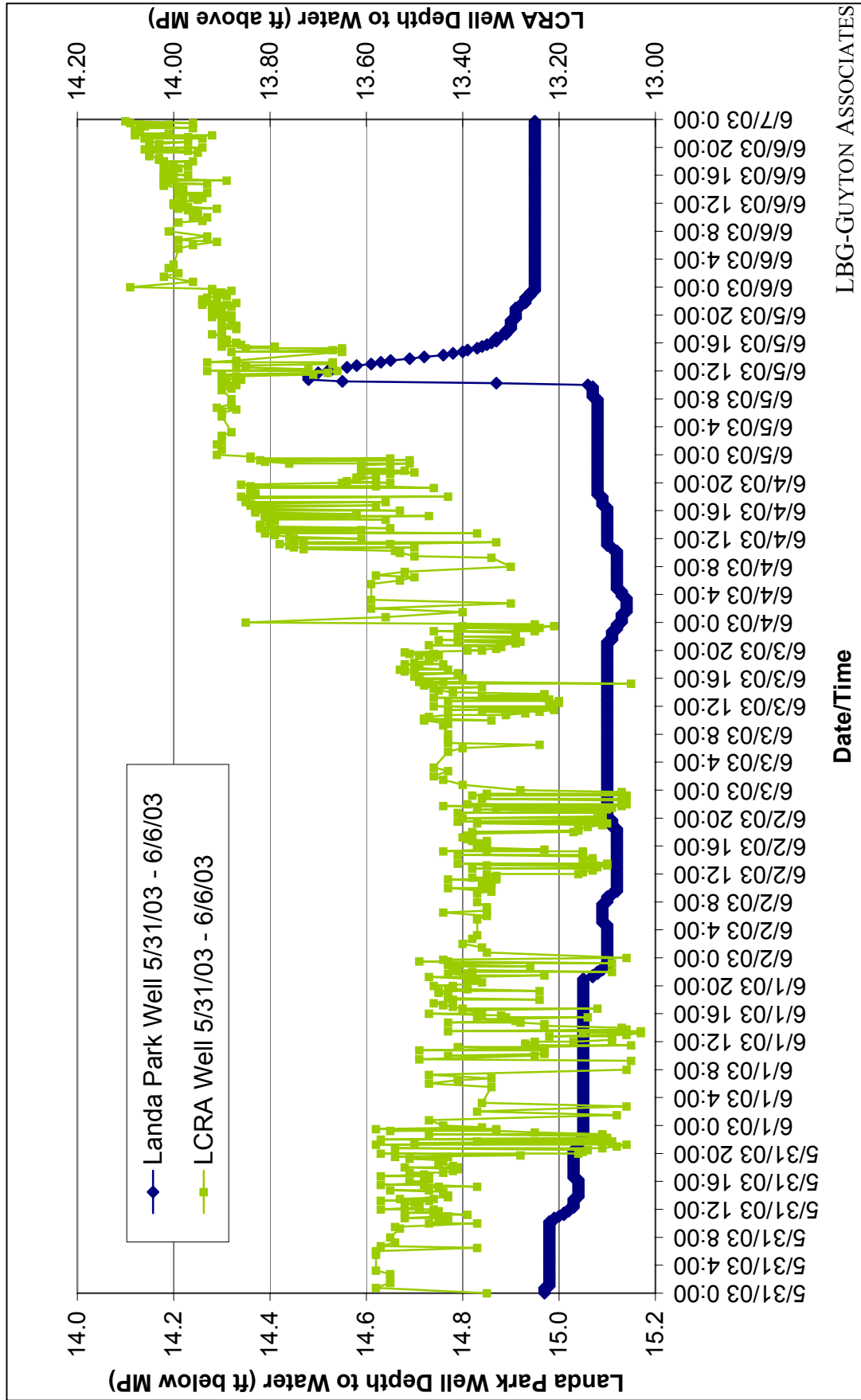


FIGURE B-3 COMPARISON OF LCRA WELL AND LANDA PARK WELL WATER LEVELS

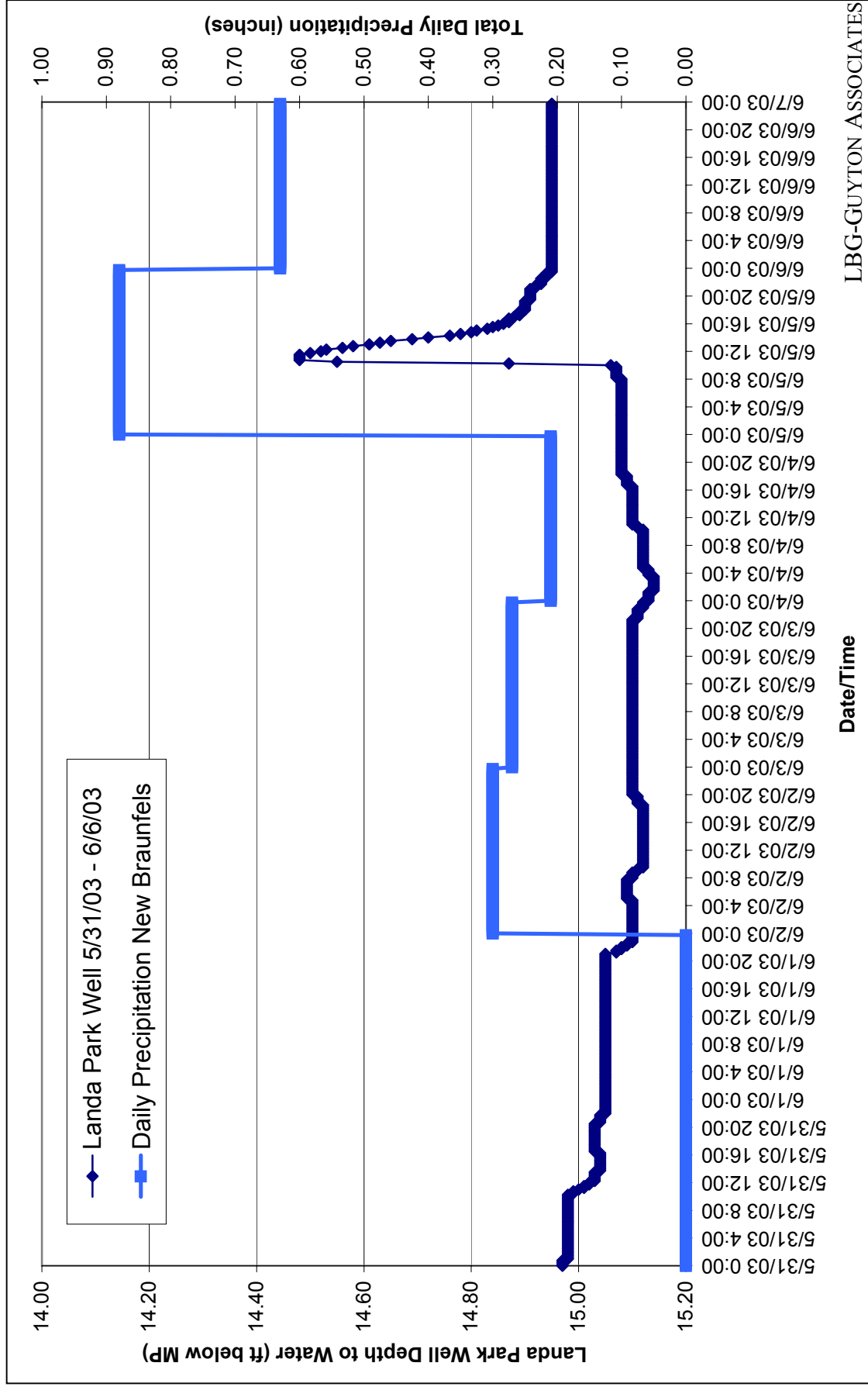


FIGURE B-4 INFLUENCE OF LOCAL STORM EVENTS ON LANDA PARK WELL WATER LEVELS

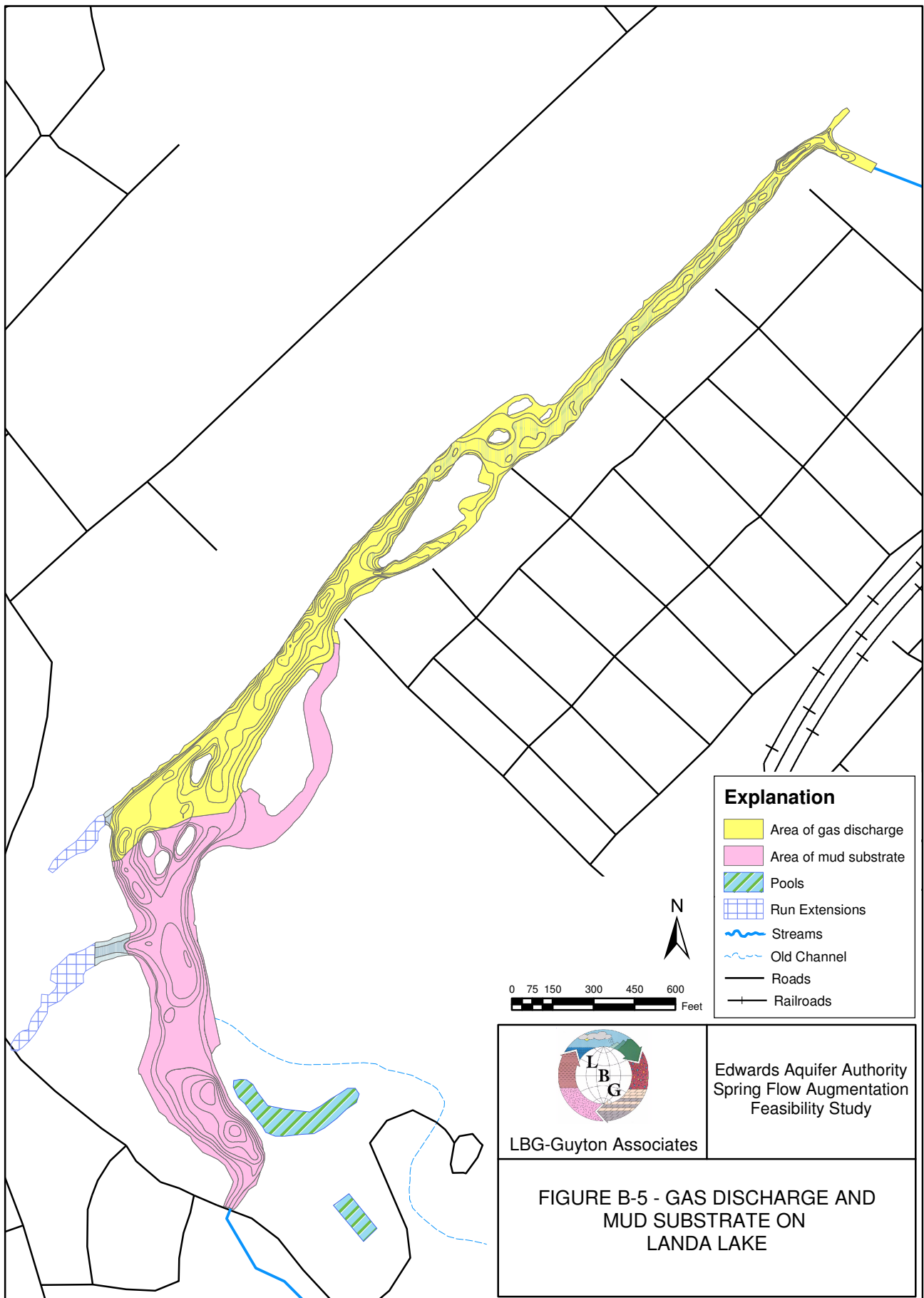
B.1.12 Location, Spring Locations (Bathymetric Map), Photographs

The springs which comprise Comal Springs issue from various points along the Comal Springs Fault in northwest New Braunfels. The individual springs discharge from two groups of springs that are considered to represent two separate flow systems. The first is a group of three springs southwest of Landa Lake, often referred to as Springs #1, #2, and #3. The second is a larger group of springs around the lake, in the lake and on Spring Island. This second group includes Spring #7, Spring Island, Saltation Springs, Spring #5, Spring A, and Spring B (Plate 3). (Plate 3 is a bathymetric map of Landa Lake. The methodology used for constructing the Landa lake bathymetric map and the Spring Lake bathymetric map is explained in Appendix 2.) Spring discharge at Comal Springs has historically been considered to be from the easily accessible orifices, which generally (in the historical newspaper articles) are considered to be Main Spring (Spring #1), the spring in Panther Canyon (referred to as Spring #2), and the springs along Spring Run #3. Brune recognized additional springs in *Springs of Texas* (1981). His additional springs were identified as Spring #7, the spring on Spring Island, Spring #5 (Nolte Apartments), Spring A, and Spring B.

A recent investigation by LBG-Guyton Associates indicates there is a significant amount of discharge from the lake bottom itself primarily along Comal Springs Fault, and these areas are included in this second group of springs. Descriptions of individual springs and locations are given in Table B-2 and Plate 3, and areas of indicated lake-bottom discharge are given in Figure B-5.

Table B-2. Spring Descriptions, Comal Springs Complex

Spring Name	Description
Spring #1	Spring #1, or Main Spring, is the spring most people are familiar with. It is composed of three orifices from which discharge flows down the long channel and under Landa Park Rd. This spring is the first spring to go dry when water levels in the aquifer decline.
Spring #2	Spring #2, or Panther Canyon Spring discharges in Panther Canyon just below the Landa Park Rd. bridge. The spring flows down the channel to the wading pool. Several bubble streams come off the bottom of the channel, indicating spring discharge is occurring in the channel as well as from the “headwaters” just below the bridge.
Spring #3	Groundwater discharges all along the west bank of this channel from the stone wall on the south end to the gazebo at the lake. Based on the presence of gas bubble trains coming off the bottom of the channel, groundwater is discharging along the bottom as well as the west wall. There are additional springs along the west bank going north towards Spring #7.
Spring #7	Spring #7 is a major spring on the western bank of Landa Lake north of Spring #3. It discharges from a cave opening with dimensions of about one foot by one foot.
Spring Island	The spring on Spring Island flows into two channels, one flowing north and the other flowing east. It has an elevation slightly higher than Landa Lake. There is gas bubble discharge all around the island with the highest rate of bubbling on the north and northeast sides.
Saltation Springs	Saltation Springs was a sampling point approximately 200 ft north of Spring Island. Groundwater was discharging from the lake bottom. Sand grains could be seen saltating (dancing) at several locations.
Spring #5	Spring #5 is a constructed spring on the east side of Landa Lake in the Nolte apartment complex. The elevation of the spring is approximately half a foot above the elevation of the lake.
Springs A & B	Spring A and Spring B are located at the north end of Landa Lake where Blieders Creek enters the lake. A small channel which drains both springs A and B discharges at this location. In addition a slightly larger channel extends toward the NBU equipment yard. Groundwater discharges into the small channel as evidenced by the presence of gas bubbles.



B.1.13 Lake Bottom Discharge of Groundwater

There appears to be extensive discharge of groundwater into the lake bottom. This spring discharge is evidenced by small sand boils (geysers), saltation of sand grains, and areas where extensive clouds of gas bubbles can emanate from the lake bottom.

Gas bubbles emanating from the bottom are considered evidence of groundwater discharge. The gas bubbles occur because the discharging groundwater is over-saturated with dissolved atmospheric gas. As Edwards groundwater rises from greater depths in the aquifer and discharges into the lake or individual springs, it depressurizes because of the decreasing hydrostatic head as it approaches land surface. As the water rises these gases come out of solution forming bubbles and bubble trains (Figure B-6). Gas bubbles are common in Springs #1, #2, #3, #7, and Spring Island Spring. When bottom sediments in the springs and in the lake are agitated, clouds of gas bubbles often emanate. These gas bubble observations were made under high spring flow conditions. Whether they are appropriate under low flow conditions is not known.

There are two different types of gases occurring within the lake: 1) the visible gas bubbles emanating from the lake bottom sediments and springs, and 2) the gases dissolved in the discharging groundwater. These two different types of gases were collected and analyzed for their compositions (Appendix 5). The composition of both gas types indicates an atmospheric origin. As surface water recharges the aquifer, air either dissolves in the water or becomes physically entrained as it is recharged as turbulent flow through karst features. As these waters discharge at the spring orifices or at the lake floor, the gas comes out of solution.

In the case of strings of bubbles coming off of the lake bottom, the gas bubbles are trapped beneath the gravel and rock rubble as if they were beneath an umbrella. Presumably, when localized gas bubble pressure becomes high enough, a train of gas bubbles escapes from the sediments. Trains of gas emanate in a sporadic fashion from the lake bottom. When viewed from underwater, there is always some point on the lake bottom where bubbles are rising.

The extensive gas bubble formation in the spring orifices may also indicate that the groundwater has been transported deep below land surface. The high dissolved concentrations of oxygen and nitrogen indicate over-saturation (Appendix 5).

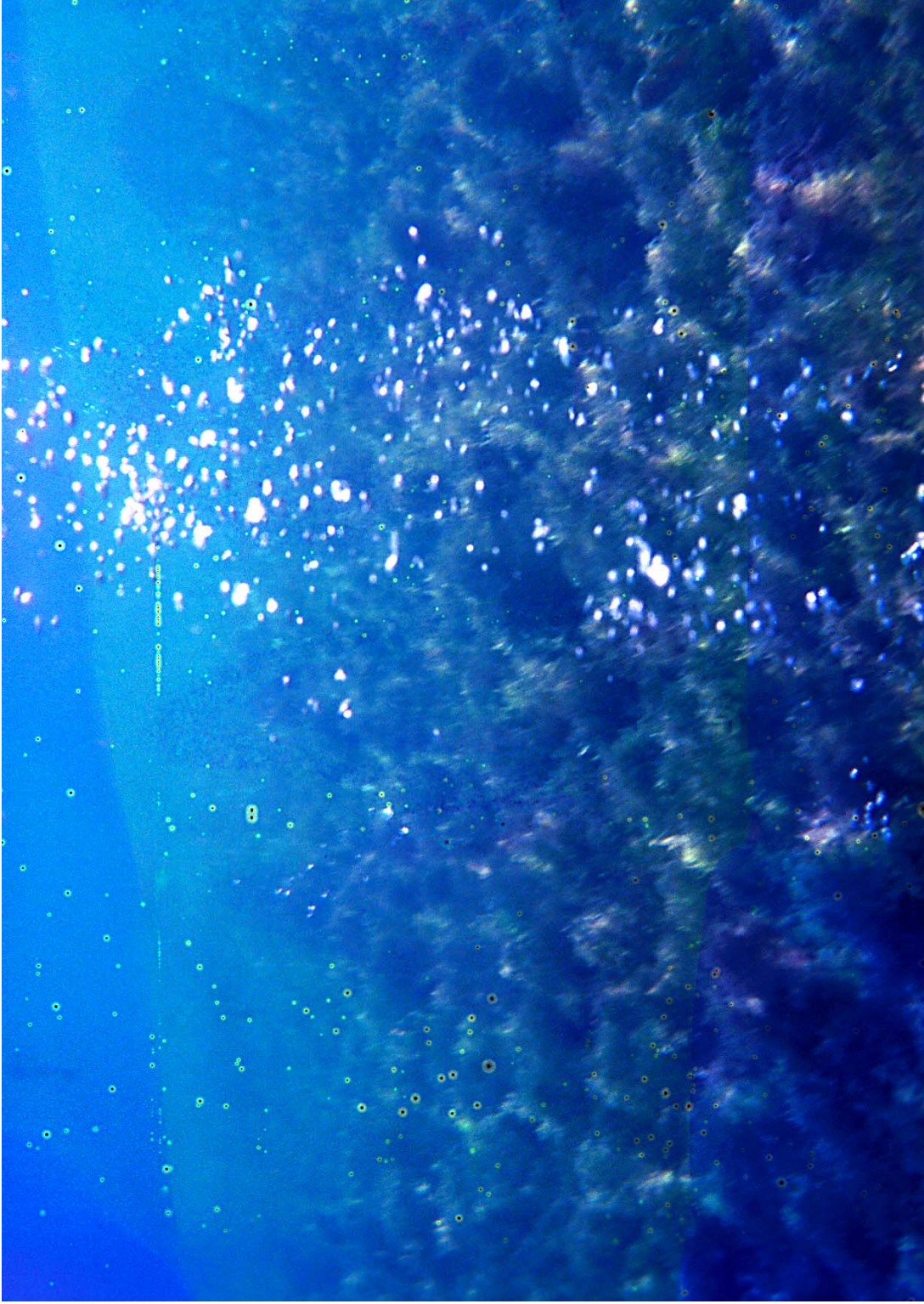


FIGURE B-6: Cloud of gas bubbles rising from the bottom of Landa Lake. Chemical composition of the gases indicate the original source is atmospheric. Photograph taken March 7, 2004 by LBG-Guyton Associates. Slight water leak in camera caused damage to original photographic negative.

Gas bubbles (and therefore spring discharge) were observed all along the west bank of the lake from the gazebo at the end of Spring #3 all the way to Spring Island. Gas bubbles were observed completely around Spring Island. The areas with most intense bubbling are on the northwest to northeast side of the island. There is not as much gas bubble discharge from about 100 yards north of Spring Island to about 200 yards south of the Bavarian Village. There is extensive gas bubble discharge in the lake next to the Bavarian Village and about 100 yards up Blieder's Creek.

Gas bubbles were not observed in the south and southeast sections of the lake bottom. This section of the lake bottom is heavily covered in vegetation. Beneath the vegetated area is an approximately one-foot thick section of mud. Spring discharge is not considered to be occurring this far from the fault.

The type of sediments that cover the bottom of Landa Lake was investigated to determine if lacustrine muds might function as an aquitard that covered certain areas of the lake bottom. An option for augmentation of spring flow in Landa Lake might be accomplished by pumping water directly into the lake (rather than injecting it into the aquifer so it would subsequently flow at the springs). The presence of an extensive aquitard might permit this approach and prevent supplemental water from flowing directly back into aquifer under low water level conditions in the lake or the aquifer.

The southern end of Landa Lake is partially covered by a mud substrate was confirmed by LBG-Guyton Associates in the field during an underwater survey of Landa Lake. The areal extent of the mud is shown in Figure B-5. This mud is up to 12 inches thick, and is accumulating in the areas of thick vegetation. There are channels that cut through the grass flats and underlying mud substrate. These channels are floored with an admixture of mud and sand. There is no mud substrate on the rest of the lake bottom. The western section (from Spring Run #3 to Spring Island and then to Blieders Creek) is composed primarily of sand and gravel. Much of this section of the lake bottom may be subject to groundwater discharge. Additionally, much of the western portion of the lake, which is gravel-bottomed, is at an elevation lower than the mud strata in the eastern part of the lake. The presence of the mud substrate in the eastern part of the lake will do little to prevent back flow into the aquifer if water levels in the lake and the aquifer get that low.

At the San Marcos Springs (and Spring Lake), there are no obvious bubbles or bubble trains emanating either from the orifices or from the lake bottom as was observed at Comal Springs and Landa Lake. However, the measured dissolved gas constituent concentrations (Appendix 5) are as high at Spring Lake as they were at Comal Springs. The points of spring discharge at San Marcos are all at depths of about 10 ft or greater. In Landa Lake, the springs are either at land surface or under about 4 ft of water – much shallower than at Spring Lake. Waters discharging at Landa Lake will start degassing within the aquifer itself rather than just in the lake. This may explain why there are no obvious trains of bubbles discharged from the individual San Marcos Springs on the bottom of Spring Lake.

B.1.14 Discharge measurements for different springs

B.1.14.1 Velocity Measurements

Discharge measurements by Ogden et al (1985a) and BIO-WEST (Ed Oborny, personal communications, 2003) indicate that only about one quarter of the total spring discharge (as measured at the USGS gage) is from Springs #1, #2, and #3. By subtraction then, most of the spring discharge is coming from the other spring orifices and from the bottom of the lake. The results of BIO-WEST's flow measurement are presented in Table B-3.

Table B-3. Spring Runs #1, #2, #3 Flow Measurements 2003

Flows			
	Spring 03	Summer 03	Fall 03
	(4/25/03)	(8/27/03)	(11/12/03)
Total Comal Spring flow (USGS) (cfs)	405.00	361.00	384.80
Spring #1 (cfs)	48.90	42.60	43.10
Spring #2 (cfs)	7.40	6.30	5.90
Spring #3 (upstream) (cfs)	40.00	37.40	37.30
Spring #3 (downstream) (cfs)	53.50	49.30	47.40
Proportion of Total			
Spring #1	12%	12%	12%
Spring #2	2%	2%	2%
Spring #3 (upstream)	10%	10%	10%
Spring #3 (downstream)	13%	14%	13%
Total Springs #1, #2, and #3 Contribution	27%	27%	27%

The downstream measurements for Spring #3 capture spring discharge in the channel, for an additional 10-13 cfs above the upstream value over the period these measurements were made. The results for Springs #1 and #3 are comparable to similar measurements collected by the Edwards Aquifer Research and Data Center (EARDC) in 1982 - 1983 (Ogden *et al*, July 1985). In these EARDC measurements, Spring #3 was gaged upstream, and Spring #2 was not gaged. These results suggest that under periods of normal to high flow the western group of springs contributes approximately one quarter of the total flow at Comal Springs. It follows that the springs in the lake contribute the remaining 75% of flow under these flow conditions. Under conditions of lower flow, the contribution of this western group of springs is reduced until these springs “go dry,” at which point the lake springs are the sole component of total flow.

Spring #1 and Spring #3 (upstream) flow data collected by EARDC in 1982 - 1983 are presented with total daily precipitation for New Braunfels in Figure B-7. As noted by Ogden *et al* (1985a), Spring #3 exhibits a greater discharge response to New Braunfels rainfall than Spring #1. This observation agrees with 15-minute water level data from the Landa Park well during storm events and positive dye traces from the Landa Park well to Spring #3.

B.1.15 Dye trace studies

Three dye trace studies have been performed in the Comal Springs area. Dye trace studies are typically performed with the goal of identifying flow paths and travel times to the springs from dye injection locations. The dye traces done near Comal Springs have typically involved injection of dye in an Edwards well or stream thought to recharge the Edwards, and subsequently monitoring some or all of the individual spring orifices. The first study, conducted by P.L. Rettman, involved the injection of dye into the Landa Park well (Rothermel and Ogden, 1987). This dye was reported to have emerged from Spring #3. This result was confirmed in the recent study conducted by the Authority.

The second study consisted of dye injection into Blieders Creek on the up-thrown block at two locations after a rain storm on 22 March 1983 (Rothermel and Ogden, 1987). Charcoal detectors were placed at Springs #1, #2, #3, and the A & B orifices at Comal Springs. The first injection location was at the crossing of Blieders Creek and River Rd. approximately 1,200 ft north of Loop 337. One pound of fluorescein dye was injected into the creek at this location. No dye was detected at any of the sampled spring orifices. The potentiometric map (Plate 2) for this study indicates their point of dye injection was downgradient from the springs, and therefore dye should not have physically flowed to or been detected at Comal Springs.

The second Blieders Creek injection location, reported by Rothermel and Ogden, was south of Route 46, approximately 3.5 miles northwest of Comal Springs. The creek was injected with 1.5 pints of rhodamine dye, with no subsequent detection of dye at the sampled spring orifices. Again, based on our current interpretation of the hydrology of the Edwards around Comal Springs, dye injected at Blieders Creek would have flowed towards San Marcos and not towards Comal Springs.

The third study was conducted by the Authority in March-April 2002. This study consisted of injecting different dyes at the Landa Park well and the LCRA well, and monitoring sampling

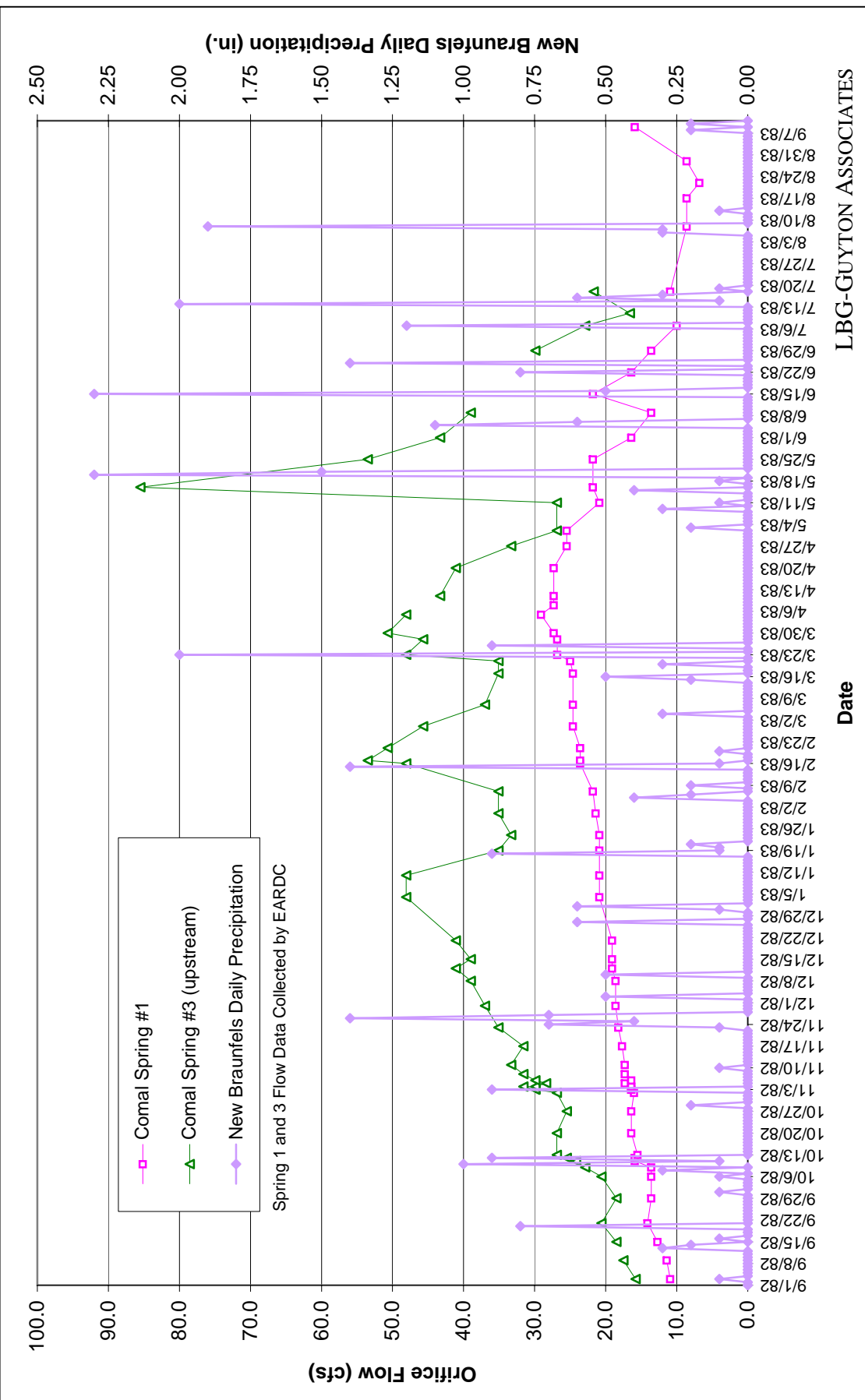


FIGURE B-7 COMAL SPRINGS #1 AND #3 WITH NEW BRAUNFELS PRECIPITATION

points at major identified individual spring orifices and locations in the lake. The Landa Park well was injected with eosine dye on 22 March 2002. The dye was subsequently visibly detected at Spring #3 (upstream and downstream orifices) after 147 minutes. The eosine dye was not detected in any of the other orifices. The LCRA well was injected with uranine dye on 22 March 2002. The dye was detected at Spring #7 and two springs near the cluster of small islands in the middle of the lake about 35 hours later. The uranine dye was detected at Spring Island 47 hours after injection. The uranine dye was also detected in the golf course well (NBU5) when this well was pumped on March 25, 2002. The dye may have reached NBU5 prior to this pumping (personal communication, G. Schindel, Authority, 2003).

The eosine trace from the Landa Park well indicates that Spring #3 discharges from the up-thrown block. The dye did not emerge from Springs #1 and #2, which indicates that since they discharge from the up-thrown block (as water level history and water chemistry suggests) the conduits through which they do so are upgradient of the Landa Park well, or otherwise hydrologically isolated from the Landa Park well.

The uranine trace indicates that the remaining springs in and around the lake discharge from the down-thrown block. Water level history and water chemistry confirm this conclusion. The uranine injected into the LCRA well (down-thrown block) did not emerge from Springs #1, #2, or #3.

B.1.16 Chemical Composition of Comal Springs

Chemistry of groundwater in the Edwards Aquifer characteristically is a calcium-magnesium bicarbonate water resulting primarily from the dissolution of the limestone and dolomite of the Edwards. Although the chemistry of most of the groundwater is predominately calcium (Ca) and bicarbonate (HCO_3) with a neutral pH, different water sources or flow paths may result in small changes in water chemistry such that slight changes in spring chemistry might indicate different sources. For example, water from the down-thrown block of the Edwards may have small amounts of water from the more saline “bad water” zone, which could change chemistry slightly.

The groundwater discharging into Comal Springs and Landa Lake originates either from the confined down-thrown block of the Edwards (east of the Comal Springs Fault) or from the unconfined up-thrown block of the Edwards (west of the Comal Springs Fault). Other data, such as water level data from the Landa Park and the LCRA well, and dye tracer data document this

hydrologic separation between the up-thrown and down-thrown blocks and that Springs #1, #2, and #3 discharge from the up-thrown block whereas Springs #7, #5, Spring Island, and the bottom of Landa Lake discharge from the down-thrown block.

Several chemical parameters for the different springs show slight variations in the up-thrown block springs and the down-thrown block springs. Small variations are seen in temperature, barium (Ba), sulfate (SO₄), chloride (Cl), and strontium (Sr)(Figures B-8 to B-12). These slight variations suggest different water sources for the different spring groups. In general, higher temperatures and greater constituent concentrations occur in the springs discharging from the down-thrown block as compared to those discharging from the up-thrown block. The water quality analyses for Comal wells and springs are summarized in a table in Appendix 5.

The water chemistry provides additional evidence for different flow paths for the up-thrown and down-thrown blocks. The chemical differences, however, are small and should not be relied on as a sole method of differentiation. More chemical data collected over time may confirm these observations.

Detailed review of the chemistry did identify slightly different chemistry at the spring on Spring Island. For the plots for SO₄, Cl, and Sr, the Spring Island (Figures B-10 to B-12) chemistry looks more similar to Springs #1, #2, and #3 (up-thrown block), than it does for samples from the down-thrown block springs. Uranine, however, was identified at this spring after the injection of uranine in the LCRA well (down-thrown block). There may be a mixing of up-thrown block and down-thrown block waters at this spring.

B.1.17 Elevation of Springs and Discharge Points Around Landa Lake

The locations and discharge elevations for the various spring orifices affect the relative discharge volumes for these orifices and ultimately determine when the individual spring orifices “run dry.” The elevations of many of the orifices which discharge outside the lake have been determined by a recent elevation survey (the Authority, unpublished survey, 2003) (Appendix 2) or from topographic contours. The bathymetric survey of Landa Lake provides the elevations of orifices discharging from the bottom of Landa Lake, and also provides important information regarding stage-volume-discharge relationships within the lake.

The bathymetric survey of Landa Lake was (Plate 3) conducted by the U.S. Fish and Wildlife Service (USFWS) in the mid-1990's. For this study, Bio-West field checked many of their survey

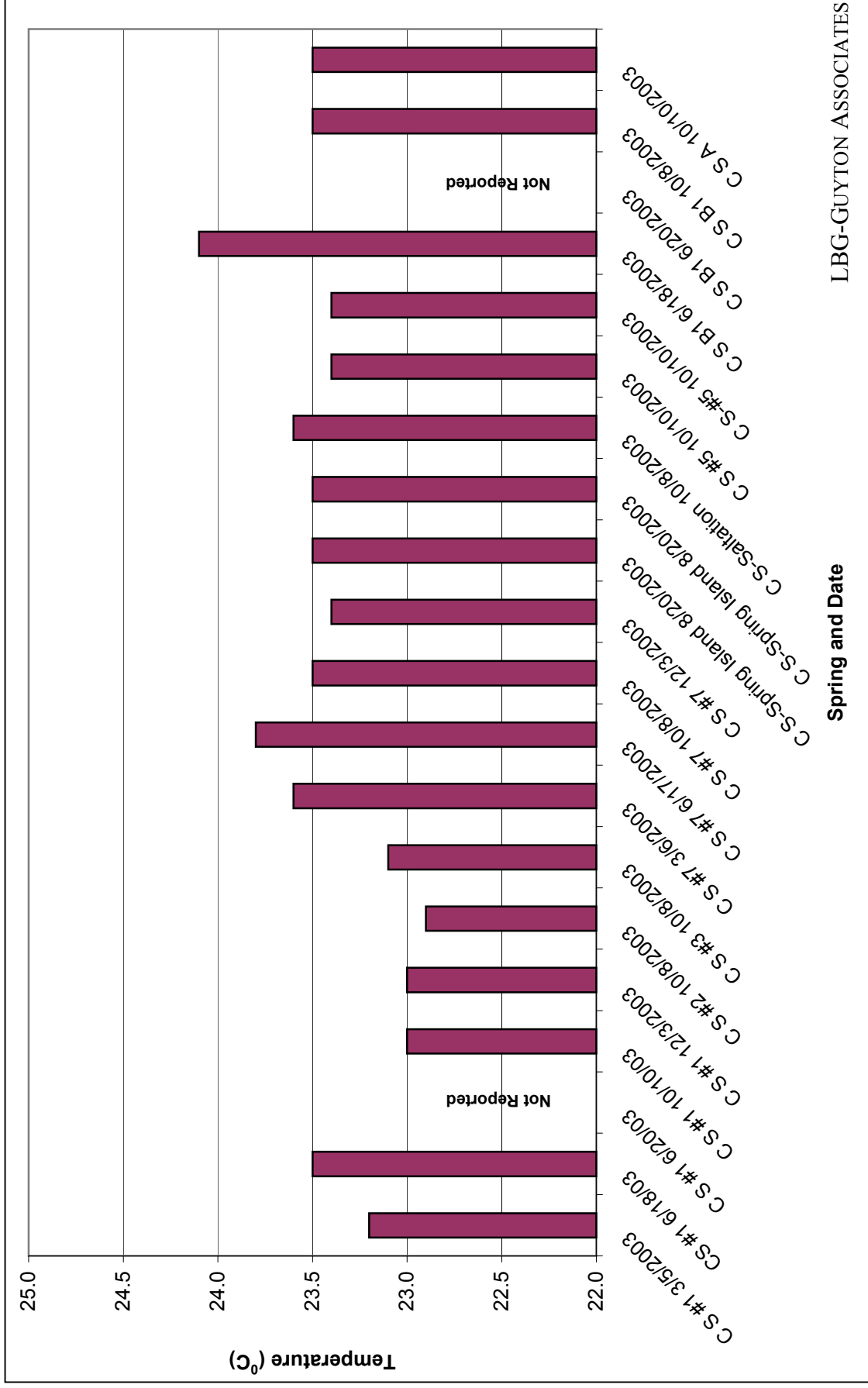


FIGURE B-8 WATER TEMPERATURE FOR SPRINGS AT COMAL SPRINGS

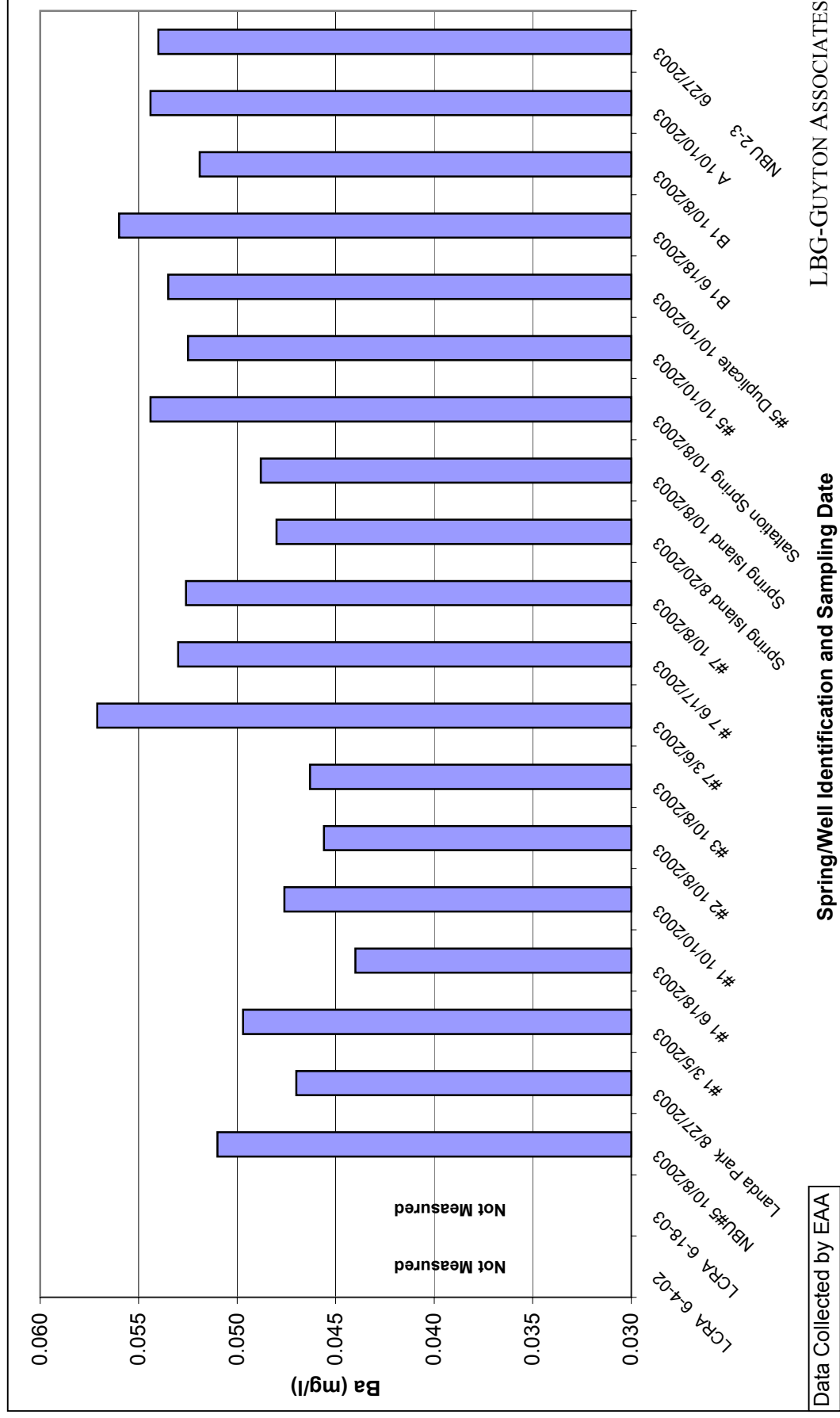


FIGURE B-9 BARIUM CONCENTRATIONS FOR SPRINGS AND WELLS AT COMAL SPRINGS (2003)

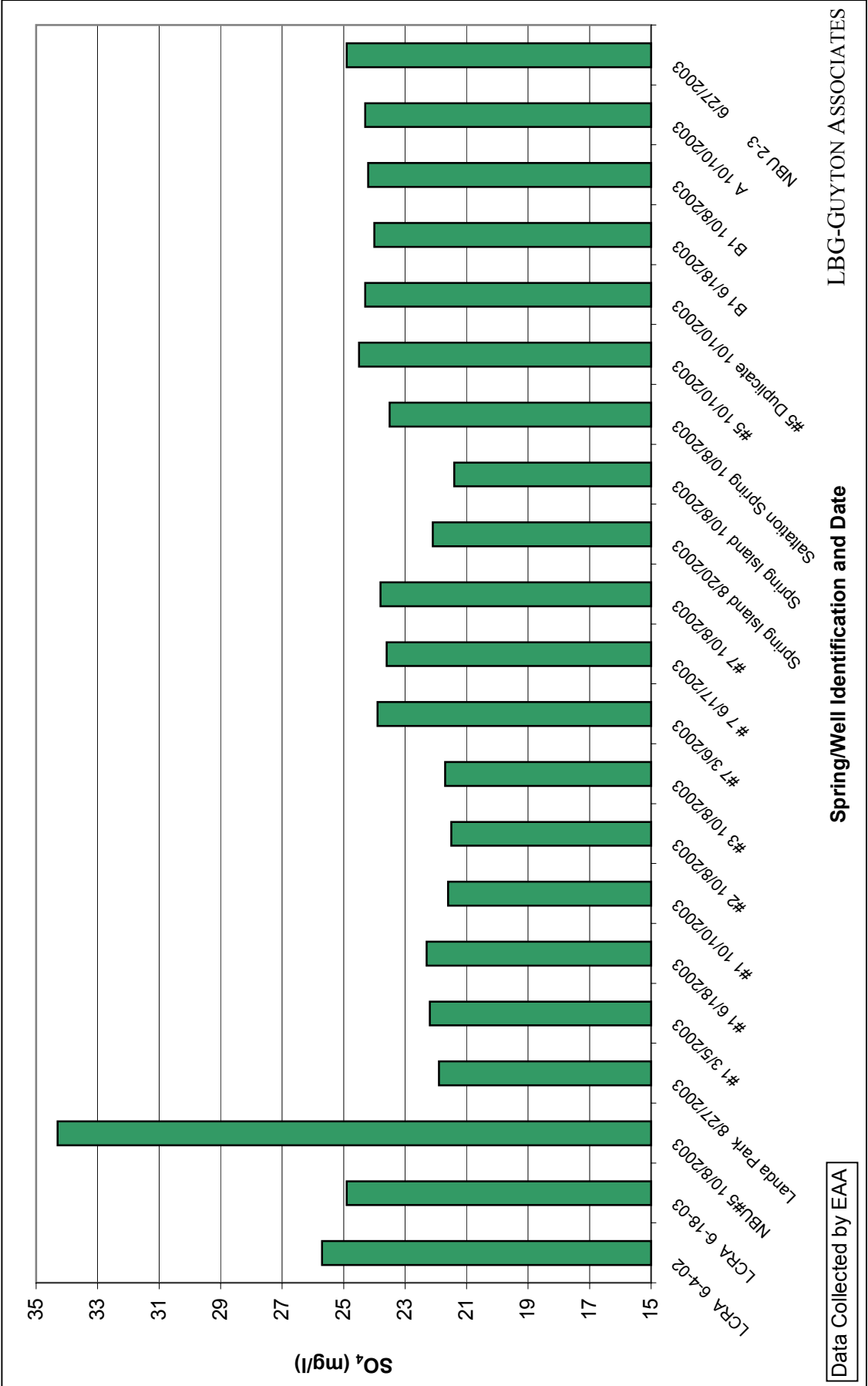


FIGURE B-10 SULFATE CONCENTRATIONS FOR SPRINGS AND WELLS AT COMAL SPRINGS (2002-2003)

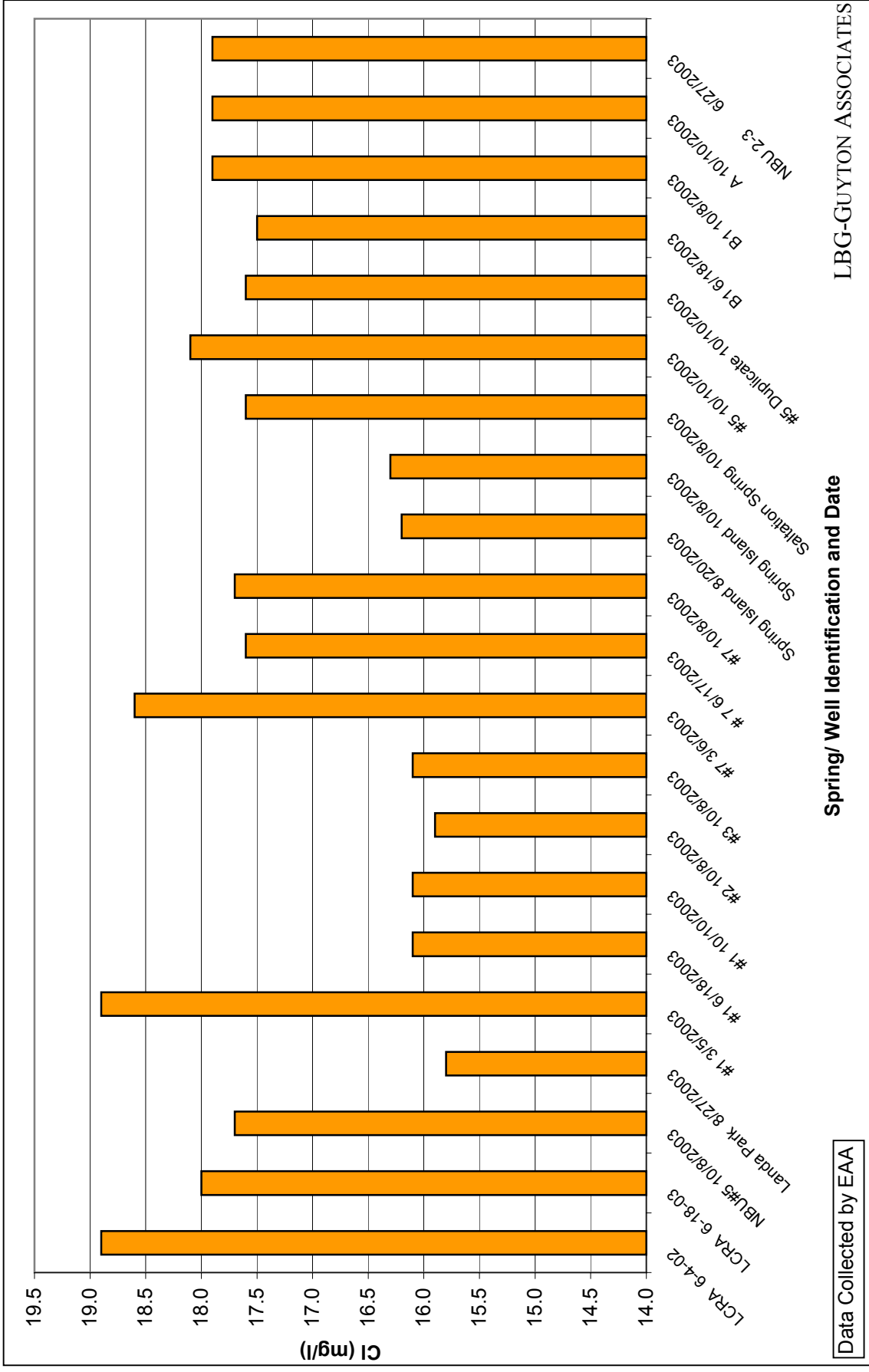


FIGURE B-11 CHLORIDE CONCENTRATIONS FOR SPRINGS AND WELLS AT COMAL SPRINGS (2002-2003)

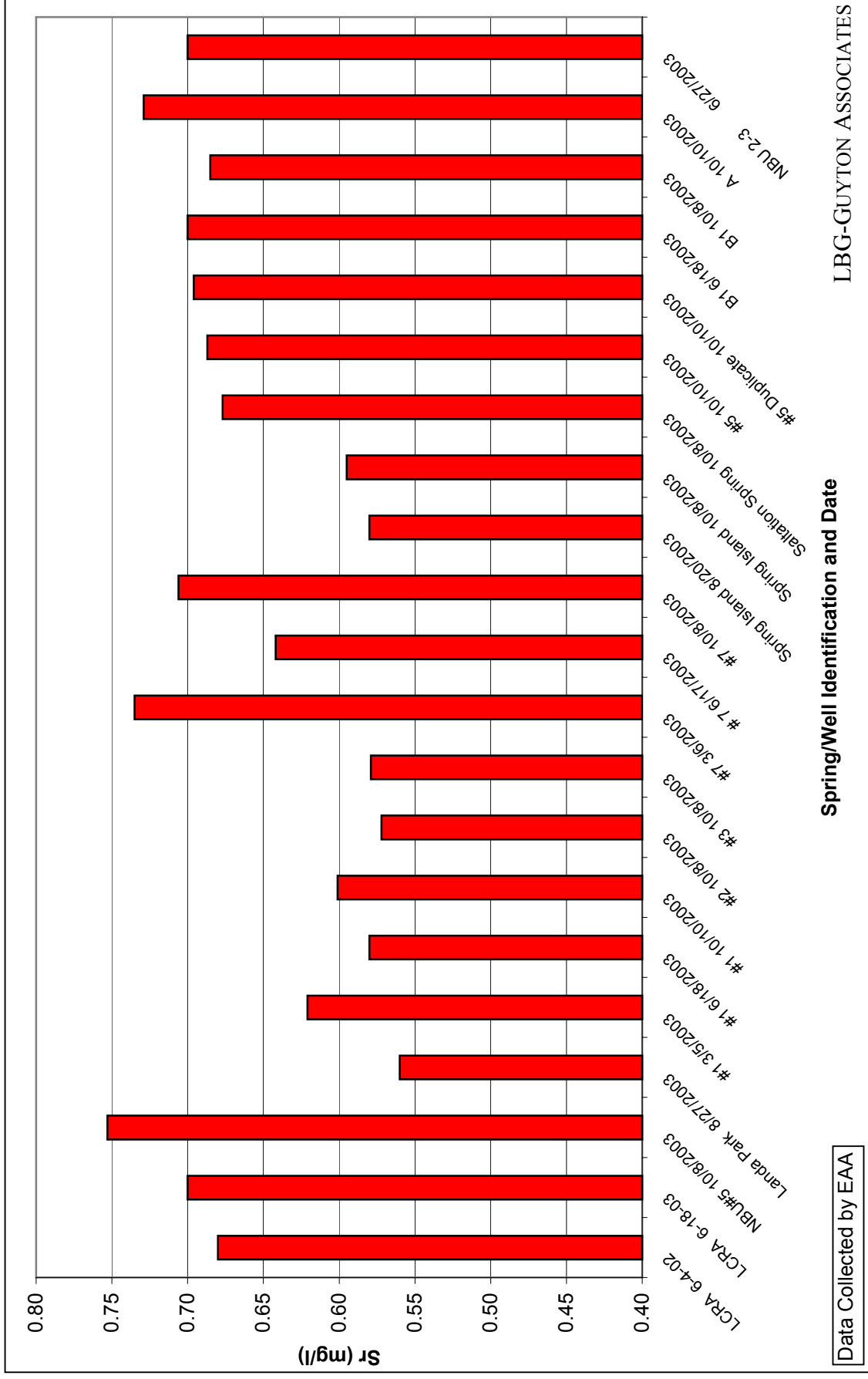


FIGURE B-12 STRONTIUM CONCENTRATIONS FOR SPRINGS AND WELLS AT COMAL SPRINGS (2002-2003)

points. Appendix 2 contains a more detailed explanation of how the maps were developed. One-foot USFWS bathymetric contours are presented in Plate 3. The lake bottom has a minimum elevation of 613 ft at two locations: between the end of Spring Run #3 and Spring Island along the western side of the lake, and at the southern end of the lake near the large pool at the water park. The lowest elevation for a spring on the lake bottom, therefore, is 613 ft. The lake has a water surface elevation of 620 ft.

According to this recent elevation survey (Appendix 2), most of the individually-identifiable springs at the edge of the lake and in the islands discharge in an elevation range of approximately 620-624 ft. The individual orifices, which comprise Spring #1, discharge at elevations of 622.1 ft, 622.6 ft, and 624.2 ft, respectively Spring #2 discharges at an elevation of 622.6 ft.. Spring #3 was not surveyed, but a discharge elevation of 620-621 ft for Spring #3 has been estimated from topographic contours.

Total discharge from the lake is controlled by the elevations of the discharge structures on the lake, and at low stage by the bathymetric contours within the lake itself. Flow leaves Landa Lake by both Old Channel (which flows to the east of the pool area and through the golf course) and New Channel (which flows past the inactive LCRA power plant). Both channels are identified on Plate 3. Landa Lake is connected to the Old Channel by a 48-inch culvert, and two 24-inch culverts. The lake-side invert elevation of the 48-inch culvert is approximately 611.4 ft. The two 24-inch culverts are installed at a lake-side invert elevation of approximately 618 ft, and were apparently installed to act as an additional lake level control when a temporary sheet-piling dam was placed in the New Channel in the late 1950s. A fourth culvert directs flow into the flow-through swimming pool, and ultimately into Old Channel. Valves can control flow in all of these culverts.

Flow leaving Landa Lake through New Channel passes over a dam across from the Landa Park headquarters. The elevation of this dam is 619.28 ft (Appendix 2). The Old and New Channels join just upstream of Clemens Dam, so the total flow from Comal Springs passes over this dam and by the gaging station located there. Under normal flow conditions, about seventy-five percent of the total flow is down New Channel, and twenty-five percent is down Old Channel.

As the lake stage becomes lower, flow is naturally controlled by these outlet elevations. Flow would stop at New Channel dam first (at 619.28 ft) and then flow would be directed towards the

lower culverts that discharge into Old Channel (assuming the valves on these were not closed to prevent flow). During the summer of 1956, it is believed that all flow for Old Channel was diverted down New Channel to provide the cooling water needed to keep the power plant generating electricity. At extremely low stage, the elevation of the lake bottom itself becomes a control on flow. As the bathymetric map indicates, the lake bottom has a local topographic high of approximately 618 ft just upstream of these discharge points, therefore at stages below 618 ft, water from the upper reaches of the lake cannot be discharged to either Old Channel or New Channel. As will be discussed in the spring history section, it is believed from photographs and newspaper accounts that lake-bottom spring discharge could have occurred in the summer of 1956, even after the lake had “dried up” to a few standing pools. The water simply had nowhere to go, and the pools represented the water level elevation on the down-thrown block.

B.1.18 Spring Flow History

Spring augmentation strategies for the Comal Springs and Landa Lake require an understanding of how the springs went dry. The most critical period of low flow at Comal Springs was during the summer months of 1956. Other critical flow periods also occurred in 1953, 1954, 1955, 1959, 1966, 1984, 1988, 1989, 1992, and 1996 when there was diminished flow at the springs. Articles from the *New Braunfels Herald* and other available newspapers help piece together the anecdotal information about the conditions of the springs going dry or, conversely, starting to flow. These news articles are included in Appendix 6. These occurrences were then compared to water levels in the Landa Park well where a daily water level measurement is available for almost every day since 1948. The other source of information that documented spring conditions is a daily journal maintained by Oliver Haas and Bill Tepe of NBU. This journal documents water levels in Landa Park well, LCRA well, total Comal Springs flow, and general spring conditions from 1984 to 1992. A summary of these sources is also included in Appendix 6.

Figures B-13 and B-14 summarize critical spring conditions when springs go dry, total spring flows, Landa Park well water levels, and LCRA well water levels (when available). Key events and dates are listed below: These springs went intermittently dry in the summer of 1952, 1954, and all of 1955 and 1956.

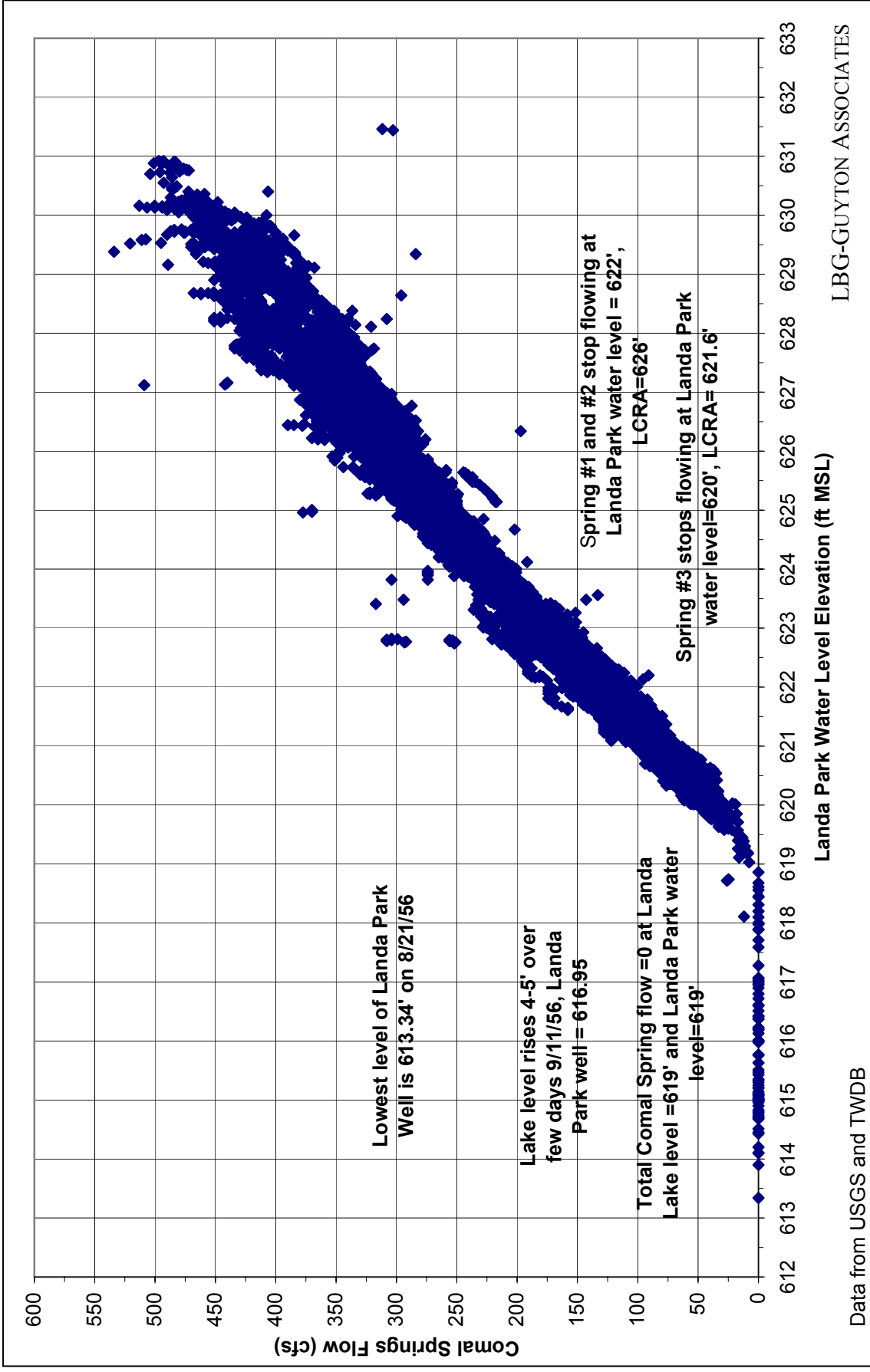


FIGURE B-13 LANDA PARK WELL LEVEL VS COMAL SPRINGS FLOW 1948 - 2001

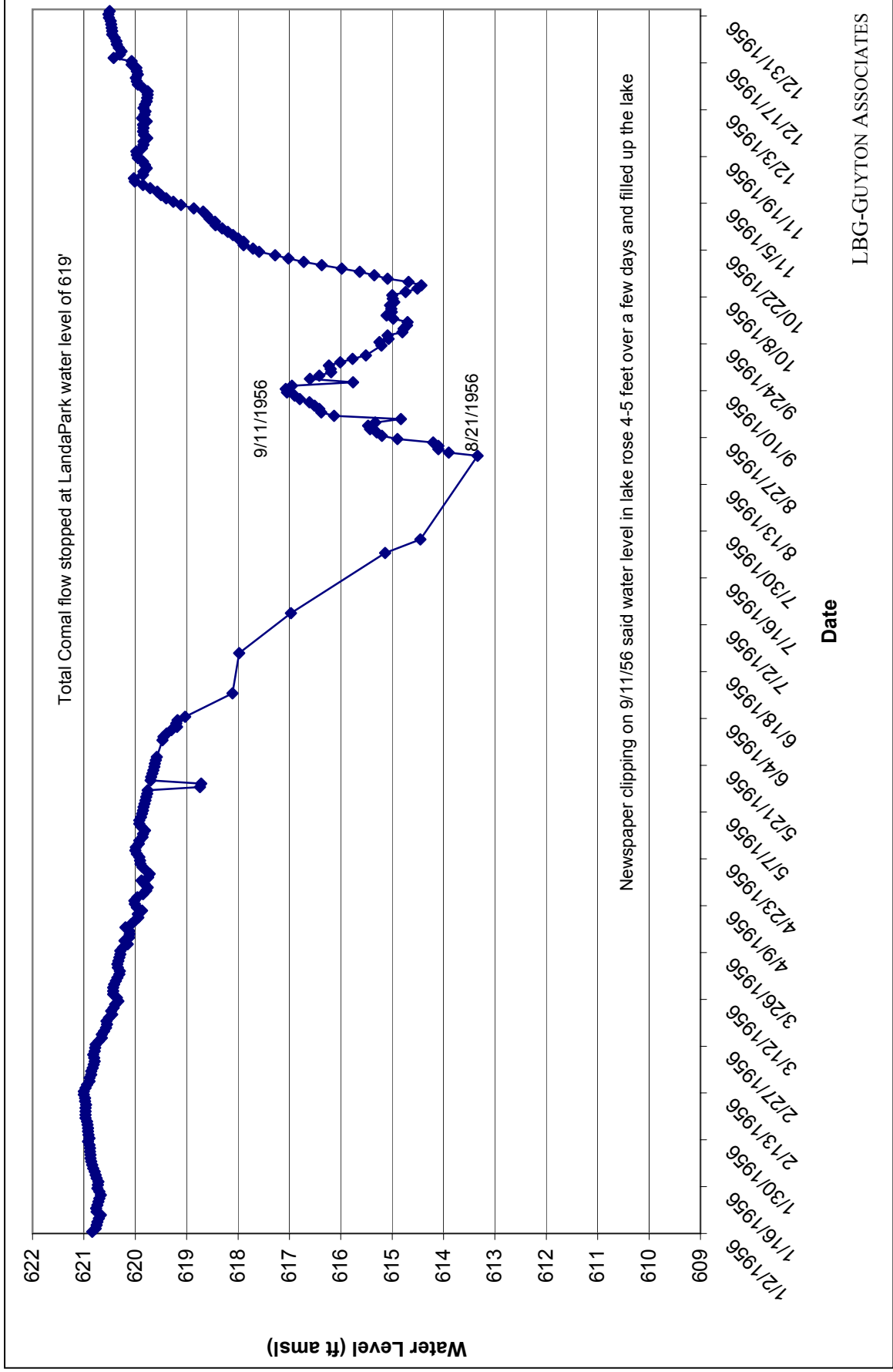


FIGURE B-14 WATER LEVELS IN LANDA PARK WELL 1956

- Springs #1 and #2 stop flowing at Landa Park well water elevation of 622 ft. concurrent. The elevation of the lowest of the three spring orifices at Spring #1 is 622 ft. The water level for the LCRA well was at 625 ft. Total Comal Springs flow is about 130 cfs. Spring #1 also went dry in the summers of 1967, 1984, 1989, and 1996.
- Spring #3 stops flowing at Landa Park well water level of 620 ft, which is also the current elevation of the lake. The concurrent water level for LCRA well was about 621.5 ft. Total Comal Springs flow was about 50 cfs. There is no record of Spring #3 going dry after the summer of 1956.
- Total Comal Springs flow is zero in early June 1956 when the water level in Landa Park well is 619 ft. 619 ft is also the elevation of the low water dam at the LCRA power plant on New Channel.
- Large parts of the lake bottom emerge at a lake elevation of 618 ft. The north end of the lake, north of Spring Island, also emerges at about 618 ft. Although there are some deeper pools at the north end, flow from north to south probably has been cut off. Figures B-15 and B-16 present photographs of the southern end of Landa Lake (courtesy of George Ozuna, USGS) sometime in the summer of 1956. The water level in the pools in the lake appear to be about 617-618 ft.
- The lowest level of Landa Park well was reached August 21, 1956. The water level in Landa Park well is 613.34 ft. The deepest pool, just south of Spring Island has a bottom elevation of 613 ft. Newspaper clippings indicate that there may be 6 inches of water left in the deep pools. The hydraulic gradient from Bracken well to Landa Park well is essentially flat on this date.
- On September 11, 1956, the lake was reported to have “filled in” the few days prior to September 11, 1956. Water level in the lake is reported to be 4-5 ft deep (this does not mean the lake returned to a full condition). Landa Park well water levels rose about 3 ft (614.2 ft to 616.95 ft) from August 25 to September 11 (Figure B-14). No explanation is given in the article as to why water levels in the lake rose.

Springs #1, #2, and #3 go dry when water levels in the Landa Park well (up-thrown block) drop below the elevation of the individual spring. LCRA well water levels remain above the elevation



FIGURE B-15. Summer 1956 photo of Landa Lake, on western shore looking southeast toward the flow-through pool. Photo date unknown. Water level elevation in pools is about 617 to 618 ft. Photo provided by George Ozuna of USGS.



FIGURE B-16: Summer 1956 photo of southern end of Landa Lake, on western shore looking north toward the escarpment. Photo date unknown. Water level elevation in pools is about 617 to 618 ft. Photo provided by George Ozuna of USGS.

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of the respective springs as they go dry. This observation further documents that Springs #1, #2, and #3 discharge from the up-thrown block. Water levels in both the Landa Park well and the LCRA well approach similar values at an elevation below 619 ft. There are no water level measurements recorded for the LCRA well below 621 ft measured during the drought of 1984. It's assumed that water levels in the LCRA well would have been slightly higher than water levels in the Landa Park well for the summer of 1956, such that when water levels in Landa Park dropped to 613.5 ft, then water levels in the LCRA well were also about 613.5 ft. Water levels in the Bracken well were about 614 ft at that time. This correlates with water levels in the lake, which declined to almost dryness (which would have been at 613 ft).

The severity of the drought of 1956 and its impact on water levels at Landa Lake is unique in the hydrologic record for central Texas. The water levels for the Landa Park well for the five years preceding the drought exhibit continuous yearly declines, but the declines were a much more subtle response to the water level declines for the summer of 1956 (Figure B-17). In 1956 Landa Lake went from being "full" in early June, to being almost dry in August. Similarly, water levels in the Landa Park well dropped five and a half feet over the same period of three months (Figure B-14). A critical question is what caused water levels to change so rapidly. The following observations are made:

- A very critical period for the health of the lake occurred after there was no flow over the LCRA plant dam. The lake levels immediately fell 5-6 feet and the lake almost went dry. This period lasted from June through October 1956. The period when Springs #1, #2, and #3 went dry started initially in the summer of '53 and ended in the winter of '56.
- Water levels in the lake and in Landa Park well dropped significantly after total Comal Springs flow (as measured in the Comal River) went to zero. Spring flow buffers water levels in an aquifer around an area of springs. Changes (rises or lowerings) of water levels in the aquifer are dampened by spring flow. When spring flow stops, changes in water levels are then controlled primarily by the storage of the aquifer. A comparison of water levels in the Bracken well (in the confined section of the Edwards near the county line between Comal and Bexar Counties) and the Landa Park well clearly shows the impact of when an aquifer block no longer discharges groundwater to springs (Figure B-18). Figure B-18 is based on water level data from 1955 to 2002. During normal flow

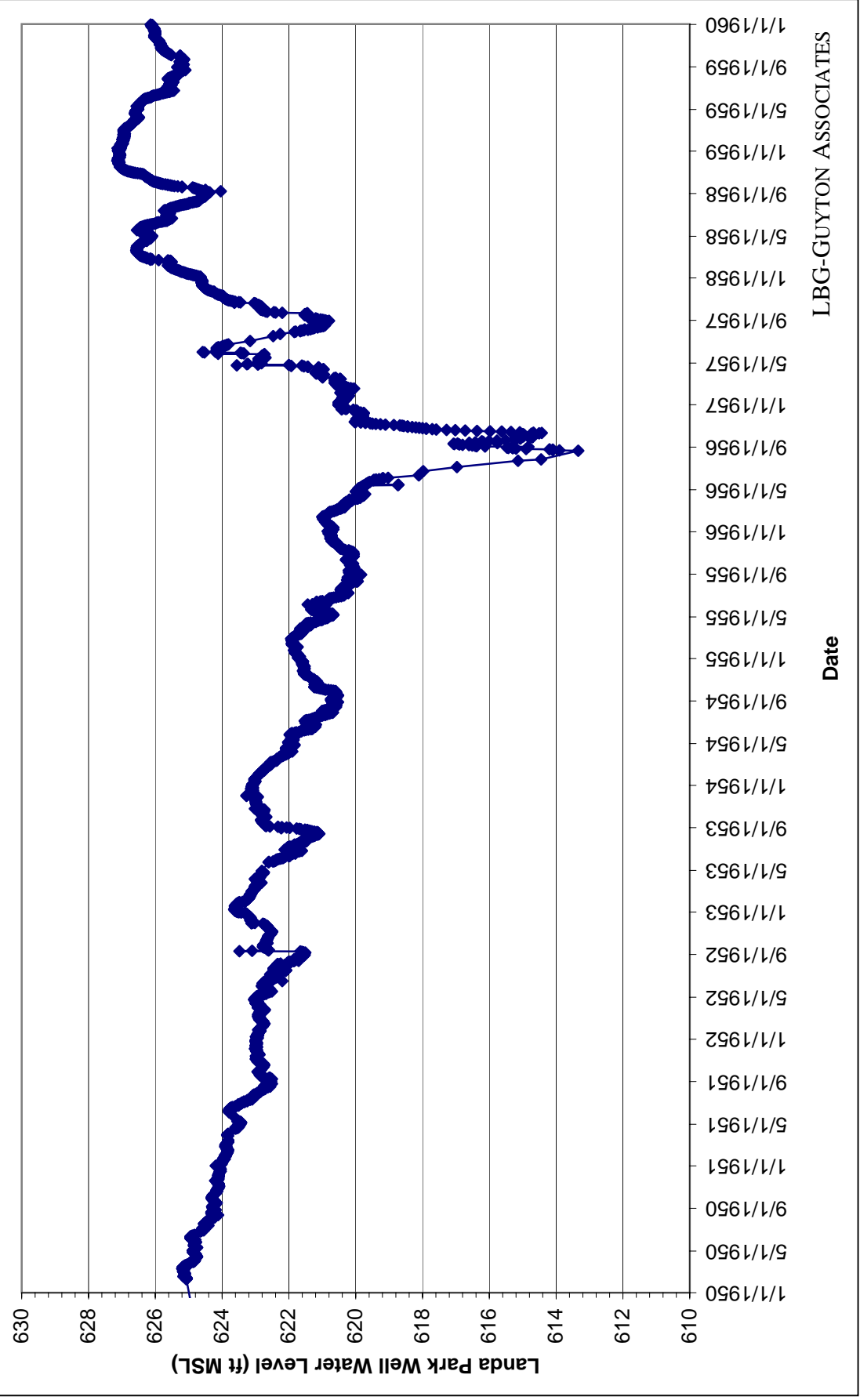


FIGURE B-17 WATER LEVEL IN LANDA PARK WELL FOR 1948 TO 1959

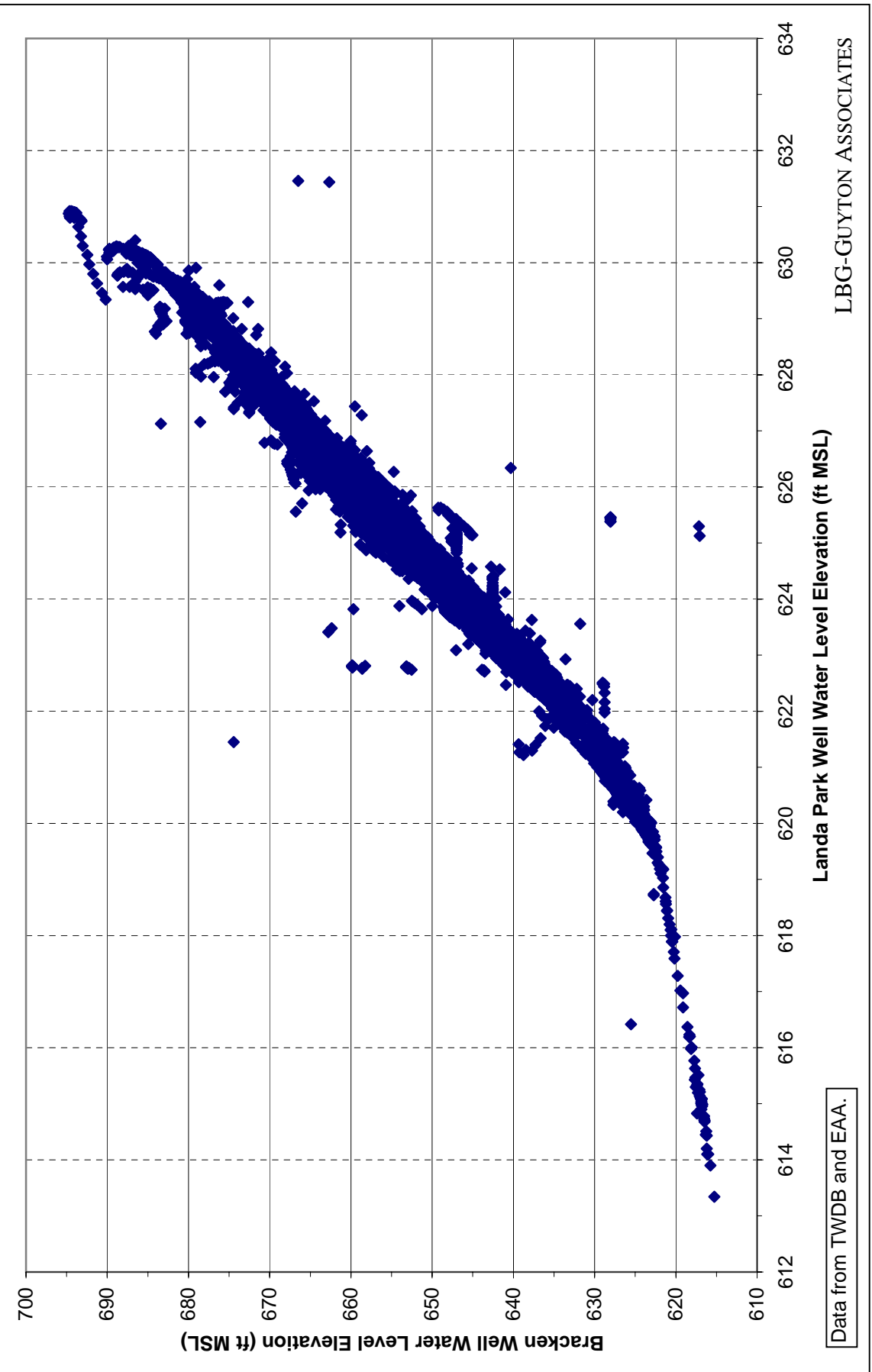


FIGURE B-18 LANDA PARK WELL VS BRACKEN WELL WATER LEVELS

conditions, the water levels between the two wells have a ratio of about 6.5 ft of rise in the Bracken well per foot of rise in the Landa Park well. Bracken well water levels rise and fall much more rapidly than do water levels in the Landa Park well. Landa Park well water level changes are dampened by the spring discharge from Springs #1, #2, and #3. When water levels in the Landa Park well drop below 620 ft, there is no more spring flow from the up-thrown block, and the water levels in the Landa Park well start declining much more rapidly. Landa Park water levels under this non-spring discharge condition are dropping at about the same rate as at the Bracken Well. (Figure B-18) In a low-storage aquifer, such as a confined limestone aquifer, water levels may drop rapidly because of pumping or lack of recharge. Landa Lake during the summer of 1956 functioned like a monitoring well after the springs stopped flowing. The amount of water in the lake (lake levels) should be dependent on water levels in the aquifer and not the amount of discharge from the lake (which was now zero).

- When water levels in the Landa Park well reached 620 ft, flow stopped at Springs #1, #2 and #3, but there was still flow out of Landa Lake because there was spring discharge from the down-thrown block into the lake itself. At about 619 ft water elevation in the lake, total spring discharge went to zero. Landa Lake then started functioning as a monitoring well in a confined, low-storage limestone aquifer. Lake levels became dependent on water levels in the aquifer. There are no water level data for the LCRA well for this period of time, so it isn't known how rapidly water levels dropped in the down-thrown block at Comal Springs, but lake levels dropped rapidly. Water levels at the Bracken well, which is also completed in the down-thrown block, did drop at least six feet for that period of time.
- The LCRA well on Fredericksburg Road was also drilled, completed and produced water for use for the power plant and for the swimming pool at Landa Park in 1956. This well produced a constant discharge of 5,000 gpm beginning on June 7, 1956. The LCRA well was pumped at a rate of 5,000 gpm until at least October 1957. Figure B-19 presents the 1956 flows for the USGS Comal River gage (flow over the dam) and the USGS Comal Springs gage (flow over the dam minus surface and other flows). In the summer of 1956 the Comal River gage flow was about 12 cfs, while the interpolated Comal Springs gage

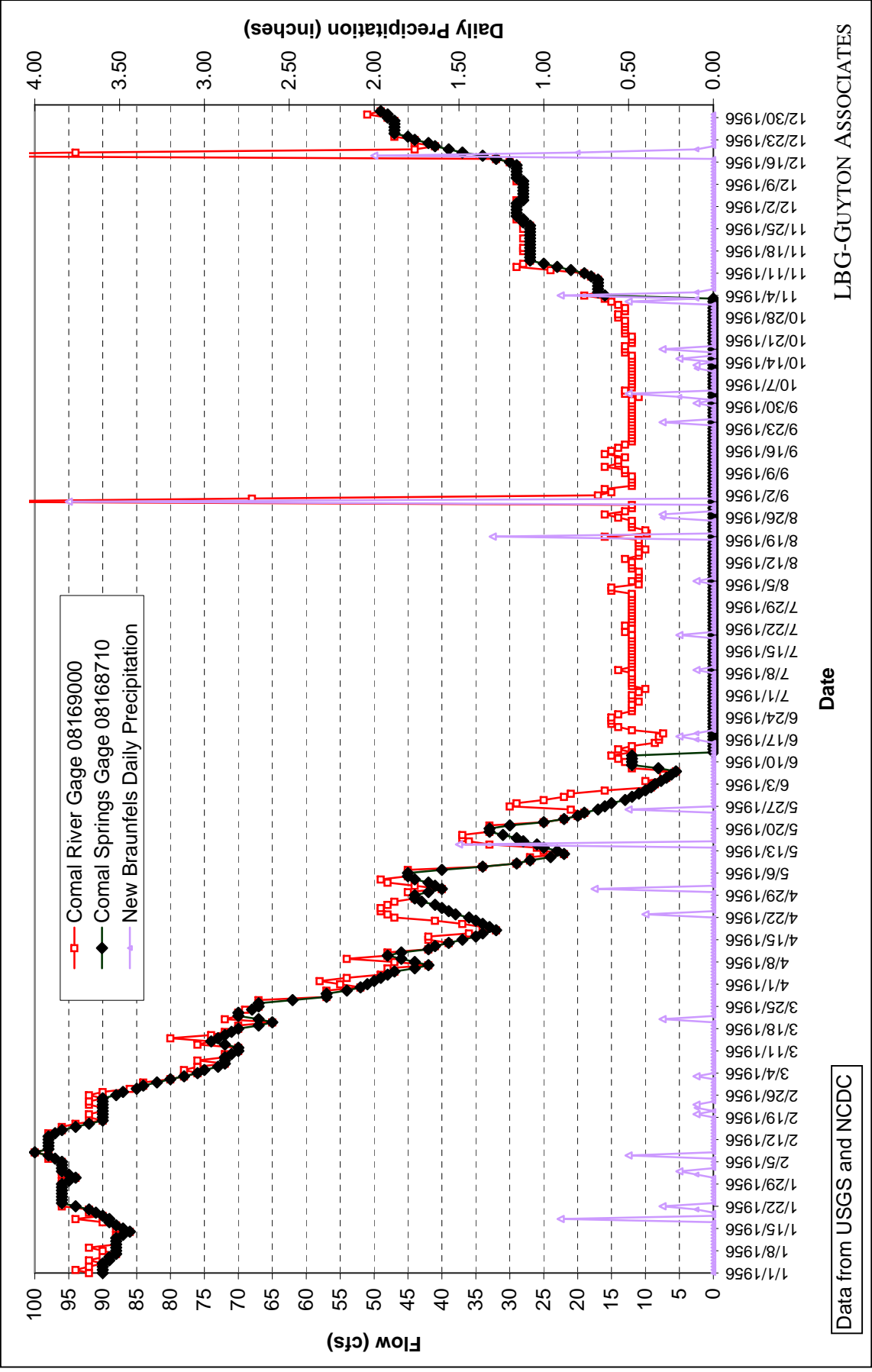


FIGURE B-19 1956 COMAL RIVER AND SPRINGS USGS GAGES WITH PRECIPITATION

flow was zero. The difference is almost entirely due to the 5,000 gpm (11 cfs) contributed by pumping the LCRA well. This is confirmed in gaging data remarks for the Comal River included in Appendix 7 (USGS, 1958 and 1959). NBU also brought on line wells #5 and #6 during 1956 for an additional capacity of 6,950 gpm, for a total of 11,950 gpm (27 cfs). The LCRA well was pump-tested in February 1956, for five hours at 5,000 gpm. After five hours, water levels in the well declined 9.1 ft (Appendix 7). The dye trace study conducted in March 2002 confirmed the direct communication between the LCRA well and the springs in the bottom of Landa Lake. During the summer of 1956, Landa Lake water levels may have been lowered because of production from the LCRA well. It has previously been argued that groundwater production by municipalities, such as New Braunfels or San Marcos, represented only a small percentage of the total average discharge from these springs. However, when spring flows approach zero, then local production may represent a significant portion of spring flow.

- The phenomena of a) spring flow stopping and the lake functioning like a monitoring well in a confined aquifer, and b) the withdrawal of large volumes of groundwater, may have caused Landa Lake levels to rapidly decline. A critical concern is how rapidly this process occurred. It is important that spring flows at either Comal Springs or San Marcos Springs not cease, because the lakes can rapidly (within 3 months) dry up once water has stopped flowing out of the lake.

B.1.19 Rate of Lake Turn Over at Different Discharge Rates

The rate at which Landa Lake “turns over” -- time required to discharge one lake volume -- provides important information that can be used in the evaluation of the physiochemical properties of the lake. Water temperature and dissolved oxygen concentrations of lake water often define the appropriate environment for a species. Long residence times of water may impact critical conditions. Landa Lake bathymetric data gathered by the U.S. Fish & Wildlife Service was used to calculate a volume of 1,900,000 ft³ for the lake at a level of 620 ft. The lake turnover rates for the long-term historical average flow of 287 cfs (as of May 2002) and various other spring flows have been calculated and are given in Table B-4.

Table B-4. Landa Lake Turnover Rates

Spring Discharge (cfs)	Approximate Time to Discharge One Landa Lake Volume (min)/hours	
	Minutes	Hours
287	110	1.8
400	79	1.3
300	106	1.8
200	158	2.6
100	317	5.3
50	634	10.6

B.1.20 Summary of Physical Setting of Comal Springs and Surrounding Aquifer

The primary geologic feature influencing on Comal Springs is the Comal Springs Fault. This fault provides a conduit for discharge to the springs. Further, the great displacement appears to prevent flow from the down-thrown block to the up-thrown block with its lower water levels. All the flow from the down thrown block is considered to discharge at the springs.

The up-thrown block discharges to the group of springs west of the lake (Springs #1, #2, and #3) which lie along the fault escarpment. Under normal flow conditions about 25% of the total flow at Comal Springs is from these springs. However, since water levels on the up-thrown block are consistently lower than those on the down-thrown block, flow from the down-thrown block to the up-thrown block does not appear to occur in the New Braunfels area. These lower water levels on the up-thrown block combined with these spring orifices being at higher elevations relative to the lake springs result in Springs #1, #2, and #3 “going dry” on a more frequent basis than those in and around the lake. The Landa Park well in Panther Canyon is the primary monitoring point for up-thrown block water levels.

The remaining springs on the island, around the lake and on the bottom of the lake discharge from the down-thrown block. Flow from these springs is therefore controlled by down-thrown

block water levels, which are best monitored in the LCRA well. Unfortunately, there are no water level measurements from the LCRA well during the summer of 1956. This down-thrown block flow accounts for approximately 75% of the total flow at Comal Springs under normal conditions, and 100% of the total discharge under low flow conditions (after Springs #1, #2, and #3 run dry). Spring discharge from the down-thrown block appears to be an end-of-the-flow-system type spring. Water flowing in the down-thrown block has nowhere to go but to discharge at Comal Springs. Groundwater flow in this block of the aquifer does not bypass the springs.

Discharge from the lake is controlled by the elevations of the discharge structures under normal conditions. As discharge from the down-thrown block declines, flow will first cease at the New Channel dam. Lake levels will be approximately 619 ft. At this point water could still flow through the culvert to the Old Channel; but below an elevation of approximately 618 ft, the elevation of the lake bottom immediately upstream of the culvert will prevent flow from reaching the Old Channel culvert. Spring discharge could presumably still occur from the down-thrown block at water levels as low as the lowest lake-bottom elevation of 613 ft. However, for such discharge to occur, an outlet at that elevation would need to be constructed that would discharge to a location (such as Old Channel) at a lower elevation.

Only a portion of the Edwards groundwater from the up-thrown block of the Comal Springs Fault appears to discharge from the western group of orifices at Comal Springs. The remainder moves eastward and is discharged at San Marcos Springs.

Water levels in Landa Lake dropped rapidly in the summer of 1956. This occurred because lake levels mimicked the rapid decrease in water levels in the low-storage aquifer and because of local high-volume pumping. An important issue that needs further study is the role of local versus regional pumping in causing the lake to dry up. Can up-gradient regional pumping cause a spring lake to dry up or can the drying of the lake only occur from local pumpage?

B.2 Hydrogeology of San Marcos Springs

B.2.1 Geologic Setting

The geologic formations of the study area are composed of Cretaceous and Quaternary age rocks. The bedrock geology in the vicinity of San Marcos Springs developed through the accumulation of thick sequences of marine sediments deposited during Cretaceous times. Subsequently, major tectonic uplifting of the Edwards Plateau along the Balcones Fault Zone (BFZ) during Miocene times increased hydraulic/topographic gradients resulting in increased erosion. A relatively thin veneer (25-40 feet) of Quaternary age alluvial deposits lies above the Cretaceous erosional surface down-dip of the San Marcos Springs Fault. The BFZ is comprised mostly of normal “down-to-the-coast” faults with some down-to-the-northwest faults occurring in the immediate vicinity down-dip of the Balcones Escarpment. San Marcos Springs occur as multiple orifices along the San Marcos Springs Fault resulting from groundwater discharging from Edwards Aquifer into Spring Lake. Additionally, the San Marcos Arch occurs as a structural arch feature along a NW-SE trend which has a central axis aligned over the San Marcos area. Whether the San Marcos Arch has had a structural impact on the location of the springs is not known.

B.2.2 Stratigraphy

The stratigraphy of the Edwards Aquifer and its confining units was determined in an investigation by the Edwards Underground Water District (EUWD) by the analysis of surface geology, borehole geophysical logs, and drillers’ logs from wells constructed in the vicinity of San Marcos Springs. This investigation identified more than 100 borehole geophysical logs from wells in the region. The majority of logs were from oil and gas wells, and contributed greatly to the understanding of the regional stratigraphic model. Wells constructed by the EUWD in an investigation to refine the location of the Edwards Aquifer freshwater/saline-water interface (“bad water line”) (Poteet and others, 1992) were the primary source for determining the hydrostratigraphy of the aquifer and the variations in the quality of water within the study area. A cross-section of the San Marcos Springs area is shown in Plate 4.

The Edwards Aquifer in the vicinity of San Marcos Springs is approximately 500 feet thick. The Edwards Aquifer is considered to include the Georgetown Formation, Person Formation, and Kainer Formation. Additionally, these formations have been subdivided into eight separate

hydrogeologic units numbered I through VIII as described by Maclay and Small (1976). A summary of the stratigraphic, lithologic, and hydrologic characteristics of the rocks in the San Marcos Springs area is summarized in Table B-1. The Edwards Aquifer is underlain by the upper member of the Glen Rose Formation and overlain by the Del Rio Clay. Only the formations occurring within the Edwards Aquifer will be described in detail for the purposes of this report.

The Edwards Group is approximately 415 feet thick in the San Marcos Springs area and is composed of the Kainer and Person Formations. The Kainer Formation is approximately 310 feet thick in the vicinity of San Marcos Springs. The lithology of the Kainer Formation ranges from mudstone to *miliolid* grainstone to crystalline limestone. The Kainer is subdivided into four informal members that include (from bottom up) basal nodular member, dolomitic member, Kirschberg evaporite member, and the grainstone member. The basal nodular member (Unit VIII) is a tan to brown, marly, nodular limestone of about 50 - 60 feet in thickness. This lowermost unit of the Edwards Group often functions as the lower confining unit for the Edwards Aquifer in the study area. Analysis of borehole geophysical data indicates that the water quality within the basal nodular member is moderately saline in the areas down-dip of the San Marcos Springs Fault.

The dolomitic member (Unit VII) is a dense, crystalline limestone with interbedded grainstone and burrowed mudstone. The dolomitic member is approximately 110 feet thick and easily identified on the combined display of the neutron and density porosity logs by numerous “crossovers” between the plots. Analysis of borehole geophysical resistivity data indicates that the water quality within the dolomitic member is moderately saline within the vicinity of San Marcos Springs.

The Kirschberg evaporite member (Unit VI) overlies the dolomitic member and is about 50 feet in thickness. This hydrogeologic unit consists of crystalline limestone interbedded with mudstone containing chert lenses. Collapse features are common. The resulting secondary porosity makes this the most prolific of the aquifer units within the Kainer Formation. Mahler (1997) identified several wells in the Barton Springs section of the Edwards that contained dolomitic sand that was characteristic of the Kirschberg evaporite and the presence of this sand therefore suggested the wells produced from the Kirschberg. A tan-white fine-grained sand is

accumulating over many of the “sand boil” areas in Spring Lake. These sands were collected and analyzed to determine if the sands were predominantly dolomite and, if so, its presence might be used to indicate that the Kirschberg evaporite is the primary permeability zone in the San Marcos area. The sands, however, are predominantly quartz and calcite. These sands do not represent a residuum from the Kirschberg. (Appendix 3)

The grainstone member (Unit V) overlies the Kirschberg evaporite as the uppermost unit of the Kainer Formation. It is composed of thick sequences of dense, tightly-cemented, *miliolid* grainstone. Primary matrix porosity as measured on geophysical logs is some of the lowest in the Edwards Aquifer. Secondary fracture porosity accounts for the bulk of effective porosity in this aquifer unit. The grainstone member is approximately 55 feet thick in Hays County.

The Person Formation of Rose (1972) is about 160 feet thick in the vicinity of San Marcos Springs. The composition of the Person Formation ranges from crystalline limestone to grainstone to mudstone and is comprised of three informal hydrogeologic units: the regional dense member; the leached and collapsed members, undivided; and the cyclic and marine members, undivided. The lowest hydrogeologic unit within the Person Formation is the regional dense member (RDM) (Unit IV). This unit often functions as a confining layer between the upper and lower portions of the Edwards Aquifer (except in areas where fracturing and faulting facilitate vertical flowpaths). The RDM is composed of a dense argillaceous mudstone and is easily identified in outcrop and on a variety of geophysical porosity logs. The nature of this unit makes it a distinctive horizon that can be easily mapped throughout the region. The RDM is 20-24 feet thick (USGS, 1994).

Overlying the RDM are the leached and collapsed members, undivided (Unit III). This sequence of interbedded mudstone and grainstone intervals has formed a highly transmissive aquifer unit. The nature of this unit results from groundwater leaching of primary evaporites. The resulting voids weaken the rock matrix to the point that extensive collapse breccias form.

The cyclic and marine members, undivided (Rose, 1972) (Unit II) is the uppermost unit of the Edwards Group. This sequence is composed of mudstone to fossiliferous packstone and is approximately 75 feet thick.

The uppermost unit of the Edwards Aquifer is the Georgetown Formation (Unit I). This marly limestone is approximately 30 feet thick in the area of San Marcos Springs and is readily

identified by the presence of the fossil brachiopod *Waconella wacoensis*. The Georgetown is identified in geophysical logs in the area but is rarely seen in outcrop with thin, very weathered exposures. In the subsurface, the Georgetown is often a confining unit and yields little water from wells. It is a readily-mapped horizon in areas where the lower Del Rio Clay is exposed.

B.2.3 San Marcos Springs Surface Geology

In the San Marcos Springs area, the local surface geology on the up-thrown block of the San Marcos Springs Fault is generally described by an exposure of confining unit members (Eagle Ford Group, Buda Limestone, Del Rio Clay), minor exposures of Georgetown Formation (Unit I) and Person Formation (Units II) (Plate 5). During this investigation a well, identified as H-72 in DeCook (1960), on Texas State University – San Marcos campus was video logged. Unit I (Georgetown) was identified at the surface at the elevation of Spring Lake, and verifies the interpretation of the cross-section of the up-thrown block in Plate 4. This well was completed to a small cavern at a depth of 195 feet and discharges fresh groundwater under artesian pressure. An earlier well at this same location was supposedly drilled to a depth of 1,495 feet and has been reported to discharge very saline water (Glenn Longley, personal communication, 2003). Although the completion details of this earlier well are not known, this information suggests that saline water may underlie freshwater on the up-thrown block in the close proximity to the San Marcos Springs Fault.

On the down-thrown side of the San Marcos Springs Fault, the shallowest geologic substrate is the Navarro Group, which is then overlain by various alluvial deposits of the Leona Formation, Quaternary-age terraces and Recent alluvium. The thickness of this veneer of alluvium ranges from 25 ft to 40 ft, with the thickest areas being in the vicinity of Spring Lake and the San Marcos River.

B.2.4 Regional Structure

The study area occurs at the physiographic boundary between the Gulf Coastal Plain and the Edwards Plateau provinces. The boundary between these two areas is generally the Balcones Fault Zone (BFZ). The BFZ is comprised of numerous, generally parallel, normal faults, with some displacements greater than 1,000 feet. The majority of the faults are displaced down to the southeast toward the Gulf of Mexico. Some faults, particularly those in the immediate front of the BFZ are down to the northwest and form small grabens.

Locally, BFZ faults have resulted in a net displacement of as much as 750 feet across the San Marcos Springs Fault in the vicinity of San Marcos Springs. In the study area, a number of monitoring wells have been constructed by the EUWD, the predecessor agency of the Edwards Aquifer Authority. These wells were constructed as a linear transect intended to locate the Edwards Aquifer freshwater/saline-water interface (Bad-water line). These wells are shown in the cross-section on Plate 4. Borehole geophysical logs from these transect wells have provided a wealth of information on local structure/stratigraphy. The EUWD investigation identified as many as five significant faults (including the San Marcos Fault, Kyle Fault, and Comal Springs Fault) in the vicinity of wells 67-01-812, -813, and -814. The cross-section in Plate 4 used these wells in the San Marcos Springs area to identify these structures.

The major displacement is across the San Marcos Springs Fault where there is about 470 ft of vertical movement on the down-thrown block down-dip of San Marcos Springs. To the east of the main fault there are at least four faults of lesser displacement that display an alternating graben-horst-graben-horst pattern. A previous examination of borehole video logs from the monitoring wells in the San Marcos Springs transect identified numerous small displacement faults distributed across the area. Although the more significant faults have been identified, the exact location of the Kyle and Comal Springs Faults should be considered as approximate on the cross-section. In the cases of both Comal Springs and San Marcos Springs, the faults with greatest displacement are considered to have the greatest affect on the hydrogeology. In the San Marcos region, the San Marcos Fault is the primary boundary between fresh water Edwards and brackish/saline Edwards.

B.2.5 Assessment of Edwards Aquifer Water Quality from Geophysical Logs

An examination of borehole geophysical logs in the San Marcos Springs area indicates that the stratigraphy is very similar to the Comal Springs area. However, an assessment of the resistivity curves, which correlate to salinity in the groundwater, shows that all three wells in the San Marcos transect are completed within the saline-water (bad water) zone of the aquifer. The most up-dip well (67-01-814), which is less than 500 feet from the San Marcos Springs Fault and close to the eastern shoreline of Spring Lake, is completed within the saline-water zone. (For an explanation of the methods used to determine water quality within the San Marcos Springs area, see the section on the Comal Springs area described as “Assessment of Edwards Aquifer Water Quality from Geophysical Logs”.)

As yet, the presence of a freshwater zone beneath San Marcos Springs has not been identified. Groundwater discharging at Spring Lake may be coming solely from the up-thrown block or through a fault zone associated with the San Marcos Spring Fault. There is no indication from the geophysical logs that fresh groundwater is moving up the lesser faults to the southeast of the San Marcos Spring Fault. This is in contrast to the case of Comal Springs, where fresher groundwater has migrated into the Upper Cretaceous formations in the down-thrown block.

B.2.6 General Potentiometric Maps for San Marcos Springs Region

LBG-Guyton Associates prepared a potentiometric surface map to assess the general movement of groundwater in the Edwards in the San Marcos Springs area and identify faults that may exert control over groundwater movement. DeCook (1960) and Ogden *et al* (1985b) previously published potentiometric surface maps for this area. This study mapped the San Marcos potentiometric surface using Authority synoptic water level data collected in January 2002. These are presented in Plate 5 and Appendix 8. Groundwater in the San Marcos area generally flows toward San Marcos Springs with the gradients becoming relatively flat in the area surrounding the springs. To the southwest of the springs, flow is northward toward the springs. Water levels between the Comal Springs Fault and the San Marcos Springs Fault (also referred to as the Hueco Springs Fault in Comal County) decrease to the northeast toward San Marcos. In the areas of the Blanco River and Kyle, flow is south toward the springs.

Synoptic water levels used in this potentiometric surface map do not cover the area north of Kyle. However, a groundwater divide has been previously documented by LBG-Guyton Associates (1994) between Kyle and Buda. Groundwater to the south of this divide is discharged from Kyle wells, San Marcos wells, and San Marcos Springs. Groundwater north of the divide flows toward Barton Springs. The January 2002 data also indicate a closed contour around Kyle that is presumably the result of municipal pumping for Kyle.

Interestingly, San Marcos' municipal pumpage is not evident as a closed contour (as was Kyle's) that was separate from spring discharge effects. It may be because San Marcos has only pumped an average of 2.9 cfs from their municipal wells in recent years. Withdrawals in January (the month the water level data of Plate 5 were collected) are typically lower than the average. The discharge of San Marcos Springs was about 310 cfs in January 2002. Spring discharge is therefore the dominant influence on San Marcos area water levels under normal spring flow

conditions. Municipal pumping should have a relatively minor effect on the shape of the potentiometric surface or the mass balance of water moving through this part of the aquifer under normal conditions.

The 2002 synoptic data indicate the elevation of the potentiometric surface around Spring Lake is 5-8 feet higher than the lake level. A continuously-monitored well completed in the Edwards, well 67-01-809, has a lengthy data record that may be used to evaluate aquifer levels near the springs. Well 67-01-809 is located approximately 0.8 miles northwest of the springs, and has been monitored frequently since 1980. A plot of well 67-01-809 water levels vs. San Marcos Springs flow is presented in Figure B-20. A linear regression of this curve implies a discharge increase of approximately 26 cfs for every foot of water level increase at this location for well 67-01-809 levels above 576 ft MSL.

Making the simplifying assumption that lake levels are 573.5 ft at all flows, the flow can be modeled as a function of height above lake elevation. Further assuming velocity heads to be negligible – i.e., velocities less than about 2 ft/s – the water level difference between well 67-01-809 and Spring Lake represents the head loss between the two locations.

For a flow regime in which laminar flow was dominant, the flow would vary linearly with this head loss and would be modeled with the Darcy equation. However, for a flow regime in which turbulent flow was dominant, the flow would vary with the square root of the head loss, and could be modeled with the Darcy-Weisbach equation. Using the assumptions noted above and calibrating both equations for unknowns (friction and dimensional factors) at 3 feet of head above dam elevation and assuming that these unknowns remain constant at all heads, the resulting curves for flow as a function of both Darcy and Darcy-Weisbach head loss are given in Figure B-21. The plot of well 67-01-809 levels versus San Marcos Springs flow (Figure B-21) appears to correspond more closely to a turbulent flow model than a laminar flow model. This suggests that under most conditions turbulent flow will dominate near the discharge orifices at San Marcos Springs. Worthington (2003) has made similar observations and analyses for Barton Springs and Comal Springs. The presence of turbulent flow may explain the water level difference of 5-8 ft between the aquifer and the lake at high flow conditions.

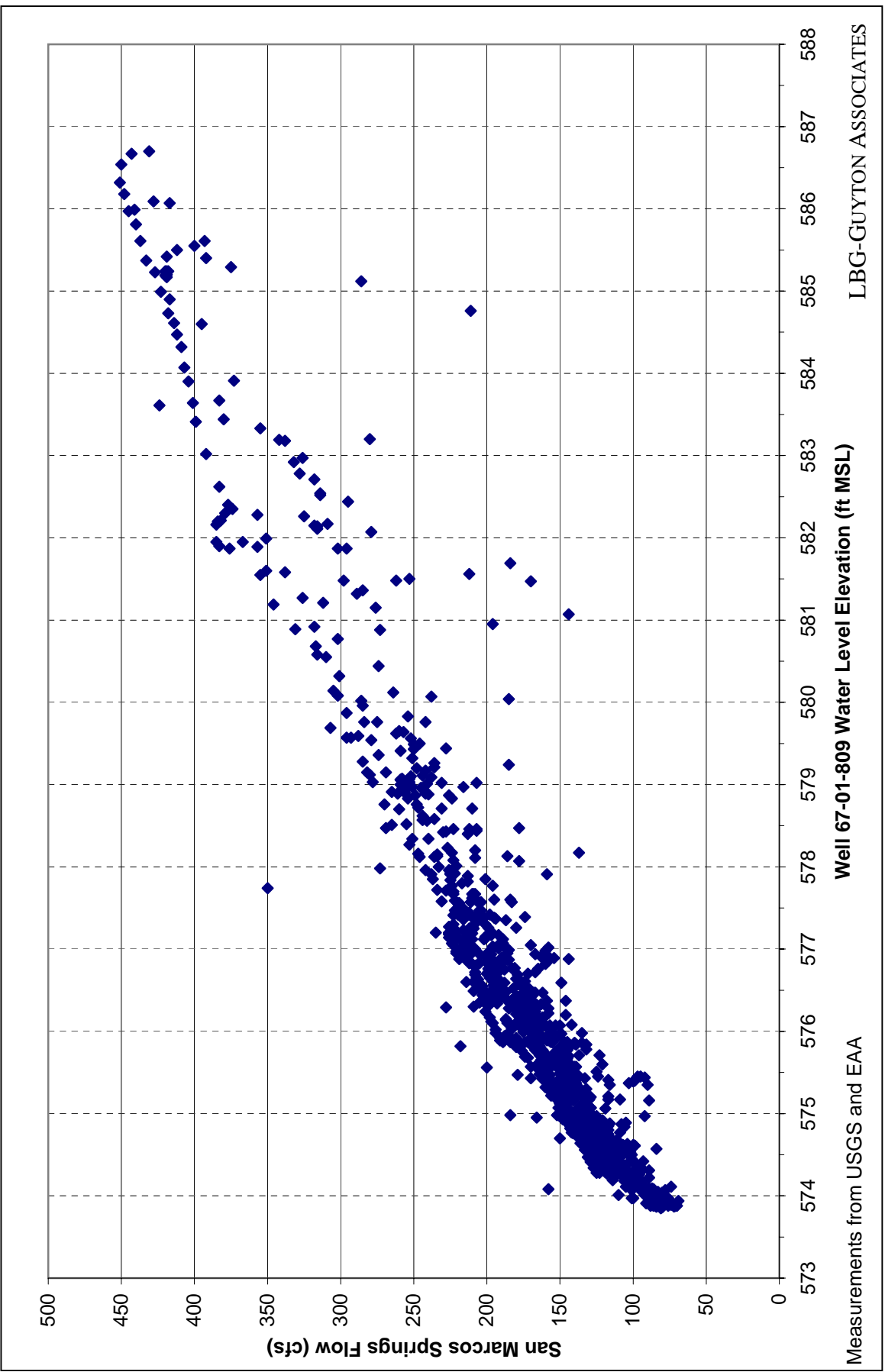


FIGURE B-20 VARIATION OF SAN MARCOS SPRINGS DISCHARGE WITH WELL 67-01-809 WATER LEVEL

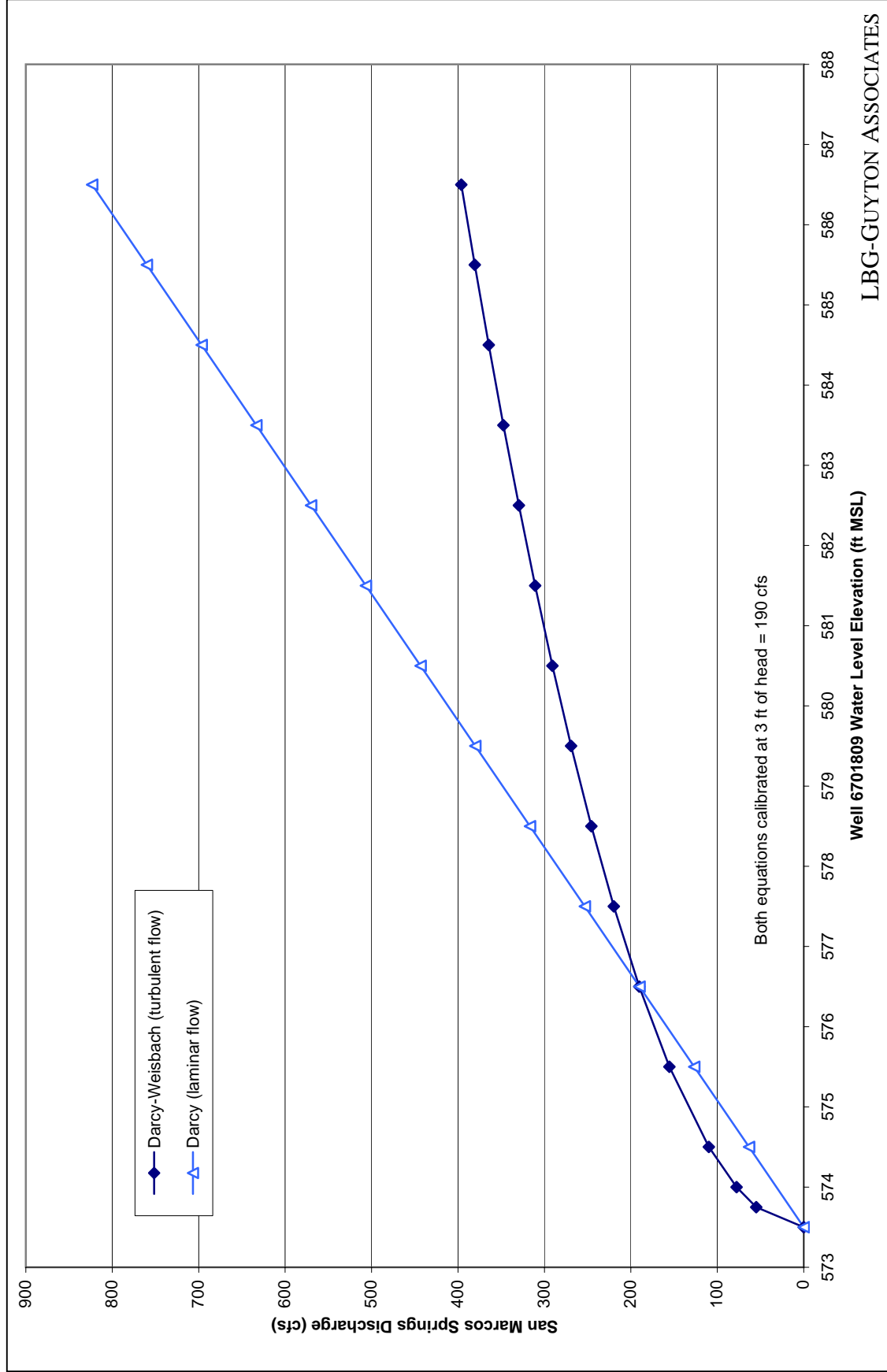


FIGURE B-21 MODELED SAN MARCOS SPRINGS FLOW VS. HEAD

San Marcos Springs Fault

San Marcos Springs discharge into Spring Lake, which lies on the San Marcos Springs Fault. The San Marcos Springs Fault is an extension of the Hueco Springs Fault into Hays County. Comal Springs Fault lies on parallel lines but approximately 0.5 miles to the southeast. The area to the northwest of San Marcos Springs is heavily faulted in the northeast/southwest strike direction, as can be seen on the geologic base map of Plate 5.

Most of the wells completed in the up-thrown block of the Edwards north of San Marcos Springs Fault are located on the outcrop of the Cyclic and Marine Members, undivided (informal hydrogeologic subdivision II), the outcrop of the Georgetown Formation, or the outcrop of upper confining units. On the up-thrown side of the San Marcos Springs Fault (Hueco Springs Fault), cross-faults with a displacement of approximately 200 ft separate the western up-thrown lower hydrogeologic units of the Edwards from the eastern down-thrown units on which many of the wells in the San Marcos area are located. These up-thrown units extend east from Comal County and receive water from north of the Hueco Springs Fault. Only one well (State Well No. 68-16-603 in southwest Hays County) in the synoptic water level data for the San Marcos Springs area is located on the up-thrown side of these cross faults. The level of fault control of flow from Comal County north of Hueco Springs Fault is therefore difficult to determine.

The one well for which there are data in these lower units does indicate some control of flow across a cross-fault. Well 68-16-603 is a 230-ft well (cased to 154 ft) owned by the City of San Marcos located on the up-thrown side of San Marcos Springs Fault in the outcrop of the leached and collapsed members, undivided (Unit III) in the southwest corner of Hays County. Water levels in this well are consistently 50-60 ft higher than those of nearby wells on the other side of the inferred transverse fault. Table B-5 provides water level data for well 68-16-603 and well 67-09-106, which is located on the outcrop of the Del Rio Clay on the up-thrown side of San Marcos Springs Fault. Both wells are shown on Plate 5, with water level data from January 2002. This difference in water levels suggests some hydraulic control of flow from the southwest on this inferred cross-fault. No data are available for similar comparisons for fault blocks to the north such as Academy Fault and Bat Cave Fault which likely receive flow from the southwest. Southwest of San Marcos, the San Marcos Springs Fault does not appear to serve as a hydrologic barrier. Locations and water levels for wells on both sides of the fault at the springs are

Table B-5
Comparison of Cross-Fault Water Levels On the Up-Thrown Block of San Marcos Springs Fault

Measurement Period	6709106 Water Level (ft)	6816603 Water Level (ft)
July 1999	580	635
October 1999	578	634
January-February 2000	578	629
July 2000	578	Not Measured
October-November 2000	578	Not Measured
February 2001	583	639
July 2001	581	637
October-November 2001	580	637
January 2002	585	642
July 2002	589	646

Source: EAA/EARDC Synoptic Water Level Measurements

Well Information

6709106

Fish & Wildlife; Total Depth 402 ft

6816603

City of San Marcos - Oakridge Station; Total Depth 230 ft

illustrated on Plate 5 for the January 2002 period. Water levels are similar on both sides of the fault.

The water levels for two wells completed on opposite sides of the San Marcos Springs Fault (well 67-09-106 up-thrown block and well 67-09-110 down-thrown block) are shown in Table B-6. A horizontal distance of approximately 0.75 mile separates these wells. Synoptic water level data collected in these two wells over a four-year period does not indicate a significant difference in hydraulic potential over time. From these data it appears that the San Marcos Springs Fault is not a significant barrier to flow in this location. Fresh groundwater is also found in the down-thrown block. However, by the time groundwater flows to San Marcos Springs there is no fresh water on the down-thrown side of the San Marcos Springs Fault. Groundwater in the region of well 67-09-110 may be being forced to the up-thrown side of the San Marcos Springs Fault. The upper zones of this well are fresh, whereas deeper zones in this well are saline (Schultz, 1993). Between well 67-09-110 and San Marcos Springs all fresh groundwater is now flowing on the up-thrown side of the San Marcos Springs Fault. There are no fresh-water water wells on the down-thrown block.

Both recent and historical Edwards water level data show that San Marcos Springs are the end of the regional groundwater for this part of the Edwards aquifer. Previous reports by LBG-Guyton Associates and others have noted the presence of a groundwater potentiometric divide between Kyle and Buda, and this divide appears to be present in the current water level data. This results in a potentiometric low around San Marcos Springs, and therefore, all groundwater from this part of the aquifer has to discharge at San Marcos Springs. Flow cannot bypass the springs and flow toward Travis County and Barton Springs. Recognizing that a spring is at the “end of the flow system” may be an important consideration in determining whether a spring could go dry during an extreme drought. As long as there is a hydraulic gradient toward a spring, and therefore water in the aquifer, groundwater should discharge at the spring. This may explain why San Marcos Springs maintained flow in the summer of 1956. A spring could go dry only if local pumpage caused water levels to drop below the elevation of the springs (i.e., local pumpage replaced the spring as the point for groundwater discharge).

Table B-6
Comparison of Up-thrown and Down-thrown Water Levels On San Marcos Springs Fault

Measurement Period	6709106 (Upthrown) Water Level (ft)	6709110 (Downthrown) Water Level (ft)
July 1999	580	579
October 1999	578	578
January-February 2000	578	577
July 2000	578	578
October-November 2000	578	577
February 2001	583	583
July 2001	581	580
October-November 2001	580	580
January 2002	585	584
July 2002	589	589

Source: EAA/EARDC Synoptic Water Level Measurements

Well Information

6709106	Fish & Wildlife; Total Depth 402 ft
6709110	USGS; Total Depth 634 ft

B.2.7 Source of Water to San Marcos Springs as Determined by Spring Hydrographs

Spring discharge hydrographs for San Marcos Springs have a different characteristic shape when compared to discharge curves for Comal Springs. Figure B-22 shows spring discharge for both Comal Springs and San Marcos Springs. For Comal Springs, spring flows can rise and fall rapidly. Discharge data for San Marcos Springs has a characteristic curve that is different than the typical curve for Comal Springs. San Marcos Springs rises rapidly, declines rapidly and then has a long “recessional” tail. For the 1986 to 1996 time period three characteristic curves are evident: from June 1987 to June 1990, from June 1992 to October 1994, and from June 1995 to October 1996 (Figure B-23). For each “event” there was a rapid rise and fall, and then a long-term slow decrease in spring flow. This “shape” to the spring discharge is analogous to a hydrograph for a rain storm on a drainage basin where the rapid rise in stream flow results after a rain and then later there is a recession part of the curve that is the transition from surface runoff to base flow from groundwater (see Pilgrim and Cordery, 1993 for examples). This type of spring hydrograph is also common in other karst settings (see Wicks and Bohm, 1997 for example). In this context, the discharge curves for San Marcos Springs are considered to indicate that two sources of water are discharging at the springs: 1) a local source (the rapidly peaking part of the curve) and 2) a more regional flow component (the slow decline that may extend for 1 to 2 years). This local source is considered to be recharge from the Blanco River and associated drainage basins in Hays Counties. The regional source is the steady flow of groundwater in Edwards fault blocks on the up-thrown side of the Comal Springs Fault that is bypassing discharge to Comal Springs. A time series plot of water level data for well 67-01-809 and San Marcos Springs flow for the time period of June 1, 1991 to March 30, 2003 shows similar shapes to their curves (Figure B-24). This characteristic shaped curve for aquifer water levels also indicates the aquifer receives recharge from two different sources, a local recharge source and a more regional flow component. It is not surprising that the water level data for well 809 has a similar curve to the discharge curve since the impact of both water sources should be present at the well and at the spring.

B.2.8.1 Local Sources

In order to document the response of San Marcos Springs flow to recharge events over the Edwards outcrop in Hays and Comal Counties, surface flow hydrographs from the Blanco River

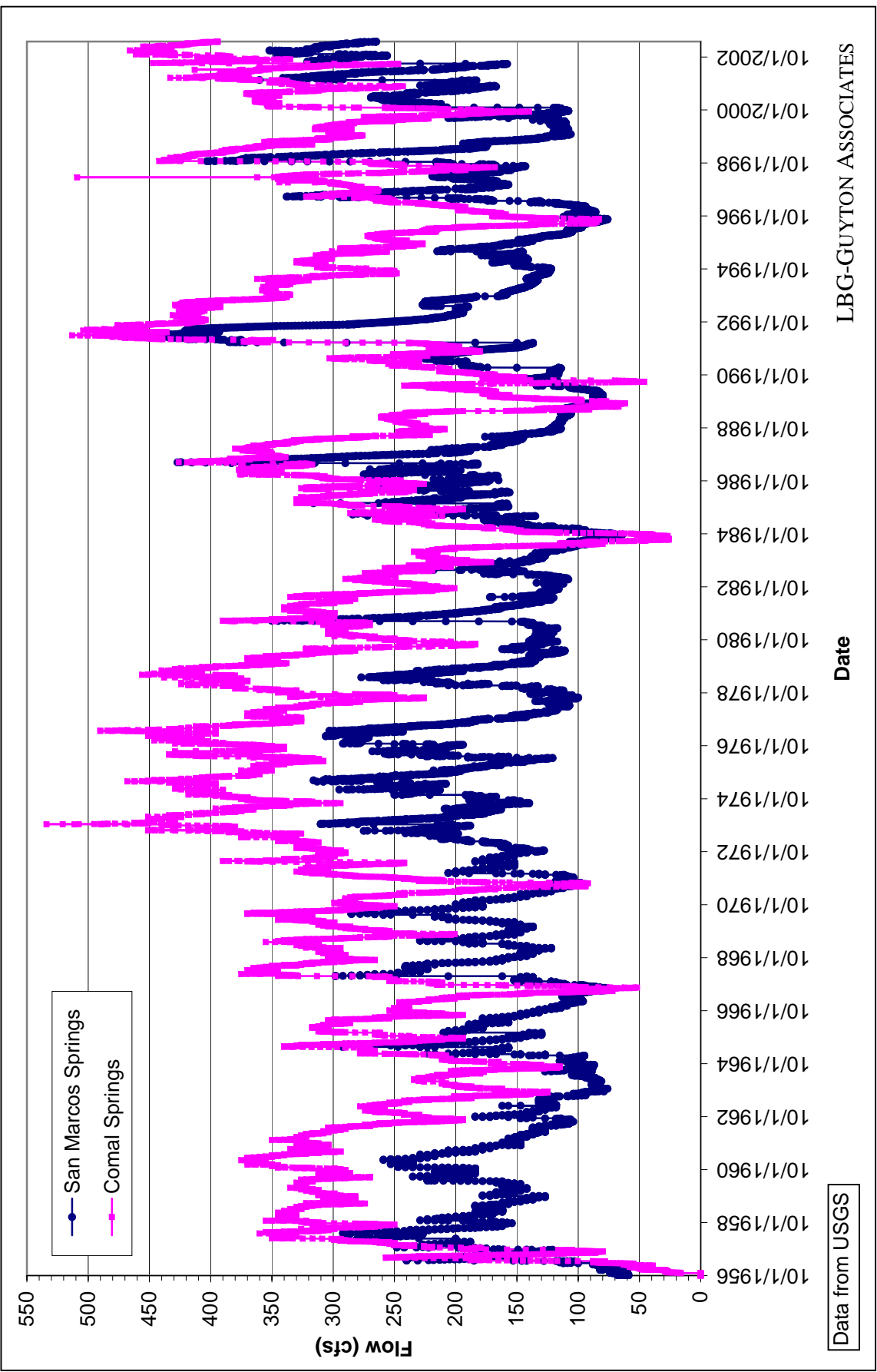


FIGURE B-22 COMAL AND SAN MARCOS SPRINGS FLOW 1956 TO 2001

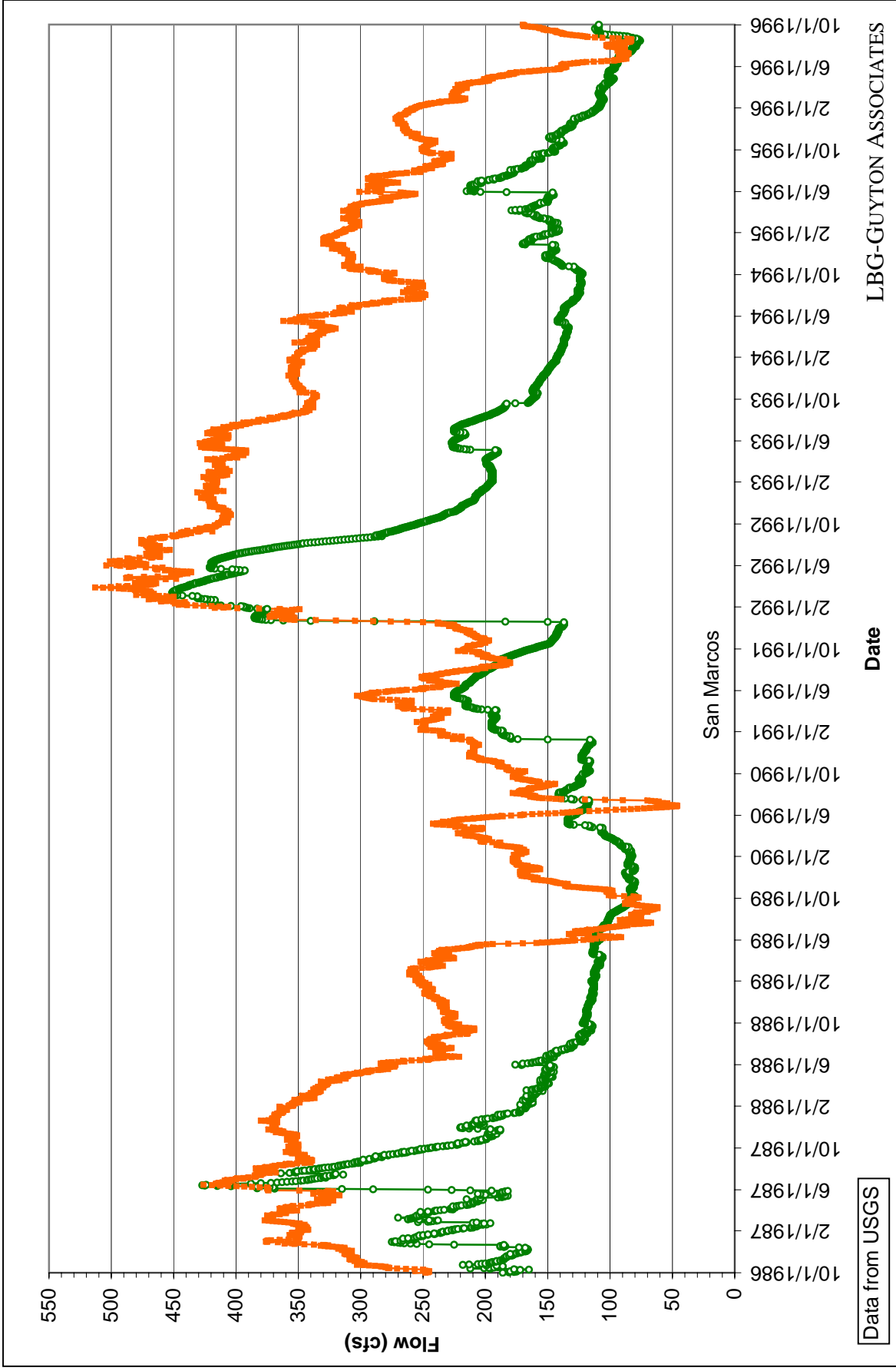


FIGURE B-23 COMAL AND SAN MARCOS SPRINGS FLOW 1986 TO 1996

Data from USGS

Date

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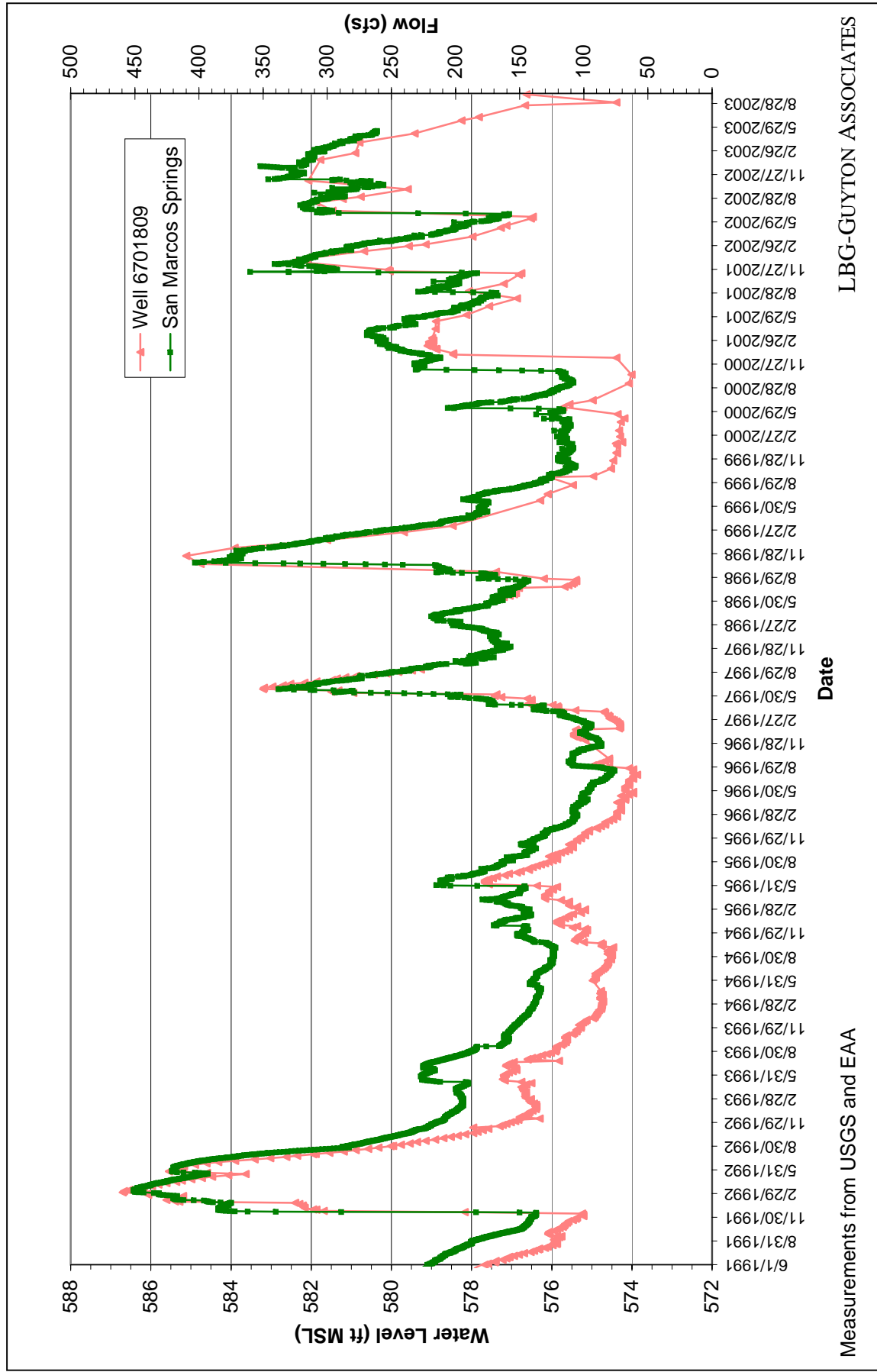


FIGURE B-24 WELL 67-01-809 WATER LEVELS AND SAN MARCOS SPRINGS FLOW 1991 - 2003

were compared to San Marcos Springs flow. Figure B-25 presents San Marcos Springs and Blanco River above Kyle discharge flow April 1985 - April 1988. The spring discharge curves mimic the flood curves in the Blanco River hydrograph, suggesting a recharge/spring discharge relationship on a similar but reduced scale. The spring discharge hydrograph demonstrates a rapid response to recharge events characteristic of conduit flow.

Discharge curves for San Marcos Springs indicate that spring discharge is strongly affected by hydrologic events in the recharge area north and west of the springs, and to a lesser extent the local recharge in the San Marcos area. Discharge curves for San Marcos Springs and the Blanco River near Kyle plotted against San Marcos daily precipitation illustrate that regional precipitation events have to be large enough to produce flow in the Blanco River before there are increases in San Marcos Springs flows (Figure B-26). In contrast, the lack of significant flow response from local precipitation events during these times suggests that local recharge such as from Sink Creek or Purgatory Creek is generally a minor component of flow from San Marcos Springs.

Three different gain-loss studies have been performed over subreaches of the Blanco to assess recharge to the Edwards from the Blanco River (TBWE, 1960 and Slade et al, 2002). These are summarized in Table B-7. All three studies were performed in the summer. All three studies reported losses of 15-16 cfs over the total Edwards outcrop on the Blanco River. Only the 1957 study separated losses over the Kainer and Person subreaches. These were 6.7 cfs and 8.9 cfs, respectively. There were no surface inflows during these studies.

Ogden and others (1986) reported a successful dye-trace to San Marcos Springs from Tarbutton's Showerbath Cave, a 30-ft deep cave adjacent to the Blanco River at the end of the subreach exposed to the Person Formation.

Gain-loss studies on the Blanco River and dye-traces from the Blanco River to San Marcos Springs demonstrate a direct recharge component to the Edwards from the Blanco River. However, the amount of recharge from the Blanco River as measured in gain-loss studies (summarized in Slade et al, 2002) is insufficient to account for all of the increased flow observed at San Marcos Springs. The Blanco River discharge hydrograph serves as an indicator of a recharge event from the north and west of both the Comal Springs Fault and the Hueco/San Marcos Springs Fault. More recharge water is needed than just what is available as loss solely

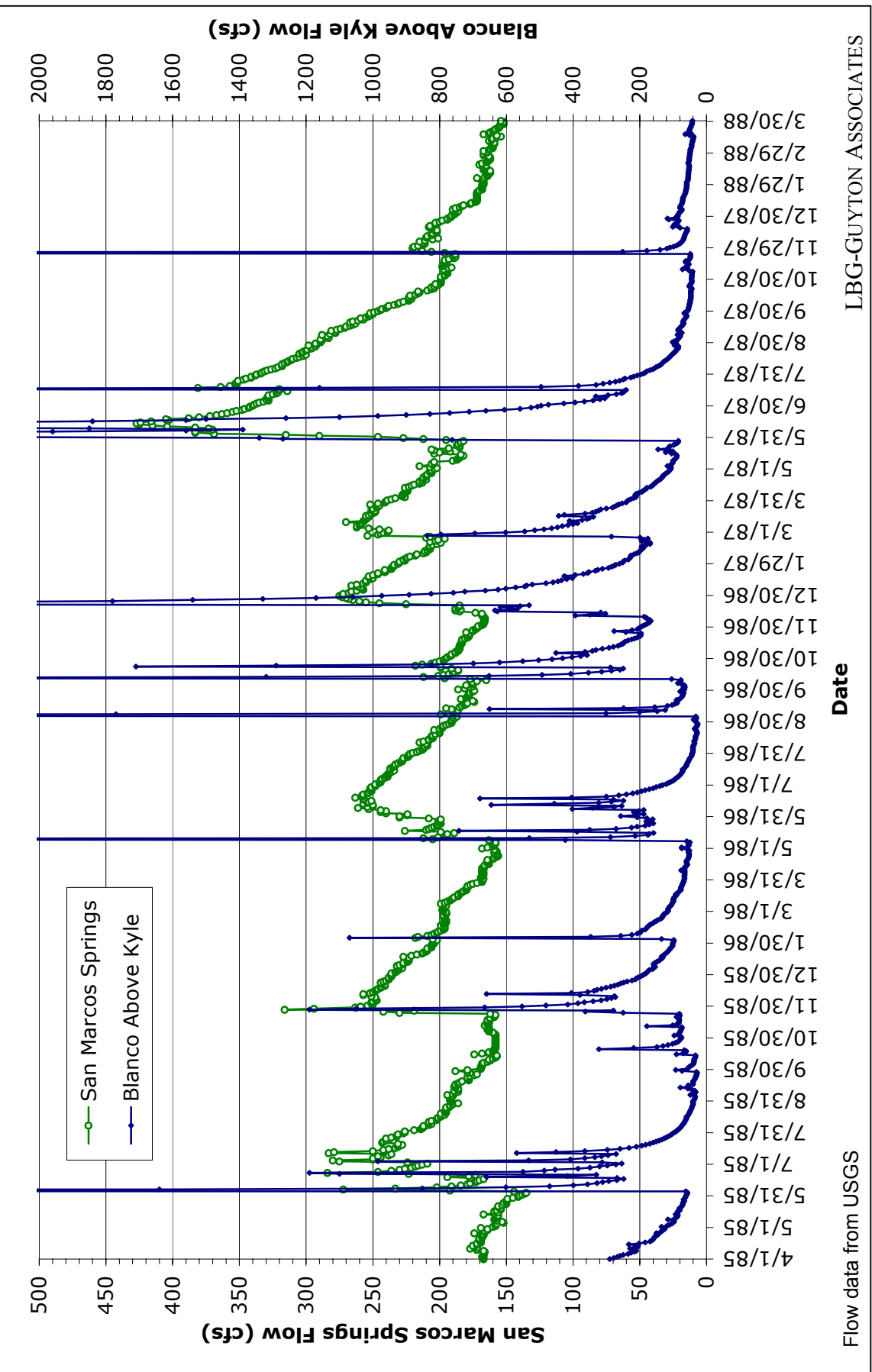


FIGURE B-25 SAN MARCOS SPRINGS AND BLANCO RIVER FLOWS APRIL 1985 - APRIL 1988

Flow data from USGS

LBG-GUYTON ASSOCIATES

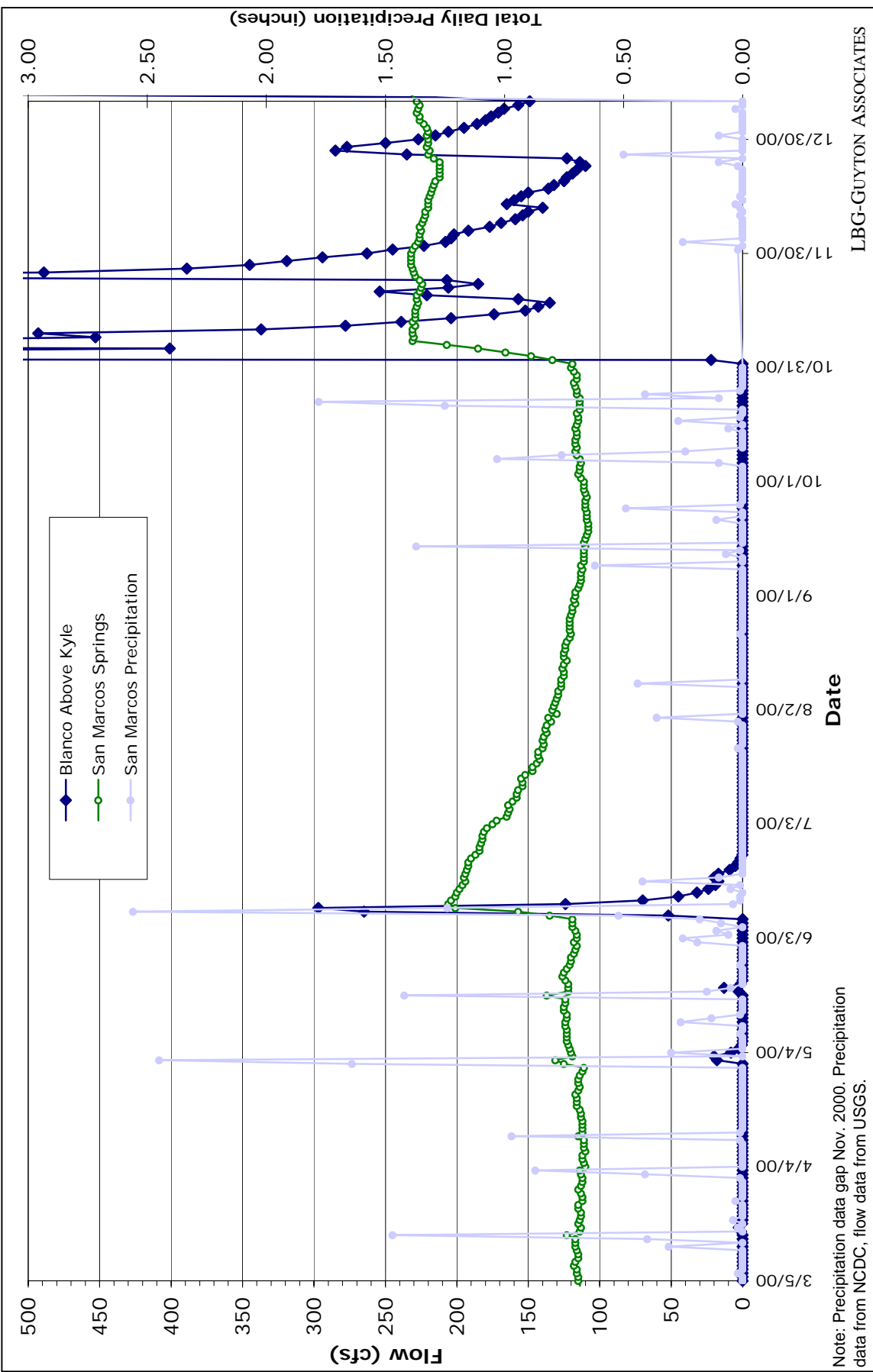


FIGURE B-26 SAN MARCOS SPRINGS AND BLANCO RIVER FLOWS WITH PRECIPITATION 2000

Streamflow Study No.	Date	Major Outcrop Intersected by Subreach	Latitude of Upstream End of Subreach	Longitude of Upstream End of Subreach	Length of Subreach (river mi)	Upstream End Discharge (cfs)	Downstream End Discharge (cfs)	Tributary or Diversion Flows (cfs)	Gain (+) or Loss (-) in Subreach (cfs)
101	July 11, 1957	Edwards (Kainer Formation)	30° 00' 15"	97° 57' 19"	1.3	64.1	57.4	0	-6.7
101	July 11, 1957	Edwards (Person Formation)	30° 00' 33"	97° 56' 09"	3.8	57.4	48.5	0	-8.9
102	June 12, 1924	Edwards (Kainer and Person)	30° 00' 23"	97° 57' 23"	8.0	231	216	0	-15
103	July 15, 1924	Edwards (Kainer and Person)	30° 00' 23"	97° 57' 23"	8.0	67.7	51.9	0	-15.8

Sources:

1. USGS Open-File Report 02-068 Results of Streamflow Gain-Loss Studies in Texas, With Emphasis on Gains From and Losses to Major and Minor Aquifers
2. TBWE Bulletin 5807 D Channel Gain and Loss Investigations in Texas Streams 1918 - 1958

from the Blanco River. Other parts of the Blanco River drainage basin need to be considered as well as other drainage basins, such as the Guadalupe River basin.

Discharge hydrographs from the Guadalupe River above the Comal River might also be used to provide a similar indication of a regional recharge event from the Guadalupe River drainage basin in the Edwards in southern Hays and Comal Counties. However, since 1964, the flow has largely been controlled by Canyon reservoir releases. The discharge hydrograph is not necessarily representative of runoff from a regional storm event. Discharge data for the Guadalupe above Comal River for the 1956-1964 period (the period for which continuous gaging is available for San Marcos Springs and the pre-Canyon Dam Guadalupe River) does show a general correlation between the Guadalupe River and San Marcos Springs flows. Post-1964 data comparisons between the Guadalupe and San Marcos Springs, however, do not. There seems to be little or no correlation between Guadalupe River flows and San Marcos Springs flows after 1964. The correlation of pre-1964 Guadalupe River flows and San Marcos Springs flow may represent regional recharge events' impact on both the Guadalupe River and San Marcos Springs flow, rather than as evidence of direct recharge from the Guadalupe River itself.

B.2.8.2 Base Flow

The base flow component of these San Marcos Springs discharge curves (Figure B-23) would suggest approximately 100 cfs resulting from "regional groundwater" for the time period from 1986-1996. For the two drought periods during 1956 and 1984 this regional flow component appears to have dropped to approximately 50 cfs, which is the lowest approximate flow observed at the San Marcos Springs. Figure B-27 compares San Marcos Springs flow to water levels in the Landa Park well. There are two components to this curve: 1) for water levels in Landa Park well from 613 ft to 620 ft, and 2) for Landa Park well water levels greater than 620 ft. The data in the first group indicate a good correlation between San Marcos Springs flow and Landa Park well water levels (up-thrown block). This confirms a hydrologic connection between San Marcos Springs and the water in up-thrown block that is bypassing Comal Springs. It should be noted that the water levels in Landa Park well are low enough that none of this groundwater in the up-thrown block at Comal Springs is discharged to Springs #1, #2, or #3. There were also no "local" recharge events in the Blanco River drainage basins to create spikes in the hydrographs during these times. Group (2) shows the impact of local recharge to San Marcos Springs flow. In

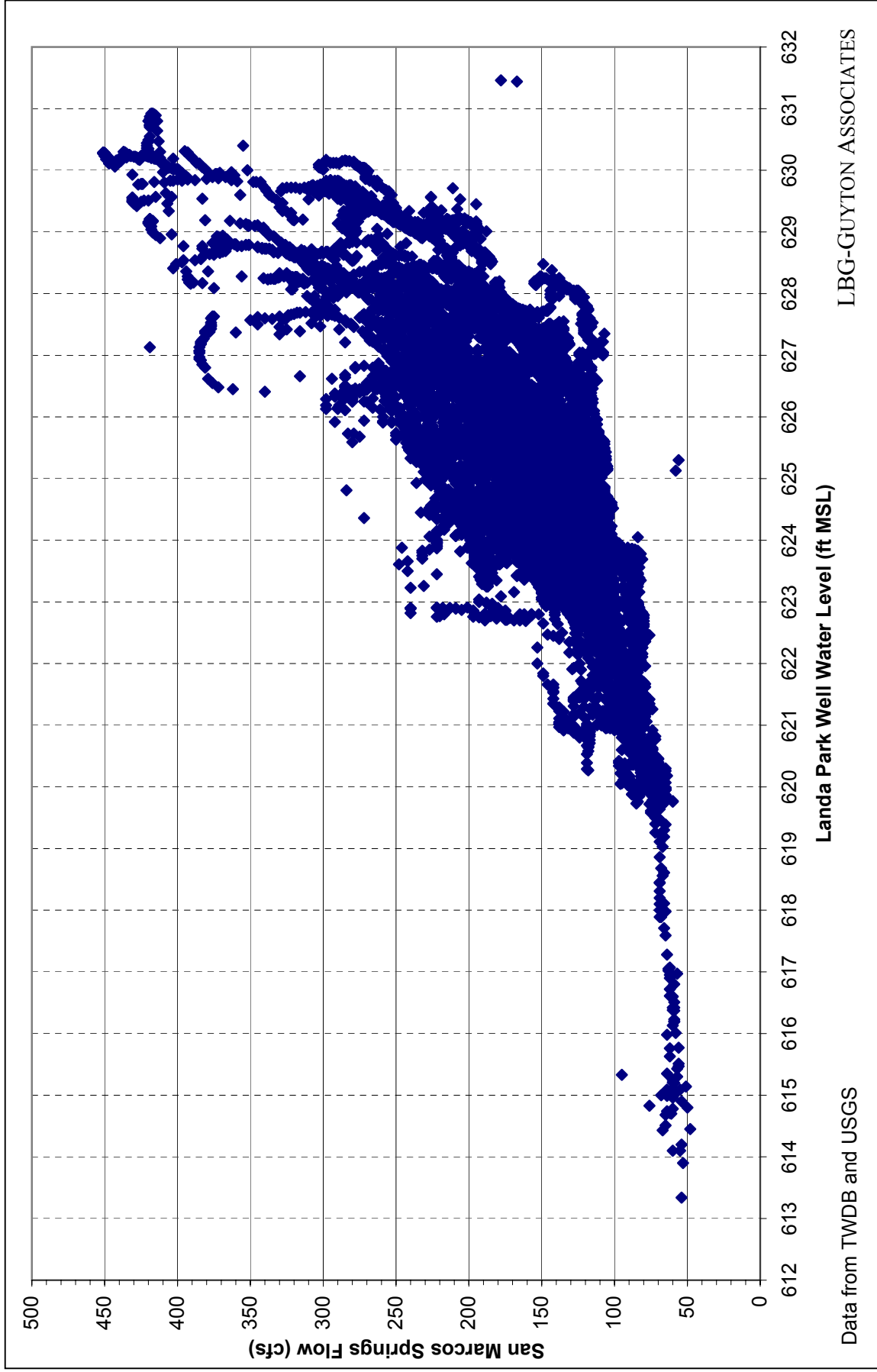


FIGURE B-27 LANDA PARK WELL VS. SAN MARCOS SPRINGS

Group (2) there is no obvious correlation between the San Marcos Springs flow and Landa Park well water levels. One can infer, however, that the linear trend observed in Group (1) would extend along the base of the Group (2) data, this would again indicate that under normal conditions the regional base flow to San Marcos Springs would be about 100 cfs.

A comparison of spring flow curves from both San Marcos Springs and Comal Springs shows that discharge at San Marcos Springs often does not track the discharge at Comal Springs. The best example of this lack of correlation is a comparison of spring flows from June 1988 to June 1990 (Figure B-28). Other examples are shown in Appendix 9. From the end of May 1988, Comal Springs flows decline from about 240 cfs to 60 cfs in the beginning of September. Then there is a rapid increase to about 175 cfs by mid-October. For this same time period, San Marcos Springs discharge showed a slow decline from about 110 cfs to 85 cfs. Spring flow at Comal Springs correlates well with water levels in the 7 well, indicating that Comal Springs discharge often is representative of groundwater levels and conditions in the general artesian aquifer upgradient from Comal Springs (San Antonio pool).

This lack of correlation between San Marcos Springs and Comal Springs discharge curves suggests that the Hays County section of the Edwards Aquifer is partly a separate pool of groundwater. The previously discussed evaluation of sources of groundwater discharging at San Marcos Springs indicated the presence of a local source of water derived from the Blanco River drainage basin. The lack of spikes in the 88-89 discharge curve for San Marcos indicates that there are few local recharge events influencing San Marcos, therefore much of the San Marcos Springs flow in this period must be related to the "regional source." Paradoxically, the rapid increase of spring flow at Comal in the fall (indicating overall higher water levels in the aquifer hydrologically upstream from Comal) is not carried through to the San Marcos section as increased spring flow. A hydrologic boundary must prevent this increase in flow at Comal from being passed on to San Marcos. The hydrologic condition must be Comal Springs itself. If about seventy-five percent of the spring discharge at Comal Springs is from groundwater flow in the down-thrown block, then the increased amount of groundwater in this part of the aquifer (the down-thrown block) ends up as increased spring discharge. And because this part of the flow system ends in Landa Lake, none of this water can continue to flow onto San Marcos. The only water that can flow to San Marcos Springs is water in the up-thrown block. Increased water levels in the up-thrown block, however, result in increases in spring discharge from Comal

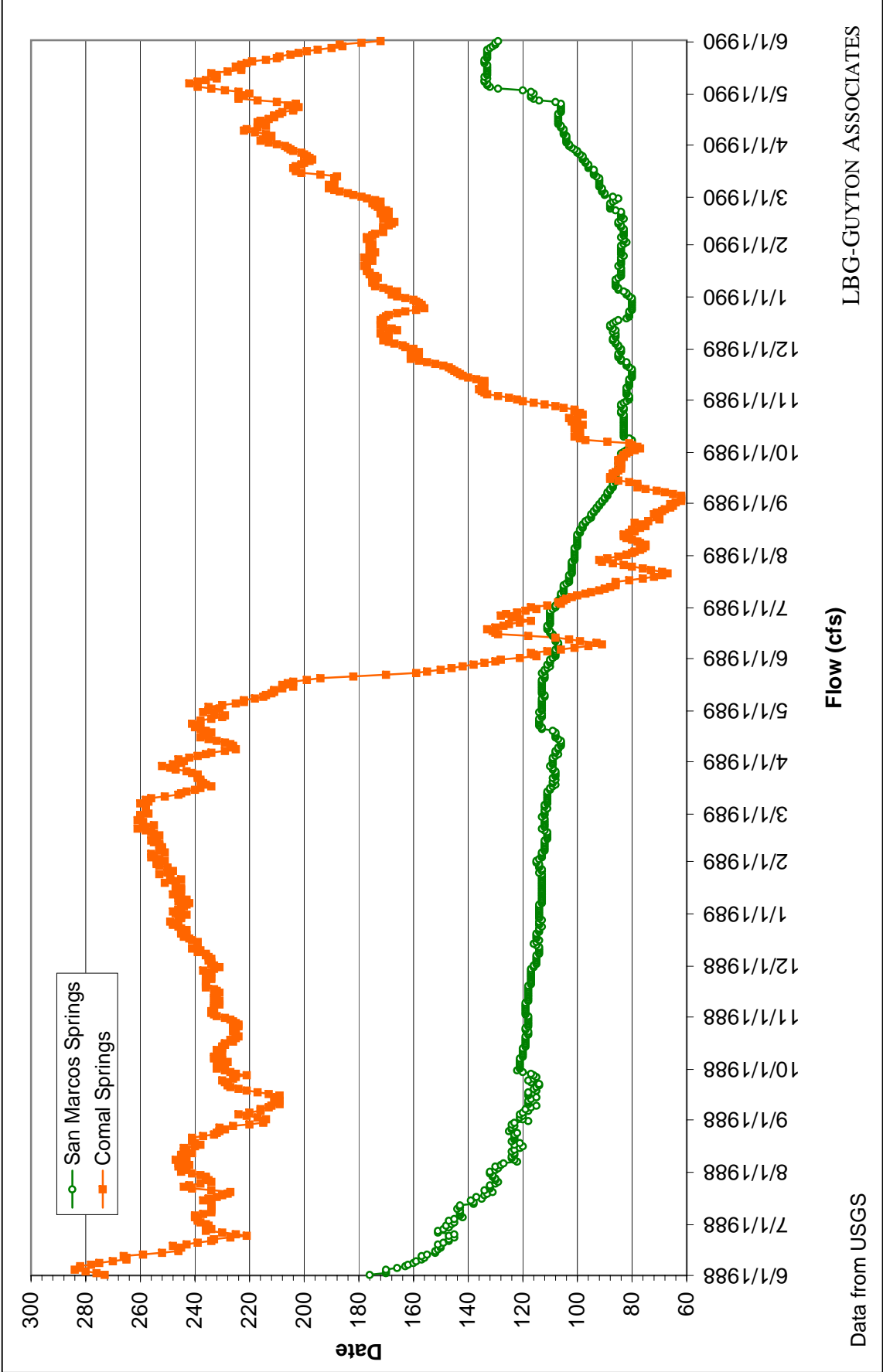


FIGURE B-28 SAN MARCOS SPRINGS AND COMAL SPRINGS FLOW JUNE 1988 TO JUNE 1990

LBG-GUYTON ASSOCIATES

Data from USGS

Springs #1, #2 and #3 rather than significant increase in flow to San Marcos Springs. Increased heads and increased flows in the up-thrown and down-thrown blocks of the aquifer (upgradient from Comal Springs) do not result in comparable increased flows at San Marcos. From low-flow to high-flow conditions the regional base flow only increases 50 to 100 cfs.

B.2.8 Location and Amount of Groundwater Produced in Area Around Springs

The amount of groundwater produced from Edwards wells in the San Marcos area is important to a discussion of spring flow and potential augmentation strategies. The Texas Water Development Board (TWDB) Water Use Survey indicates that in 2000 the city of San Marcos began to obtain approximately two-thirds of its municipal water supply from surface water, with the remaining one-third from groundwater. These groundwater withdrawals averaged 2.9 cfs in 2001. Before 2000, the city was completely on groundwater, and withdrawals averaged approximately 10 cfs.

B.2.9 Hydrogeologic Conditions at San Marcos Springs

B.2.9.1 Location, Spring Locations (Bathymetric Map), Photographs of Springs

San Marcos Springs (also known as Aquarena Springs) are located in the City of San Marcos in southeast Hays County. The springs discharge into Spring Lake and ultimately into the San Marcos River. Sink Creek flows into Spring Lake from the east. Two connected dams control outflow from the lake on the western end. One of the earliest photographs of Spring Lake was published by Taylor (1904). This view was presumably taken in the late 1800's or early 1900's. The dams were constructed before 1900 (Figure B-29). The springs were later a part of a developed resort area purchased in 1926. The construction and development of the resort hotel and water park began in 1928. The springs were purchased by Texas State University in 1994.

The springs at the San Marcos Springs are all within Spring Lake (Plate 6). No subaerial springs discharge at land surface and flow to the lake as occurs at Comal Springs. Thirteen spring areas, or craters, are on the lake bottom. The names of the individual springs were bestowed over the years by the glass-bottom boat guides at Aquarena Springs and included Crater, Hotel, Johnny Weissmuller, Cabomba, Salt and Pepper I, Salt and Pepper II, Diversion, Cream of Wheat, Ossified Forrest, Riverbed, Catfish Hotel, Deep (Hole) and Kettleman's. The northern most spring is Crater Spring and the southern most spring area is Kettleman's Spring. Although there are depressions south and east of Kettleman's Spring, no groundwater discharge was observed in these areas toward the dam.



VIEW AT SAN MARCOS, TEX., SHOWING POWER PLANT AND END OF LAKE.

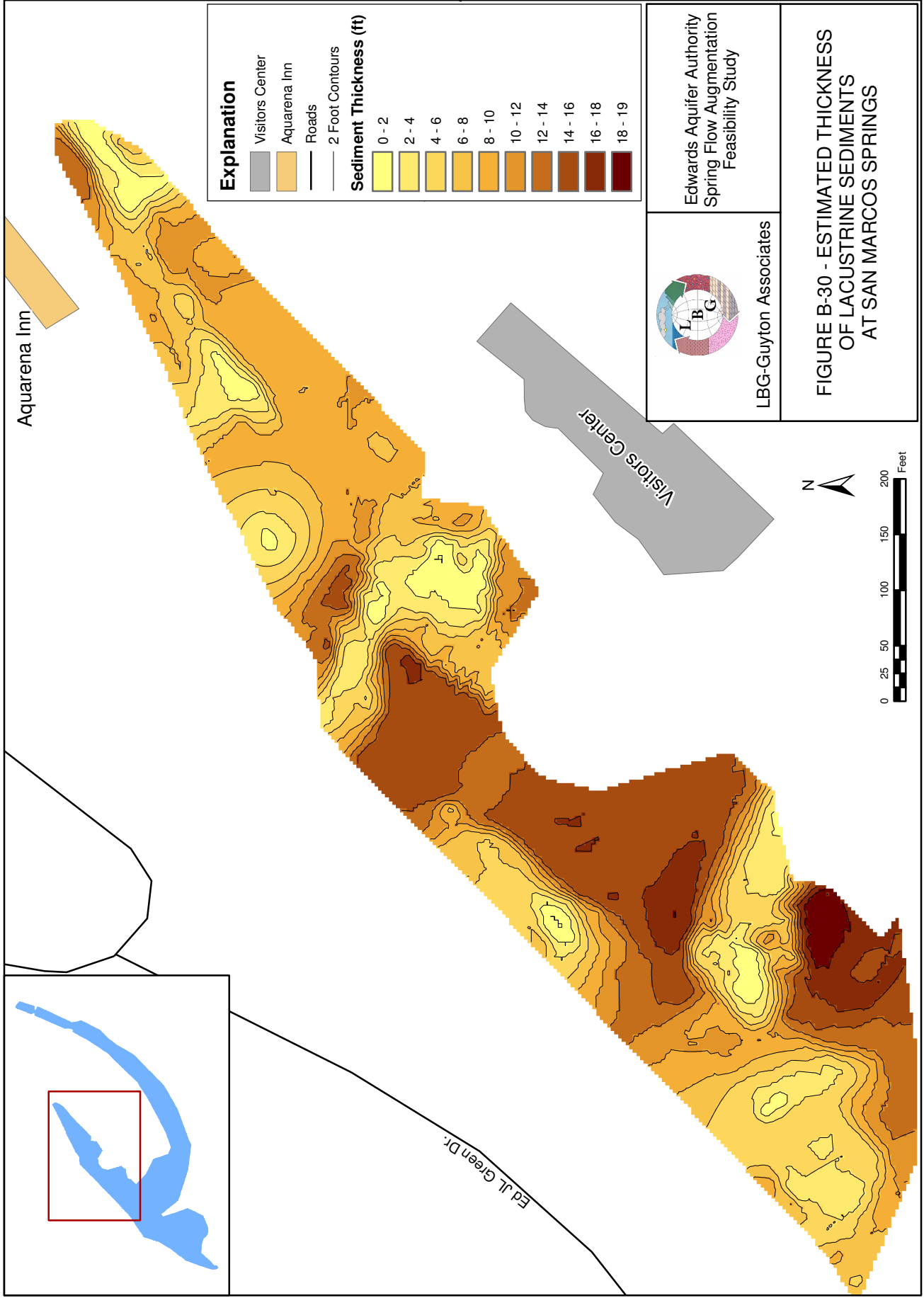
FIGURE B-29. Spring Lake, San Marcos, Texas, showing power plant and western end of lake. Photographed about 1900.
(Taylor, 1904)

All springs are either closed depressions or interconnected depressions. Most are on the north side of the lake where their locations may be controlled by a stream that existed before the construction of the lake, and possibly from an underlying structural feature. Many of the springs area are parallel to sub-parallel to the strike of the faulting. The springs are within individual craters down cut and eroded into a thick (up to twenty feet) layer of lacustrine or marsh sediments (Figure B-30). (Thickness calculations in Figure B-30 were derived by subtracting the general elevation of the spring craters from the bathymetric elevation of the lake bottom). The sediment composition of this lacustrine/marsh strata is predominately fine-grained, although some of non-spring areas are composed of sands and cobble-sized limestone rubble. Most of the non-spring area is covered in extensive growth of grasses, which make it difficult to document in detail the sediment type of the substrate. Some of the springs may have been excavated at the time when Aquarena Springs Resort was built. Photographs of select individual springs are presented in Figures B-31 to B-34.

B.2.9.2 Discharge Rates, Total Spring Flow, Individual Spring Flow

Daily discharge from San Marcos Springs is measured at USGS Station 08170000 on the San Marcos River approximately 500 ft south of Spring Lake. Recorded daily average discharge rates for San Marcos Springs range from a low of 46 cfs (August 1956) to a high of 451 cfs (March 1992). The historical long-term daily average discharge is 172 cfs (1956-2003). The gage can receive relatively small amounts of non-spring flow - perhaps 3 cfs under normal conditions – from Sessom Creek (just above the gaging station at Aquarena Springs Drive) and from Sink Creek (which discharges into the slough of Spring Lake). Surface storm runoff hydrograph spikes from these are often short in duration, and these spikes are not typically included in the USGS average daily flow calculation for the springs.

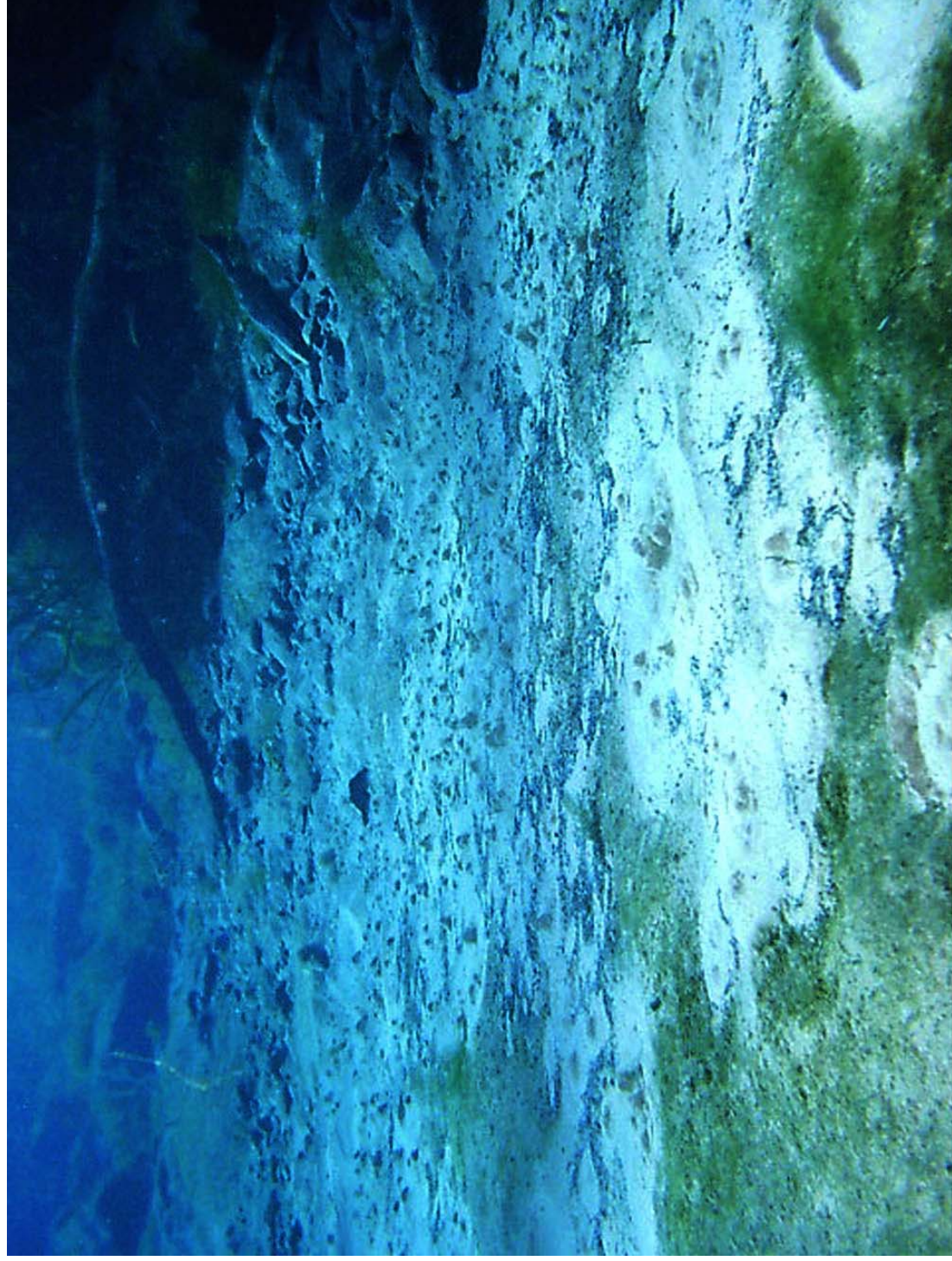
Discharge from the 13 spring areas occurs as either 1) discrete flow out of a defined orifice, such as a fissure (Figure B-34), 2) diffuse flow out of rubble of angular blocks (Figure B-31), or 3) as sand boils or sand geysers out of sand plains composed of white and tan, fine-grained quartz and calcite sands and black organic materials (Figures B-32 and B-33). Spring areas with specific orifices are Crater, Johnny Weissmuller, Diversion, and Deep Springs. Discharge from rock rubble can be observed from Riverbed, Cabomba, Hotel, and Catfish Hotel. The best example of a spring where sand geysers and sand boils are observed is Cream of Wheat. (A description of each spring area is included in Appendix 4.) In the sand boil, or sand plain areas, groundwater is





Spring discharge from rock rubble in Riverbed Spring area.

FIGURE B-31 RIVERBED SPRING AREA



Cream of Wheat Springs is an extensive sand plain composed of “hundreds” of small sand boils. The sand in the boils is composed of predominantly tan sand and white shell fragment material with a black ring of organic material about 1 foot away from the center of the boil.

FIGURE B-32 CREAM OF WHEAT SPRINGS



The geyser of the taller of the two sand boils in the photograph is about 1-foot high. The geysers often have a tan color indicating the predominance of the buff/tan minerals in the boil.

Photo taken by Bridget Lewin, Texas State University.

FIGURE B-33 DETAIL OF A SAND BOIL AT CREAM OF WHEAT SPRINGS



Spring discharge at Johnny Weismuller Spring is predominantly from a single 11-foot long fissure at the bottom of the V-shaped crater. There is little evidence of sand boils at this spring.

Photo taken by Bridget Lewin, Texas State University

FIGURE B-34 JOHNNY WEISMULLER SPRING

discharged either as 1) small amounts of discharge where the sand grains appear to dance (saltate), 2) large boils where the sand is fluidized, 3) larger sand geysers that can be twelve inches high.

Groundwater discharge appears to be predominately through the sand plain and rubble areas, rather than through the discrete spring orifices. To estimate the amount of discharge from the orifices, the approximate size of each orifice (length and width) was measured and the velocities were measured with a General Oceanic mechanical flow meter, which could measure velocities as low as 0.2 ft/s. The dimensions and velocities for each orifice are included in Table B-8. The total discharge from all of the orifices was 38 cfs, whereas total discharge from the lake was 180 cfs for that time period (October 28 and 29, 2003); therefore, only about 25% of the total discharge was coming from discrete orifices and 75% of the discharge was coming from the sand boils or rubble areas. The dimensions of the sand boil areas were estimated (Table B-9). Discharge measurements could not be made in the sand plain area, because flow velocities were below the lower limit of the flow meter (0.2 ft/sec). Assuming that 75% of the flow is through these sand boil plains, then an average discharge rate would be about 0.03 cfs/ft².

The table below presents the measured discharge for individual orifices and the estimated sand boil discharge, as calculated by the total discharge deficit.

Table B-8. Measured Flow Orifices at San Marcos Springs

Individual Orifice	Measured Velocity (ft/sec)	Area (ft²)	Approximate Discharge (cfs)
Crater	1.47	3.5	5.1
Deep (average of 3 measurements)	0.72	15	11
<i>Diversion A</i>	1.64	2.0	3.4
<i>Diversion B</i>	5.25	0.5	2.6
Diversion Total			6.0
Hotel	0.59	1.0	0.59
Johnny Weissmuller	2.79	5.5	15
Total Orifice Flow (cfs)			38
Total Discharge at Gage (cfs) (10-28-03, provisional)			180
Implied Sand Boil Discharge			142

Since the boil velocity was too low for a reliable measurement, the boil areas were measured and flows were computed based on an estimated velocity of 0.03 ft/s. The flows implied by this estimated maximum velocity and discharge area are given in the table below. The “relative approximate discharge” values are only estimates. A lower velocity method is needed to measure these diffuse discharges.

Table B-9. Sand Boil Flow at San Marcos Springs

Sand Boil Area	Estimated Velocity (ft/sec)	Area (ft²)	Relative Approximate Discharge (cfs)
Cabomba	0.03	25	1
Catfish	0.03	375	11
Crater	0.03	12	0
Cream of Wheat	0.03	719	22
Deep	0.03	400	12
Diversion	0.03	145	4
Hotel	--	--	0
Johnny Weissmuller	--	--	0
Kettleman	0.03	1386	42
Ossified Forest	0.03	454	14
River Bed	0.03	1264	38
Salt & Pepper #1	0.03	55	2
Salt & Pepper #2	0.03	162	5
Total Boil Discharge Based on Estimated Velocity (cfs)			151

B.2.9.3 Water chemistry of the Individual Springs

Samples from five individual springs were collected and evaluated for this study and from previous samplings by Authority staff (Tables B-10 and B-11). The chemical and isotopic composition of water discharging from Deep and Catfish Hotel differ slightly from Diversion, Johnny Weissmuller, and Hotel. Deep and Catfish are slightly warmer, have, in general, lower D.O. measurements, field conductivities, lighter oxygen isotope values and higher nitrates (Figures B-35 to B-39). The lighter oxygen isotope values in Deep and Catfish imply recharge farther to the west. The high nitrate values in Deep and Catfish are more characteristic of nitrate values in the main part of the aquifer. The higher temperatures of these southern springs may indicate deeper circulation. The dominant source of groundwater discharge for specific springs at San Marcos is considered to change from north to south. Based on the higher DO values, the higher temperatures and the lighter oxygen isotope values, the southern springs discharge water from the regional flow system. The northern springs discharge from the local groundwater flow system. Additional sampling is needed.

B.2.10 Dye Trace Studies

Recent dye tracer studies by the Authority corroborate these chemical observations. Dye injected south of the springs in Ezell's and Primer's Fissure only was observed at Deep Spring (a southern spring), whereas dye injected at Rattlesnake Cave (north of Spring Lake) was observed at the northern springs (Weissmuller, Diversion, Cabomba, Crater, Salt and Pepper 1, Salt and Pepper 2, and Cream of Wheat.) Ogden and others (1986b) made similar observations with basic water chemistry and dye tracer studies.

Based on the differences in chemical composition and the dye tracer data, the groundwater discharging from the southern springs is considered to be from the south, and represent the regional groundwater flow in the Edwards. The groundwater in the northern springs is presumed to be from a more localized groundwater flow system located to the north and west where recharge may be predominantly in the Blanco River drainage basin. Discharge rates for the southern springs are expected to be more constant, because they appeared to be sourced from the regional flow system. Discharge rates for the northern springs are expected to be more variable, because their source appears to be the local flows, which show greater variability.

Table B-10 Water chemistry analyses for individual springs beneath Spring Lake as well as Artesian well at TSU. Samples collected by Edwards Aquifer Authority

	ARTESIAN WELL 10/6/2003	DEEP 8/28/1997	DEEP 2/7/2001	DEEP 6/6/2002	DEEP 10/9/2002	DEEP 3/12/2003	DEEP 6/23/2003	DEEP 10/6/2003	DEEP 12/29/2003	CATFISH 10/6/2003	CATFISH 12/19/2003	DIVERSION 10/6/2003	DIVERSION 12/19/2003	HOTEL 8/31/1993	HOTEL 8/19/1994	HOTEL 8/19/1994	HOTEL 8/19/1994	HOTEL 5/28/1996	HOTEL 8/31/2000	HOTEL 2/7/200	HOTEL 12/10/2001	HOTEL 6/6/2002	HOTEL 10/9/2002	HOTEL 3/12/2003	HOTEL 6/19/2003	HOTEL 10/10/2003	HOTEL 12/4/2003	WEISMUELLER 10/6/2003	WEISMUELLER 12/19/2003
Date	10/6/2003	8/28/1997	2/7/2001	6/6/2002	10/9/2002	3/12/2003	6/23/2003	10/6/2003	12/29/2003	10/6/2003	12/19/2003	10/6/2003	12/19/2003	8/31/1993	8/19/1994	8/19/1994	8/19/1994	5/28/1996	8/31/2000	2/7/200	12/10/2001	6/6/2002	10/9/2002	3/12/2003	6/19/2003	10/10/2003	12/4/2003	10/6/2003	12/19/2003
Total Discharge San																													
Marcos (cfs)	193.00	188.00	275.00	173.00	276.00	300.00	229.00	193.00	156.00	193.00	160.00	193.00	160.00	186.00	125.00	212.00	252.00	94.00	118.00	275.00	311.00	173.00	276.00	300.00	229.00	192.00	166.00	193.00	160.00
Alkalinity	258.00	222.00	252.00	262.00	256.00	260.00	271.00	268.00	267.00	263.00	278.00	260.00	264.00		196.00	262.00	<5		250.00	256.00	259.00	251.00	265.00	261.00	268.00	260.00	274.00	252.00	261.00
Bicarbonate	258.00	317.00		262.00	256.00	260.00	271.00	268.00	267.00	263.00	278.00	260.00	264.00		25.00	307.44					259.00	251.00	265.00	261.00	268.00	260.00	274.00	252.00	261.00
Chloride	23.00	17.00	25.00	20.60	17.70	18.40	18.80	20.10	21.00	17.00	18.60	18.60	19.60	19.00	25.00	27.00	27.00	32.00	22.00	26.00	18.70	22.50	17.90	20.10	18.80	18.80	18.60	20.00	20.50
Fluoride	0.24	0.20	0.12	0.19	0.25	0.18	0.21	0.26	0.30	0.22	0.22	0.26	0.25	0.20	0.13	0.31	0.42	0.40	0.21	0.18	0.30	0.19	0.23	0.21	0.23	0.22	0.26	0.27	0.25
Sulfate	29.30	21.00	28.00	25.90	22.80	24.80	24.10	25.80	26.50	22.10	23.60	23.90	24.80	24.00	26.00	27.00	24.00	24.00	22.00	33.00	26.00	27.80	23.70	26.70	23.80	24.00	25.20	25.80	26.20
Total Dissolved Solids	350.00	332.00	330.00	330.00	330.00	360.00	360.00	330.00	360.00	340.00	340.00	330.00	320.00	332.00	266.00	236.00	328.00	328.00	280.00	336.00	328.00	320.00	300.00	360.00	360.00	360.00	360.00	340.00	330.00
Nitrate-Nitrite as N	1.54	1.49	1.91	1.39	1.52	1.27	1.37	1.47	1.53	1.40	1.27	0.99	0.98	1.29	1.29	1.01	1.00	1.00	1.32	1.10	0.95	1.11	0.95	1.01	0.97	0.82	0.94	0.82	0.82
Barium	0.04		0.04	0.04	0.04	0.07	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.03
Calcium	95.60	92.00	93.00	81.90	83.10	85.80	88.50	91.80	77.40	91.80	93.30	85.80	86.40	85.00	86.00	83.00	79.00	87.00	87.00	91.00	90.00	77.50	81.00	85.60	160.00	167.00	80.00	85.90	83.20
Magnesium	16.70	16.00	16.00	14.40	14.30	15.00	15.80	16.10	14.00	15.90	16.40	17.70	18.20	18.00	17.00	20.00	19.00	19.00	17.00	19.00	18.20	17.40	17.20	18.70	36.30	36.10	18.30	18.50	18.10
Potassium	1.61	1.20	0.00	0.95	0.70	1.48	1.41	1.69	1.16	0.96	1.28	1.64	1.12	1.30	2.00	1.00	0.00	0.00	0.00	1.00	1.40	0.55	0.84	1.55	1.24	2.12	1.41	1.81	1.16
Silica	5.58	12.00	4.90	4.88	4.78	4.84	5.19	5.41	4.72	5.42	5.58	5.11	4.94	11.00	4.70	5.50	5.10	5.10	5.10	4.40	4.50	4.55	4.59	4.67	9.24	10.30	5.00	5.17	5.12
Sodium	13.10	11.00	10.00	9.29	9.34	9.73	10.70	11.20	10.10	9.58	9.77	10.20	10.10	11.00	13.30	11.80	10.40	10.40	9.00	10.00	10.50	9.58	9.49	10.90	20.30	20.80	10.90	11.10	10.50
Strontium	0.55		0.496	0.108	0.513	0.929	0.512	0.516	0.005	0.458	0.468	0.513	0.555					0.49	0.54	0.52	0.53	0.54	0.54	0.54	0.55	0.66	0.55	0.57	0.57

Table B-11 Isotope Analyses for San Marcos Springs 2003

Sample	Date	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	Tritium (t.u.)	\pm (t.u.)
LR-67-01-8SW (SWT Artesian Well)	10/6/03	-4.41	-24.97	2.6	0.6
San Marcos Springs-Deep	10/6/03	-4.37	-25.30	3.3	0.7
San Marcos Springs-Catfish	10/6/03	-4.43	-26.11	1.6	0.6
San Marcos Springs-Diversion	10/6/03	-4.13	-24.91	2.3	0.6
San Marcos Springs-Weismueller	10/6/03	-4.17	-22.77	2.3	0.6
San Marcos Springs-Hotel	10/10/03	-4.22	-25.64	3.1	0.6

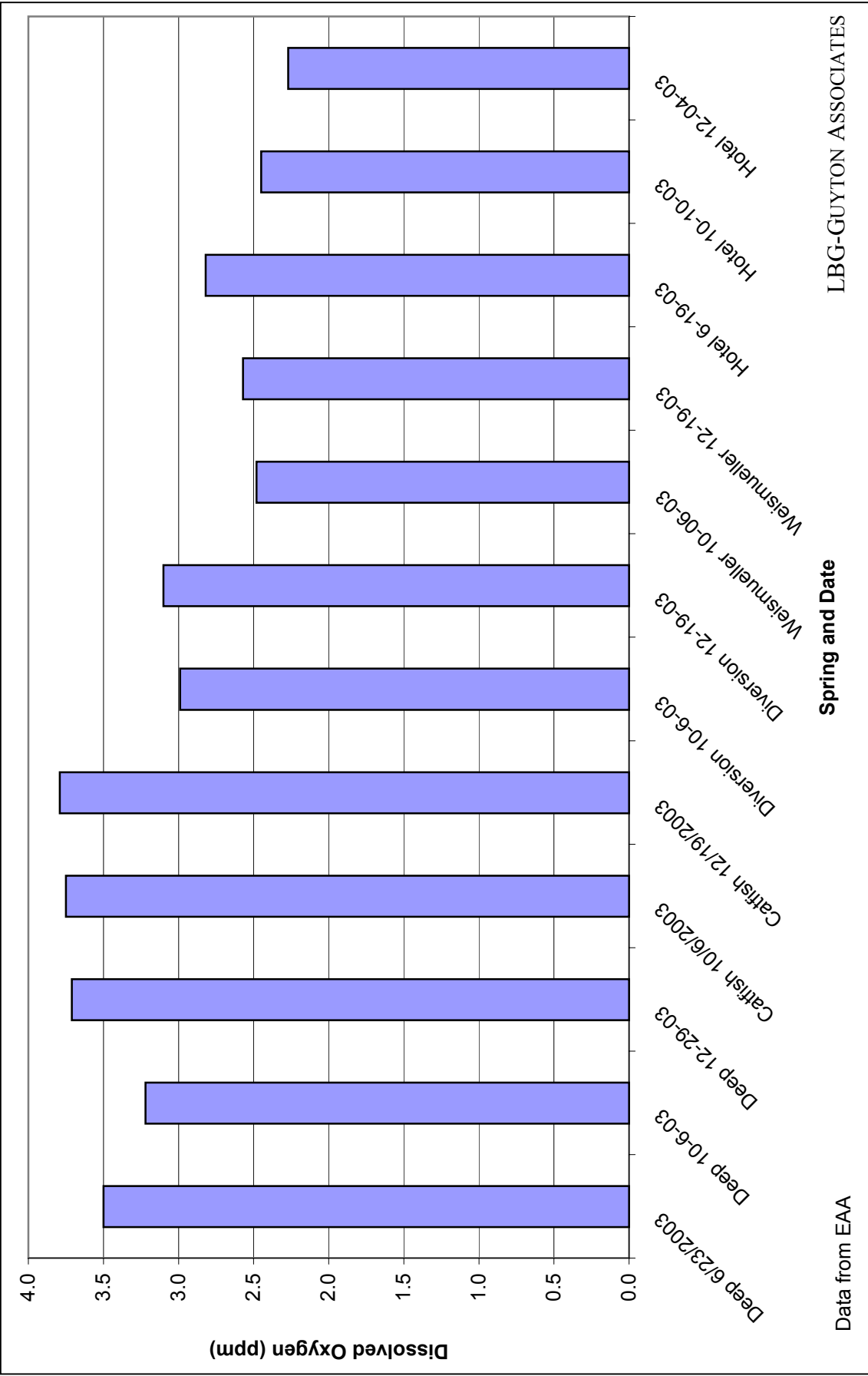


FIGURE B-35 FIELD DO VS. SPRING FOR SAN MARCOS SPRINGS 2003

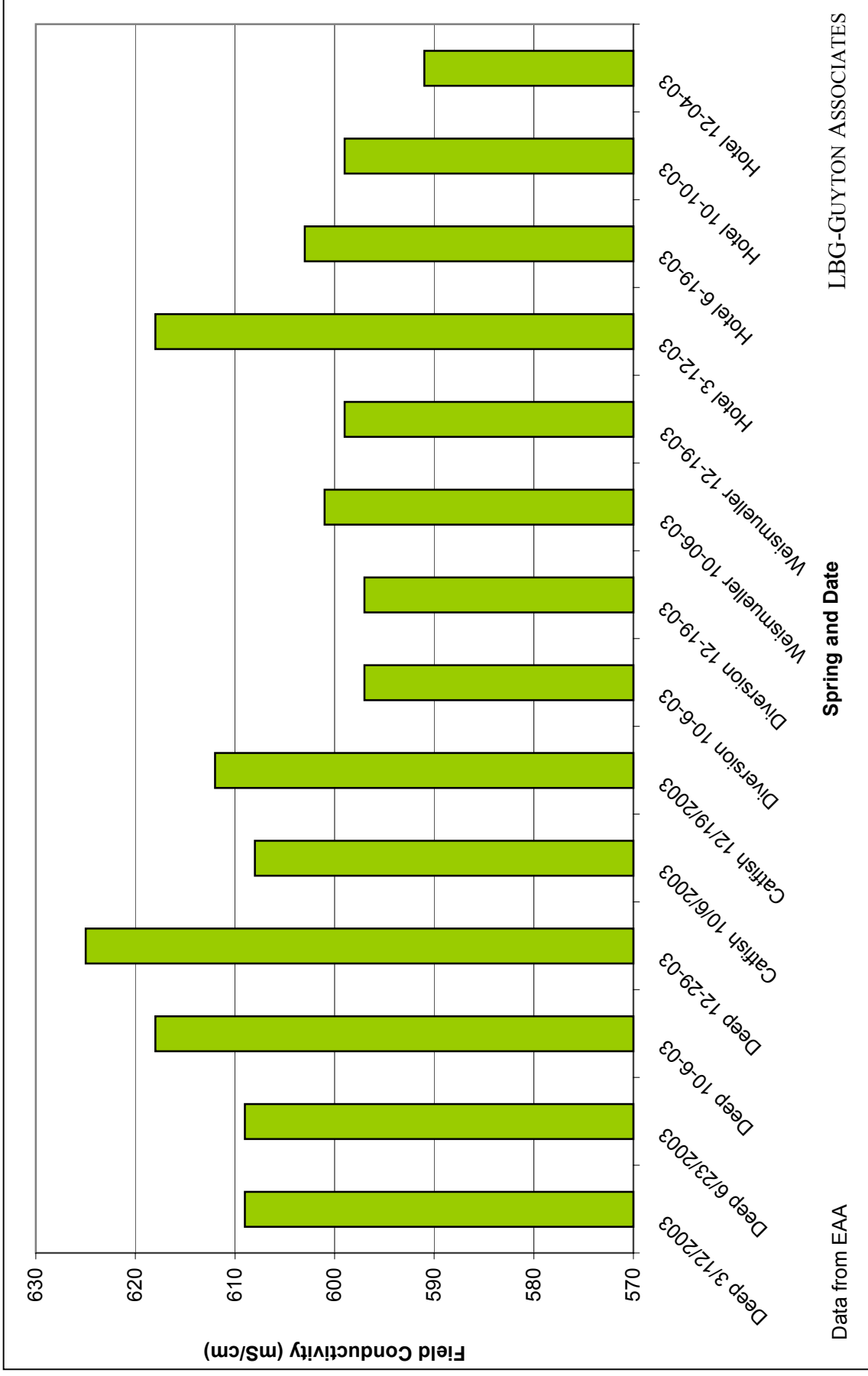


FIGURE B-36 FIELD CONDUCTIVITY VS. SPRING--SAN MARCOS SPRINGS 2003

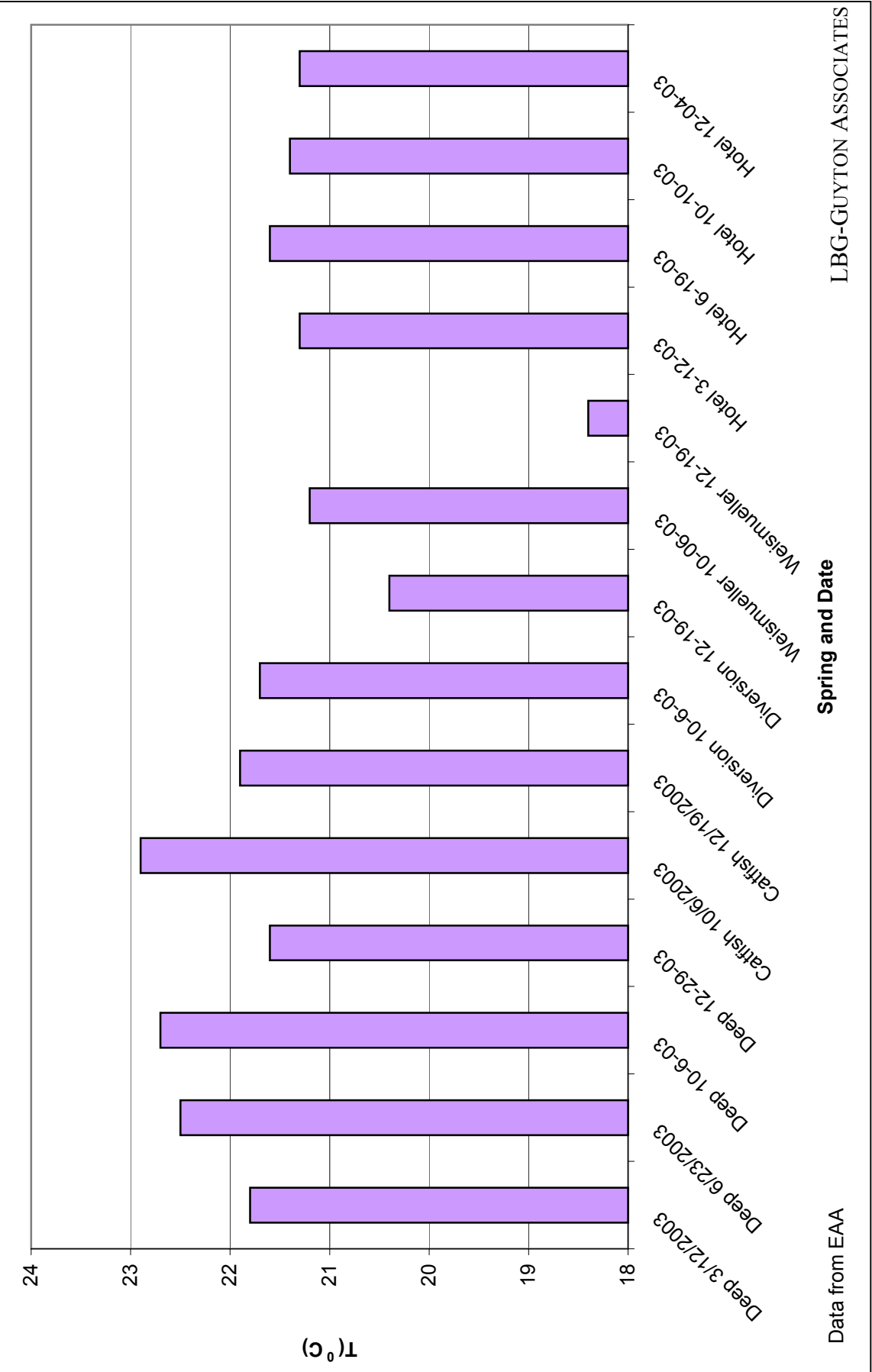


FIGURE B-37 FIELD TEMPERATURE VS. SPRING--SAN MARCOS SPRINGS 2003

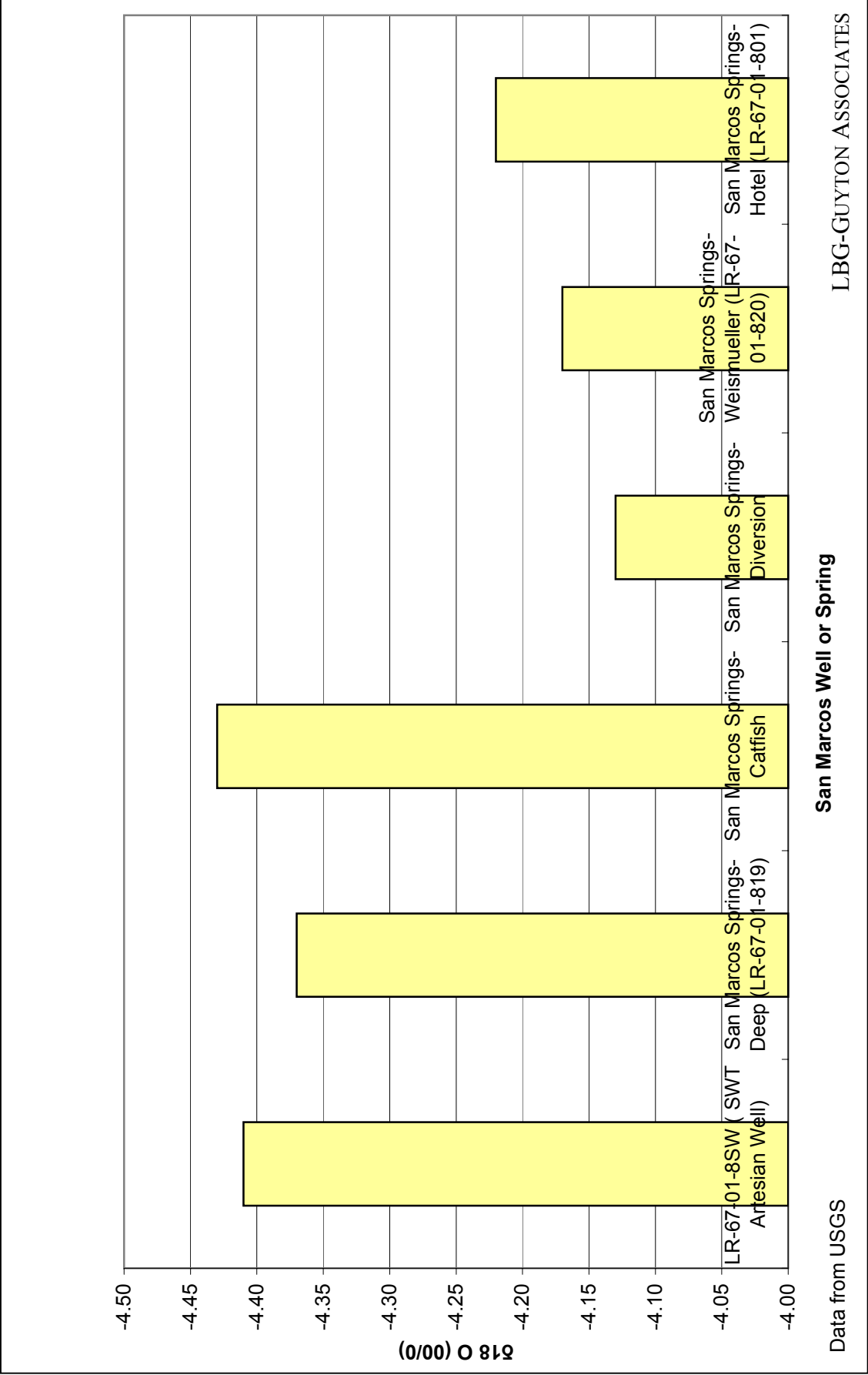


FIGURE B-38 $\delta^{18}\text{O}$ VS. SPRING AT SAN MARCOS SPRINGS OCTOBER 2003

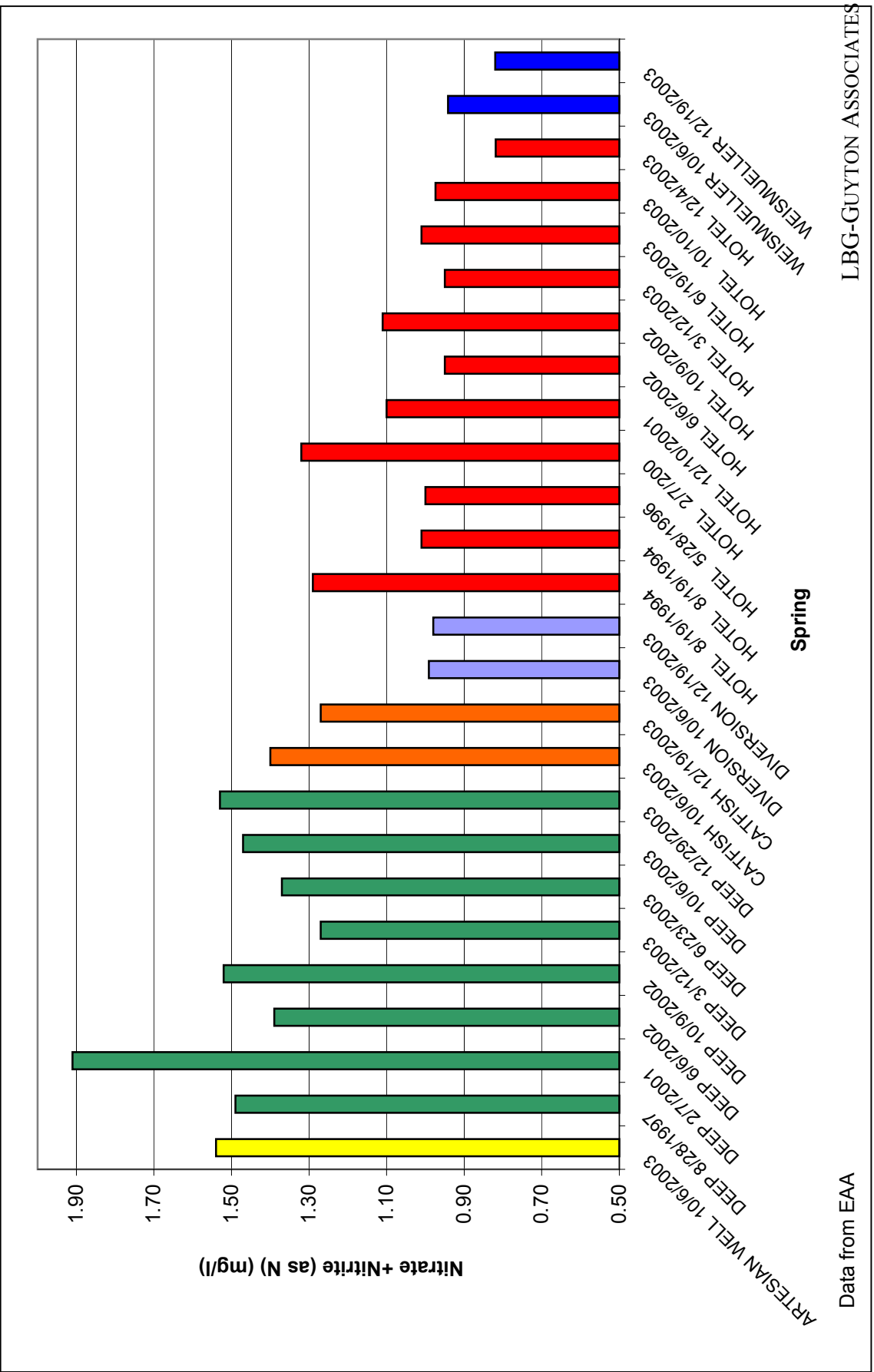


FIGURE B-39 NITRATE+NITRITE VS. SPRING--SAN MARCOS SPRINGS

The source of groundwater for individual springs may shift as the total discharge rate declines. Ogden and others (1986b) observed that at low flow conditions, a dye trace was observed at a northern spring, but was not observed in the same spring when a tracer study conducted by the Authority was performed during high flow conditions. Changes in localized hydraulics of limestone spring complexes are often observed as flow condition changes.

B.2.11 Important Engineered Structures on Spring Lake

B.2.11.1 Origin of Spring Craters

The origin of the spring craters as naturally occurring geologic features is perplexing. It is difficult to envision what naturally occurring hydrologic/geologic process could create this dimpled bathymetric surface beneath Spring Lake. An alternative explanation is that they are man made. Historical accounts indicate that many of the spring orifices may have been modified or created by excavation and blasting during the building of Aquarena Springs resort by the owner Arthur B. Rogers in the late 1920s. Articles describing the construction of the hotel and park at San Marcos Springs appeared in the local paper in June 1928 and April 1929. One article describes a large amount of modification of the hillside slope by blasting to accommodate hotel construction (*San Marcos Record*, 6/29/28). A second article describes dredging "thousands of [cubic] yards" of dirt and mud from the head of the pool, and clearing vegetation from the headwaters (*San Marcos Record*, 4/19/29). These accounts indicate that areas surrounding the spring orifices and possibly some orifices themselves were modified during park construction activities.

B.2.11.2 Ice House Dam - Keeps Water in the Lake

The elevations of the two outlet structures at the southwest end of Spring Lake -- the east lake dam spillway and the west headgate by Joe's Crab Shack restaurant -- serve as a control on flow from Spring Lake. Elevations of these two outlet structures were measured in a recent survey. In November 2003, the elevation of the spillway was 573.44 ft and the elevation of the headgate was 572.67 ft (Authority, 2003). The water level surface elevation at the dams is typically near 574 ft.

From December 1994 to March 1995 the Texas Parks and Wildlife Department studied the effects of headgate elevation changes on discharge from the lake (Mayes *et al*, 1996). Headgate boards were removed in successive 7.5-inch increments for a maximum reduction in height of

1.8 ft, which resulted in a total decrease in water surface elevation of 0.82 ft at the headgate. Only the third 7.5-inch reduction resulted in a significant incremental decrease in water level elevation across the lake. This third reduction resulted in a water level decrease of approximately 0.3 ft in the lake over most of the 12-day period this third reduction increment was extant. Gaging sites were located at the headgate, spillway, boat dock, and the slough that leads from Sink Creek. Discharge at the San Marcos Springs gage (USGS Station 08170000) increased 6 cfs to 147 cfs after this third lowering. No major recharge events occurred over this third increment (February 9-21 1995). TPWD concluded that the 6 cfs increase might be attributable to the decrease in headgate elevation, but noted that the change was within the 5% margin of error for the USGS gage measurements.

Assuming the linear correlation of 26 cfs increase in flow per foot of aquifer head discussed previously holds at this flow condition, the approximately 0.3-ft drop in lake levels would correlate to a flow increase of approximately 7.8 cfs. The 6 cfs measured increase is comparable to the 7.8 cfs predicted increase.

B.2.11.3 Residence Time of Water in Lake With Varying Discharge Rates

Spring Lake bathymetric data based on the U.S. Fish & Wildlife Service surveys have been used to calculate a lake volume of 3,763,870 ft³ at a level of 573.5 ft. The lake turnover rates for the long-term historical average flow of 172 cfs (as of May 2003) and various other spring flows have been calculated and are given in the following Table B-12:

Table B-12. Spring Lake Turnover Rates

Spring Discharge (cfs)	Time to Discharge One Spring Lake Volume (min)/hours	
	Minutes	Hours
172	365	6.1
400	157	2.6
300	209	3.5
200	314	5.2
100	627	10.5
50	1,255	20.4

B.2.12 Summary of Hydrogeologic Setting

San Marcos Springs is at the end of a flow system for the Edwards aquifer which includes most of the outcrop and streams and the Blanco River in Hays and Comal Counties. The springs receive recharge from this area, and they often exhibit a rapid flow response to storm events in this region. The rapid response to these recharge events would also indicate the quick response of karstic flow.

San Marcos Springs also appears to receive a regional base flow through the up-thrown block at Comal Springs of about 50 to 100 cfs that bypasses discharge at Comal Springs. Although San Marcos Springs did not go dry in the summer of 1956, spring discharge declined to 46 cfs.

Seasonal water level rises and increased flows in the artesian section of the aquifer (San Antonio pool), however, do not result in increases in discharge at San Marcos Springs. The increased flow is in large part captured as increased discharge at Comal Springs. The City of San Marcos and Texas State University have a water right of about 10 cfs, but currently only use about 2 cfs. Under average flow conditions, their pumpage is a minor amount of daily spring flow, but under drought conditions, pumping their water right allotment could constitute a significant percentage of the spring discharge.

All the spring discharge at San Marcos is through spring complexes in the bottom of Spring Lake. There are no subaerial springs, as occur at Comal Springs. Spring discharge is from the

up-thrown block since there is no evidence of fresh groundwater in the down-thrown block of the San Marcos Springs Fault near San Marcos Springs. Although some of the springs have distinct orifices where discharge can be measured, most of the spring discharge appears to be through rock rubble or sand boils in large flat sand plain areas.

The southern springs appear to discharge groundwater from the regional flow system. The northern springs receive their discharge from the more localized recharge zone of Hays County. Discharge rates in the southern springs would be expected to be far more stable under varying flow conditions than the northern springs. The discharge rates for the northern springs should be more variable in proportion to total spring discharge values.

C. Important Habitats at the Springs

C.1 Endangered species in spring habitats

The Edwards Aquifer, including its two largest spring ecosystems, Comal and San Marcos Springs, maintains a diversity of species, many of which are endemic (found only in a certain locality or region). Eight species found in the Edwards Aquifer, Comal Springs, and San Marcos Springs ecosystems are currently listed as threatened or endangered by the U.S. Fish and Wildlife Service. Endangered species include the Comal Springs dryopid beetle (*Stygoparnus comalensis*), Comal Springs riffle beetle (*Heterelmis comalensis*), fountain darter (*Etheostoma fonticola*), Peck's Cave amphipod (*Stygobromus pecki*), San Marcos gambusia (*Gambusia georgei*) Texas blind salamander (*Eurycea rathbuni*) and Texas wild-rice (*Zizania texana*). The one threatened species is the San Marcos salamander (*Eurycea nana*). Some of these species are subterranean (Comal Springs dryopid beetle, Peck's Cave amphipod and Texas blind salamander) while others are found in surface habitats near spring openings (Comal Springs riffle beetle and San Marcos salamander). The fountain darter is found in the upper reaches of both the Comal and San Marcos Springs ecosystems while Texas wild-rice is found only in the upper reaches of the San Marcos River. The San Marcos gambusia is considered extinct, but previously existed in the upper reaches of the San Marcos River.

C.2 Water requirements for endangered species

Currently, the U.S. Fish and Wildlife Service considers "take" of the Comal Springs fountain darter population to occur at 200 cfs total discharge in the Comal River measured at the USGS gage located downstream of Torrey Mill dam. "Jeopardy" of that population is considered by the U.S. Fish and Wildlife Service to occur at 150 cfs total discharge (USFWS 1996). In the San Marcos River, the US Fish and Wildlife Service considers both "take" and "jeopardy" of the fountain darter population and Texas wild-rice population to occur at 100 cfs total discharge measured at the USGS gage located at the University Drive Bridge. For the San Marcos salamander the take and jeopardy numbers are both 60 cfs, and for Texas blind salamander both levels are 50 cfs (USFWS 1996). No take or jeopardy discharge levels were provided when the three Comal invertebrate species were listed as endangered. These impact levels were based on limited available life-history information, including distribution and habitat requirements for

many species. More data are currently available than when the take and jeopardy levels were introduced. A current Authority-funded study is evaluating the influence of variable flows on the threatened and endangered species and assessing potential impacts under very low discharge conditions that is providing detailed information for many of these species.

An additional difficulty in defining springflow requirements is that many of these species are subterranean. It is difficult to know what habitat requirements they have or predict what impact a severe reduction in springflow would have on these species. Presumably, as long as their habitat remains wetted and some subterranean movement of water prevents deterioration of localized water quality, these species should be capable of withstanding a decrease in the aquifer level to a level that springflow ceases. However, for those species that are associated with spring openings at the surface and in areas immediately downstream, a complete cessation in springflow, or reduction to very low levels for extended periods may have serious consequences. Therefore, the main focus of providing alternative water sources is to preserve habitat for those species found near spring openings and in the surface-water habitat downstream of the spring openings. If alternative water sources could be provided in specific habitat locations it may be possible to preserve habitat during extended periods of low recharge for species found in these areas.

C.3 Biologic Assemblage in Springs

C.3.1 Biologic assemblage of Comal Springs, Landa Lake, and Associated waters

C.3.1.1 Species

Four of the eight threatened/endangered species associated with the Edwards Aquifer are found in the Comal Springs ecosystem. These include the Comal Springs dryopid beetle, Comal Springs riffle beetle, fountain darter, and Peck's Cave amphipod. The Comal Springs dryopid beetle is a small (approximately 1/8-inch long) subterranean species from the family Dryopidae. Individuals are translucent, slightly pigmented, and have vestigial (non-functioning) eyes (Barr and Spangler 1992). The Comal Springs riffle beetle is similar in size to the dryopid beetle and found in surface waters in and around spring openings in Comal Springs. It is a member of the family Elmidae and although some riffle beetles are capable of flight, this species is flightless (Federal Register 1997). Both larvae and adults are entirely aquatic with adults feeding mainly

on algae and detritus scraped from submerged weeds and rocks (Brown 1987). The fountain darter is a member of the family Percidae and is endemic to the San Marcos and Comal Rivers. Fountain darters are small (<1.8 inches), olive-green in color with dark markings along the lateral line, dark spots at the base of the tail, opercule, dorsal fin, and around the eye (Gilbert 1887; Schenck and Whitside 1976). Peck's Cave amphipod is a subterranean aquatic species in the family Crangonyctidae. It is eyeless and unpigmented, which indicates that its primary habitat lies within the aquifer in permanent darkness. If found outside the spring orifice, individuals are easy prey and so are typically found in the crevices of rocks and gravel (Arsuffi 1993, Barr 1993).

C.3.1.2 Locations Within Springs, Spring Runs, and Lake, and Runs Down Stream From Lake

Very little information is available for the distribution of the Comal Springs dryopid beetle, except that it is a subterranean, aquatic (stygobiotic) species that has been collected primarily from spring run 2 in Comal Springs. A few specimens have also been collected from Spring Runs #3 and #4 (also called Spring A at the upper end of Landa Lake) and from Fern Bank Spring in Hays County (Barr and Spangler 1992). Although it is blind, it does have vestigial eyes and slight pigmentation. This suggests that it is more recently adapted to subterranean life than other organisms found in the aquifer (such as the eyeless Peck's Cave amphipod) and may be more closely associated with spring openings with a less extensive subterranean distribution.

Comal Springs riffle beetles (*Heterelmis comalensis*) are found in surface habitats where springflow is evident around Landa Lake in the Comal River. This includes Spring Runs #1, #2, and #3 (Bosse et al. 1988, Bowles et al. 2002) and spring upwellings associated with both shoreline habitat and deeper water within the lake (BIO-WEST 2002a).

Fountain darters are found in a wide range of habitat types in the upper reaches of both the San Marcos and Comal Springs ecosystems. In the Comal system, the fountain darter occupies all areas of the river from the headwaters to the confluence with the Guadalupe River (USFWS 1996). The population is greatest in Landa Lake and the Old Channel, while the area upstream of Landa Lake, the New Channel and the portion of the river below the confluence of the Old and New Channels maintain lower densities of the species (BIO-WEST 2002b, 2003a, 2004a).

Peck's Cave amphipod is a subterranean invertebrate that is occasionally found in crevices of rocks and gravel directly adjacent to spring openings in Comal Springs (Arsuffi 1993). Barr (1993) collected a single specimen at Hueco Springs (4 miles north of Comal Springs) and individuals have been collected from Landa Park well (60 ft deep), less than 500 ft from Comal Springs (Fries et al. 2003). The vertical distribution of this species is unknown, but the fact that they have only been captured in springs and wells in Comal Springs and nearby areas suggest it is limited to these areas horizontally. Because it is eyeless and primarily non-pigmented, it is likely that this species is found deeper in the aquifer than the Comal Springs dryopid beetle, they may be found deeper than the 60 ft samples from Landa Park well.

C.3.1.3 Water Requirements for Species

C.3.1.3.1 Habitat (Water Chemistry, Importance of Variable Flow and Residence Times)

As with the distribution of the Comal Springs dryopid beetle, very little is known about the Peck's Cave amphipod's habitat requirements. Because it is subterranean and associated with spring openings, springflow keeps habitats wetted and prevents localized deterioration of water quality. Individuals maintain a thin air bubble within a mass of small hydrophobic (unwettable) hairs on their underside, which allows gas exchange (BMWD 1998; Chapman 1982). This method of respiration loses its effectiveness as water flow decreases and dissolved oxygen levels decline. It is not clear what minimum springflow would be necessary to meet the water quality needs of this species, but it presumably is much less than the amount needed to preserve habitat for species found in surface habitats. It would be difficult to provide an alternate water source to supplement natural springflow to preserve habitat for this species.

Because of a relative paucity of ecological data, it is difficult to define environmental requirements for the Comal Springs riffle beetle. Bowles et al. (2002) suggests that the primary requirements relate to high-quality springflow and maintenance of physical habitat. A laboratory study suggested that the beetles may move deeper into the substrate with decreasing flows (BIO-WEST 2002d), which may explain how the species survived the drought of record. However specific springflow requirements and hyporheic habitat usage for the species in the wild remain unknown and individuals have been collected from a wide range of substrate sizes. Because springflow requirements cannot be accurately defined, conservative management has dictated that historic conditions should be maintained. Bowles et al. (2002) was unable to determine the

appropriateness of current take and jeopardy limits set by the USFWS and simply suggested that the springs should not be allowed to stop flowing for extended periods or become permanently dry. Without any other data on water chemistry parameters, it is assumed that standard parameters (temperature, dissolved oxygen, pH, and conductivity) should remain within the historic range observed in the natural habitat for the species. Properly positioned supplemental or re-circulated water supplies may permit some natural habitats to maintain the necessary physical and chemical requirements when natural springflow is severely reduced.

Habitat requirements for the fountain darter (*Etheostoma fonticola*) include clear, clean, flowing, and thermally constant waters, adequate food supply, undisturbed sand and gravel substrates and areas of submergent aquatic vegetation for cover (Schenck and Whiteside 1976, McKinney and Sharp 1995, Linam et al. 1993). BIO-WEST has conducted habitat mapping (vegetation) for fountain darters in several locations in the Comal and San Marcos Springs complexes from 2000-present through the Authority's Variable Flow Study. Mapping was conducted by BIO-WEST in each of these areas quarterly (except in the winter of 2003-2004) and following two high flow occurrences during that time frame. The relative value of the various plant species has been documented through fountain darter sampling efforts conducted by BIO-WEST in the same effort. The fountain darter habitat quality maps for the Comal River were developed by BIO-WEST for this study using all of this data and information from the USFWS and others (Linam 1993, Linam et al. 1993, USFWS 2000). Figures C-1 to C-5 show the variation in fountain darter habitat quality from the headwaters of the Comal River down to Torrey Mill Dam (below the confluence of the Old and New Channels). The habitat classifications in these figures were developed using the best available biological data including Variable Flow study observations and sampling, and professional judgement. Water temperature is an important parameter for this species and laboratory studies have shown a significant decrease in reproductive capacity above 27°C (Brandt et al. 1993, Bonner et al. 1998). The critical thermal maximum for the species is 34.8°C according to Brandt et al. (1993). Fluctuations in discharge affect the residence time of water in Landa Lake and subsequently affect downstream water temperatures. The relationship between discharge and water temperature has been modeled by the USFWS (1996) and is being studied under variable flow conditions by BIO-WEST (2002b, 2002c, 2003a, 2003b, 2004a, 2004b). Vegetation composition is another very important determinant of habitat suitability and different types support different greatly different densities of fountain darters from virtually zero



Figure C-1. Fountain Darter Habitat Quality: Comal River



Figure C-2. Overview of fountain darter habitat quality in the upper reaches of the Comal River (upstream of Landa Lake). Areas in green are highest quality habitat followed by yellow (intermediate) and red (low quality). Yellow areas with red cross-hatching are variable habitat quality (low-intermediate) depending on vegetation composition. Areas of Comal Springs riffle beetle habitat in spring upwelling areas upstream of Spring Island are indicated.



Figure C-3. Overview of fountain darter habitat quality in Landa Lake. Spring Runs have very low quality fountain darter habitat and a significant portion of Landa Lake is intermediate in quality due to *Vallisneria sp.* as the primary vegetation type. The area of Comal Springs riffle beetle habitat along the western shoreline of the lake is indicated.



Figure C-4. Overview of fountain darter habitat quality in the lower reaches of Landa Lake and upper reaches of Old Channel and New Channel. The short upper section of the Old Channel is intermediate in quality and the section below the pool release is low quality, but the rest of the Old Channel is high quality habitat. The New Channel provides intermediate quality habitat down to the dam across from the New Braunfels city park office, below which habitat quality is low.



Figure C-5. Overview of fountain darter habitat quality in the Old and New Channels. Habitat is generally poor to intermediate in the New Channel and high in the Old Channel. Downstream of Clemons Dam, the habitat is similar to the New Channel.

per square meter on bare substrate to over 30 per square meter in filamentous algae in the Old Channel. Variation in flow affects the composition of the plant community and thus the fountain darter habitat. A decrease in spring flow to very low levels would most likely influence this species first (and thus it would be most important to find alternative ways to maintain habitat for it under low discharge conditions).

Very little is known about the habitat requirements of Peck's Cave amphipods. As with the Comal Springs dryopid beetle, it is assumed that at least a small amount of springflow would be important to prevent a decline in local water quality conditions. However, even when water is not flowing out of spring openings, subsurface water flow would probably continue to provide suitable water quality for a large portion of the population. This is difficult to predict or verify in the aquifer, but presumably, subterranean water movement would replenish dissolved oxygen and support whatever food source the species depends upon. Some habitat near spring openings may suffer degraded water quality with no movement of water through the spring opening, but because the population is found at least 60 ft deep, the majority of the habitat would remain suitable if the water level dropped to the point that springflow was severely reduced or even ceased completely.

C.3.1.3.2 Recommended Spring Discharge Rates

In the Comal Springs ecosystem the focus should be to maintain habitat for two species, the Comal Springs riffle beetle and fountain darter. The subterranean invertebrates (Peck's Cave amphipod and Comal Springs dryopid beetle) would experience some habitat loss around spring openings with a dramatic loss or cessation of springflow, but some subterranean habitat would remain. Habitat for the two species dependant on surface flow would be in much higher risk under such conditions. It would also be very difficult to provide artificial spring upwelling that would ensure that these habitats remain suitable for the subterranean species. Currently, in the unforeseen event that results in cessation of springflow and substantial localized reduction of the aquifer level in the Comal Springs area, captive propagation may be the only way to ensure persistence of these species.

Currently, take and jeopardy discharge values for the fountain darter species in the Comal River are 150 and 200 cfs, respectively. Maintaining springflow at those levels would theoretically provide suitable conditions for the species at all times. However, providing supplemental water

to augment springflow at these levels may deplete a supplemental water source before natural springflow drops to levels that becomes truly necessary. A more achievable goal, and greater use of a limited resource, would be to supplement natural spring discharge with enough water to maintain a minimum of 60 cfs for a very limited period of time until wetter conditions return. A portion of this should be designed to simulate springflow in Comal Springs riffle beetle habitat (see recommendations below) and the rest should be divided among the lower sections of Spring Run #3, at the confluence of Spring Runs #1 and #2, and immediately downstream of Spring Island to maximize the amount of suitable habitat that remains available for fountain darters. This latter portion of supplemental water could be introduced as surface flow primarily to support fountain darter habitat downstream of the input areas.

In addition to maintaining this minimum discharge level, water can be more efficiently routed through the ecosystem to reduce water temperature concerns for fountain darter habitat. This type of intensive management strategy is recommended for initiation at 80 cfs total discharge in the Comal River. Below this value for natural discharge, the high retention time of water in Landa Lake would potentially reduce a substantial amount of suitable habitat in the lower reaches of the fountain darter range in that river. This would be particularly important in the higher quality habitat of the Old Channel and less so in the marginal habitat of the New Channel. To reduce this potential effect, channels could be created to route water through a smaller portion of Landa Lake and substantially reduce retention times at 80 cfs total discharge and below. The re-directed water would flow over all known springs in the lake and through areas of high quality habitat for fountain darters. In addition, the relative proportion of water travelling down the Old and New Channels could be adjusted to maximize the availability of fountain darter habitat with the reduced discharge levels.

For the Comal Springs riffle beetle, maintaining 60 cfs (or any amount) of total discharge in the Comal River would be ineffective if the location of supplementation was not appropriately placed. Individual springs that support this species may need very little discharge to continue to support the beetles, but it must presumably be provided in the natural spring opening to maintain suitable conditions in current habitat. Several locations would need to have small amounts of water supplemented in very precise placements to maintain surface habitat for Comal Springs riffle beetles (the beetles may use subsurface habitat when springs stop flowing but to what extent is unknown). Some of this water may emerge from individual spring openings and flow

into losing sections of the aquifer, but overall the supplemented springflow should contribute to the total water supplement to maintain the recommended 60 cfs total discharge in the river.

The cost of providing the minimum recommended discharge in the Comal Springs/River ecosystem to maintain endangered species populations (60 cfs) is high. A preliminary cost estimate for using water from Canyon Reservoir (discussed later in text) on an as-needed basis is approximately 13 million dollars. However, it is absolutely imperative that some water continues to flow in the highest quality endangered species habitat and that Landa Lake, which contains a substantial portion of this habitat, remain full during any future drought. History tells us, that once springflow stops, water levels in the lake can drop rapidly. In the severe drought during the summer of 1956, Landa Lake was full in early June, but was nearly dry by August. To prevent the lake levels from rapidly declining, local large-scale production should be stopped.

C.3.1.4 Feasibility of Engineered Structures

There are three conceptual areas for maintaining habitat for the Comal Springs riffle beetle and fountain darter. These include: 1) small amounts of supplemented water should be provided to individual spring openings in areas that Comal Springs riffle beetle habitat occur; 2) provide a more direct pathway for moving water through Landa Lake to reduce retention time and maintain suitable water temperature, and 3) develop an intensively managed area in the Old Channel to maintain fountain darter habitat and possibly create riffle beetle habitat.

Supplemented water for Comal Springs riffle beetle habitat may be from an outside source or it may be re-circulated from Landa Lake but it will have to maintain water quality characteristics similar to natural springflow, primarily water temperature and dissolved oxygen. Water with these characteristics should be directed into major spring openings that support the Comal Springs riffle beetle in Spring Run #3 (Figures C-6 and C-7), a small area along the western shoreline of the lake (Figure C-8) and areas of spring upwelling just upstream of Spring Island (Figure C-9). Each area would need a small amount of water introduced into the ground and allowed to seep out of the shoreline habitat (in Spring Run #3 and the western shoreline habitat) or emerge up through the substrate (upstream of Spring Island). Surface flow directed along the edge of the Spring Run #3 channel would also be valuable for maintaining the large area of riffle beetle habitat in that area. A total of 8-12 cfs in Spring Run #3 divided among several lateral seeps and surface flow should support some habitat for the species when springflow decreases to



Figure C-6. Overview of riffle beetle habitat in Spring Run 3. The brown polygons represent highest quality areas where individuals have been collected; yellow polygons are areas that appear to have high quality habitat, but sampling has not been extensive in these areas and individuals have not been captured. The headwater area likely has many individuals and drift net sampling in spring openings have yielded some observations, but the area has not been sampled extensively by BIO-WEST to identify precise habitats. Along the north shoreline, several areas have been identified as high quality habitat with beetles present during regular sampling.

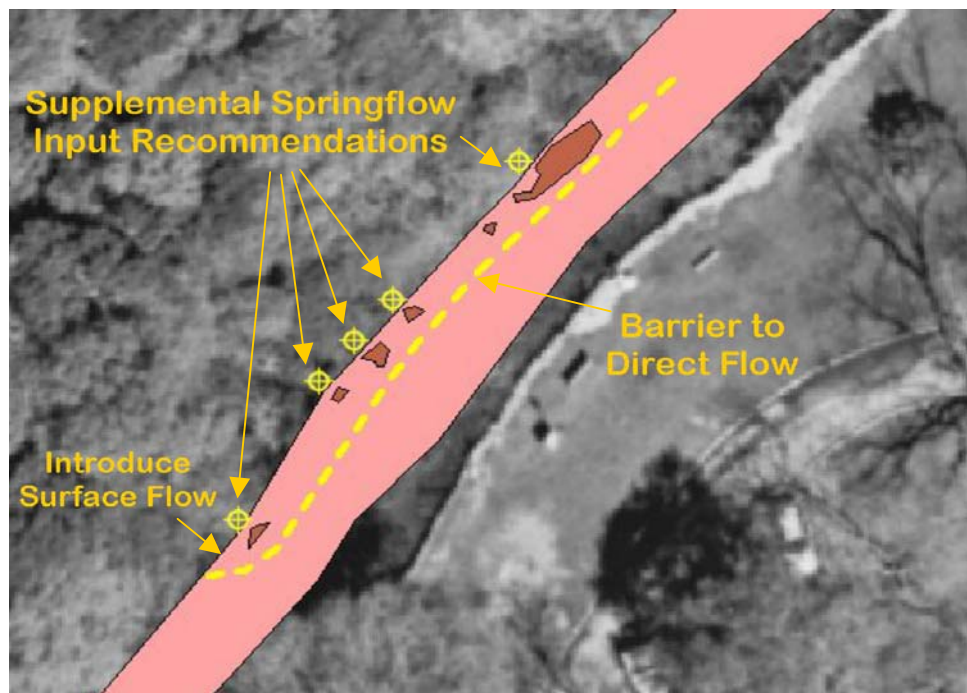


Figure C-7. A close-up of the Comal Springs riffle beetle habitat along the north shoreline of Spring Run 3. Simulated spring seeps along the shore are recommended for at least five of the six largest high quality habitats. A secondary recommendation would be to introduce surface flow at the upstream-most habitat and direct it along the shoreline over the downstream habitats.



Figure C-8. Close-up of the western shoreline riffle beetle habitat. This is an isolated area with relatively high densities of beetles sampled here regularly, but not in nearby habitats. Small upwelling habitats in the lake have also produced adult and larval Comal Springs riffle beetles. A simulated spring seep along the shoreline is recommended for this site.

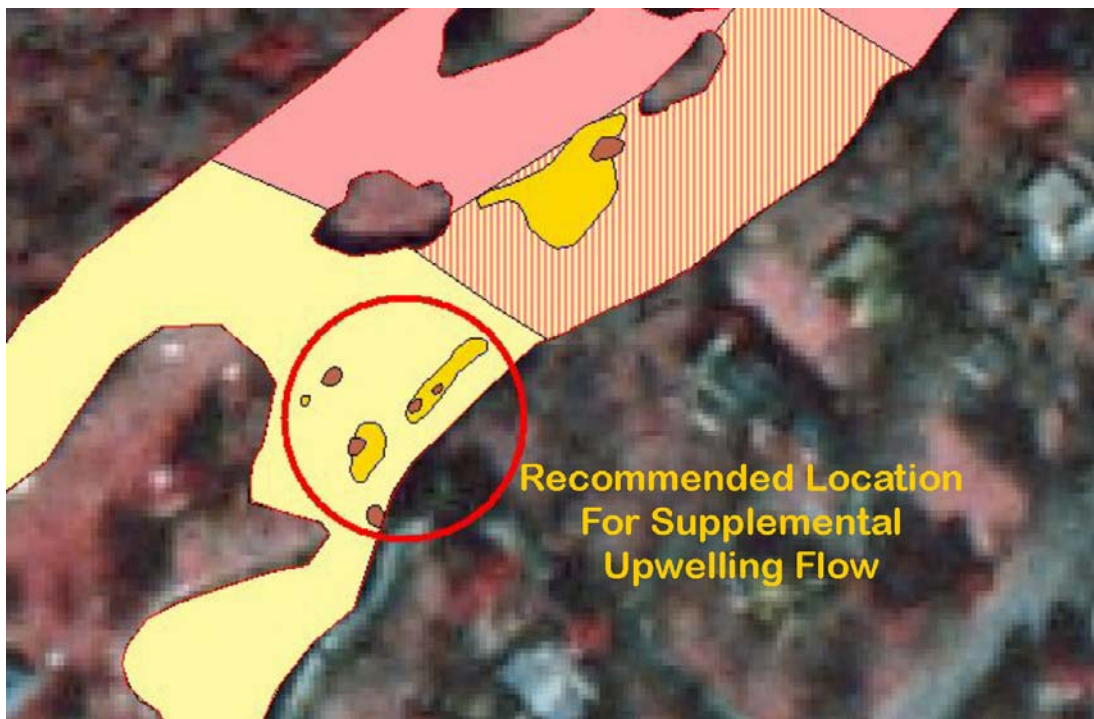


Figure C-9. Close-up of Comal Springs riffle beetle habitat upstream of Spring Island. These habitats are formed by upwelling springflow, which supplemental water should attempt to simulate. If introduced as surface flow, the supplemental water would not be as beneficial in this area. Areas within the red circle should receive highest priority for water supplementation.

the point that the natural springs stop flowing. The western shoreline should have a similar design of 2-3 lateral seeps with 2-5 cfs percolating through the habitat in this area. The upwelling area upstream of Spring Island should receive 5-8 cfs supplemental flow. The upwelling design could be a series of PVC pipes permanently buried in the substrate and designed to direct flow up through the primary habitat areas. It is critical that supplemental water be supplied to these habitats slightly before natural springflow ceases to prevent emigration (vertical or horizontal) of beetles into other habitats that may be less suitable. The design is such to keep the riffle beetles in the natural habitat and supply enough water to simulate natural conditions for short periods. If individuals move they may not respond to the artificial water supply and move back into the original habitat rendering the design ineffective. It should also be noted that this design has not been tested; a pilot project is necessary before a design like this could be fully implemented and relied upon to protect natural habitat for the species. There is no guarantee that providing a small amount of supplemented water in a way that appears to simulate natural springflow will provide all necessary requirements to maintain similar habitat suitability.

If some of the supplemental water needed for the 60 cfs minimum requirement is re-circulated from Landa Lake back into upstream habitats, it would minimize dependence on other water sources. If water quality, primarily temperature, can be maintained using this method it may make better use of limited supplies. For instance, the 15-25 cfs recommended for individual springs to maintain Comal Springs riffle beetle habitat could be designed to use re-circulated water and another source used to supply the 35-45 cfs for fountain darter habitat. Re-circulated water would largely be of the same quality (with some potential increases in temperature). The modified channel design described below would reduce retention time and significantly reduce instream heating, but water temperature may also increase in transit through the re-circulation process. This problem of water heating during transit could be significant if pipes are exposed to summertime air temperatures; underground pipes would improve the design greatly. A recapture location in the deep area at the beginning of the New Channel would be most beneficial since it would be downstream of the Old Channel (to maximize water quantity there) but close enough to natural spring inputs that heating would be minimal (Figure C-10). A net loss of streamflow in the New Channel would occur, but this habitat is lower quality than in the Old Channel.

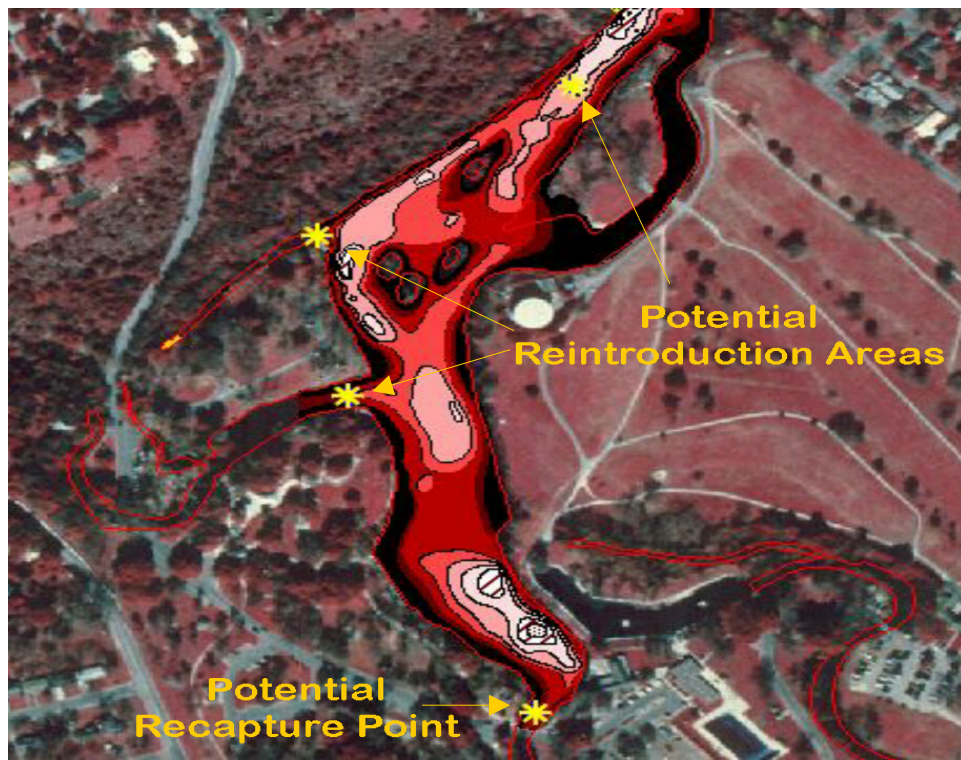


Figure C-10. Overview of potential areas for re-capturing water in Landa Lake for re-circulation to upstream areas. Potential re-introduction sites are also indicated that would attempt to maximize fountain darter habitat.

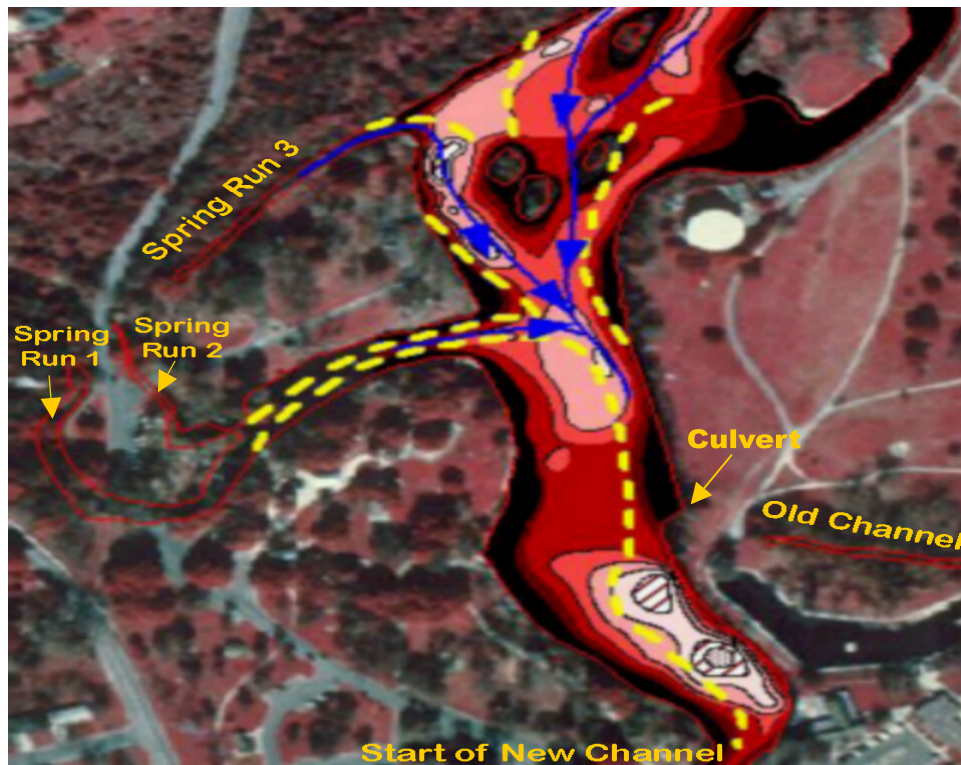


Figure C-11. Overview of conceptual design to redirect flow through Landa Lake more efficiently. Dashed yellow lines represent approximate locations of temporary structures to direct flow along the eastern shoreline of Landa Lake downstream of inputs from Spring Runs 1 and 2. Blue arrows represent direction of flow. The design involves reducing surface area significantly downstream of the Spring inputs and directing flow along the east shoreline of Landa Lake toward the Old Channel diversion.

A more direct pathway of spring discharge through Landa Lake would benefit the fountain darter by reducing retention times (and water heating) in the lake and maintaining a greater amount of usable habitat in downstream areas (primarily the Old Channel). This would be accomplished by placing structures in the water to direct springflow through pathways that include the most valuable habitats and springs in the deepest areas of the lake (Figure C-11). Much of the lake contains the aquatic macrophyte *Vallisneria* sp. a relatively low-quality habitat for fountain darters. By reducing the surface area of the lake in areas that contain only this plant or bare silty substrates, retention time would be reduced with relatively little loss of fountain darter habitat in the lake. A net increase in fountain darter habitat would occur because more Old Channel habitat would remain usable. The primary recommendation for this feature would be to narrow the channel at the confluence of Spring Runs #1 and #2 and direct this water out to the eastern one-third of the current lake and bypass all *Vallisneria* sp. habitat along the western two-thirds from the current confluence downstream (Figure C-12). It would be important to restrict the channel to the eastern rather than western edge of the lake because that is the side where a culvert allows water into the Old Channel. Downstream of that culvert, the water can be directed through the deep area and into the New Channel. Additional options for this design would be to direct Spring Run #3 flow to the eastern portion of the lake in a similar manner and narrow the channel downstream of Spring Island to reduce surface area in those sections of the lake as well (Figure C-13).

The third design to protect critical habitat would have a dual purpose. The primary feature would be an intensively managed area in the upper portions of the Old Channel to protect the vegetation that provides high-quality fountain darter habitat during low-flows and potentially create Comal Springs riffle beetle habitat. The design would involve a relatively small-scale re-circulation setup and a temporary dam across New Channel. A water transfer mechanism (possibly a pipeline) would be necessary to move water up from just below the low-water crossing (access to the golf course) to an area about 300 ft upstream to convert the intervening section to an intensively managed area (Figure C-14). Re-circulation would be initiated when total discharge in the ecosystem falls below 80 cfs. The riffle beetle habitat would be created and permanently maintained in a method similar to the spring seep design described for Spring Run #3. A series of pipes would create simulated seeps along the shoreline and some upwelling flow where riffle beetles would be introduced. This habitat could be maintained as an additional

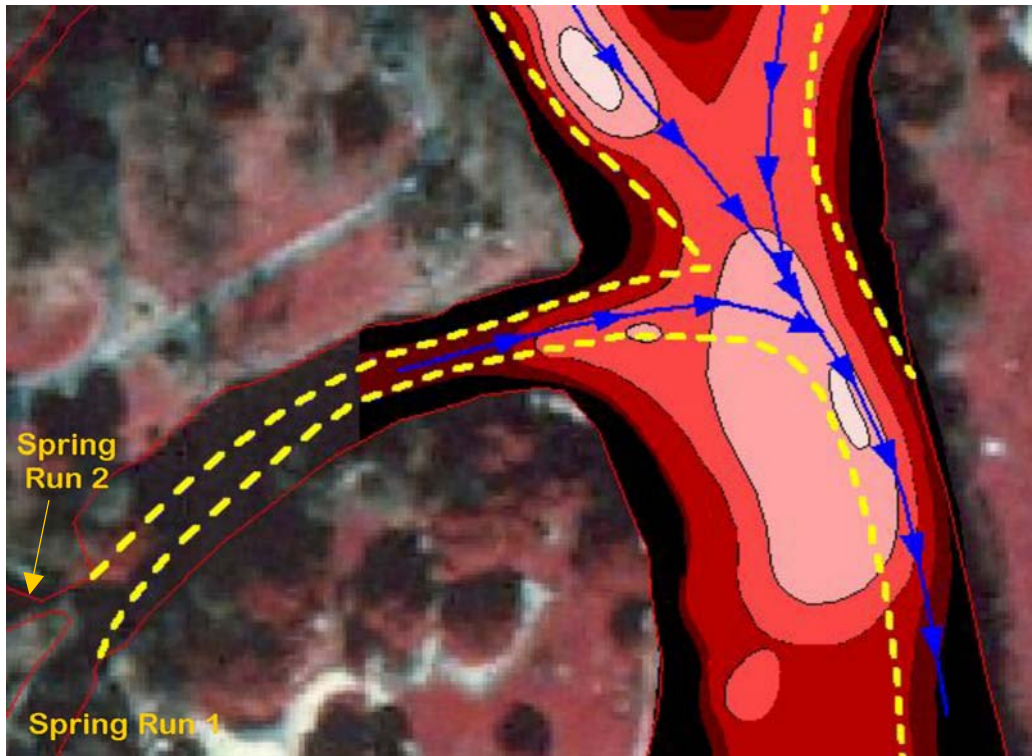


Figure C-12. Close-up of confluence of Spring Runs 1 and 2 in the design to redirect flow in Landa Lake. This is the primary recommendation and would minimize residence time in low quality habitat and reduce water heating during critical low-flows.

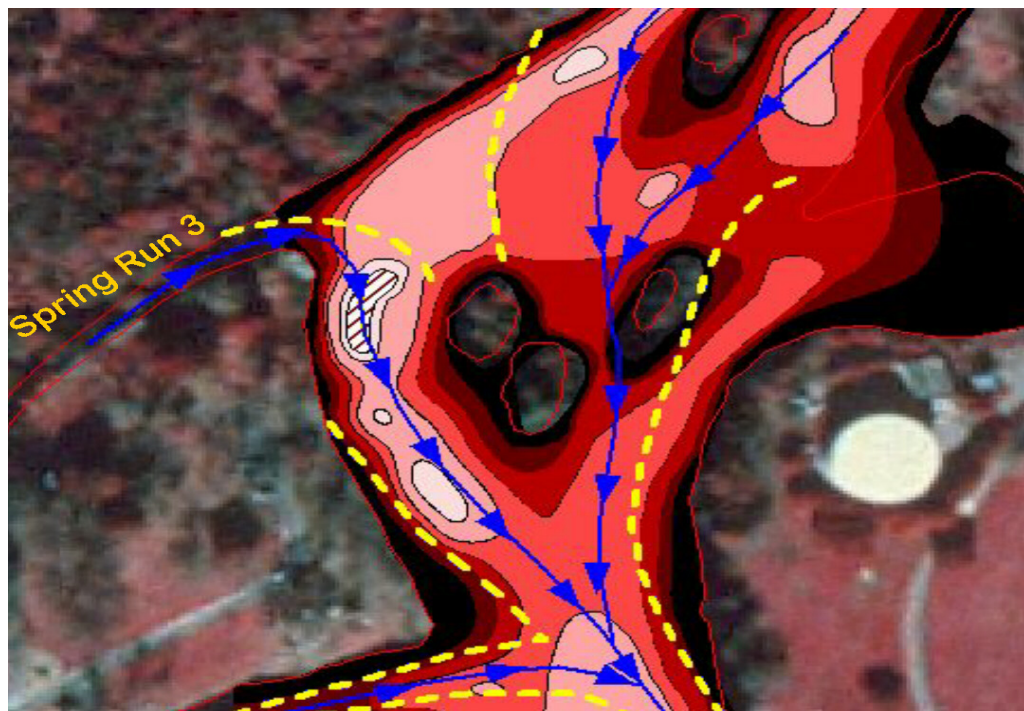


Figure C-13. Close-up of Spring Run 3 and areas just upstream in the design to redirect flow in Landa Lake. This is a secondary recommendation that would direct water from Spring Run 3 more quickly to downstream areas and reduce surface area for streamflow from upstream areas.

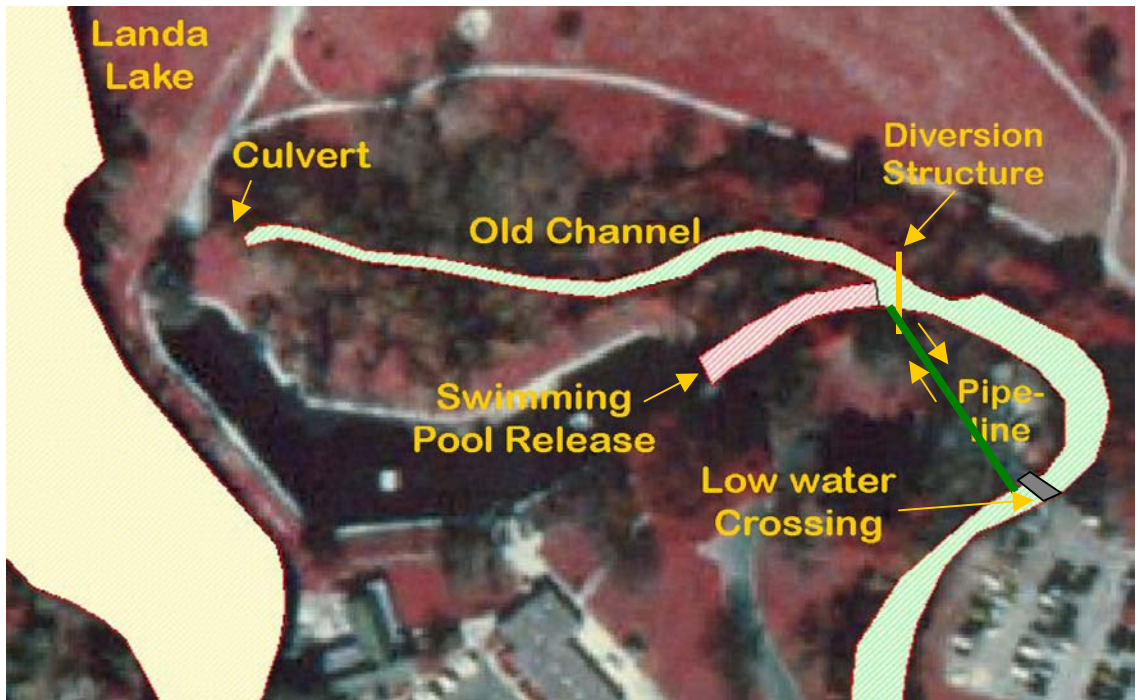


Figure C-14. Overview of recommended refugia in upper section of Old Channel Reach. A pipeline would recapture a portion of in-stream water from below the low-water crossing (path to golf course) and bring it back upstream to the diversion structure during low flow to increase water quantity in about 100 meters of high quality fountain darter habitat. The diversion structure and pipeline would also allow water to be routed around the area during high-flows for experimentation. The approximately 100-meter long habitat could also benefit from restoration activities designed to remove lower quality vegetation and increase vegetation that provides high quality fountain darter habitat. Comal Springs riffle beetle habitat could also potentially be created in this area.

area of protection during extremely low-flow conditions to maximize the total areas available for the population. In addition to providing habitat for fountain darters and Comal Springs riffle beetles during periods of low flow, an intensively managed area in this section of the Old Channel could provide a setting for natural-laboratory experiments during periods when flows are high and habitat is plentiful throughout the fountain darter range. Flows could be manipulated in the intensively managed area during these normal-to-high flow conditions to evaluate impacts of various scenarios such as extreme low-flows or scouring flood events or some combination of these. As with previous suggestions, this design has not been tested and a pilot project is a necessity before a design like this could be fully implemented and relied upon to create and/or protect natural habitat for these species.

C.3.1.4.1 Permanent structures

These conceptual designs would require some permanent structures and some temporary ones that are used only during low-flow periods. Re-circulation of water from the lake back to upstream habitats would require a pipeline and machinery for pumping water back up to upstream locations. Water should be collected from a deep section of Landa Lake, preferably downstream from the culvert that directs flow into the Old Channel. An area of deep water near the downstream most location on the lake where the New Channel originates would be an ideal location.

A system of pipes/hoses would also be necessary to route water to critical habitat for riffle beetles along the western shoreline of Landa Lake, to upwelling areas just upstream of Spring Island, and to habitat along the shoreline of Spring Run #3. Perforated pipes or some similar design could be put in place immediately before initiating supplementation directly into individual springs/seeps, and a temporary pump could be used to move water from Landa Lake back into the spring run and western shore line habitat. The buried section of pipe to create upwelling in the Spring Island area would be permanent, as would a design in Spring Run #3 and the western shoreline habitat that buried pipes horizontally to distribute simulated seep-flow broadly rather than a vertical placement of pipes to simulate springflow in more specific locations.

The intensive management area in the Old Channel would require permanent pumping machinery and pipes or a system of pipes to re-circulate water in that channel and also allow water to bypass the management area (for simulated low-discharge research) during normal-to-high flow conditions.

C.3.1.4.2 Temporary Structures During Low Flow

The direction of water through Landa Lake to reduce retention times and maintain suitable water temperatures for downstream habitats would be accomplished most efficiently with permanent structures. However, this would greatly impact recreational use and aesthetics of the lake, not to mention the likely high costs of such permanent structures. Therefore, inflatable dams or similar temporary structures would probably be best suited for use in this situation, and could be put in place when total discharge drops to 80 cfs.

C.3.2 Biologic assemblage of San Marcos Springs, Spring Lake, and San Marcos River

C.3.2.1 Species

Six of the eight threatened/endangered species associated with the Edwards Aquifer are found in the San Marcos Springs ecosystem. These include the fountain darter, San Marcos gambusia, Texas wild-rice, Texas blind salamander, San Marcos salamander and the Comal Springs riffle beetle. The fountain darter and Comal Springs riffle beetle are described above. The San Marcos gambusia is a member of the family Poeciliidae and described by Hubbs and Peden (1969). Individuals range in size from 1.0 to 1.5 inches with adult females being larger than males (Whiteside 1976). Texas wild-rice is a primarily aquatic, perennial grass of the family Poaceae that is endemic to the San Marcos River. It is usually immersed and prostrate in the swift flowing waters of the river, but during times of low-flow, the upper portions of the culms (stems) and leaves become emergent (Terrell et al. 1978, USFWS 1996). The Texas blind salamander is a smooth, unpigmented troglobitic (cave-adapted) species and has a maximum length of 4.7 inches. It has a broad head, reduced eyes, long and slender limbs, four toes on the forelegs and five on the hind legs (Longley 1978). The San Marcos salamander is a member of the lungless salamanders of the family Plethodontidae. San Marcos salamanders are small, reaching a maximum length of 2.3 inches, slender and light brown in color. Prominent features include large eyes with a dark ring around the lens, we-developed and highly pigmented external gills, moderately short and slender limbs, four toes on the forefeet and five on the hind feet, and

a well-developed dorsal fin. San Marcos salamanders are distinct when compared to other neotenic *Eurycea* from Texas in that they are smaller, more slender, have different coloration, have more costal grooves, larger eyes relative to their head, and fewer teeth (Tupa and Davis 1976, USFWS 1996).

C.3.2.2 Locations Within Springs, Spring Lake and San Marcos River Downstream From Spring Lake

Fountain darters are found in a wide range of habitat types in the upper reaches of both the San Marcos and Comal Springs ecosystems. In the San Marcos ecosystem, the fountain darter occupies all areas of the river from Spring Lake at the headwaters down to an area between the outfall of the San Marcos wastewater treatment plant and the confluence with the Blanco River (USFWS 1996). The population is greatest in Spring Lake while the riverine sections downstream maintain lower densities of the species (BIO-WEST 2002c, 2003b, and 2004b).

The San Marcos gambusia was historically sampled most frequently between the Interstate Highway 35 bridge crossing and the areas surrounding Thompson's Island. When observed in the past, the population was sparse relative to the similar mosquitofish (*Gambusia affinis*). Since it has not been collected since 1982 and the population appeared to be in decline prior to that (USFWS 1996), the San Marcos gambusia is considered extinct.

Texas wild-rice is currently distributed in the upper 1.5 miles of the San Marcos River from Spring Lake at the headwaters of the river down to the confluence with the Blanco River (Poole and Bowles 1999). The population is most abundant between the Spring Lake dam tailrace and the Interstate Highway 35 bridge crossing. A few plants occur in the downstream sections of Spring Lake and a sparse distribution occurs between the Interstate Highway 35 bridge crossing and the San Marcos wastewater treatment plant outfall.

Texas blind salamanders occur only in the San Marcos area of the Edwards Aquifer (all collections have occurred in Hays County). The species was initially recovered from the artesian well drilled to supply the Federal Fish Hatchery in San Marcos with water in 1895 (Longley 1978). Since then, it has been observed in Ezell's Cave, San Marcos Springs, Rattlesnake Cave, Primer's Fissure, Texas State University's artesian well, and Frank Johnson's well (Russell 1976, Longley 1978). It was also found in Wonder Cave prior to 1977, but searches in that year

did not reveal any individuals (Longley 1978). The distribution may be the Edwards Aquifer beneath and near San Marcos in an area as small as 25.9 square miles (USFWS 1996).

San Marcos salamanders occur near all major spring openings scattered throughout Spring Lake and in rocky areas in the San Marcos River just below Spring Lake for approximately 500 ft (Tupa and Davis 1976, Nelson 1993, BIO-WEST 2002c, BIO-WEST 2003b, BIO-WEST 2004b).

A single individual of the Comal Springs riffle beetle was also collected in Spring Lake at the headwaters of the San Marcos River (Barr 1993) but subsequent sampling has not resulted in additional observations. It is possible that the species is still present in the San Marcos Springs, but recent surveys by USFWS have identified 50 additional specimens (adult and larvae) in the crater spring openings (R.Gibsonm, USFWS biologist, personal communication. Water Requirements for Species

C.3.2.2.1 Habitat (Water Chemistry, Importance of Variable Flow and Residence Times)

Habitat requirements for the fountain darter in the San Marcos River are similar to the population in the Comal River. Important variables are clear, clean, flowing, and thermally constant waters, adequate food supply, undisturbed sand and gravel substrates and areas of submergent aquatic vegetation for cover (Schenck and Whiteside 1976, McKinney and Sharp 1995, Linam et al. 1993). Water temperature is similarly important in the San Marcos River. Fluctuations in discharge affect the residence time of water in Spring Lake and subsequently affect downstream water temperatures. The relationship between discharge and water temperature in the San Marcos River has been modeled by the TPWD (2000) and is being studied under variable flow conditions by BIO-WEST (2002c, 2003b, and 2004b). Vegetation composition is also very important in the San Marcos River, but a more narrow range of suitability exists among plant types found in this river compared to the Comal River (bare substrate generally does not provide suitable habitat). Variation in flow affects the composition of the plant community in the San Marcos River as in the Comal River and thus affects fountain darter habitat.

The San Marcos gambusia is considered extinct; however, it was previously captured in quiet waters adjacent to sections of moving water. Water temperature was also an important factor determining habitat suitability. The species was found mostly over muddy substrates but generally not silted habitats and appeared to require shade from over-hanging vegetation or

bridge structures (Hubbs and Peden 1969, Edwards et al. 1980). One hypothesis for the disappearance of the species is that the exotic elephant ears that currently occur in great abundance along margins of the river reduced the suitability of habitat previously used by the species.

Texas wild-rice is generally found in high to moderate current velocities and shallow water depths (<3 ft) and coarse and sandy substrate (Poole and Bowles 1999). Power (1996a) found that substrate composition and current velocity affects plant biomass and stem density. The literature on this species suggests that wetted perimeter and stream flow are important variables that affect the health of the population. In addition, Bio-West (2004c) observed that variation in carbon dioxide (CO₂) concentration significantly affects growth of the species. Since much of the population is currently found in shallow areas, significant reductions in streamflow could expose many plants and may also reduce the growth of these plants. A TPWD (2000) report predicted that approximately 20% of usable area for Texas wild-rice would be lost with a decline in springflow from 140 cfs to 50 cfs using an approach that combined habitat requirements and hydraulic modeling components. Herbivory is a potential problem for Texas wild-rice; decreased flows leave the plants more susceptible to waterfowl, introduced nutria, and ramshorn snails (Rose and Power 1992). Lower flows also increase the likelihood of developing vegetation mats on top of Texas wild-rice plants. These vegetation mats may interfere with vegetative culm emergence, block sunlight and interfere with photosynthesis, and slow current velocity further (Power 1996b). Another concern is competition with exotics, which may gain a competitive advantage when conditions are sub-optimal for Texas wild-rice. Texas wild-rice is frequently found in areas with dense growth of the non-native aquatic macrophytes *Hygrophila polysperma* and *Hydrilla verticillata* (Poole and Bowles 1999, Bio-West 2002d).

As with the other subterranean species very little is known about the habitat requirements of the Texas blind salamander. It is assumed that at least a small amount of springflow would be important to prevent a decline in local water quality conditions, particularly temperature and dissolved oxygen concentrations. Subsurface water flow may continue to provide suitable water quality for a portion of the population if springflow ceases, but the vertical distribution of the species is unknown.

San Marcos salamanders are found under silt-free rocks around spring openings and rocky areas to approximately 150 m downstream of Spring Lake dam. They are also abundant in the filamentous algae found in the upper end or “hotel reach” section of Spring Lake (Tupa and Davis 1976, Nelson 1993). The primary concerns facing the San Marcos salamander are water temperature and other water quality parameters, available physical habitat, and wetted perimeter. Temperature requirements are known only from research conducted to determine critical thermal maximum for the species: 96.4° F (35.8° C) and 99.1° F (37.3° C) for juveniles and adults, respectively (Berkhouse and Fries 1995). Because of the constancy of the water temperature issuing from the springs (Groeger et al. 1997), it is extremely unlikely that this temperature maximum will ever be reached. Downstream of Spring Lake Dam, there is a greater potential for water temperatures to increase; however, studies have shown that the temperature in this portion of the San Marcos salamander’s range remains virtually unchanged from the temperature at the spring orifice (Espey, Huston & Associates 1975, Groeger et al. 1997). Thermal requirements of the San Marcos salamander should be met as long as water continues to flow from the spring openings in Spring Lake. This will also meet the need for physical habitat (silt-free rocks around the spring openings) within Spring Lake and, to a lesser degree, downstream of the dam (Tupa and Davis 1976, Nelson 1993).

Wetted perimeter is another concern for the San Marcos salamander, though the relative constancy of the water level in Spring Lake, even with changes in discharge, minimizes this concern. Unlike habitat in the lake itself, portions of the San Marcos salamander range found downstream of Spring Lake are subject to changes in wetted perimeter as discharge fluctuates. At a site immediately downstream of the San Marcos salamander’s range (just upstream of University Drive Bridge), information gathered from TPWD (2000) reveals that a wetted width of 60.8)ft occurs when flows reach 172 cfs. At a discharge of 125 cfs, 56.8 ft (93%) of the wetted width remains, and at 81 cfs, 50.4 ft (83%) remains.

The Comal Spring Riffle beetle has recently been confirmed in Spring Lake.. As in the Comal Springs complex, springs should not be allowed to stop flowing so as to provide adequate protection of this species. Also, without any other data on water chemistry parameters, it is assumed that standard requirements, (temperature, dissolved oxygen, pH, and conductivity) should remain within the historic range observed in the (presumed) natural habitat for the species.

C.3.2.2.2 Recommended Spring Discharge Rates

Among the six threatened/endangered species found in the San Marcos Springs ecosystem, the focus should be to maintain habitat for three species: the fountain darter, Texas wild-rice, and San Marcos salamander. The San Marcos gambusia is considered extinct; however, any efforts to protect habitat for the fountain darter should provide adequate downstream habitat for this species. The Texas blind salamander is similar to the subterranean invertebrates in the Comal River in that it would experience some habitat loss around spring openings with a dramatic loss or cessation of springflow, but some subterranean habitat would remain. Habitat for the species dependant on surface flow would be in much higher risk under such conditions. It would also be very difficult to provide artificial spring upwelling that would ensure that these habitats remain suitable for the subterranean species. Currently, in the unforeseen event that results in cessation of springflow and substantial localized reduction of the aquifer level in the San Marcos Springs area, captive propagatim may be the only way to ensure persistence of this species. As in the Comal River, the location of springflow supplementation is critical for the Comal Springs riffle beetle. More information is needed on the distribution of this species in the San Marcos River to properly develop a strategy to supplement springflow for it.

Currently, take and jeopardy discharge values for the fountain darter species in the San Marcos River are both 100 cfs.. Maintaining springflow at those levels would theoretically provide suitable conditions for the species at all times. However, providing supplemental water to augment springflow at those levels may deplete available water before natural springflow drops to levels that becomes truly necessary, when the water could be put to better use. A more achievable goal, and greater use of what would become a very limited resource under such conditions, would be to supplement natural spring discharge with enough water to maintain 60 cfs for a very limited period of time until wetter conditions return.

In addition to maintaining this minimum discharge level, water can be more efficiently routed through the ecosystem to reduce water temperature concerns. This type of intensive management strategy is recommended for initiation at 80 cfs total discharge in the San Marcos River. Below this value for natural discharge, the retention of water in Spring Lake would potentially reduce a substantial amount of suitable habitat in the lower reaches of the fountain darter range in that river. To reduce this potential effect, a barrier could be placed across the

slough arm of Spring Lake (Sink Creek) to direct water more efficiently through the lake and reduce retention times and the heating of that water (Figure C-15). This would also allow the water to travel further down the river before the temperature rises to a level that begin to have impacts to fountain darters. At low flow (50 cfs) residence time in the lake is estimated to be approximately 22 hours. By blocking off circulation in the slough, residence time in the main body of the lake would theoretically decrease to approximately 12 hours. A 12-hour residence time equates to approximately 100 cfs total discharge.

Texas wild-rice will benefit from water supplementation used to protect habitat for the fountain darter. Although its requirements focus more on wetted width and water depth than temperature (as with fountain darters) the two species have similar take and jeopardy discharge levels and water used to reduce temperatures will support habitat for this species. Ideally, 100 or even 80 cfs would provide a substantial amount of suitable habitat, but based on TPWD estimates of habitat loss at lower discharge values, 60 cfs should be adequate to provide sufficient habitat for the species. Higher discharge will also maintain CO₂ levels for a greater portion of the species' range.

For the San Marcos salamander, the current take and jeopardy discharge values are each 60 cfs, therefore maintaining that amount with supplementation should be sufficient. Although the species is generally found near spring upwellings, they are not often found down in spring openings, but on nearby rocks that remain silt-free from the springflow. Therefore the supplemented water would not necessarily have to issue from the current spring openings, but would have to provide water of similar quality as natural springflow in several locations within the lake and maintain the silt-free rock habitat. The population found below the dam would have some reduction in habitat with a reduction to 60 cfs discharge, but the majority would remain suitable.

C.3.2.3 Feasibility of Engineered Structures

There are three conceptual areas for maintaining habitat for the fountain darter, Texas wild-rice plants and San Marcos salamander. The first is to manage flows between the two spillways of Spring Lake dam when total discharge in the San Marcos River drops to 80 cfs and below such that 60 cfs is allowed to travel down the eastern spillway at all times. The second is to supplement water immediately downstream of the eastern spillway (and a smaller amount of



Figure C-15. Recommended modification to Spring Lake during low flow conditions to minimize retention time: a temporary dam across the slough arm where Sink Creek enters the lake. Bathymetry lines in the lake are at approximately 4-ft intervals and darker colors indicate deeper water.

water introduced into the headwaters) to maintain 60 cfs total discharge in the river. The third design is to place a temporary structure across the area where Sink Creek enters into Spring Lake during critical low-flow periods to reduce retention time of spring discharge in Spring Lake and reduce water heating during these periods.

Under normal discharge conditions, streamflow from Spring Lake is divided among two spillways on the eastern and western sides of the dam. There is habitat for fountain darters and San Marcos salamanders in both segments; however, the eastern side supports a dense population of Texas wild-rice plants. The two spillways are not easily sampled for fountain darters, but it appears that the deep, fast currents of the western spillway and minimal vegetation coverage there would support far fewer individuals than the eastern spillway. Thus, for two of the three critical species found in these habitats, the eastern spillway is substantially more important and flows in that section should be of greater priority. San Marcos salamanders are regularly sampled in the eastern spillway as part of the Authority's Variable Flow Study and salamanders are captured in this area in numbers as high as 5.2 individuals per square meter, but on average about 1.9 are observed per square meter (BIO-WEST 2004b). A survey in 2001 resulted in an estimate of 3.5 - 4.0 salamanders per square meter in small areas in the western spillway (Bio-West unpublished data). However, the total area that provides suitable habitat in the eastern spillway is greater. A design that maintained springflow in the eastern spillway at the expense of reduced flows in the western spillway would result in degraded conditions for salamanders in the latter section, but overall, the scenario would benefit the species relative to allowing conditions to deteriorate in both sections. It is therefore recommended that streamflow in these two spillways be manipulated so that below 80 cfs discharge, 60 cfs travels down the eastern spillway to maintain suitable habitat for all three species. The elevation of the western spillway is approximately 6 inches lower than the elevation of the eastern spillway. Therefore, the majority of the water flows over the western spillway under current conditions. Slightly raising the elevation of the western spillway (either permanently or temporarily during low-flow conditions) would increase the relative discharge over the eastern spillway.

In addition to directing up to 60 cfs natural spring flow down the eastern spillway, supplemented water is recommended for any deficit resulting from a decline in natural springflow below this value. The supplemented water should primarily be introduced at the upstream portion of the eastern spillway to provide the highest quality water directly into this area (rather than allow it to

travel through the lake and heat up). This supplemented water should maintain sufficient water quality to support suitable habitat for the species. The primary concern with water quality is water temperature, but CO₂ should also be maintained at relatively high levels to support downstream Texas wild-rice plants and dissolved oxygen should be high enough to support aquatic organism. In addition to supplemented water at the dam spillway, a small portion of the water should also be directed to the headwaters of the lake at extremely low natural discharge levels to support the dense populations of San Marcos salamanders and fountain darters found there. The lowest recorded discharge at San Marcos Springs was 46 cfs in the summer of 1956. However, if natural springflow falls to below 20 cfs, it is hypothesized that the low discharge will not keep the substrate sufficiently free of silt deposition and may reduce habitat for San Marcos salamanders. These conditions may also result in higher temperatures and insufficient water movement to support vegetation and food for fountain darters. Therefore, in the event of total natural discharge falling below 20 cfs, supplemented water should be directed into the large spring opening (upstream most site where springs emerge from under the walkway) at the headwaters of the San Marcos River. This supplemented water should maintain 20 cfs regardless of the total decline of natural springflow.

Supplemented water for the two locations on the San Marcos River should probably be from an outside source since re-circulation of water may have more impacts on downstream habitat than in the Comal ecosystem. The most likely location for recapturing water for re-circulation would be in deep water just upstream of the second pedestrian bridge crossing in Sewell Park on the Texas State University Campus. Allowing the water to travel much further before recapture would result in increasingly higher temperatures. However, such a diversion would deteriorate conditions downstream of the recapture point by resulting in a net decrease of streamflow and higher water temperatures. This would not affect San Marcos salamanders since they are not found greater than approximately 500 ftdownstream of Spring Lake dam. The areas upstream of this point also have the greatest densities of Texas wild-rice plants and fountain darters; however, a substantial portion of the total range of each species would be compromised under that scenario. If outside water supplies are not sufficient in terms of availability or quality, re-circulation using this recapture location would support the highest quality habitats, but would provide less protection to all existing habitat than an outside source.

The final recommendation for the San Marcos ecosystem is to reduce residence time of spring discharge in Spring Lake to maintain suitable temperature for a greater portion of existing downstream habitat. As springflow declines, increasing residence time in the lake will increase water temperatures and reduce the suitability of some habitat at the downstream edges of the fountain darter and possibly the Texas wild-rice population ranges. The slower movement of the water will also allow more time for CO₂ concentration of the water to be used up and/or escape into the atmosphere. The CO₂ concentration is important for Texas wild-rice growth (Bio-West 2004c) and a reduction for extended periods may have negative impacts on plants at the downstream edge of the population. To reduce the residence time of water in Spring Lake a more direct path could be designed that blocked off the slough arm of the lake where Sink Creek enters (Figure C-15). This section of the lake results in increased heating and any water that moves into the slough will take longer to move downstream and interact with the higher temperature water there. A structure that prevented springflow from flowing into the slough and intermingling with the water there would benefit downstream habitat for the fountain darter, Texas wild-rice and San Marcos salamanders. Habitat conditions in the slough may deteriorate with the structure in place and some native plants and potentially some fountain darters may be negatively affected, but the design would benefit the species of concern.

C.3.2.3.1 Permanent

Manipulating flow between the western and eastern spillway can be conducted with existing structures. The chute in the western spillway can be elevated/blocked to reduce or completely stop flow through the structure. Supplementation will require a system of pipes to provide up to 40 cfs discharge to the eastern spillway under worst-case conditions of zero natural springflow and up to 20 cfs natural discharge to the headwaters of the river under worst-case conditions (drought of record). If water is re-circulated the intake structure and pump machinery would have to be permanently fixed and maintained.

C.3.2.3.2 Temporary During Low Flow

As in the Comal ecosystem, the direction of flow in Spring Lake could be done more effectively with temporary structures. Under normal flow conditions, blocking of the slough would unnecessarily degrade conditions in this area. High runoff events would also result in substantial flooding of the golf course and other low-lying areas adjacent to Sink Creek. A temporary structure would allow more control to maximize localized habitat conditions with minimal secondary impacts.

C.4 Approaches for Management of Flow in Comal and San Marcos Springs to Maintain Critical Habitat for Endangered Species

The endangered species that are primarily subterranean should have relatively high quality habitat up until the point at which springflow ceases entirely, after which some habitat will be lost near spring openings, but subterranean water movement will still maintain some natural habitat. Because of this, and the difficulty in developing any sort of feasible intensive management area design, no recommendations are given for these species. Captive propagation is the only option for these species if the aquifer level drops to extremely low conditions and water quality conditions become degraded. In contrast, those species that are dependent on surface flow from the springs begin to lose habitat before springflow ceases entirely.

Supplemental water sources and other intensive management area designs may greatly enhance habitat suitability in the wild when natural springflow conditions do not provide enough water to effectively maintain natural habitat. Under these conditions, habitat can be temporarily supported as suitable (not optimal) for short-term maintenance of these populations. This springflow has to be properly targeted to areas of known high-quality habitat for each species and must be of sufficient quality to allow for species survival. Other intensive management area projects are designed to maintain water quality conditions and direct water to the highest quality habitats. Although these designs are based upon the best biological knowledge of each species, most will have to be tested with small-scale pilot projects to gauge their effectiveness in the wild.

C.4.1 Costs for Re-circulation at Comal Springs

Several alternatives for re-circulating water in the Comal Springs system were described in the previous sections. These scenarios also listed several alternatives for engineered structures that would enhance the flow of water in the spring reaches as well as through and out of Landa Lake

into the Old Channel. The engineered structures utilized are inflatable dams. These inflatable dams are placed in the desired location in the spring reaches or in the lake itself and filled with water. The dams can range in size from 1 to 16 ft in height. For this study, the options for the length of the inflatable dams range from 100 ft (blocking flow to the new channel) to over 3,000 ft (for improving flow in several spring reaches and limiting the amount of time the water is actually in Landa Lake). The cost of the inflatable dam ranges from \$6.25 to \$295.00 per linear foot for dams ranging in height from 1 to 16 ft, respectively.

For Comal Springs the height on the inflatable dam is assumed to be approximately 10 ft. The 10-ft dam costs approximately \$160.00 per linear foot. It is recognized that not all of the height will be this large for the alternatives with significant lengths. However, for a conservative cost estimate the height is assumed to be 10 ft. Therefore, the resulting cost estimates range from \$16,000 to \$300,000 depending on the length of the dams utilized. The maximum cost is based on a series of inflatable dams in several spring reaches as well as in Landa Lake itself. A pilot study should be conducted on the inflatable dams to insure the effectiveness of the structures to meet the goals of the project prior to purchasing the total length.

C.4.2 Additional Re-circulation Costs for Comal Springs

Additional costs associated with the re-circulation alternatives described in the previous text also include costs for equipment to re-circulate water and provide water for keeping Spring Run #3 wet. These costs include pumps to re-circulate water, PVC pipe to transport the water from Landa Lake to Spring Run #3, and pumps to inflate the inflatable dams. A conservative cost estimate for these items is \$250,000 depending on the number of submersible, number of pumps required to fill inflatable dams, pumps, pump sizes, amount and diversion point of the water to be re-circulated and length and size of PVC pipeline.

C.4.3 Costs Associated with San Marcos

Several alternatives for inflatable dams utilized at San Marcos Springs were described in the previous sections. These scenarios also utilize different lengths and heights of inflatable dams. The alternatives range from an inflatable dam to prevent flow into the slough to adding an inflatable dam that is two ft in height on top of the existing dam structure at Spring Lake to channel the flow out of the dam to the east side. As discussed before, the costs of the inflatable dams range from \$6.25 to \$295.00 per linear foot for dams ranging in height from 1 to 16 ft,

respectively. For this study, the options for the length of the inflatable dams range from 100 ft (adding additional height to the western end of Spring Lake dam) to over 400 ft (for limiting flow into the slough). The 100-ft section would be approximately two ft in height (\$15.00 per linear foot) while the 400-ft section for the slough would be approximately 15 feet in height (\$295.00 per linear foot). Therefore the cost range would be \$1,500 for the smaller dam to \$118,000 for the larger dam. Additional cost would also include \$10,000 for pumps to fill the inflatable dams.

D. Augmentation Approaches

Five basic approaches for augmentation at Comal Springs and San Marcos Springs are considered for maintaining springflow at these Springs. They are:

1. Regional groundwater management to maintain water levels as high as possible during drought periods.
2. Importing water to the spring complex and augmenting flow by injecting the water directly into the aquifer, importing the water into Landa Lake or Spring Lake or in the specific case of Comal Springs discharging the water into the Old Channel where there is a large population of endangered species. A variety of different water sources are also considered.
3. Pumping Edwards water locally to augment surface waters either in Landa Lake or Spring Lake .
4. Replacing current local large groundwater users with non-Edwards water.
5. Construction of engineered structures to focus flow to specific habitats.

These alternatives are discussed in greater detail below.

D.1 Regional Groundwater Management

Groundwater production in the Edwards Aquifer is regulated by the Authority (to slow the rate of decline of springflow in Comal and San Marcos Springs. Slowing the rate of decline of springflows will allow more time for the return of normal precipitation events resulting in an increase of aquifer levels, and an increase in spring levels. This goal is accomplished by regulating pumpage during times of drought. During drought conditions, water right permit holders are required to reduce their production by different percentages for several trigger water levels for index wells located in different regions (e.g. J-17 for the San Antonio pool) or when springflows drop below certain discharge rates for each of the springs. In the San Antonio pool there are four different stages. Stage I of the Demand Management plan is triggered when water levels decline below 650 ft, and/or when Comal Springs declines below 220 cfs or when San Marcos Springs is below 110 cfs. Stage II of Demand Management plan is triggered when water levels drop below 640 ft, when Comal Springs is less than 154 cfs, or when San Marcos's flow is

less than 96 cfs. Stage III is within the Critical Period and is triggered when water levels decline below 630 ft, and/or when Comal Springs flows decline below 80 cfs, or when San Marcos Springflow declines below 86 cfs. Stage IV is triggered when water levels at J-17 drop below 627 ft.

At each trigger level, groundwater users are required to reduce production by a certain percentage. The percentage is defined by type of user, the level of the drought and the annum cap. The overall impact will limit the frequency or occurrence of low flow conditions at Comal and San Marcos Springs. By having this regional aquifer management program, the needs for more specific management approaches, such as the importation of water to add to the springs, pumping of Edwards groundwater or use of engineered approaches, will hopefully be limited to the most severe drought conditions.

D.2 Importation of Water

Importation of water is the second approach considered for maintaining springflow at Comal and San Marcos Springs. Major considerations for importation of water are:

- **Volume and peak flow rate of water needed for importation.** The volume and peak flow rate of water needed for augmentation will be a critical component when determining the location, availability and cost of the different source alternatives.
- **Source of imported water.** Several question need to be addressed to determine the most appropriate source of water. Is the source of the imported water pumped from the Edwards or from an external source of surface water, groundwater, or treated water (treated sewage effluent)? What is the distance that the water has to be piped?
- **How water will be put into a spring complex.** Should water be injected into the Edwards and flow out the springs or can water be placed directly into Landa Lake or Spring Lake? The input of water into a spring complex also depends on the hydrologic conditions of the spring over the time period that the springs would be augmented.

D.2.1 Volume and Peak Flow Rate of Water Needed for Importation

The Edwards Aquifer is a dynamic body which responds to: recharge inputs, natural discharge (springflow at various locations), and consumptive withdrawals (pumpage). Historic water levels and springflows can be used to estimate the water deficit between actual historic flows versus “required” flows. This approach of using only the historic data does not consider the impact of current drought management strategies developed by the Authority, nor the severity or duration of historic droughts if more current pumping rates had occurred at the time of these historic droughts.

D.2.1.1 Comal Springs Volume Requirement

Historic water levels in the Edwards have been simulated with the numerical groundwater model GWSIM4. The impact of pumpage reductions (through the Authority’s drought management requirements) on water levels has also been simulated. By using results from this modeling, it was found that the most significant Comal Springs flow declines with the Authority drought management program operation would have theoretically occurred in 1964, 1971, and 1984. The amount of water needed to make up the deficit between modeled flow and required flow (Biologic needs) was then estimated. This amount of additional water is the estimated amount of water needed for augmentation for Comal Springs.

Thus, the results of the groundwater models provide an approach to estimate augmentation needs, in other words, deficits of springflow relative to groundwater pumping and management in the Edwards Aquifer. To provide a framework of discussion relevant to the biologic criteria and potential augmentation strategies, deficits relative to six flow thresholds were initially calculated for three different management scenarios, and for four “recharge year” assumptions in each of the three management scenarios.

The initial flow thresholds selected were: 30 cfs, 60 cfs, 75 cfs, 100 cfs, 150 cfs, and 200 cfs, representing various biologic criteria and regulatory constraints. The following table relates these threshold flow levels to their equivalencies in other units of measurement:

Cubic feet per second (cfs)	Gallons per minute (gpm)	Million- Gallons per day (MGD)	Acre-Feet per day (ac-ft/day)	Acre-Feet per year (ac-ft/yr)
30	13,465	19.4	59.5	21,719
60	26,930	38.8	119.0	43,438
75	33,662	48.5	148.8	54,298
100	44,883	64.6	198.3	72,397
150	67,325	96.9	297.5	108,595
200	89,766	129.3	396.7	144,793

The three management scenarios initially considered in this study were: Scenario C (a 400,000 acre-feet per year (ac-ft/yr) withdrawal scenario, and reduction triggers for Stage IV of 15%); Scenario F (a 450,000 ac-ft/yr withdrawal scenario, and reduction triggers for Stages IV of 23%); and Scenario K (a 550,000 ac-ft/yr withdrawal scenario for Stage IV of 37%). These scenarios were selected because they provided a range of pumpage amounts and differing groundwater pumpage reduction management alternatives (pumpage reduction triggers).

Four years were selected to determine the volume and rate of augmentation water would be required in each of the three modeled scenarios. The four selected years represent the three “driest” years modeled, outside of the drought of record, and then, for the sake of comparison, one year within the drought of record of the 1950s. In order of severity of drought, the recharge years selected were: 1954, 1964, 1971, and 1984.

To determine the springflow deficit (in other words the volume of water required) for each combination of management strategy and the drought year, the daily difference between model-estimated springflow and each considered flow threshold was calculated. This provides a daily distribution and an annual total deficit of augmentation demand, as well as a peak flowrate required to meet this demand. Each of these flow components are important in the design and costing of each water augmentation alternative. For example, the total augmentation volume needs to be known so that that amount of water can be acquired from an alternate source. The peak flowrate is also important because that is the maximum rate that must be delivered to the springs, thus the design of the pipeline and/or treatment capacities must be able to facilitate that rate of water.

Assuming that management scenario F is in effect (450,000 ac-ft per year withdrawals from the aquifer, 23% reductions at the trigger level for Stage IV) and drought severity is described in terms of 1964, maintaining 60 cfs at Comal Springs throughout the year would require the input of 21,724 ac-ft in that year (represented by the yellow area and described in the text box at the left upper corner)(Figure D-1). Maximum delivery rates of nearly 25,000 gallons per minute (gpm) are required in parts of June thru September. It can also be interpreted from this chart that to sustain 60 cfs, some amount of augmentation water would be required for the entire year. In contrast, if the 30 cfs augmentation rate was to be utilized, the water would be required over an approximate six month period (mid May to early November). As the augmentation rate increases (30, 60, 75 cfs...) the amount of augmentation volume and peak flowrate also increase. Appendix 9 of this report includes representative charts reflecting the augmentation demand for each of the different combinations of management scenarios and recharge years. To evaluate potential sources of supply and transport of augmentation waters, the most realistic scenario of management alternatives and drought intensities must be chosen. For the purposes of this report, Scenario F was deemed the most “realistic”. Again, Scenario F is defined as 450,000 ac-ft/yr withdrawal from the Edwards Aquifer, and triggers for reduction of pumpage at Stage IV of 23%. The recharge year 1964 was selected because it represents the most severe drought outside of the drought of record. This year was also selected because it represents a significant drought period that can still be managed with more realistic augmentation volumes. The 1954 recharge year was not selected, because it represents conditions which may necessitate virtually unobtainable quantities of augmentation water. Consequently, the augmentation scenarios and corresponding cost estimates developed in this report and described in the next section are based on the example chart and description given above. The amount of augmentation water needed can range between USFWS's recommended jeopardy level of 150 cfs minus the modeled deficit for 1964, which would be 86,879 ac-ft/year to this report's recommended threshold of 60 cfs (for Comal Springs) minus the modeled deficit for 1964, which would be 21,724 ac-ft/year. In the sections that follow the costs for augmentations strategies are included that serve a range from 30 cfs to 200 cfs.

D.2.1.2 San Marcos Volume Requirement

As shown earlier, the San Marcos springflows often do not show the same trends as spring discharges or groundwater levels at Comal Springs. When water levels rise in the San Antonio

Augmentation Demand Distribution Scenario F 450 (23), Recharge Year 1964

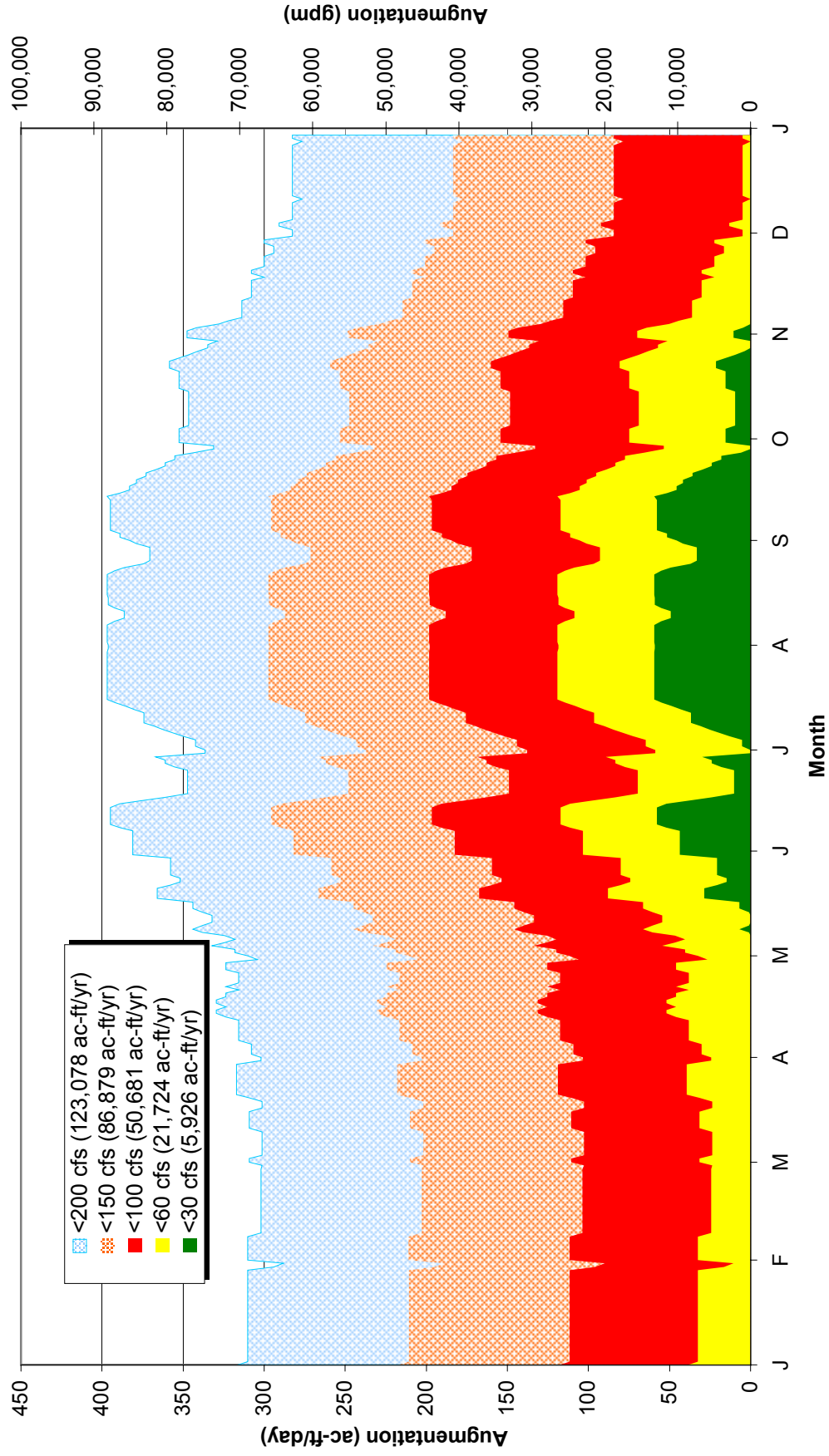


FIGURE D-1 AUGMENTATION DEMAND DISTRIBUTION FOR COMAL SPRINGS

region there often is not a similar rise of springflow at San Marcos Springs. Only at very low flow conditions is there is linear relationship between the San Marcos and the Comal regions. It appears that only 50-100 cfs of water bypasses Comal Springs on the up-thrown block and flows on to San Marcos Springs. Based on this observation, it does not appear that pumping reductions, as required by the Authority to the west of Comal Springs, cause significant increases in discharge rates at San Marcos. Pumpage reductions in Hays County during drought periods would undoubtedly help maintain higher water levels in the county and maintain higher springflows at San Marcos Springs. GWSIM IV has problems simulating flows at San Marcos Springs and was not used to estimate the impact of pumpage reduction on San Marcos springflow (as was done for Comal Springs), and provide a more realistic estimate of the amount of augmentation water needed for San Marcos Springs during the drought conditions. Trying to estimate the Authority's Critical Period Management Plan with GWSIM-IV was considered beyond the scope of this study. Therefore, the volume of water needed for augmentation for San Marcos was estimated by subtracting the lowest flow in 1956 (46 cfs) from an optimum minimum flow of 60 cfs for biologic health, which indicated that 14 cfs or 10,135 ac-ft/year was needed for San Marcos. A flow deficit, based on the USFWS's jeopardy number of 100 cfs minus the lowest flow of 46 cfs is 54 cfs or about 43,000 ac-ft/year.

D.2.2 Sources of Imported Water

One management strategy of springflow augmentation is to bring water from an outside source, and distribute it to the desired locations at the springs. This section provides a broad overview of possible external sources of augmentation water to the spring ecosystem, including a discussion of the means and costs of delivery from each source to the spring locations.

Determining the best source of augmentation water is dependent on a number of variables, including: 1) volume availability of that source to meet the augmentation requirements at the initiation time of in-situ measures, and for a range of augmentation flowrates, 2) the relative ease of acquisition of the right to pump/divert from the perspective of legal and political feasibility, 3) a comparatively cost-effective means of delivery, with respect to the differing range of augmentation flowrates, 4) a water quality that will not adversely affect the survival of the species when supplied to the local ecosystem, 5) a means of production or diversion that does not pose an adverse impact to the location where the augmentation water was acquired, 6) a level of cost, both initial and annualized over the expected project life-cycle, which is sustainable in

permitting the Authority to meet all of its statutory and functional obligations, and 7) is consistent with the goals and recommended strategies of the Regional Water Plan.

Table D-1 provides a summary of potential sources considered for augmentation, and is narratively described in the following sections with respect to the criteria above. It is assumed in each instance that the localized delivery system (how the water is input into the spring reach) is a constant cost, and thus the evaluation of the augmentation sources and delivery means does not take this cost into account.

The volume and rate of augmentation water required for the selected scenario (Scenario F, 1964) were illustrated in Figure D-1 in the above section. Preliminary cost projections were prepared as part of this report to create a tool to help determine the best augmentation strategy (See Appendix 10 for detailed examples). Several augmentation rate alternatives must be considered in sufficient detail to understand the cost-benefit relationship. As mentioned before, initial flow thresholds representing various biologic criteria and regulatory constraints selected were: 30 cfs, 60 cfs, 75 cfs, 100 cfs, 150 cfs, and 200 cfs. However, as can be seen in Figure D-1, for Scenario F, 150 cfs and 200 cfs flows would require volumes of 86,879 and 123,078 ac-ft/yr and peak flowrates of approximately 65,000 and 89,000 gpm, respectively. Acquisition and design of facilities for these augmentation volumes are not considered technically or economically feasible. (If the purchasing of the water rights alone at \$1,500/ac-ft is considered, the minimum cost of augmentation strategies that require 86,879 and 1123,078 ac-ft/yr, is \$130 million and \$184 million, respectively). Preliminary cost estimates developed in this report were prepared for augmentation flows needed to discharge thresholds of 30 cfs, 60 cfs, 75 cfs, and 100 cfs. A 200 cfs cost estimate is considered in Option G-W-C-1.

D.2.2.1 Water Source - Edwards Aquifer - Comal Springs Augmentation

D.2.2.1.1 Pumping from the Down-thrown Block of the Edwards Aquifer in the Vicinity of Comal Springs (Option GW-LE-1)

In the immediate vicinity of Comal Springs there are several groundwater wells that are large producers from the Edwards Aquifer. Two of these wells, the New Braunfels Utilities (NBU) Well #5 and the LCRA well are (or were) very productive. NBU Well #5 is located on the golf course adjacent to Landa Lake approximately 50 ft from Landa Lake. This well has a capacity of 4,200 gpm, or 9.4 cfs. A local Edwards well field could be envisioned proximal to the springs.

Assume model Scenario F 450,000 ac-ft/yr withdrawal 1964 Recharge Year														
SOURCE & STRATEGY		AUGMENTATION DEMAND QUANTITY (ac-ft/yr)	TOTAL QUANTITY (ac-ft/yr)	POTENTIALLY AVAILABLE TO EAA (% of total)	POTENTIALLY AVAILABLE TO EAA (ac-ft)	OWNERSHIP	TIME	MEANS OF DELIVERY	WATER QUALITY PARAMETER OF CONCERN	GROUNDWATER MANAGEMENT	TOTAL CAPITAL COST	ANNUAL M&O COST	TOTAL ANNUAL COST (Assume 50-yr life)	
Groundwater														
	Edwards													
	Local Edwards Well to produce:													
	30 cfs / 13,465 gpm	5926	5926	100%	5926		est. 2-5 yrs	Pump/Pipeline	Edwards Quality	possible safe yield constraints	\$15,967,193	\$507,024	\$826,368	
	60 cfs / 26,930 gpm	21724	21724	100%	21724		est. 2-5 yrs	Pump/Pipeline	Edwards Quality	possible safe yield constraints	\$49,867,681	\$1,325,512	\$2,322,865	
	75 cfs / 33,657 gpm	32582	32582	100%	32582		est. 2-5 yrs	Pump/Pipeline	Edwards Quality	possible safe yield constraints	\$73,078,289	\$1,888,060	\$3,349,626	
	100 cfs / 44,883 gpm	50681	50681	100%	50681		est. 2-5 yrs	Pump/Pipeline	Edwards Quality	possible safe yield constraints	\$111,265,943	\$2,825,762	\$5,051,081	
	Carizzo													
	Schertz/Sequin LGC current wellfield/pipeline -->	10000	10000	10%	1000	Schertz/Sequin LGC	est. 2 yrs	cost-share existing pipeline / construct new pipeline	Already Treated					
	Schertz/Sequin LGC wellfield expansion -->	10000	10000	25%	2500	Schertz/Sequin LGC	est. 5-10 yrs.	cost-share existing pipeline / construct new pipeline	Already Treated					
	Develop Carizzo Wellfield (Comal Springs)													
	30 cfs / 13,465 gpm	5926	5926	100%	5926	EAA	est. 2-5 yrs.	Pump/Pipeline/Pump Station(s)	H ₂ S, Fe, Mn, Temp	possible safe yield constraints	\$45,296,278	\$1,521,369	\$2,427,294	
	60 cfs / 26,930 gpm	21724	21724	100%	21724	EAA	est. 2-5 yrs.	Pump/Pipeline/Pump Station(s)	H ₂ S, Fe, Mn, Temp	possible safe yield constraints	\$67,642,025	\$2,911,275	\$4,264,116	
	75 cfs / 33,657 gpm	32582	32582	100%	32582	EAA	est. 2-5 yrs.	Pump/Pipeline/Pump Station(s)	H ₂ S, Fe, Mn, Temp	possible safe yield constraints	\$80,318,781	\$4,366,561		
	100 cfs / 44,883 gpm	50681	50681	100%	50681	EAA	est. 2-5 yrs.	Pump/Pipeline/Pump Station(s)	H ₂ S, Fe, Mn, Temp	possible safe yield constraints	\$97,163,552	\$6,458,909	\$8,402,180	
	200 cfs/89766	123078	123078	100%	123078	EAA	est. 2-5 yrs.	Pump/Pipeline/Pump Station(s)	H ₂ S, Fe, Mn, Temp	possible safe yield constraints	\$295,380,938	\$15,234,697		
	Carizzo Aquifer - Gonzales & Bastrop (CZ-10D)		220000	10%	22000		not available for 36 yrs	cost-share existing pipeline / construct new pipeline?	?		\$112,445,300	\$4,442,500		
Surface Water														
	NBU Effluent Reuse (7MDG Total)													
	30 cfs / 13,465 gpm	5926	7230	90%	6507	NBU	2-5 years	Pipeline and Water treatment plant	N, P, TSS, pH, temp	Treatment costs of effluent and won't meet peak flowrate				
										Insufficient volume for stand-alone strategy				
										Total permitted discharge is approximately 7MGD.				
	Purchase from Canyon (GBRA)													
	30 cfs / 13,465 gpm	5926	21719	100%	21719	GBRA	2-5 years	Guadalupe River and Pipeline	N, P, TSS, pH, temp	Treatment costs. Amount of water contracted by GBRA	\$ 7,458,715	\$ 882,954		
	60 cfs / 26,930 gpm	21724	43438	100%	43438	GBRA	2-5 years	Guadalupe River and Pipeline	N, P, TSS, pH, temp	Treatment costs. Amount of water contracted by GBRA	\$ 13,189,907	\$ 2,570,332		
	Lower Guadalupe (SARA/SAWS/GBRA)		94500	20%	18900	SARA/SAWS/GBRA	not available for 36 yrs							
SOURCE & STRATEGY		TOTAL QUANTITY (ac-ft/yr)	POTENTIALLY AVAILABLE TO EAA (% of total)	POTENTIALLY AVAILABLE TO EAA (ac-ft)	OWNERSHIP	TIME	COST	MEANS OF DELIVERY	WATER QUALITY PARAMETER OF CONCERN	Constraint Comments	TOTAL CAPITAL COST	ANNUAL M&O COST	TOTAL ANNUAL COST (Assume 50-yr life)	
Other Strategies														
	McKinney/Sharp (1995) strategies													
	Injection Wells	assumed sufficient			EAA	5 yrs +		Pipeline and Injection Facilities	Edwards Quality		\$ 200,000,000	\$ 14,600,000		
	Infiltration Galleries	assumed sufficient	1 50000+		EAA	5 yrs +		Pipeline (input of water through Landa Lake)	Edwards Quality	Environmental/Construction	\$ 200,000,000	\$ 14,600,000		
	Direct Addition (Edwards Source)	assumed sufficient	1 50000+		EAA	5 yrs +		Pipeline (input of water through Landa Lake)	Edwards Quality	Environmental/Construction	\$ 201,000,000	?		
	Enhanced Surface Recharge	assumed sufficient	1 50000+		EAA	5 yrs +		Infiltration from Recharge Structure	Edwards Quality	Insufficient supply for Augmentation	\$ 55,090,247	?		
	Aquifer Baffles	assumed sufficient	1 50000+		EAA	5 yrs +		Pipeline (input of water through Landa Lake)	Edwards Quality	Environmental/Construction	\$ 234,000,000	\$ 14,000,000		

TABLE D-1 SPRINGFLOW AUGMENTATION OPTIONS MATRIX

To develop a well field at this location as a viable option for springflow augmentation at Comal Springs, the Authority would need to: 1) purchase the well, facilities and Edwards water rights from NBU, 2) develop up to 9 additional series of wells to produce up to 100 cfs (assuming that each additional well is capable of producing 2,000 gpm), and 3) construct a short transmission pipeline to the lake. Although other options for acquiring the rights to the water from this well are certainly possible, it is assumed for conservative purposes for this cost estimation that the Authority purchases the facility in fee simple. It is also assumed that the Authority would need to acquire sufficient water rights to meet its augmentation demand needs, and pay an annual use fee. The following table presents a summary of both the initial capital costs and estimated annual maintenance and operations costs associated with 30 cfs, 60 cfs, 75 cfs, and 100 cfs augmentation demand requirements. Interest costs are not included in this summary table. A detailed cost breakdown is shown in Appendix 10.

Summary of Initial Capital Cost and Annual O/M Costs (excl. interest)

Option GW-LE-1

	30 cfs	60 cfs	75 cfs	100 cfs
Total Initial Capital Cost	\$15,967,193	\$49,867,681	\$73,078,289	\$111,265,943
Total Annual O/M Cost	\$507,024	\$1,325,512	\$1,888,060	\$2,825,762

Utilizing a local Edwards source water offers some advantages. The Edwards Aquifer water is in close proximity to the spring reaches and thus reduces the need for long pipelines. The Edwards Aquifer water is the same water quality as the existing spring discharge thus no treatment costs would be required for this alternative. Also, because of the proximity of a local well field, the temperature of the augmentation water is not considered a problem.

Potential drawbacks to utilizing the Edwards Aquifer for augmentation water include the cost of purchasing of Edwards water rights from existing water right holders. For this analysis the water rights are estimated to cost \$1,500 per acre-foot and no limitation was placed on the amount of water rights that could be obtained. In other words, in each of the augmentation alternatives (30, 60, 75 cfs...) the amount of water needed was assumed to be purchased from an existing water right holder. Another potential problem with pumping water at this location from the Edwards

Aquifer for augmentation is the fact that there is a direct hydraulic connection between the LCRA well and several springs around Landa and that the down-thrown block provides about seventy-five percent of the total water in Comal Springs. If the water is already flowing to the spring through a natural aquifer course, there is no reason to pump it to the land surface and then pipe it to the springs. In addition, if total springflow has stopped and water levels in the lake are dropping, the groundwater that is pumped into the lake will flow back into the aquifer. The only scenario in which pumping of water from a local down-thrown block field would be reasonable is if the lake has dried up and water needs to be pumped directly to the Old Channel to maintain those critical habitats.

D.2.2.1.2 Pumping From the Up-thrown Block of the Edwards Aquifer in the Vicinity of Comal Springs

Pumping groundwater from the up-thrown block to supply water to Landa Lake was another option considered. Such a well field would be close to the springs, have an appropriate chemistry and temperature, and potentially be hydrologically isolated from the majority of the water that flows to the springs. There are several problems with such an option.

- Water levels in the up-thrown block would have to be below a Landa Park well water level of 620. Since the up-thrown block provides water to Spring Runs #1, #2, and #3, pumping of water from the up-thrown block to the lake only reroutes water already flowing to the springs. Pumping should only occur after Spring Runs #1, #2 and #3 go dry.
- Developing a large well field on the up-thrown block of the Edwards may not be possible. Most of the municipal water supply wells in New Braunfels are in the down-thrown confined block. NBU does have two large productive wells on the up-thrown block. Several small domestic water wells produce from the up-thrown block of the Edwards in the Preiss Heights Subdivision (just south west of Gruene) but no hydrologic information is available which would indicate that the up-thrown block could sustain production of 100 cfs.
- Groundwater in the up-thrown block ultimately discharges at San Marcos Springs. Any production of groundwater from the up-thrown block would deplete flow that would

eventually discharge at San Marcos. This problem would become critical under drought conditions, when probably all the flow (50-75 cfs) at San Marcos is derived from flow that bypasses Comal Springs in the up-thrown block.

- Because of the technical problems with this option the cost of a well field were not estimated. Cost would be similar to (option GW-LE-1), the hypothetical Edwards well field on the down-thrown block close to Comal Springs.

D.2.2.2 Water Source - Edwards Aquifer - San Marcos Springs Augmentation

Pumping “local” Edwards groundwater in the vicinity of San Marcos Springs would have to be from the up-thrown block as defined by the San Marcos Spring fault. Brackish to saline water is considered to be beneath Spring Lake in the down-thrown block. Fresh water discharging to Spring Lake, therefore, has to come from the up-thrown block. Texas State University and the City of San Marcos have several production wells. So the potential for large-scale production on the up-thrown block is there, but producing from this block would only decrease the amount of spring discharge that would occur naturally. Cost estimates for a well field near San Marcos Springs are estimated to be less than \$16 million for initial capital costs. These costs are based on the estimated cost of a well field for Comal Springs assuming the field would only need to produce less than 30 cfs for spring augmentation(Option GW-LE-I). If a threshold of 60 cfs is used for San Marcos minimum flow then the cost rises to \$50 million.

D.2.2.3 Importation of Non-Edwards Water - Groundwater

Alternative water supplies from groundwater sources other than the Edwards was considered by reviewing several options. These options included developing new groundwater supplies in non-Edwards aquifers, such as the Carrizo aquifer, and constructing new pipelines to San Marcos and/or Comal Springs or piggy backing the transport of the new water in already developed pipelines or pipelines in the development stage to carry water to the springs. These options are explained in the following section.

D.2.3 Comal Springs Augmentation

D.2.3.1 Carrizo Aquifer

To the south and east of the spring systems lies the Carrizo-Wilcox formation. Large-scale development of well fields in this aquifer has recently been undertaken to secure water supplies for municipal use along the I-35 corridor in Guadalupe and Bexar counties. There are several

options for considering the extraction and delivery of Carrizo waters for use in an augmentation scenario at Comal Springs or San Marcos Springs. The following sections describe these options with respect to the cost of implementation and other factors.

D.2.3.2 Option GW-C-1

This option explores the feasibility of a water supply project from the Carrizo-Wilcox Aquifer that is exclusively owned by the Authority. Although this option does not necessarily preclude cost-participation by other entities, it is intended to provide a baseline scenario in which the Authority is in control of all of the variables in developing this supply. Other cost-sharing or “piggybacking” alternatives are described in following GW-C options.

The assumptions made in developing this option would require the Authority to: 1) purchase or lease land in a productive area; 2) construct a number of wells capable of producing a combine production rate of 30 cfs, 60 cfs, 75 cfs, 100 cfs or 200 cfs 3) construct a transmission pipeline from this location to a delivery point at Comal Springs, 4) purchase right of way easements for the pipeline route, and 5) construct a treatment plant facility designed to remove constituents potentially detrimental to the species.

In developing preliminary cost estimates for this option, it was assumed that a well field comprising approximately 5,000 acres in a fee simple or lease disposition could be acquired and developed in northwestern Gonzales County, approximately 30 miles from Comal Springs. Further, this would assume that easements could be acquired along a likely transmission route. A broad per acre cost assumption was made with respect to these land requirements. In order to counteract appreciable head losses in the distribution, given the length of the pipeline and the static head differential (est. 225’), the required pipeline diameters were increased by a factor of 10% and three booster-pump stations with ground storage were assumed along the hypothetical route. Pipeline diameters were estimated based on the required volume throughput, and a “safe” velocity of 10 feet per second.

It should be noted that estimating costs for a major supply project such as this usually involves specific assumptions about the proposed location and route, and that changes in these assumptions can result in significantly different cost figures. The following table is a summary of preliminary estimated costs to provide water to Comal Springs at the 30 cfs, 60 cfs, 75 cfs, and 100 cfs and 200 cfs thresholds. A detailed cost breakdown is shown in Appendix 10.

Summary of Initial Capital Cost and Annual O/M Costs

Option GW-C-1

	30 cfs	60 cfs	75 cfs	100 cfs	200 cfs
Total Initial Capital Cost	\$90,927,309	\$132,174,048	\$152,467,776	\$180,474,035	\$295,380,938
Total Annual O/M Cost	\$1,521,369	\$2,911,275	\$4,366,561	\$6,458,909	\$15,234,697

The cost for treatment of this water, to remove H₂S and some metals (iron and manganese), is included in the estimates. It is also likely that the temperature of this water transported across 30 miles (and having been in storage en route) will be an issue before it can be introduced to the spring complex. Accounting for temperature in the treatment process is a very difficult parameter to estimate, and would require additional study before this alternative could be considered practical to meet the augmentation needs of the Comal Springs system.

An additional concern is the ability of a well field (or well fields) of this size to provide the required yield and not impact other users in the area of the proposed well field. Detailed hydrogeological investigations would need to be performed to determine proper well spacing, depths, and safe rates of withdrawal.

D.2.3.3 Option GW-C-2

The Schertz-Seguin Local Government Corporation (SSLGC) has recently completed the first phase of a water supply project to bring Carrizo water to Seguin and Schertz. This project is one of the recommended strategies in the Region L Water Plan. The current phase involves the production of up to 10,000 ac-ft/yr from a well field in western Gonzales County, treatment of the water, and distribution along a 43" transmission main to a junction south of the City of Seguin. From there, the water is carried into Seguin by way of a 24" diameter main, and continues towards Schertz. At a bend in State Highway 78 east of Marion is the possibility of extending this distribution system towards New Braunfels. The water in the pipeline has already been treated and could be added to either the NBU distribution system or to an existing elevated storage tank.

The critical issue with respect to the viability of this option, however, centers around the availability of water within this project for entities outside of the SSLGC. Reportedly, nearly all of the available production is committed by SSLGC. And although a future phase of this project is described in the Region L Plan, the full planned production of this project is 20,000 ac-ft/yr. To meet the augmentation amount needed to maintain 30 cfs would require obtaining a commitment of 60% of the additional 10,000 acre-feet proposed with this future expansion phase. Meeting 60 cfs or any threshold amount above that would require an expansion of the entire capacity of the project. Given the small likelihood of this option and considering the number of variables in even the simplest configuration of this option, a detailed cost estimate is not included here.

D.2.3.4 Option GW-C - Others

There are a number of additional Carrizo projects contemplated as part of the Region K and L Water Plans. The Gonzales-Bastrop project is listed in the Region L plan as one of the recommended strategies for Comal County (CZ-10D). However, this project is not expected to be completed before 2040 and would require significant coordination (as well as cost-sharing) with other entities.

D.2.3.5 Option GW-GC

Further to the south and east of the Carrizo aquifer is the Gulf Coast aquifer, which may offer enough volume and compatible water chemistry. However, the Gulf Coast aquifer is located far from the Comal and San Marcos Springs systems and the cost of delivery makes this option cost prohibitive. Cost associated with this alternative would be greater than those estimated for GW-C-1. Consequently, development of the Gulf Coast aquifer was not considered as a viable option for supplying augmentation to Comal Springs and no costs are presented.

D.2.4 San Marcos Augmentation

The augmentation options for non-Edwards water sources from Comal Springs are equally applicable for San Marcos Springs. The only differences being that less water is needed and transport distances are slightly different. Augmentation costs for the different options for San Marcos Springs can be estimated from the previously presented tables for Comal, but by using a lower volume of augmentation water.

D.2.5 Importing Non-Edwards Water-Surface Water

Surface water, like an external groundwater source, may be an excellent augmentation supply. Pumping surface water from a source such as the Lower Guadalupe, however, were considered as expensive as the option of groundwater from the Gulf Coast aquifer and therefore was not costed out. Surface water from the Canyon Reservoir on the Guadalupe River, however, could almost flow on its own as surface water to Comal Springs, or be injected into the Edwards so that the water would then flow to San Marcos. Using surface water from Canyon reservoir, and transporting this water to Comal and/or San Marcos Springs appears as technically feasible and an innovative approach for spring augmentation.

Water from Canyon Reservoir would flow in the Guadalupe River to just upstream from Gruene, Texas. At this location both Comal and San Marcos Springs could be augmented. Water from Canyon would be off the hypolimnion of the reservoir. It would have a calcium bicarbonate water chemistry. Being that the water is from the bottom of the reservoir, it would be cold and have a low dissolved oxygen concentration and some ammonia. The turbulent flow in the river, however, will result in well-oxygenated water and any ammonia would be converted to nitrate. The chemistry will be quite similar to the chemistry of the waters currently discharging Comal and San Marcos Springs. At a point upstream from Gruene, Texas, water could either be diverted to Comal Springs down Blieders Creek for surface discharge into the north end of Landa Lake or injected into the Edwards where it crosses beneath the Guadalupe River and flows to San Marcos.

D.2.5.1 Surface Water Augmentation to Comal Springs (SW-CY-1)

Water would be pumped out of the Guadalupe River, and pumped through a pipeline for a distance of approximately one mile and discharged into Blieders Creek where it would discharge into the north end of Landa Lake. This option appears technically feasible as long as Landa Lake remains full. If water levels in the lake drop, then these augmentation waters would be expected to recharge the aquifer. If these augmentation waters are needed to recharge the up-thrown block to maintain flow in Spring Runs #1, #2, and #3, then they would need to be pumped into injection wells or recharge structures in the area of Panther Canyon. If these recharge waters are needed to recharge the aquifer in the down-thrown block, then recharge dams or injection wells could be located along Blieders Creek, after the creek crosses onto the down-thrown block of the Edwards and just upstream from Landa Lake. Letting Guadalupe River water flow down

Blieiders Creek and enter Landa Lake as surface water conceptually seems a simple and a more cost effective approach. Cost estimates for thresholds of 30 and 60 cfs are shown below. Cost for thresholds of 75 cfs and 100 cfs were not made because there is not enough excess capacity currently in Canyon Reservoir to meet a 75 or 100 cfs demand.

Summary of Initial Capital Cost and Annual O/M Costs

Option SW-CY-1

	30 cfs	60 cfs
Total Initial Capital Cost	\$7,458,715	\$13,189,907
Total Annual O/M Cost	\$882,954	\$2,570,332

D.2.5.2 Surface Water Augmentation through the Edwards to San Marcos Springs

At San Marcos Springs there is a regional flow component that discharges at the springs. This groundwater flows presumably beneath the Guadalupe River in the fault blocks in the recharge zone (upstream from Gruene). In the Preiss Heights subdivision, just southwest of the Guadalupe River, there are probably more than twenty domestic wells into the Edwards. The presence of these wells indicates a possible pathway in the Edwards passing beneath the Guadalupe River at this location. Gain/loss studies conducted by U.S. Geological Survey do not indicate any significant gains or losses in this stretch of the Guadalupe, indicating there are no natural pathways for recharge or discharge to or from the Edwards. Construction of recharge wells or basins would be required so that groundwater would recharge to the Edwards. Based on groundwater gradient in the Edwards, flow would be towards San Marcos Springs rather than towards Comal Springs. Since San Marcos Springs is considered as an end-of-the-flow system type of spring, all injected water at the Guadalupe should result in increased spring flow.

Treatment costs associated with this alternative were estimated similar to that of surface discharge into Comal Springs. Since the water would be injected or put into recharge features the treatment costs may be reduced or eliminated. The cost estimates given below include treatment costs and therefore are conservative. Costs for this type of approach are given below:

Summary of Initial Capital Cost and Annual O/M Costs

Option SW-SM

	30 cfs	60 cfs
Total Initial Capital Cost	\$8,054,000	\$13,514,000
Total Annual O/M Cost	\$882,954	\$2,570,332

Engineered Structures

Engineered structures are considered to be modifications of the physical setting of both springs to provide more optimum conditions for the endangered species. The engineered structures considered are inflatable dams, pipe and pumps. The specifics of each proposed structures and associated costs are described in Section C.

D.2.6 Augmentation Water from Reuse of Wastewater Treatment Effluent

Using treated effluent from San Marcos or New Braunfels was considered. These waters historically are discharged back to a local river and might be available for augmentation. Lack of adequate volumes for augmentation and the amount of treatment that would be required before "treated" wastewater could be discharged into the springs will probably prevent the use of these waters as a treatment option.

D.2.6.1 San Marcos

San Marcos has one wastewater treatment plant (permit # 10273.002). The plant currently discharges approximately 4.5 mgd (5,044 ac-ft/yr). The plant capacity is 9 mgd (10,088 ac-ft/yr). This plant will not be expanded to greater than 9 mgd. There are current plans to build another WWTP within the next 10 years to provide service for additional demand.

The current wastewater is being discharged into the San Marcos River. However, currently a power generation facility has contracted to buy the water for cooling purposes (but are currently not using the water due to the energy market). It is uncertain how much the treated effluent is currently under contract for but it is not the entire 4.5 mgd. Therefore, when utilized there will

still be some volume of water discharging into the stream. The amount of flow remaining at current conditions would not provide enough water for an augmentation strategy.

D.2.6.2 New Braunfels

New Braunfels has three wastewater treatment plants (North Kuehler, South Kuehler and Greune) that currently discharge approximately 4 mgd to the Guadalupe River. The total current plant capacity is 8.4 mgd. Currently, the North and South Kuehler plants discharge into a tributary and then into the Guadalupe river upstream of Lake Dunlap. The South Kuehler plant is currently going through a renewal of its wastewater discharge permit. Future expansion of the North and South Kuehler plant are planned within the next 10 years.

The current wastewater from all three plants is discharged into the river. The current discharge of approximately 4 mgd or 4,480 ac-ft/yr would not provide enough augmentation water for even the 30 cfs scenario. As the treatment plants expand the amount will be enough for the 30 cfs scenario but not enough for any of the other augmentation strategies. Treatment costs of the water prior to input into the Comal Springs system would be high because of the associated nutrients loadings. The water quality needed for augmentation needs to be comparable with that of the natural spring water. Therefore, for this option the cost of treatment of the effluent is high and it would only yield enough water for the lowest flow augmentation strategy.

D.2.7 Reducing Water Rights for Local Pumpage of Edwards Aquifer

The Edwards water right for New Braunfels is approximately 10 cfs. The Edwards water right for San Marcos and Texas State University is approximately 10 cfs. Reducing local groundwater production is an important option that needs to be seriously considered. Importing external water for augmentation of a spring where groundwater is still being locally produced defies the laws of logic. In particular, local groundwater production in New Braunfels and San Marcos during critical periods, has the potential of significantly impacting springflow during low springflow conditions. Two options should be considered. Revise critical period management rules for New Braunfels and San Marcos (and other large users) so that New Braunfels and San Marcos' required pumping reduction could go to 100% during specific critical periods. Or, "buy out" their Edwards ground water right so these communities are completely off of groundwater

at all times. The feasibility and cost of "buying out" San Marcos and New Braunfels (NBU) Edwards ground water rights and replacing their groundwater with additional surface water was evaluated.

D.2.7.1 San Marcos

Water Supply

Current Water Rights

CA	3867	8/16/04	7 ac-ft for Recreational use
Permit	5092	9/2/86	150 ac-ft for Municipal use
Contract GBRA	1989		5,000 ac-ft for Municipal use
Edwards Aquifer Water Right			5,425 ac-ft
			(Firm - 4,865 ac-ft, interruptible - 560 ac-ft)
			(Interruptible can not be used if J-17 is below 665')

Water Demand

Current water demand for San Marcos is approximately 6,500 ac-ft/yr. Future demand is projected to be 15,100 ac-ft in 2030 and 23,600 ac-ft in 2047. These estimates are based on population projections for San Marcos and use of 123 gal per person per day. Currently, the demand is met by GBRA surface water and Edwards Aquifer groundwater. The split is approximately 70 – 80% surface water and 20 – 30 % groundwater.

System Requirements/Infrastructure

Surface water from GBRA is diverted from the Guadalupe River at Lake Dunlap and transported through a 20-mile pipeline with a maximum existing capacity of 14 mgd (15,693 ac-ft/yr). The capacity may be increased with booster stations and storage facilities. The current 5,000 ac-ft/yr of water from GBRA is equivalent to 4.46 mgd. San Marcos owns 9 mgd capacity in the pipeline, the remaining 5 mgd is owned by GBRA to supply water to other communities in Hays County (Kyle or Buda).

San Marcos has one surface water treatment plant that is currently rated at 6 mgd. The facility is currently being expanded to 9 mgd. The plant was initially developed to allow for a full

development capacity of 24 mgd. The plant treats water for San Marcos as well as water supplied to other communities such as Kyle (GBRA supplier). The plants total capacity of 24 mgd (26,880 ac-ft/yr) could meet the projected needs of San Marcos (23,600 ac-ft) for 2047 (if the pipeline from Lake Dunlap is expanded or maximized to transport 24 mgd). However, the additional water supply for other communities (Kyle or Buda) would have to be considered.

Groundwater from the Edwards Aquifer is pumped from seven primary wells. San Marcos has had more than these wells but most of the older wells have been abandoned. The primary pumping is near Spring Lake and on Comanche Street on Campus.

There are several pressure zones in San Marcos that are independent systems supplied solely by Edwards groundwater. The infrastructure for these areas is not connected to the surface water distribution system. These systems pump Edwards groundwater, add chlorine and pressurize the system. If all Edwards groundwater is removed these areas will have to be incorporated into the surface water distribution system.

D.2.7.2 Texas State University (TSU)

Water Supply

Edwards Aquifer Water Right 2001 ac-ft

Water Demand

TSU currently uses some water provided by San Marcos as well as its own production from Edwards wells.

D.2.7.3 New Braunfels Utilities

Water Supply

CA 3824 9/2/86 2,240 ac-ft run-or-river, for Municipal use

Contract GBRA 1989 6,720 ac-ft for Municipal use

Edwards Aquifer Water Right 7,271 ac-ft

Water Demand

Current water demand for New Braunfels is between 6,000 – 7,000 ac-ft/yr. Future demand is projected to be 16,500 ac-ft in 2030 and 25,000 ac-ft in 2050. These estimates are based on population projections for New Braunfels from a recent study (2004). Currently, the demand is

met by surface water rights owned by New Braunfels, GBRA surface water contract and Edwards Aquifer groundwater. The split is approximately 70 - 80% surface water and 20 - 30 % groundwater. Up to 1991 New Braunfels was 100% groundwater from their five wells.

Since 1992, there has been a mix of surface water and groundwater. The surface water treatment plant is an 8 mgd plant and is located about 1,700 ft from the river on Greene and Albert Streets. The following averages illustrate the division of surface water and groundwater from 1992 to 2002. The averages are yearly, the monthly percentages can change significantly (the summer months generally have closer to 50/50 split because they use GW for peaking).

<u>Year</u>	<u>SW</u>	<u>GW</u>	
1992	86%	14%	
1993	89%	11%	
1994	90%	10%	
1995	93%	7%	
1996	91%	9%	
1997	81%	18%	
1998	62%	38%	Flood: Surface water plant shut down 2-3 months
1999	51%	49%	Flood: Surface water plant shut down 2-3 months
2000	80%	20%	
2001	81%	19%	
2002	71%	29%	

2003 High Daily peak is 14 mgd, monthly peak is about 11 - 12 mgd.

New Braunfels currently utilizes about 2,500 ac-ft/yr of its 7,271 ac-ft/yr of Edwards water rights. However, it also contracts small portions of its water rights in and around New Braunfels.

System Requirements/Infrastructure

Surface water from the New Braunfels water right and the GBRA contracted surface water is diverted from the Guadalupe River at Lake Dunlap and transported to the water treatment plant located about 1,700 ft from the river. The current demand for New Braunfels can be met with surface water from the two water rights.

New Braunfels Utility has one surface water treatment plant that is currently rated at 8 mgd. The plant can be expanded to allow for a full development capacity of 28 mgd. The plants total capacity of 28 mgd (31,300 ac-ft/yr) could meet the projected needs of New Braunfels (25,000 ac-ft) for 2050 if only surface water was used.

There were originally five groundwater wells to supply the Edwards groundwater to the city. Three wells by the old yard are approximately 100 ft deep. These two wells pump at 1200 gpm and 2750 gpm, respectively.. The other three wells (NBU calls them 4, 5 and 6) are located as follows: Number 4 is on HWY 46 at Walnut Avenue and is about 365 feet deep and produces at 2,100 gpm; Number 5 is on or close to the golf course and is 1,045 deep and can produce at 4,200 gpm; and Number 6 is at Moss Rock and is 745 feet deep and can produce at 2,750 gpm. Moss Rock is the furthest away from the plant and requires the most pumping costs. Therefore, NBU utilizes this well the least.

One of the advantages New Braunfels offers is that all of the cities customers are on the surface water distribution system. When groundwater is added to the system it is simply treated with chlorine and pumped into the distribution system. There are no separate systems in New Braunfels that are solely on groundwater. Therefore, the removal of groundwater and shifting to 100% surface water would require no additional infrastructure tie-in.

D.2.7.4 Conclusion

An estimated cost of a “buyout” for each community based on an approximate water right of 7,200 ac-ft and a per ac-ft cost of \$1,500, would be about \$11 million.

E. Options

To determine the best options for preserving springflow at both Comal Springs and San Marcos Springs, several separate issues have been compiled and summarized in this final section. The following information has been considered for each spring:

- Hydrology of the Springs

- Regional hydrogeology
- Spring hydrology
 - Spring conditions during drought

Importance of regional pumping and drought management plans

Importance of local pumping

- Habitat for species

- Flow requirements
 - Original USFWS
 - From this study
- Habitat locations

- Water supplementation strategies

- Imported water
 - Source
 - Groundwater
 - ◆ Edwards
 - ◆ Other aquifers
 - Surface Water - Guadalupe
 - How the water gets used at the Springs
 - Injected into aquifer to flow to Springs

- Direct import into lakes
- Buyout of groundwater users
- Engineered structures to optimize flow for critical habitat locations
- Cost - cost is taken into consideration for all augmentation options

With this information recommended augmentation options can be made.

E.1.1 Comal Springs

1. Hydrogeology of Comal Springs

a. Regional hydrogeology

Comal Springs is impacted by regional groundwater flow and regional pumping. There is a well recognized correlation between water levels at J-17 (index well in Bexar County) and Comal spring flow.

b. Local hydrogeology and Spring hydrology

The Comal Springs fault compartmentalizes groundwater flow at the Springs into an up-thrown block and a down-thrown block. The up-thrown block discharges groundwater to springs 1, 2, and 3, which is about twenty-five percent of total flow at the springs. These springs are at higher elevations than the others and will go dry when water levels in the up-thrown block drop below the elevation of the spring orifices. Part of the groundwater in this fault block bypasses discharge at Springs #1, #2, and #3 and flows to San Marcos. Groundwater in the down-thrown block discharges into several springs around the lake and in the lake itself. About seventy-five percent of the total Comal spring flow discharges to these springs. All the water in this fault block is considered to discharge to Comal Springs and none bypasses the springs and flows to San Marcos. When water levels in the down-thrown block drop below about 618-619 feet, discharge out of Landa Lake goes to zero. This is the approximate elevation of the dam at the abandoned LCRA power plant. Water levels in the lake are considered to mimic water levels in the down-thrown block. Changes in water levels in the aquifer are buffered by spring discharge. When spring (lake) discharge goes to zero then water levels in the aquifer (and therefore the lake) can drop rapidly because they

are now being controlled by the low storativity values of a confined aquifer and not the water being discharged out of the springs. Landa Lake went from being full to almost dry in less than 3 months in the summer of 1956. The LCRA well, which has a direct hydraulic connection to Landa Lake and produces 5000 gpm, started production in early June, 1956. NBU also brought NBU 5 and NBU 6, which produce from the down-thrown block, online in 1956. Land Lake started going dry in early June, 1956. Local pumpage, and specifically pumpage of the LCRA well, may have had a significant impact on causing Landa Lake to go dry.

2. High Quality Habitat of Comal Springs

At Comal Springs, three locations are considered to be the most important to be maintained during a drought. They are:

- a. Along Spring Run #3 and in a small area upstream of Spring #7 (Figure C-6). This is part of the habitat for the riffle beetle.
- b. The lake bottom just upstream of Spring Island (Figure C-1). This is an important habitat for the fountain darter and the riffle beetle.
- c. Old Channel (Figure C-1). This is an important habitat for the fountain darter.

USFWS recommended total spring discharge of 150 cfs to meet jeopardy levels. A minimum total spring flow of 60 cfs is recommended from this study.

3. Authority Drought Management Plan for Comal Springs

The Authority drought management program is expected to significantly reduce the amount of spring declines, their duration and their frequency during severe droughts. A drought management plan is the first line of defense toward preserving spring flow to Comal Springs.

4. Augmentation Sources

Groundwater and surface water sources that could potentially be imported to the springs were evaluated to determine their technical feasibility, their availability, and their costs.

a. Groundwater Supplies Sources

Large-scale pumpage from the Edwards was not considered a viable option. Pumping large volumes of water from the Edwards, either locally or from a well field up dip from the springs (as discussed in McKinney and Sharp, 1995) would produce groundwater that would eventually deplete spring discharge at Comal or San Marcos Springs. Pumping groundwater from the down-thrown block close to the springs is expected to have a direct and immediate impact on Comal Springs flow. Pumping groundwater from the up-thrown side of Comal Springs Fault in the New Braunfels area would deplete flow at San Marcos Springs, especially during drought periods. A well field capable of producing 60 cfs is estimated to cost about \$50 million. A well field producing 100 cfs is expected to cost \$111 million.

Large-scale pumping of groundwater from a non-Edwards aquifer, such as the Carrizo aquifer are technically feasible, but because of the distance required to pump water to Comal Springs, would be very expensive. Pumping large volumes of groundwater to Comal Springs could not use already existing pipelines or planned pipelines, because these pipelines do not have the capacity or the planned design capacity to carry the additional amount of water needed for augmentation. Pumping groundwater from an aquifer, such as the Carrizo, would be in competition for other current or planned water needs from these aquifers. A 60 cfs well field from the Carrizo aquifer is estimated to cost about \$152 million. A well field producing 100 cfs is expected to cost \$180 million. A well field producing 200 cfs is expected to cost \$295 million.

b. Surface Water Sources

Using surface water sources, such as is proposed in the Lower Guadalupe Project (pumping from Refugio County), are not considered as viable options because of the high cost of pumping water from the coast back to the springs, and the direct competition for these waters by other users during water deficit times. Because of the required distance to pump water, surface water sources would be more expensive than pumping groundwater from the Carrizo.

Canyon Reservoir waters as a water source for both Comal and San Marcos is considered an option that should be further investigated. For Comal Springs, Canyon waters could be used in two ways: 1) as direct input of surface water into Landa Lake, or 2) to reduce/eliminate the use of Edwards Aquifer water rights of New Braunfels and any other large-scale users during the most critical periods of a drought. This could be accomplished by revising the Critical Period Management rules for Comal County so that required pumping reductions could go to 100% during the most critical drought period. A second option would be to “buy out” the Edwards ground water right of the large ground water users so that they would be completely off of ground water at all times. These water users would need an alternate non-Edwards water such as additional water from Canyon Reservoir or the Guadalupe River to meet their current demands and future needs. Municipalities might also consider off-channel storage, such as abandoned quarries, that could be used as surface water reservoirs during wet periods and supplemental water supplies during drought periods. A buyout of water rights would cost about \$11.0 million. Although local users’ total pumpage is small in comparison to average spring flow or water use elsewhere in the aquifer, it can be a significant portion of the spring water budget during a drought. It is imperative that Comal Springs total flow does not go to zero. If that happens then there is the potential that the lake could rapidly dry up. Buying out local groundwater rights will prevent local pumpage during a drought, but a buyout alone does not provide enough additional water to guarantee 60 cfs at the springs. A “buyout” plus providing Canyon Reservoir water as surface flow to Landa Lake may need to be considered. Routing Canyon Reservoir water via Blieders Creek to Landa Lake is estimated to cost about \$13 million. If Landa Lake starts going dry, water imported directly into the lake would be expected to drain back into the aquifer.

5. Engineered Approaches at Comal Springs

Water could be moved to critical habitats within the Comal Springs complex to maintain a suitable hydrologic environment. These recommendations are not considered as alternative options, in lieu of importing water, but as supplemental to any strategies for

importing water. If the springs go dry all the engineering approaches are for naught. Four approaches are recommended for a more detailed feasibility study or a pilot plant level study. These approaches are considered as temporary only and would only be used as spring discharge levels approached a critical threshold (e.g. 60 cfs)

- a. It is proposed that an irrigation system be constructed over the Spring Run #3 area so that these spring orifices are kept wet to preserve the habitat of the riffle beetle. Irrigation would be initiated when total spring flow dropped to about 80 cfs. Estimated cost to install a recycled water irrigation system is \$500,000.
- b. Place temporary (inflatable) dams on either side of the fountain darter habitat along the west side of the lake (Figure C-2) and toward the Old Channel to focus flow and maximize velocities across this priority habitat. This would keep water temperatures down and dissolved oxygen content at higher levels. Estimated cost for installation of inflatable dams is \$300,000.
- c. Install a temporary dam across New Channel during low flow conditions so that spring flow would go down Old Channel to help preserve the high quality habitat. Currently three-fourths of spring flow goes down New Channel. This ratio could be adjusted to maintain optimal flow in the Old Channel during droughts. Estimated cost to install a temporary dam across New Channel is \$30,000.
- d. Develop a re-circulation program for Old Channel such that water that has already flowed part of the way down Old Channel could be re-circulated back to a point above important critical habitat. Higher levels of flow could be maintained in stretches of the Old Channel during a drought. Estimated cost for a re-circulation system is \$500,000.

6. Recommended Option for Comal Springs

The recommended option is to:

- a. Reduce/ eliminate major groundwater use in the New Braunfels area during critical drought periods by either “buying out” their water right or by revising critical period management rules(cost \$11 million).

- b. Develop the Canyon Reservoir option to flow surface water to Landa Lake (cost \$13 million),
- c. Further develop engineering options to be used in drought conditions (total cost \$1.5 million).

E.1.2 San Marcos Springs

1. Hydrology of San Marcos Springs

a. Regional Hydrology

San Marcos Springs is an end-of-the-flow-system type spring. The springs are the lowest part of the potentiometric surface for the Edwards aquifer extending from Uvalde County to Hays County. There is no by-pass of groundwater onto another spring such as Barton Springs in the Austin area. Spring discharge comes from two sources, a “local” source and a “regional” source. The “local” source is considered to be from river recharge in the Blanco River and drainage areas in Hays and parts of Comal County. The “regional” component is considered to be the flow coming out of Bexar and Comal Counties on the up-thrown side of the Comal Springs Fault that does not end up as spring discharge in Spring Run #1, #2, and #3 at Comal Springs. When water levels increase in the main part of the aquifer (up gradient from Comal Springs), the increased water moving toward Comal Springs predominately discharges as spring flow at Comal and not as significant increases in the flow that goes to San Marcos. Groundwater discharge at San Marcos appears to be solely from the up-thrown block of the San Marcos Springs Fault. The down-thrown block does not appear to contain fresh water. The City of San Marcos and Texas State University-San Marcos are the prime groundwater producers in the area. Together they hold Edwards aquifer water rights for 7,245 acre/ft/yr (10 cfs).

b. Spring Hydrology

All thirteen springs at San Marcos Springs are within Spring Lake. There are no subaerial springs along the lakeshores as occurs at Comal Springs. Based on water chemistry, a northern set of springs are recharged by the “local” source, where as the southern springs appear to be recharged by the regional flow in the aquifer. Spring flow at San Marcos declined to 46 cfs during the summer 1956. Spring Lake remained full during the drought.

2. Critical Habitat for Species

The spring areas and the San Marcos River downstream of the dam for Spring Lake are considered to be the most critical habitats. The slough (where Sink Creek drains into Spring Lake) is considered to be a lower priority habitat. The USFWS initially recommended a take and a jeopardy level of 100 cfs. This study recommended a minimum flow of 60 cfs. Based on the differences between the recommended limit of 60 cfs and the 1956 drought flow of 46 cfs, approximately 14 cfs is needed to supplement from the minimum historical level (46 cfs) to a minimum recommended level (60 cfs).

3. Authority Drought Management Plan for San Marcos Springs

Edwards Aquifer Authority drought management plan for water users upstream from Comal Springs presumably will not be effective for maintaining flow at San Marcos Springs during low flow periods. There appears to be a limited hydrologic connection between the main part of the aquifer and the San Marcos “pool.” The Authority's drought management plan currently applies to San Marcos and TSU groundwater production and therefore would abate in the rate of decline at San Marcos. The Edwards Aquifer Authority should consider whether the Edwards Aquifer downstream of Comal Springs should be designated as a partially separate aquifer pool (the San Marcos pool) and develop a separate set of water pumpage regulations for it.

4. Imported Water

a. Groundwater Supply Sources

The arguments made for the feasibility of pumping groundwater to Comal Springs are applicable for pumping groundwater to San Marcos Springs. The amount of water needed for San Marcos is less (15 cfs, about 10,000 acre-ft.) where as the Comal Springs augmentation need is 60 cfs (43,000 acre-ft/year). Supplying this amount of water, however, is still expensive.

Pumping groundwater from the Edwards aquifer in the San Marcos pool is specifically not recommended, since these waters would naturally flow to San Marcos Springs and also that “local” pumpage could potentially dry up the springs during severe drought. Recharge structures on the Blanco River and its tributaries are not recommended either. Such structures will increase local recharge under normal climate conditions, but not during drought periods. Local recharge did not occur either during the drought of 1956 or 1984.

b. Surface Water Supply Sources

Using surface water sources (other than Canyon Reservoir) at San Marcos are not recommended as an augmentation source for the same reason as given for Comal Springs.

Surface water from Canyon Reservoir is an augmentation option that should be considered. Surface water could be injected into the Edwards Aquifer along the Guadalupe River in the area of Gruene, Texas and would then flow to San Marcos through the aquifer (\$13 million). Another option is to buyout the water rights of San Marcos Springs and Texas State University (\$11 million). Municipalities might also consider off-channel storage, such as abandoned quarries, that could be used as a surface water reservoirs during wet periods and supplemental water supplies during drought periods.

5. Engineering Approaches at San Marcos Springs

Water flow could be focused toward critical habitat in the San Marcos Springs complex to maintain or enhance a suitable hydrologic environment.

- a. Adjusting the spillway elevation of San Marcos dam so that more flow goes over the eastern spillway during drought conditions. Important endangered species' habitats are located immediately downstream of the eastern spillway. The western spillway appears to be about 0.5 ft lower than the eastern spillway. Estimated cost to install temporary dam across western spillway is \$30,000.
- b. Installing an inflatable dam across the slough during drought conditions would keep the spring water flowing over the critical habitat areas more effectively. Estimated cost for an inflatable dam across the slough is \$150,000.
- c. Re-circulating San Marcos River water to the base of Spring Lake dam to maintain the Texas wild rice and San Marcos salamander habitat at this location. Estimated cost for re-circulation to base of dam is \$250,000.

6. Recommended Option for San Marcos Springs

The recommended option is:

- a. "Reduce / eliminate major groundwater use in the San Marcos area during critical drought periods by either "buying out" the water right of major users(\$11 million) or by revising critical period management rules. If additional water is required at San Marcos, use Canyon Reservoir water to supplement spring discharge(\$13 million).
- b. Further develop the suggested engineering options so that they could be implemented if spring discharge drops below a threshold value of 60 cfs(\$430,000).

7. The amount of excess capacity in Canyon Reservoir may limit the amount of water available for buyout and augmentation at both New Braunfels and San Marcos. The preference of this report is to focus on the reduction or elimination of local or water rights during critical drought periods or buyout of the water rights of the major water users.

F. Recommended Studies

1. A better understanding is needed of regional pumping vs local pumping on water levels at LCRA well, Landa Park well, and Landa Lake. This can be accomplished by:
 - a. Conducting a long-term pump test with NBU-5 as the pumping well, the LCRA well and Landa Park well as monitoring wells and monitor discharge rates of representative springs to determine the impact of local pumping on the hydrology of the springs.
 - b. Using the new MODFLOW groundwater model to look at several hydrogeologic factors that impact flows at Comal Springs and San Marcos Springs. This would include the relative impacts between local and regional pumping and how the western group of orifices at Comal Springs reduces flows to San Marcos Springs. The hydrogeologic framework of the model may need to be modified to account for the new hydrogeologic interpretation of Comal Springs presented in this report.
2. Considering that San Marcos Springs has a limited connection to rest of the aquifer up gradient from Comal Springs, ground water management approaches need to be reconsidered for the San Marcos area.
3. Develop a strategy to reduce/eliminate large volume water users in the New Braunfels and San Marcos regions.
4. Develop an engineering plan/pilot study for using Canyon Reservoir water to augment waters to Landa Lake through Blieders Creek and recharging the Edwards aquifer as a way to supplement flow at San Marcos Springs.
5. Additional dye trace studies need to be conducted. These would include:
 - a. Injection of dye in a water well in the Priess Heights subdivision to confirm hydrologic connection between New Braunfels and San Marcos.
 - b. Redo the tracer studies in LCRA well and Landa Park well and monitor San Marcos springs to determine if either dye makes it to San Marcos. This study could be done in conjunction with a dye trace in the Priess Heights region.

- c. Inject dye in the Bracken well to see whether flow goes to the Landa Park well, a specific spring at Comal Springs, LCRA well, or San Marcos Springs.
6. Add monitoring wells in the down-thrown block between Bracken and LCRA to increase the synoptic water well database in the down-thrown and up-thrown blocks upgradient from Comal Springs. Install a new monitoring well down gradient from Comal Springs on the down thrown block to confirm there is no fresh water.
7. Conduct detailed studies on engineered alternatives for preserving critical habitat in Comal Springs complex and the San Marcos Springs complex.
8. Conduct additional studies at San Marcos Springs to better understand the hydrodynamics of the specific springs under different flow conditions.
9. Routinely measure spring flow at Comal Springs 1, 2 and 3 to further understand relative contributions of spring discharge from up-thrown block and down-thrown blocks.
10. Lower the transducer in LCRA water well to extend water level monitoring range for this well especially during drought periods.

G. References

- Arsuffi, T.L., 1993, Status of the Comal Springs riffle beetle (*Heterelmis comalensis*), Peck's cave amphipod (*Stygobromus pecki*), and the Comal Springs dryopid beetle (*Stygoparnus comalensis*): Prepared for the U.S. Fish and Wildlife Service.
- Aziz, K., J.R. Fields, and R.E. Moss., 2000, An evaluation of spring flows to support the Upper San Marcos Spring ecosystem, Hays County: Texas. Texas Parks and Wildlife Department.
- Barr, C.B, 1993, Survey for two Edwards Aquifer invertebrates: Comal Springs dryopid beetle *Stygoparnus comalensis* Barr and Spangler (*Coleoptera: Dryopidae*) and Peck's Cave amphipod *Stygobromus pecki* Holsinger (*Amphipoda: Crangonyctidae*): Prepared for U.S. Fish and Wildlife Service, Austin, Texas.
- Barr, C.B., and P.J. Spangler, 1992, A new genus and species of stygobiontic dryopid beetle, *Stygoparnus comalensis* (*Coleoptera, Dryopidae*), from Comal Springs, Texas, Proceedings of the Biological Society of Washington 105(1): 40-54.
- Berkhouse, C.S., and J.N. Fries, 1995, Critical thermal maxima of juvenile and adult San Marcos salamanders (*Eurycea nana*): Southwestern Naturalist 40(4).
- BIO-WEST, 2002a, Riffle beetle habitat and population evaluation Final Report, Edwards Aquifer Authority, San Antonio, Texas, 11p.
- BIO-WEST, 2002b, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs / River aquatic ecosystem. Draft 2001 Annual Report, Edwards Aquifer Authority, San Antonio, Texas, 35p.
- BIO-WEST, 2002c, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the San Marcos Springs / River aquatic ecosystem. 2001 Annual Report, Edwards Aquifer Authority, San Antonio, Texas, 33p.
- BIO-WEST, 2002d, Comal Springs riffle beetle laboratory study: evaluation under variable flow conditions: Final Report, Edwards Aquifer Authority, San Antonio, Texas. 22p.

- BIO-WEST, 2003a, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs / River aquatic ecosystem: 2002 Annual Report, Edwards Aquifer Authority, San Antonio, Texas, 45p.
- BIO-WEST, 2003b, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the San Marcos Springs / River aquatic ecosystem: 2002 Annual Report, Edwards Aquifer Authority, San Antonio, Texas, 42p.
- BIO-WEST, 2004a, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs / River aquatic ecosystem: 2003 Annual Report, Edwards Aquifer Authority, San Antonio, Texas, 42p.
- BIO-WEST, 2004b, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the San Marcos Springs / River aquatic ecosystem: 2003 Annual Report. Edwards Aquifer Authority, San Antonio, Texas, 30p.
- BIO-WEST, 2004c, Aquatic vegetation laboratory study: Phase 1: Observations of water quality changes and plant growth under various flows, Phase 2: Effects of carbon dioxide level on aquatic plants found in the Comal and San Marcos Springs/River ecosystems: Final Report, Edwards Aquifer Authority, 23 p.
- (BMWD) Bexar Metropolitan Water District, 1998, Habitat conservation plan in support of Edwards Aquifer withdrawals affecting Edwards Aquifer dependent species for Endangered Species Act Section 10(a)(1)(B) Permit; Bexar Metropolitan Water District.
- Bonner, T.H., T.M. Brandt, J.N. Fries, and B.G. Whiteside., 1998, Effects of temperature on egg production and early life stages of the fountain darter: Transactions of the American Fisheries Society 127:971-978.
- Bosse, L.S., D.W. Tuff, and H.P. Brown, 1988, A new species of *Heterelmis* from Texas (*Coleoptera, Elmidae*): Southwestern Naturalist 33(2):199-204.
- Bowles, D.E., C.B. Barr, and R. Stanford, 2002, Habitat and phenology of the endangered riffle beetle, *Heterelmis comalensis*, and a coexisting species *Microcyllloepus pusillus* (*Coleoptera: Elmidae*), at Comal Springs Texas: Archiv fur Hydrobiologie.

- Brandt, T.M., K.G. Graves, C.S. Berkhouse, T.P. Simon, and B.G. Whiteside, 1993, Laboratory spawning and rearing of the endangered fountain darter: *The Progressive Fish-Culturist* 55:149-156.
- Brown, H.P., 1987, Biology of riffle beetles: *Annual Review of Entomology* 32:253-273.
- Brune, G., 1981, *Springs of Texas Vol. I*: Texas A&M University Press, College Station, Texas, 566 p., 8 plates
- Carr, Jr., J.T., 1967, The climate and physiography of Texas: Texas Water Development Board Report 53, 27 p.
- Chapman, R.F., 1982, The insects: structure and function: Harvard University Press, Cambridge, MA.
- Crowe, J.C., 1994, Detailed hydrogeologic maps of the Comal and San Marcos Rivers for endangered species habitat definition, Texas: University of Texas at Austin, M.A. Thesis, 154 p.
- DeCook, K.J., 1960, Geology and groundwater resources of Hays County, Texas: Texas Board of Water Engineers; Bulletin 6004, 167p.
- Edwards, R.J., E. Marsh, and C. Hubbs, 1980, The status of the San Marcos gambusia, *Gambusia georgei*. Endangered Species Report 9, U.S. Fish and Wildlife Service.
- Espey, Huston & Associates, Inc., 1975, Investigation of flow requirements from Comal and San Marcos Springs to maintain associated aquatic ecosystems, Guadalupe River Basin, Texas: Espey, Huston & Associates, Inc., Austin, Texas, 141 pp.
- Federal Register, 1997, Endangered and threatened wildlife and plants: final rule to list three aquatic invertebrates in Comal and Hays Counties, Texas, as endangered: Volume 62, Number 243, December 18, 1997.
- Fries, J.N., J.R. Gibson, T.L. Arsuffi, 2003, Edwards Aquifer spring invertebrate survey and captive maintenance of two species: Annual Report to U.S. Fish and Wildlife Service Ecological Services Division, Austin, Texas, 11p.
- George, W.O., W.W. Hastings,, and S.D. Breeding, 1947, Geology and ground-water resources of Comal County, Texas: Texas Board of Water Engineers and USGS, 142 p., 5 plates

- George, W.O., W.W. Hastings,, and S.D. Breeding,1952, Geology and ground-water resources of Comal County, Texas: U.S. Geological Survey Water Supply Paper 1138, 126 p., 6 plates
- Groeger, A.W., P.F. Brown, T.E. Tietjen, and T.C. Kelsey, 1997, Water quality of the San Marcos River, Texas Journal of Science 49:279-294.
- Guyton, William F. & Associates, 1958, Report on Hueco Springs: Consulting report prepared for City Water Board, San Antonio, Texas
- Guyton, William F. & Associates, 1979, Geohydrology of Comal, San Marcos, and Hueco Springs: Texas Department of Water Resources Report 234, 85 p.
- Hanson, J.A. and T.A. Small, 1995, Geologic framework and hydrogeologic characteristics of the Edwards Aquifer outcrop, Hays County, Texas: U.S. Geological Survey, Water-Resources Investigations Report 95-4865, 10 p., 1 pl.
- Hubbs, C., and A.E. Peden, 1969, *Gambusia georgei* sp. from San Marcos, Texas: Copeia 2:357-364.
- Jorgensen, D.G., 1989, Using geophysical logs to estimate porosity, water resistivity an intrinsic permeability: U.S. Geological Survey Water-Supply Paper 2321, 24. p.
- LBG-Guyton Associates, 1994, Edwards Aquifer ground-water divides assessment, San Antonio Region, Texas: report prepared for Edwards Underground Water District, 58 p.
- Linam, L.A. 1993. A reassessment of the distribution, habitat preference, and population size estimate of the fountain darter (*Etheostoma fonticola*) in the San Marcos River, Texas. Section 6 Report, Texas Parks and Wildlife Department, Job 2.5. 34 p.
- Linam, G.W., K.B. Mayes, and K.S. Saunders, 1993, Habitat utilization and population size estimate of fountain darters, *Etheostoma fonticola*, in the Comal River, Texas: Texas Journal of Science 45(4):341-348.
- Longley, G., 1978, Status of *Typhlomolge* (=Eurycea) *rathbuni*, the Texas blind salamander: U.S. Fish and Wildlife Service Endangered Species Report 2.

- Maclay, R.W., and T.A. Small, 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. Geological Survey Open-File Report 76-627, 65 p.
- Mahler, B.J., 1997, Mobile sediments in a karst aquifer, University of Texas at Austin, Ph.D. Dissertation, 170 p.
- Mayes, K., K. Saunders, R. Moss, K. Aziz, 1996, Effects of changes in Spring Lake headgate elevation on water levels in the San Marcos River, Hays County, Texas: Texas Parks and Wildlife Department River Studies Report No. 13, Austin, Texas, 31 p.
- McKinney, D.C., and J.M. Sharp, 1995, Springflow augmentation of Comal Springs and San Marcos Springs, Texas: phase I - feasibility study: Technical Report CRWR 247, Center for Research in Water Resources, Austin, Texas, 416 p.
- Nelson, J.M., 1993, Population size, distribution, and life history of *Eurycea nana* in the San Marcos River: Southwest Texas State University, San Marcos, Texas, M.S. Thesis, 43 p.
- Ogden, A.E., R.A. Quick, and S.R. Rothermel, 1986a, "Hydrochemistry of the Comal, Hueco, and San Marcos Springs, Edwards Aquifer, Texas" in Abbott, P.L., and C.M. Woodruff, Jr., eds., *The Balcones Escarpment: Geology, Hydrology, Ecology and Social Development in Central Texas*: Geological Society of America, p. 115-130.
- Ogden, A.E., R.A. Quick, D.L. Lunsford, and S.R. Rothermel, 1986b, Hydrogeological and hydrochemical investigation of the Edwards Aquifer in the San Marcos area, Hays County, Texas: Edwards Aquifer Research and Data Center Report, no. R1-86, p. 364.
- Ogden, A.E., A.J. Spinelli, and J. Horton, 1985a, Hydrologic and hydrochemical data for the Edwards Aquifer in Hays and Comal Counties, October 1981 to September 1983 San Marcos, Texas: Southwest Texas State University, Edwards Aquifer Research and Data Center, Report R1-85. 102 p.
- Ogden, A.E., A.J. Spinelli, and J. Horton, 1985b, Hydrologic and hydrochemical data for the Edwards Aquifer in Hays and Comal Counties, October 1983 to June 1985 San Marcos, Texas: Southwest Texas State University, Edwards Aquifer Research and Data Center, Report R2-85. 83 p.

- Pearson, Jr., F.J., P.L. Rettman, and T.A. Wyerman, 1975, Environmental tritium in the Edwards aquifer, central Texas 1963-1971: U.S. Geological Survey Open-File Report 74-362, 32 p.
- Pilgrim, D.H. and I. Cordery, 1993, "Flood Runoff" (Chapter 9) in Maidment, D.R., 1993, *Handbook of Hydrology*: McGraw Hill, Inc.
- Poole, J. and D.E. Bowles, 1999, Habitat characterization of Texas wild-rice (*Zizania texana* Hitchcock), an endangered aquatic macrophyte from the San Marcos River, Texas, USA, *Aquatic Conservation: Marine and Freshwater Ecosystems* 9:291-302.
- Poteet, D., H. Collier, and R.W. Maclay, 1992, Investigation of the fresh/ saline-water interface in the Edwards Aquifer in New Braunfels, and San Marcos, Texas: Edwards Underground Water District Report 92-02, 172 p.
- Power, P., 1996a, Effects of current velocity and substrate composition on growth of Texas wild-rice: *Aquatic Botany* 55:199-204.
- Power, P., 1996b, Direct and indirect effects of floating vegetation mats on Texas wild-rice (*Zizania texana*): *The Southwestern Naturalist* 41(4): 463-464.
- Puente, C., 1976, Statistical analysis of water-level, springflow, and streamflow data for the Edwards Aquifer in south-central Texas: Edwards Underground Water District, 58 p.
- Rose, F. and P. Power, 1992, Effects of habitat and herbivory on growth and reproduction in Texas wildrice (*Zizania texana*): Prepared for U.S. Fish and Wildlife Service, Austin, Texas.
- Rose, P.R., 1972, Edwards Group, surface and subsurface, central Texas: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 74, 198 p.
- Rothermel, S.R., A.E. Ogden, 1987, Hydrochemical investigation of the Comal and Hueco Spring systems, Comal County, Texas San Marcos, Texas: Southwest Texas State University, Edwards Aquifer Research and Data Center Report R1-87, 182 p.
- Russell, B., 1976, Distribution of troglobitic salamanders in the San Marcos area, Hays County, Texas: Texas Association for Biological Investigations of Troglobitic *Eurycea* (BITE) Report 7601.

- Schenck, J.R., and B.G. Whiteside, 1976, Distribution, habitat preference, and population size estimate of *Etheostoma fonticola*: *Copeia* 76(4):697-703.
- Schlumberger, Ltd., 1969, 1972, Log interpretation charts: Schlumberger, Ltd., N.Y., N.Y., 76 p., 92 p.
- Schlumberger, Ltd., 1972, Log interpretation principles, Volume 1: Schlumberger, Ltd. N.Y., N.Y., 113 p.
- Schultz, A.L., 1992, Using geophysical in the Edwards aquifer to estimate water quality along the freshwater/saline water interface (Uvalde to San Antonio, Texas): Edwards Underground Water District Report 92-03, 47 p.
- Schultz, A.L., 1993, Defining the Edwards aquifer freshwater/saline-water interface with geophysical logs and measured data (San Antonio to Uvalde, Texas): Edwards Underground Water District Report 93-06, 81 p.
- Schultz, A.L., 1994, Review and update of the position of the Edwards aquifer freshwater/saline-water interface from Uvalde to Kyle, Texas: Edwards Underground Water District Report 94-05, 31 p.
- Slade, R.M., Jr., J.T. Bentley, D. Michaud, 2002, Results of streamflow gain-loss studies in Texas, with emphasis on gains from and losses to major and minor aquifers: U.S.G.S Open File Report 02-068, Austin, Texas, 131 p.
- Small, T.A. and Hanson, J.A., 1994, Geologic framework and hydrogeologic characteristics of the Edwards Aquifer outcrop, Comal County, Texas: U.S. Geological Survey, Water-Resources Investigations Report 94-4117, 10 p., 1 pl.
- Taylor, T.U., 1904, The water powers of Texas, U.S.G.S. Water Supply and Irrigation Paper No. 105, 116 p.
- Terrell, E.E., W.H.P. Emery, and H.E. Beaty., 1978, Observations on *Zizania texana* Texas wildrice, and endangered species: Bulletin of the Torrey Botanical Club 105:50-57.
- (TBWE), 1960, Channel gain and loss investigations, Texas streams, 1918-1958: Texas Board of Water Engineers Bulletin 5807-D, 270 p.

- (TPWD), K.S. Saunders, K.B. Mayes, T.A. Jurgensen, J.F. Trungale, L.J. Kleinsasser, K. Aziz, J.R. Fields, and R.E. Moss., 2000, An evaluation of spring flows to support the Upper San Marcos Spring ecosystem, Hays County, Texas. Texas Parks and Wildlife Department.
- Tupa, D.D., and W.K. Davis, 1976, Population dynamics of the San Marcos, Texas salamander *Eurycea nana*, Texas Journal of Science 27(1): 179-195.
- Uliana, M.M., 1995, The potential for springflow augmentation at Comal and San Marcos Springs, central Texas: University of Texas at Austin, M.A. Thesis, 146 p.
- University of Texas, Bureau of Economic Geology, 1974, Geologic Atlas of Texas, San Antonio sheet: Scale 1:250,000
- University of Texas, Bureau of Economic Geology, 1974, Geologic Atlas of Texas, Seguin sheet: Scale 1:250,000
- (USFWS) U.S. Fish and Wildlife Service, 1996, San Marcos and Comal Springs and Associated aquatic ecosystems (revised) recovery plan: U.S. Fish and Wildlife Service, 121 p.
- (USFWS) Hardy, T.B., N.R. Bartsch, D.K. Stevens, and P.J. Conner. 2000. Development and application of an instream flow assessment framework for the fountain darter (*Etheostoma fonticola*) in Landa Lake and the Comal River system. U.S. Fish and Wildlife Service, draft report.
- (USGS) U.S. Geological Survey, 1958, Surface Water Supply of the United States 1956 Part 8 – Western Gulf of Mexico Basins: U.S. Geological Survey Water-Supply Paper 1442, 423 p.
- (USGS) U.S. Geological Survey, 1959, Surface Water Supply of the United States 1957 Part 8 – Western Gulf of Mexico Basins: U.S. Geological Survey Water-Supply Paper 1512, 536 p.
- Whiteside, B.G., 1976, *Gambusia georgei* Hubbs and Peden, 1969, San Marcos gambusia: Report to U.S. Fish and Wildlife Service, Endangered Species Division.

Wicks, C.M., and B. Bohm, 2000, "Application of Unit Hydrograph Technique to the Discharge Record at Big Spring, Carter County, Missouri" in Sasowsky, I.D., and C.M. Wicks, eds., *Groundwater Flow and Contaminant Transport in Carbonate Aquifers*: A.A. Balkema Publisher, p. 31-42

Worthington, S.R.H., 2003, Conduits and turbulent flow in the Edwards Aquifer: report prepared for Edwards Aquifer Authority, 42 p.