Stephen F. Austin State University
SFA ScholarWorks

Faculty Publications | Department of Geology

4-2011

Spring Hydrology of Colorado Bend State Park, Central Texas

Kevin W. Stafford
College of Sciences and Mathematics, Department of Geology, Stephen F. Austin State University, staffordk@sfasu.edu

Melinda G. Shaw-Faulkner
College of Sciences and Mathematics, Department of Geology, Stephen F. Austin State University, mgshaw@sfasu.edu

Jessica L. DeLeon
College of Sciences and Mathematics, Department of Geology, Stephen F. Austin State University

Spring Hydrology of Colorado Bend State Park, Central Texas

By Kevin W. Stafford, Melinda G. Shaw, and Jessica L. DeLeon
Department of Geology, Stephen F. Austin State University, 1901 N. Raguet, Nacogdoches, TX 75962

Abstract

Karst development in Ellenburger carbonates near Colorado Bend State Park in central Texas exhibits complex polygenetic origins, with porosity development dominated by an early hypogene phase that has subsequently been overprinted to varying degrees by epigene processes. Quarterly physicochemical and continuous thermal monitoring analyses of eight springs in the study area indicate that modern groundwater flow paths are highly variable. Springs exhibit patterns that range from shallow, distributed recharge into diffuse-flow dominated systems, to focused recharge into well-connected conduit systems, to deep-circulation systems that equilibrate with bedrock. All springs, except Sulphur Spring, exhibit physicochemical characteristics indicative of proximal epigenic groundwater flow through Ellenburger carbonates, while Sulphur Spring shows elevated temperature and dissolved-ion concentrations indicative of longer groundwater flow paths through deeper strata. The polygenetic nature of karst development in the Colorado Bend State Park has created an enhanced porosity structure which forms a complex modern groundwater flow network.

INTRODUCTION

Colorado Bend State Park (CBSP) is located on the northern edge of the Texas Hill Country on the flank of the Llano Uplift (Figure 1, 2). Here Ordovician Ellenburger carbonates crop out along a highly entrenched segment of the Colorado River, immediately upstream from Lake Buchanan. Proximal to the river, numerous springs discharge including subaqueous springs, springs within a few meters of the river and springs that discharge hundreds of meters from the river (Figure 1). Most springs discharge with normal epigenic karst chemistries; however, one spring in the region, Sulphur Spring, discharges with a slightly thermal component, an elevated sulfate content and easily discernable odor of hydrogen sulfide.

CBSP is located approximately 180 kilometers northwest of Austin, Texas in San Saba and Lampasas Counties. The park covers 21.6 square kilometers including a seven kilometer long stretch of the Colorado River. The area is located along the boundary between subtropical steppe climate and subtropical subhumid climate, with average annual temperature of 20ºC and minimum and maximums of 8ºC and 30ºC respectively (Estaville and Earl, 2008). Annual precipitation averages 30 cm, with most precipitation occurring during Spring (March – May) and Fall (September – November).

More than 400 karst features have been identified within CBSP and surrounding properties, including more than 100 physically mapped caves. Most caves exhibit characteristics of complex, polygenetic origins,

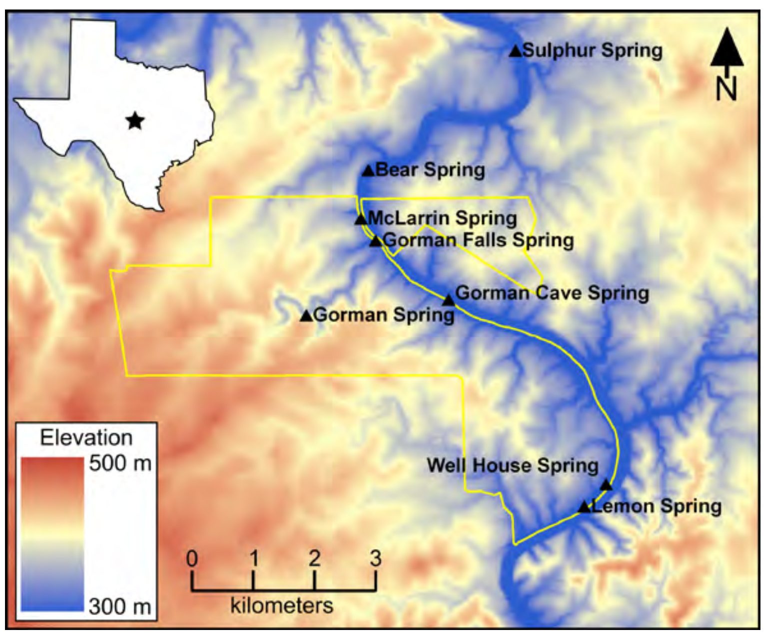

Figure 1. Map of study site showing location of springs, outline boundary of CBSP in yellow and approximate location of study site with reference to the state of Texas.

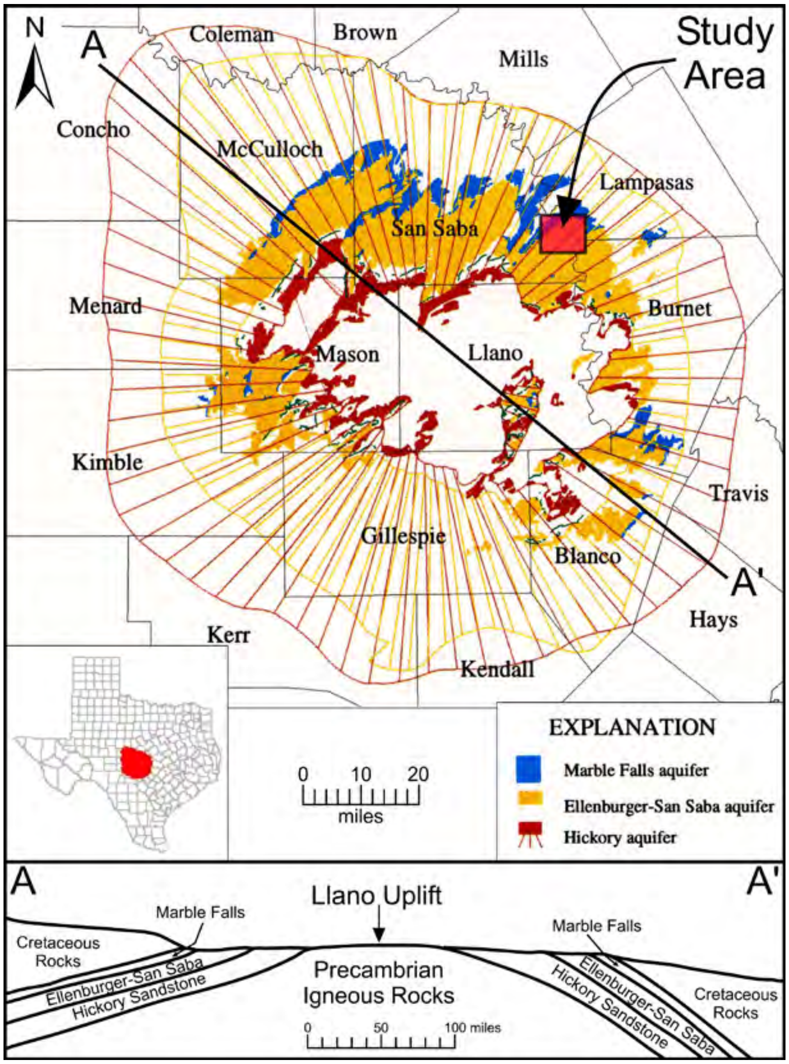

Figure 2. Spatial distribution of Llano Uplift aquifers in relation to project study area (red box) with ~10X vertically exaggerated cross section (modified from Preston and others, 1996).

including many that exhibit classic hypogene MSRF (Morphologic Suite of Rising Flow) (Klimchouk, 2007) characteristics with varying degrees of epigenic overprinting, while other caves are more purely epigene in origin. DeLeon (2010) showed that at least two thirds of caves developed within the CBSP region exhibit hypogene origins with variable degrees of epigene overprinting, while less than one fourth of all caves showed clear dominance of epigene origins. Eight known perennial springs discharge subaerially within the park, while two other springs discharge upstream within the commercially operated Sulphur Springs fish camp (Figure 1). Stream mapping conducted by Mitchell and others (2011) suggests that at least ten additional springs also discharge subaqueously within the Colorado River in this region. The polygenetic nature of karst development with abundant springs that discharge from subaqueous position in the Colorado River to more than sixty five meters above river level suggests a complex hydrogeologic system that has not completely equilibrated with current climatic and geomorphic conditions.

GEOLOGIC OVERVIEW

The Llano Uplift, and greater Texas Hill Country, is dominated by Precambrian (~1.0 bya - ~1.2 bya) basement rocks which form a large structural dome overlain unconformably by Cambrian and Ordovician clastics and carbonates (Figure 2) (Sellards and others, 1932). Ordovician strata are unconformably overlain by Carboniferous rocks that are subsequently overlain unconformably by Cretaceous strata that compose the northern extension of the Edwards Plateau (Rose, 1972). Precambrian strata were emplaced as part of the Grenville orogenic event, while these and overlying Paleozoic rocks in the study area were modified by tectonism associated with the Ouachita Orogeny, primarily resulting in minor tilting and faulting (Standen and Ruggiero, 2007). Throughout the Cenozoic, all strata within the region have seen additional brittle deformation and minor tilting as a result of uplift of the Edwards Plateau and down-dropping of the gulf coastal plain, with intense faulting along the Balcones Fault Zone, approximately 80 kilometers east of the study area (Collins, 1995).

Karst development within the study area is largely limited to Ordovician Ellenburger carbonates, including cave and spring development in all three Ellenburger units, oldest to youngest — Tanyard, Gorman and Honeycutt Formations. The Tanyard Formation is ~170 meters thick and consists of fine- to coarse-grained, irregularly bedded dolomite deposited as high-energy, restricted, subtidal facies, including common ooidic zones and cryptalgal laminae (Kerans, 1990). The Gorman

Formation is ~130 meters thick and consists of micro-granular dolomite associated with deposition in a low-energy, restricted-shelf environment, including common macrofossils, distributed zones of intense burrowing and cryptalgal laminae, as well as zones indicative of subaerial exposure that include rip-up clasts and siliciclastic sediments (Kerans, 1990). The Honeycutt Formation is ~40 meters thick and consist of thinly interbedded limestones and dolomites that were deposited in an open, shallow-water shelf environment, including common structures indicative of periods of brief subaerial exposure (e.g. desiccation cracks, rip-up clasts) and structures indicative of variable current energies (e.g. ooids, current ripples, cryptalgal laminae) (Kerans, 1990).

Within the study area, three minor aquifers collectively referred to as the Llano Uplift aquifers are developed in the Paleozoic rocks, including from bottom to top: Hickory aquifer, Ellenburger-San Saba aquifer, and Marble Falls aquifer (Preston and others, 1996). The aquifer system dips gently into the subsurface away from the central Llano Uplift, dipping mainly to the north in the study area. The Hickory aquifer is developed in the Cambrian Hickory Sandstone, which is underlain by Precambrian basement rocks. The Ellenburger-San Saba aquifer includes all three formations of the Ellenburger Group plus the San Saba member of the underlying Wilberns Formation. The Ellenburger-San Saba aquifer is compartmentalized in regions due to local and regional block faulting, with significant solutional overprinting and is in some regions locally connected hydrologically with the overlying Marble Falls aquifer (Preston and others, 1996). The Marble Falls aquifer is developed in corresponding Carboniferous limestone, which exhibits highly variable permeability due to well-developed secondary porosity. All three of the Llano Uplift aquifers show gradual increases in total dissolved solids in the down-dip direction away from the main Llano Uplift dome, with deep, distal components containing total dissolved solids greater than 10,000 mg/L (Preston and others, 1996).

In the CBSP area, Ellenburger strata are exposed at the surface and most associated springs exhibit normal, epigene karst chemistries, while one spring exhibits anomalous characteristics. The seven springs that exhibit normal epigene karst chemistries, include Bear Spring, Gorman Cave Spring, Gorman Falls Spring, Gorman Spring, Lemon Spring, McLarrin Spring and Well House Spring (Figure 1, Table 1). Sulphur Spring, as the name implies, exhibits anomalous patterns. Bear Spring discharges from a solutionally widened fracture in the Honeycutt Formation that is located four meters above and twenty five meters away from the river. Gorman Cave Spring is associated with Gorman Cave and discharges from the Gorman Formation. Gorman Cave Spring discharges directly into the Colorado River through alluvial sediments, but the spring is accessible for sampling in a stream passage in Gorman Cave, which is more than one hundred meters from the river and six meters above. Gorman Falls Spring is located immediately adjacent to the Colorado River with discharge from a decimeter-scale conduit in the Gorman Formation. Gorman Spring is located at the headwaters of Gorman Creek with discharge occurring as artesian flow from a vertical fracture more than a kilometer from the river and sixty five meters above (England and others, 2010). Lemon Spring discharges horizontally from a thin bedding

Table 1. Average physiochemical characteristics of springs with standard deviation (stdev) based on three month sampling.

	TDS		pH		Conductivity		Sulphate	
	ppm	stdev	pH	stdev	mV	stdev	ppm	stdev
Bear Spring	345	41	6.8	0.1	-8	9	1.3	0.4
Lemon Spring	386	139	6.8	0.2	-16	3	1.0	0.2
Gorman Cave Spring	325	88	6.6	0.2	-5	10	1.3	0.5
Gorman Falls Spring	344	26	6.7	0.2	-16	12	1.2	0.6
Gorman Spring	351	22	6.7	0.3	-9	19	0.7	0.4
McLarrin Spring	309	46	6.9	0.2	-17	13	0.4	0.4
Sulphur Spring	2067	235	6.6	0.1	-1	14	3.0	0.3
Well House Spring	361	8	6.8	0.1	-13	12	1.1	0.3

plane in the Tanyard Formation approximately seventy five meters from the river and six meters above. McLarrin Spring discharges through a conduit in the Gorman Formation within twenty meters of the river and less than two meters above. Well House Spring has been encased and is used as the primary water supply for CBSP. Well House Spring discharges under artesian pressure from the Tanyard Formation approximately one hundred meters from the river and five meters above. Sulphur Spring discharges under artesian pressure from the Honeycutt Formation and is channelized into an artificial impoundment for recreation. Sulphur Spring is located fifty meters from the river and five meters above.

SPRING MONITORING

Springs in the CBSP area were monitored in order to evaluate spatial and temporal variations in groundwater discharge from the Ellenburger karst system along the Colorado River. Onset HOBO Pendant Temperature Data Loggers were installed at each of the springs to record thermal variations through the course of the study. At three-month intervals, starting in March 2009 and concluding in June 2010, the temperature data loggers were downloaded and redeployed. At each of these intervals, chemistry of spring discharge was measured in the field with Oakton Portable meters (i.e. Oakton pH 300 and CON 400 meters) in order to evaluate spring pH, conductivity and total dissolved solids. Also at each sample period, a water sample was collected for sulfate analysis, which was conducted in the Stephen F. Austin State University Geochemistry Lab with use of an Agilent 8453 UV-Vis Spectrophotometer through precipitation of sulfate ions as barium sulfate induced by the addition of barium chloride (methodology after Shaw, 2006).

Throughout the study, gaps in data exist for various springs. Gaps in thermal data collected with data loggers occur as a result of loss of loggers either from theft or as a result of being dislodged from springs and lost due to natural conditions. Gaps in data collected with hand-held meters are the result of temporary inaccessibility to spring sites either as a result of bat hibernation (e.g. Gorman Cave Spring) or seasonal hunting activity (e.g. Bear Spring). However, in the case of all springs, except Bear Spring from which deployed data loggers were lost in every sample interval, sufficient data were collected to provide initial characterization of each springs based on temporal and spatial variability.

RESULTS

The seven springs with typical epigenic karst characteristics (i.e. Bear, Gorman, Gorman Cave, Gorman Falls, Lemon, McLarrin and Well House) exhibited average total dissolved solid values of 346 ppm, average pH values of 6.7, and average conductivities of -11.8 mV (Table 1). Sulfate concentrations in these seven springs were more variable with an average of 0.98 ppm, with slightly elevated concentrations for Gorman Spring, Gorman Falls Spring and Bear Spring and significantly lower concentrations in Gorman Cave Spring and McLarrin Spring (Table 1). In contrast, Sulphur Spring consistently exhibited sulfate levels with an average of 2.98 ppm and correspondingly elevated total dissolved solids averaging 2067 ppm, elevated average temperature of 23.0°C, elevated average conductivity of -1.3 mV and a slightly lower pH of 6.6 (Table 1).

Temporal monitoring of spring temperature (Figure 3) coupled with monitoring of surface temperature and precipitation (Figure 4) showed greater variability amongst springs as expected from quarterly spot sampling with hand-held meters. Springs exhibited variable seasonal fluctuation (Figure 3, Table 2), with maximum fluctuation observed at Gorman Falls Spring and virtually no seasonal fluctuation at McLarrin and Sulphur Springs. Lags in seasonal fluctuation of one to two days occurred with Gorman Cave Spring and Gorman Spring, one to two weeks in seasonal fluctuation was observed in Lemon, Forman Falls and McLarrin Springs; while no data were collected for Bear Springs because of logger loss. Thermal shifts associated with precipitation events show that Lemon Spring, Well House Spring and Sulphur Spring waters thermally equilibrate completely with host rock and do not show thermal response to individual precipitation events. Daily thermal fluctuations are observed in Well House Spring because the data logger was installed in a parkwater

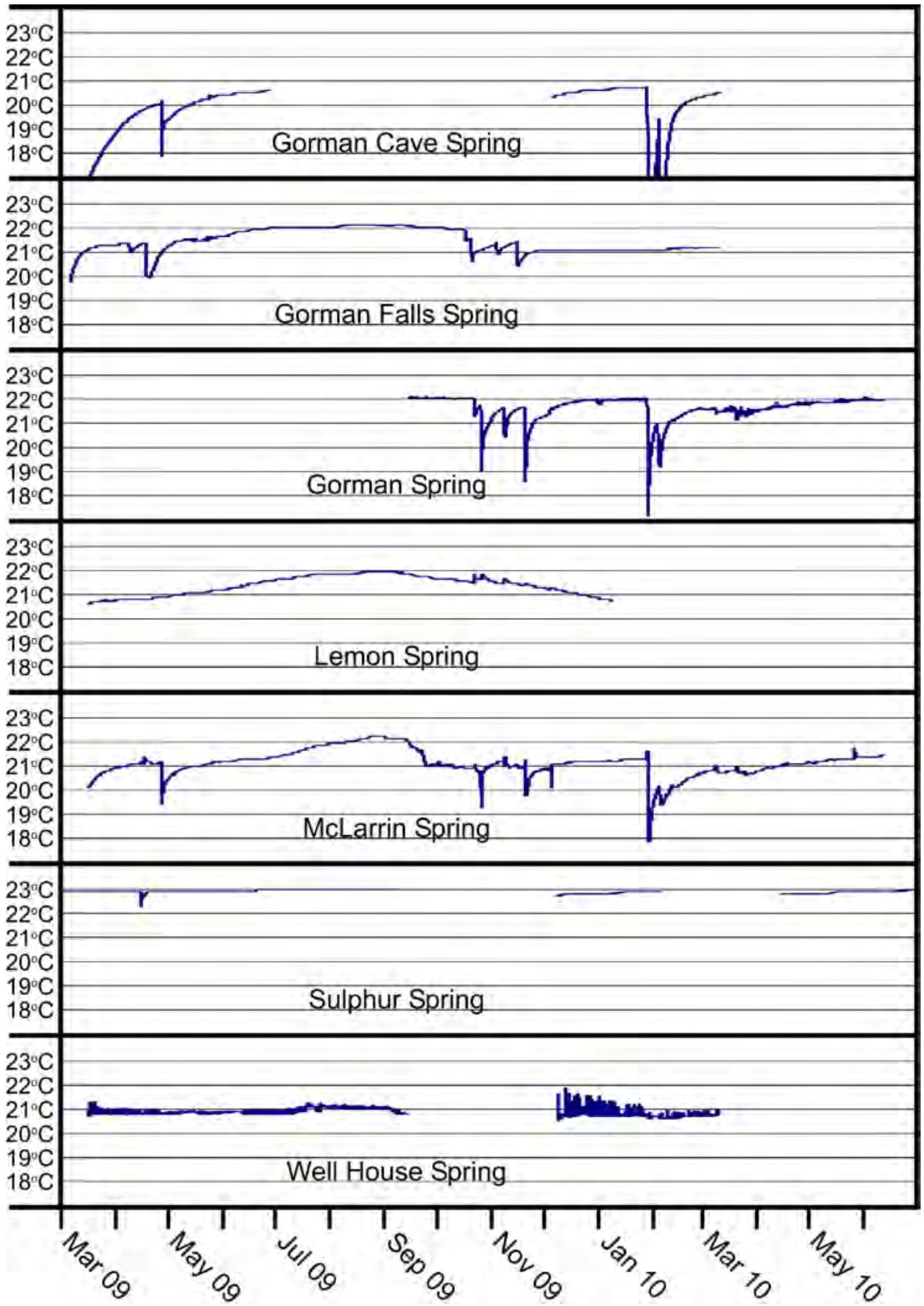

Figure 3. Thermal spring data for springs in study. Note that gaps in data represent lost data loggers, data logger malfunction or inability to retrieve data during hunting seasons.

overflow discharge pipe that is exposed to diurnal heating that overprints spring behavior.

Gorman Cave Spring, Gorman Spring, McLarrin Spring and Gorman Falls Spring, show varying degrees of thermal equilibration between precipitation recharge and discharge, ranging from one degree of equilibration to ten degrees of equilibration, respectively (Table 2).

DISCUSSION

Significant variability in chemical and thermal characteristics is observed in the springs within the CBSP study area. Physicochemical characteristics measured with portable meters suggest that all of the springs in the study area except Sulphur Spring are associated with relatively shallow flow through Ellenburger Strata, because they exhibit consistent values for temperature and ion activity. In contrast, Sulphur Spring exhibits elevated concentrations of dissolved ions, including significantly greater sulfate content, which combined with the mild thermal component, ~2°C higher than the other springs, suggests a deeper / longer relative flow path (Table 1, 2).

Thermal patterns provide insight into the relative flow paths of the groundwater systems associated with heat-transfer between water and conduit walls. Various researchers have made great progress towards characterizing karst

Table 2. Thermal variability of spring discharge, including seasonal response and response to storm events with temperature variations significant enough to show responses in spring temperature. Note that no data is available for Bear Spring because the data logger was lost during all sampling periods.

	Annual Temperature (°C)			Sesonal Variation		Precipitation Event Response	
	avg	min	max	°C Change	lag time (days)	avg °C temp shift	residence time
Bear Spring	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Gorman Cave Spring	21.0	20.5	21.5	0.5	2.0	1.2	hours
Gorman Falls Spring	21.8	20.9	22.8	0.9	14.0	10.5	hours
Gorman Spring	21.8	21.5	22.1	0.3	1.0	4.8	hours
Lemon Spring	21.3	20.7	21.9	0.6	11.0	equilabrated	days
McLarrin Spring	21.1	20.6	21.6	0.5	10.0	7.0	hours
Sulphur Spring	23.0	22.9	23.0	0.1	30.0	equilabrated	weeks
Well House Spring	20.9	20.7	21.0	0.1	21.0	equilabrated	weeks

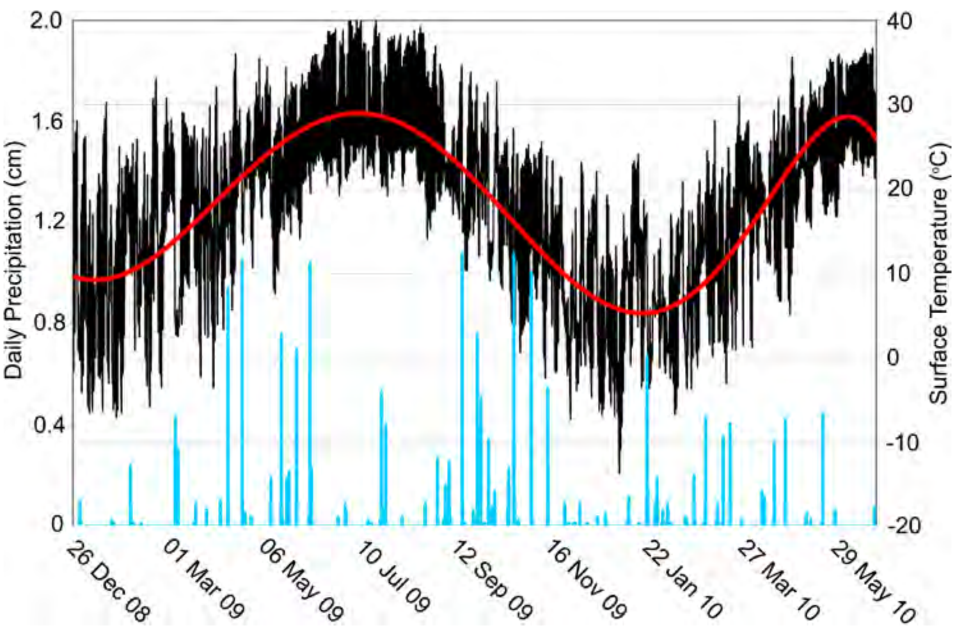

Figure 4. Surface temperature with daily averages (black) and seasonal average (red) compared with precipitation events (blue).

systems with temperature being used as a groundwater tracer (e.g. Long and Gilcrease, 2009; Manga, 2001); however, the complexities of karst systems and the relative effectiveness of heat-transfer in different karst systems greatly complicate interpretation. Luhmann and others (*in press*) have developed qualitative methods for comparing karst systems based on thermal patterns observed at spring discharge, in which effectiveness of heat-transfer exchange is evaluated. Storm hydrographs, coupled with thermal monitoring, can provide significant insight into the configuration of karst systems (Birk and others, 2006), but the installation of weirs and level loggers for monitoring of discharge are often not possible because of location and economics.

Thermal patterns analyses indicate that at Lemon Spring, Sulphur Spring and Well House Spring effective heat exchange occurs on the flow paths which is associated with distributed recharge. Well House and Sulphur Spring appear to be largely decoupled from surficial processes and represent deep-circulation flow paths with artesian discharge. Lemon Spring is a shallow karst system influenced by seasonal temperature fluctuations and likely dominated by matrix flow. Gorman Cave Spring, Gorman Falls Spring, Gorman Spring and McLarrin Spring all exhibit ineffective heat exchange along flow suggesting that these systems are controlled by localized recharge through well-integrated fractures and conduits. Gorman Falls Spring and McLarrin Spring show significant thermal response to individual storm events, indicating that flow velocities through these systems are sufficiently high to prevent thermal equilibration with conduit walls. Gorman Cave Spring and Gorman Springs show greater thermal equilibration with individual storm events indicating longer flow paths than Gorman Falls Spring and McLarrin Spring.

CONCLUSION

Karst development in Ellenburger carbonates proximal to CBSP is of complex polygenetic origin, with current groundwater flow paths exhibiting highly variable behavior. Two springs, Sulphur and Well House Springs, are associated with deep-circulation flow paths associated with distal, distributed recharge. Lemon Spring is a shallow, karst system associated with shallow, distributed recharge and diffuse groundwater flow that is being focused as discharge along a bedding plane. Gorman Falls Spring and McLarrin Spring are associated with well-connected, conduits and localized recharge that rapidly respond to storm events and seasonal fluctuations. Gorman Cave Spring and Gorman Spring also exhibit well-connected conduit systems, but localized recharge appears to be significantly distal to spring discharge based on the degree of equilibration between storm-event water and conduit channels.

These four observed patterns of thermal response suggest that groundwater circulation within the study area likely occurs across multiple horizons of groundwater flow that cross one another at different depths in the subsurface as flow ultimately directed to the potentiometric low imposed by the locally deep incision of the Colorado River. Variability in flow paths may be associated with varying degrees of epigenic overprinting of previously existing hypogene conduits, where unconfined groundwater flow is now occurring through solutional paths established during confined conditions.

In conjuction with thermal patterns, physicochemical characteristics indicate that all spring flow paths, except Sulphur Spring, are effectively limited to flow within the Ellenburger carbonates, even though thermal patterns indicate that the Well House Spring system is associated with deeper / longer circulation flow paths. Elevated temperature and dissolved ions in Sulphur Spring discharge, coupled with degassing of hydrogen sulfide, indicates that this deep-circulation system is likely associated with regional groundwater flow in contact with mineralized zones near to underlying basement rocks. Reported occurrences of sulfide minerals are associated with lead mineralization proximal to basement rock (Barnes, 1956), which could provide the source for observed fluid chemistry at Sulphur Spring.

Currently, investigations in the study area are attempting to delineate the stratigraphic and structural controls on local and regional karst development. Spring monitoring continues and isotopic studies are planned, including tritium analysis, in order to better delineate the age of water discharging from Sulphur Springs. Heavy metal and trace element analyses are planned to determine the source of sulfur associated with anomalous springs in the Llano Uplift and Texas Hill Country region.

ACKNOWLEDGMENTS

The authors are grateful to Colorado Bend State Park, and specifically Cory Evans and Kevin Ferguson, for their assistance and access to research sites within the study area. The authors also thank Wesley Brown, Phillip Hays and Andy Grubbs for their constructive reviews of this manuscript which helped to improve it.

REFERENCES

Barnes, V.E., 1956, Lead Deposits in the Upper Cambrian of Central Texas, Report of Investigations No. 26; University of Texas, Bureau of Economic Geology, Austin, Texas, 68 p.

Birk, S., Liedl, R., and Sauter, M., 2006, Karst spring response examined by process-based modeling; Groundwater, Vol. 44, No. 6, p. 832-836.

Collins, E.W., 1995, Structural framework of the Edwards Aquifer, Balcones fault zone, central Texas; Transactions – Gulf Coast Association of Geological Societies, Vo. 45, p. 135-142.

DeLeon, J.L., 2010, Characterizing the Temporal and Spatial Variability of Spring Discharge Along the Colorado River Near Colorado Bend State Park, Central Texas [Master's Thesis]; Stephen F. Austin State University, Nacogdoches, TX, 156 p.

England, J. Suter, A., and Stafford, K., 2010, Tufa diagenesis in a carbonate karst fluvial environment; Geological Society of America Abstracts with Programs, Vol. 42, No. 2, p. 88.

Estaville, L.E. and Earl, R.A., 2008, Texas Water Atlas; Texas A&M University Press, College Station, TX, 129 p.

Kerans, C., 1990, Depositional Systems and Karst Geology of the Ellenburger Group (Lower Ordovician), Subsurface West Texas, Reports of Investigations; University of Texas, Bureau of Economic Geology, Austin, TX, 63 p.

Klimchouk, A., 2007, Hypogene Speleogenesis: Hydrolgeologic and Morphometric Perspective; National Cave and Karst Research Institute, Carlsbad, NM, 106 p.

Long, A.J. and Gilcrease, P.C., 2009, A one-dimensional heat-transport model for conduit flow in karst aquifers; Journal of Hydrology, Vol. 378, p. 230-239.

Luhmann, A.J., Covington, M.D., Peters, A.J., Alexander, S.C., Anger, C.T., Green, J.A., Runkel, A.C., and Alexander, E.C., *in press*, Classification of thermal patterns at karst springs and cave streams; Groundwater.

Manga, M., 2001, Using springs to study groundwater flow and active geologic processes; Annual Reviews in Earth and Planetary Sciences, Vol. 29, p. 201-228.

Mitchell, K., Dornak, S., and Stafford, K.W., 2011, Geochemical spatial variability of the Colorado River associated with karst springs, Colorado Bend State Park, Central Texas; Geological Society of America Abstracts with Programs, Vol. 43, No. 3, p. 10.

Presont, R.D., Pavilcek, D.J., Bluntzer, R.L., and Derton, J., 1996, The Paleozoic and Related Aquifers of Central Texas, Report 346; Texas Water Development Board, Austin, TX, 76 p.

Rose, P.R., 1972, Edwards Group, Surface and Subsurface, Central Texas; University of Texas, Bureau of Economic Geology, Austin, TX, 198 p.

Sellards, E.H., Adkins, W.S., and Plummer, F.B., 1932, The Geology of Texas, v. 1, Stratigraphy; University of Texas, Bureau of Economic Geology, Austin, TX, 1007 p.

Shaw, M.G., 2006, Geologic Controls of Stream Water Composition in Cherokee, Smith and Rusk Counites, Texas [Master's Thesis]; Stephen F. Austin State University, Nacogdoches, TX, 193 p.

Standen, A. and Ruggiero, R., 2007, Llano Uplift Aquifers: Structure and Stratigraphy; Texas Water Development Board, Austin, TX, 78 p.