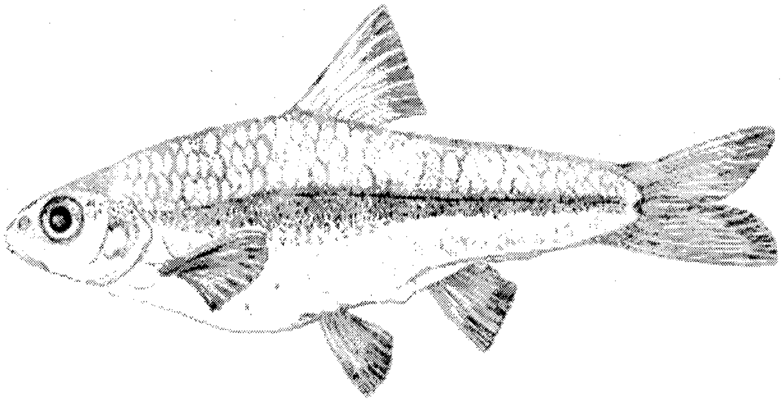
SPECIAL PUBLICATIONS

Museum of Texas Tech University

NUMBER 46 12 May 2003

AQUATIC FAUNA OF THE NORTHERN CHIHUAHUAN DESERT



CONTRIBUTED PAPERS FROM A SPECIAL SESSION WITHIN
THE THIRTY-THIRD ANNUAL SYMPOSIUM OF
THE DESERT FISHES COUNCIL

HELD
17 NOVEMBER 2001
AT
SUL ROSS STATE UNIVERSITY, ALPINE, TEXAS

EDITED BY
GARY P. GARRETT AND NATHAN L. ALLAN

GROUNDWATER SYSTEMS FEEDING THE SPRINGS OF WEST TEXAS

JOHN M. SHARP, JR., RADU BOGHICI, AND MATTHEW M. ULIANA

ABSTRACT

Major existing and former springs of the northern Trans-Pecos, Texas, include the Balmorhea Springs (San Solomon, Phantom Lake, Giffin, and East and West Sandia) in Reeves and Jeff Davis Counties and Comanche Springs, Leon Spring, and Diamond-Y Springs in Pecos County. Understanding the regional groundwater flow systems that feed or fed these springs is needed to manage regional water resources, including the springs that provide islands of aquatic habitat. Some springs have ceased to flow or now flow at greatly diminished rates. Data indicate that spring discharges have been gradually declining for at least the last 100 years. In addition, groundwater extraction for municipal, domestic, and irrigation uses threatens continued spring flows. The individual groundwater basins are connected through regional flow systems in fractured, karstic carbonate rocks. Regional fracture trends connect the major recharge and discharge areas and localize discharge from carbonate aquifers. Analysis of fracture systems allows interpretation of regional flow systems and regional-scale permeability. Recharge is from fractures in the highlands, losing streams on proximal portions of alluvial fans, irrigation return flow, and interbasin flow. Discharge is to the springs, by wells, and in the past to the Pecos River. $^{87}Sr/^{86}Sr$ ratios and other chemical and isotopic data confirm the inferred regional flow systems and suggest that some of the springflow recharged during the Pleistocene. The groundwater system is evolving because of both climatic trends and anthropogenic effects.

INTRODUCTION

Trans-Pecos Texas encompasses the general area of Texas west of the Pecos River (Figure 1) and is the most southeastern portion of the Basin and Range physiographic province in the United States. It has a subtropical semiarid climate. Average annual precipitation is less than 300 mm, and precipitation increases with increasing elevation (e.g., Schuster, 1996). With the exception of a few significant springs and the brackish Pecos River and Rio Grande, surface water resources are minimal. A number of individual groundwater basins form parts of regional groundwater flow systems. Regional-scale structural features create a template for fractures and karst features that control the flow systems. The regional flow systems, in turn, discharge at springs that provide unique wetland habitats for endangered aquatic species. Through wells and spring flow, these systems have been developed to meet much of the area's municipal, domestic, and agricultural needs.

Brune's (1981) compendium listed the important springs of the region. This study concentrates on those in the northern Trans-Pecos associated with endangered species and the groundwater systems associated with these springs. Figures 1 and 3 show the locations of the springs. The unique biotas that inhabit the spring systems suggest persistent, long-term springflow discharge. However, data indicate that discharge from these springs may have been in decline for the past 100 years and, possibly, for the past several thousand years (Hall, 1990; Sharp et al., 1999; Musgrove, 2000) as is this case for most of the southwestern U. S. A.

Increased groundwater pumpage for municipal and agricultural use has hastened or caused springflow declines and changes in the regional flow systems. Proper management of the groundwater in this region is important to maintain spring flows and the habitats

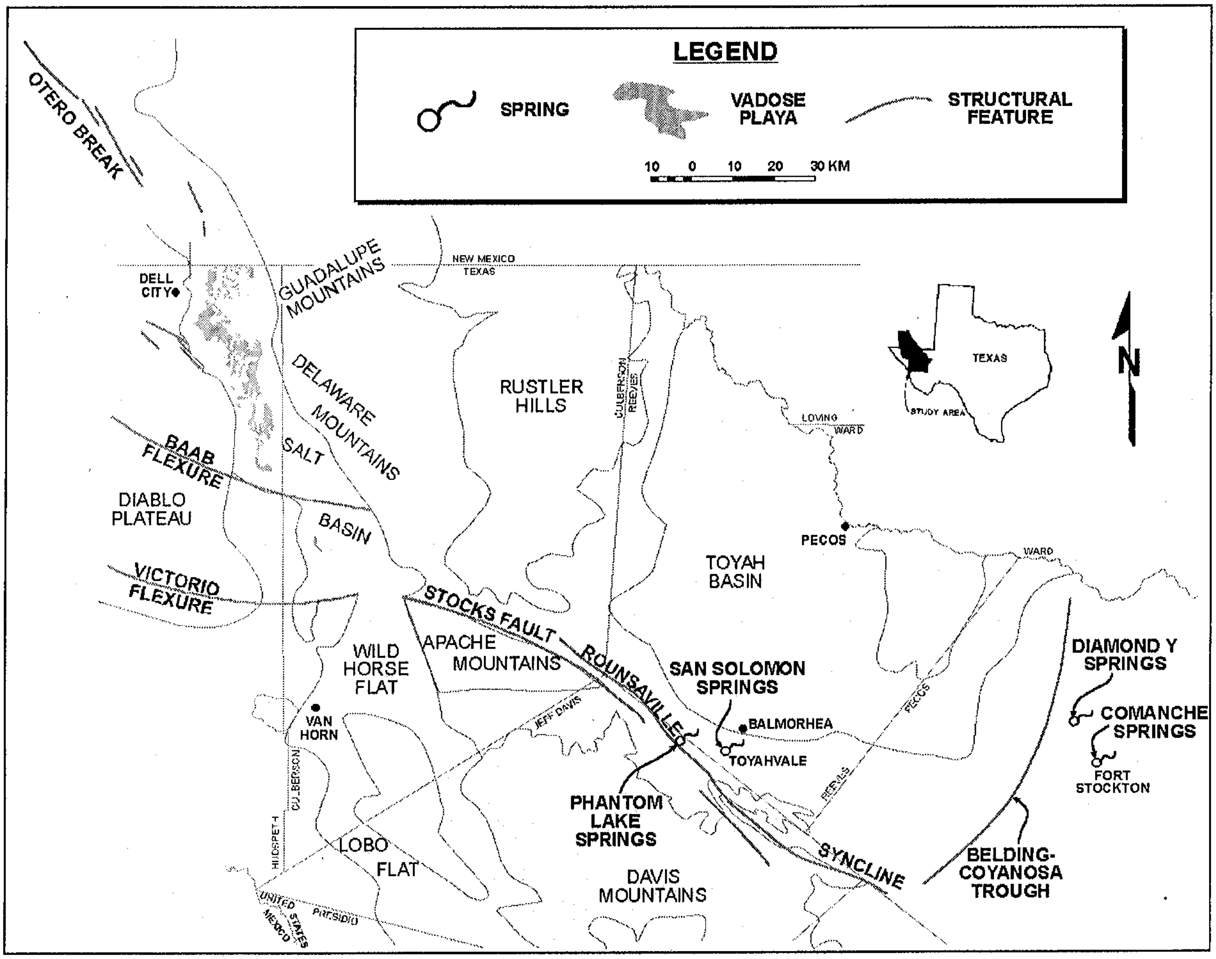


Figure 1. Study area is located in northern Trans-Pecos Texas and southeastern New Mexico. The Salt Basin, Wildhorse Flat, Lobo Flat, and the Toyah Basin are clastic basin fills; the Davis Mountains are volcanic rocks. The major springs are delineated. Giffin Spring is adjacent to San Solomon Springs in Toyahvale and East and West Sandia Springs are in the town of Balmorhea. Phantom Lake Springs is closely linked to the springs in Toyahvale. Leon Springs formerly discharged between Comanche and Diamond Y Springs.

for the endangered species and to meet the region's municipal and agricultural needs. Herein we review the regional hydrostratigraphy and structural geology and discuss the hydrostratigraphy, hydrogeology, structural geology, regional hydrogeology, fracture controls on permeability, some springwater chemistry, and implications for spring discharge and water resource management.

HYDROSTRATIGRAPHY

Geologic units range in age from Precambrian to Holocene, but the most significant units hydrogeologically are: 1) the Permian shelf, reef, and basinal sediments of the Delaware Basin; 2) Cretaceous carbonates; 3) Tertiary igneous rocks in the Davis and Barilla Mountains; and 4) Cenozoic alluvium. Permian rocks are subdivided into three hydrostratigraphic facies (Figure 2) with highly different hydraulic properties (Hiss, 1980; Nielson and Sharp, 1985; Boghici, 1997; Mayer and Sharp, 1998; Boghici and van Broekhoven, 2001). The Guadalupian shelf margin (reefal facies) provides excellent aquifers as exemplified by the Capitan aquifer, which has high porosity and permeabilities that are the result of extensive karstification (e.g., Carlsbad Caverns and associated caves in southeast New Mexico, the Apache Mountains, and the Glass Mountains). Aquifers in the Per-

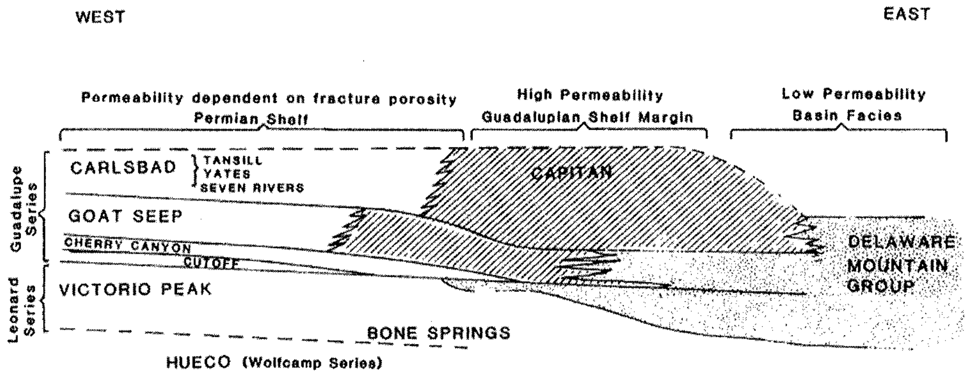


Figure 2. Permian hydrostratigraphic facies (after Nielson and Sharp, 1985). The stippled pattern denotes sandstones and carbonates overlying basinal evaporite-rich rocks; the crosshatched pattern denotes highly permeable reefal facies rocks of the shelf margin.

mian shelf facies have highly variable fracture-dependent permeability. Karstification is controlled by the fracture set characteristics (e.g., the Bone Spring aquifer that supplies Dell City). The basin fill facies rocks, including the Rustler Formation generally possess low permeability and extensive evaporite deposits. They form aquifers with low permeabilities, poor quality water, and low well yields. The Rustler provides brackish water to wells and along a deep fault system to Diamond Y Springs.

Lower Cretaceous rocks crop out in the eastern, southeastern and southwestern parts of the Toyah Basin and on the Diablo Plateau (Figure 1). These rocks represent mostly marginal, near-shore, and marine facies. They supply irrigation and livestock wells with fresh to slightly brackish water (Ogilbee et al., 1962; Boghici, 1997). The Cretaceous Edwards-Trinity is the most important aquifer in the Diamond Y area. It underlies most of Pecos County, as well as parts of Reeves, Culberson, and Jeff Davis Counties (Anaya, 2001). The more permeable units in the Edwards-Trinity are the lower Cretaceous sands and limestones, which are hydraulically connected with the overlying Pecos Cenozoic alluvial aquifers of the Coyanosa and Toyah Basins. In some locales, Cretaceous carbonate units are juxtaposed with Permian reefal rocks and form parts of the same flow system, such as the one that flows to Balmorhea and the Toyah Basin (LaFave, 1987; Uliana and Sharp, 2001). Phantom Lake Springs issue from a cave opening in Lower Cretaceous limestone. The Cretaceous carbonates of the Diablo Plateau support a regional aquifer and a less extensive perched aquifer. These rocks can be extremely transmissive because of fracture and solution porosity (Scalapino, 1950; Kreitler and Sharp, 1990). Groundwater flows to the northeast and discharges into the Salt Basin, where it evaporates in gypsum flats.

Tertiary igneous rocks are mostly ash-flow tuffs and lava flows that overlie the Cretaceous rocks. The volcanic rocks of the Davis Mountains do not contain significant regional aquifer systems (Hart, 1992; Chastain-Howley, 2001), but runoff from them contributes to recharge of the Toyah Basin alluvial aquifer (LaFave and Sharp, 1987; Uliana, 2000) and, presumably, other surrounding basins.

Thick Cenozoic fluvial siliciclastic deposits occur in the Toyah and Salt Basins. Other recent deposits include fluvial terraces, playa muds and evaporites, aeolian deposits, and colluvium. Aquifers in these units provide significant amounts of water to wells and municipalities in the Toyah Basin and in Wild Horse Flat (Gates et al., 1980; Sharp, 1989; Ashworth, 1990). The Toyah Basin was formed by dissolution of underlying Permian evaporites and is filled with up to 470 m of Cenozoic alluvium (Maley and Huffington, 1953). The alluvial sediments filling in the Salt Basin reach a thickness of over 750 m (Gates et al., 1980). Groundwater divides separate the basin into three different flow systems. The northern and the middle areas are closed basins with recharge occurring through the bounding faults on the east and west of the basin, and discharge through the gypsum flats or vadose playas in the center of the basin (Boyd, 1982; Nielson and Sharp, 1985). The Wild Horse Flat part of the basin, however, lacks playas. In addition, the oldest mapped potentiometric surface (Nielson and Sharp, 1985; Sharp, 1989) indicates interbasin flow through the Apache Mountains towards the east.

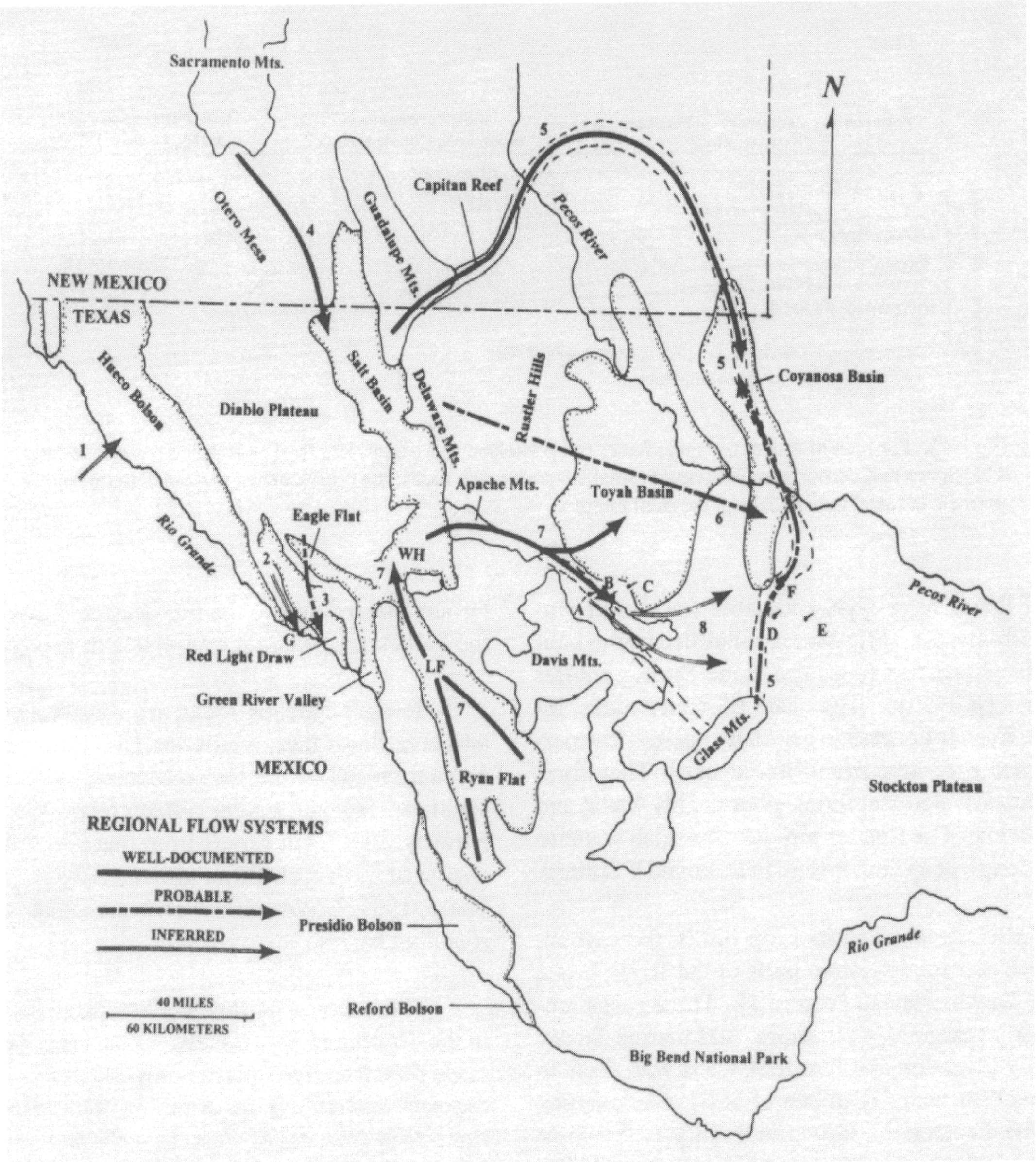


Figure 3. Regional flow systems of Trans-Pecos Texas (Sharp, 2001). WH and LF denote Wild Horse Flat and Lobo Flat of the Salt Basin. Springs are denoted by letters - A, Phantom Lake Spring; B, San Solomon and Giffin Springs; C, East and West Sandia Springs; D, Leon Springs; E, Comanche Springs; F, Diamon-Y Springs; and G, Indian Hot Springs. A, D, and E no longer flow. The regional flow systems are: 1 and 2, the discharge at the Fabens artesian zone and Indian Hot Springs (G), respectively; 3, Eagle Flat - Red Light Draw flow system; 4, Sacramento Mountains - Dell City flow system; 5, flow systems in the Capitan Reef; 6, eastward flow in the Delaware Basin, perhaps discharging at Diamond-Y Springs (F); 7, the Salt Basin - Toyah Basin - Pecos River system that also feeds Balmorhea Springs (A, B, and C); and 8, speculative eastwards extensions of this last flow system.

STRUCTURAL GEOLOGY

Trans-Pecos Texas has been subjected to at least five major tectonic episodes that formed fault zones and structural trends that have been repeatedly reactivated throughout the history of the area. Precambrian compressional events generated the basic northwesterly trends that are still predominant and that influenced subsequent structures. The early Pennsylvanian Ouachita collision was responsible for the formation of the Delaware Basin and the thick sequences of Permian sedimentary rocks that form a significant part of the regional groundwater systems. The morphology of the Delaware Basin has influenced later fault patterns. For example, major faults in the Apache Mountains and the Guadalupe Mountains run parallel to the Permian paleoreef front. Later events include the Mesozoic rifting of the Gulf of Mexico, the early Cenozoic Cordilleran/Laramide Orogeny, and Eocene Basin and Range extension. These events caused the repeated reactivation of the earlier structural features. Faulting is active today (Goetz, 1977). Details of the region's tectonic/structural setting are given in Dickerson and Muehlberger (1985) and Muehlberger and Dickerson (1989).

REGIONAL HYDROGEOLOGY

Groundwater production in Trans-Pecos Texas is concentrated in the Permian and Cretaceous rocks and in the Cenozoic alluvial fill in the Salt and Toyah basins (Davis and Leggat, 1965; Couch, 1978; Hiss, 1980; Ashworth, 1990; Sharp, 2001). Evidence exists for significant groundwater flow in fractures and in karst conduits (LaFave and Sharp, 1987; Mayer and Sharp, 1998; Uliana, 2000; Sharp, 2001). Both local and regional flow systems exist in the area. Figure 3 shows the major regional flow systems inferred for northern Trans-Pecos Texas. The major springs discharge both from regional and local flow systems associated with Permian/Cretaceous carbonate rocks (White et al., 1941; LaFave and Sharp, 1987; Uliana and Sharp, 2001). The flow systems that feed the currently active springs harboring endangered aquatic species (San Solomon, Giffin, East and West Sandia, and Diamond Y Springs) are only two on the documented, probable, or inferred regional flow systems in northern Trans-Pecos Texas and southeastern New Mexico. The other flow systems may have once discharged to springs (i.e., Crow Springs near Dell City) that have also have once harbored unique biota. All these regional flow systems are in fractured carbonate rocks.

FRACTURE CONTROLS ON GROUNDWATER FLOW

The regional flow systems are controlled by fracture systems. The density and orientation of fractures in the Trans-Pecos region reveal a definite relationship between the regional structural trends and the fracture orientations. LaFave and Sharp (1987) and Uliana (2000) document fracture orientations in the Apache and Delaware Mountains that follow the prevalent N10W orientation of regional structural trends. Mayer (1995) and Uliana (2000) used aerial photos and field studies to map lineaments and fractures. They document the correlation between fault orientations and the regional structural grain. Fault patterns in the Salt Basin (Goetz, 1977) show a similar correlation between fracture patterns and the regional structural grain.

Fracturing of the carbonate rocks influenced their subsequent karstification. Nielson and Sharp (1985), LaFave and Sharp (1987), and Uliana (2000) document regional connections between Wildhorse Flat and the Toyah Basin, including the springs at Balmorhea. Fracturing of Permian reefal rocks and karstification create a high permeability zone along the Stocks Fault-Rounsaville Syncline trend (Figures 1 and 3). Hydraulic head data show that water discharged from Wildhorse Flat at one end of the structural trend and flowed into the Toyah Basin along its southwestern edge, near the springs. Additional evidence supporting the regional flow hypothesis includes the lack of discharging playas in the Wildhorse Flat section (Figure 1), fracture trends in the Apache Mountains, and isotopic data (Uliana, 2000; Uliana and Sharp, 2001). The northern parts of the Salt Basin contain extensive vadose playas that are primary natural discharge features. The lack of playas in Wildhorse Flat is consistent with groundwater discharge by interbasin flow through the Apache Mountains. Uliana and Sharp (2001) examined the $^{87}Sr/^{86}Sr$ distributions in Trans-Pecos groundwater. High $^{87}Sr/^{86}Sr$ values occur at the up-gradient end of the flow system; these are caused by groundwater interaction with Precambrian rocks (including clasts in alluvial fans) along the west edge of Wildhorse Flat. $^{87}Sr/^{86}Sr$ values decrease along the hypothesized regional flow paths. This suggests that the high $^{87}Sr/^{86}Sr$ values in the Wildhorse Flat groundwater equilibrate with the Permian and Cretaceous carbonates and fluid mixing with other waters recharged or displaced along the flow path. Phantom Lake Springs formerly issued from an opening in Cretaceous limestone. This opening leads into a network of caverns. Cave divers have mapped and surveyed over 2300m and measured groundwater discharge in the caverns. Their map (Tucker, 2000, reproduced in Uliana, 2000, p. 21) indicates that the cave network follows a linear trend that parallels the Stocks Fault - Rounsaville Syncline trend. In January 1999, Phantom Lake Springs ceased to flow for the first time in probably at least 200 years (Figure 4).

A similar high-permeability structural trend (the Otero Break) connects the Sacramento River recharge area in southern New Mexico and the Dell City, Texas, irrigation district (Mayer and Sharp, 1998). This inferred conduit flow (Flow system 4 on Figure 3) is confirmed by both geochemical and hydraulic head data. This flow system formerly discharged at Crow Springs in the Salt Basin (Ashworth, 2001). Flow system 3 from Eagle Flat is presumed to discharge to the Rio Grande (Darling and Hibbs, 2001). Indian Hot Springs (G on Figure 3) discharge from carbonate rocks and the flow is through fractured carbonate rocks in the U. S. A., and, perhaps, Mexico. Although undocumented, similar regional flow systems may exist in southern Trans-Pecos Texas and Northern Mexico.

Comanche Springs (Figures 1 and 3) formerly issued from a 673-m long, fracture-controlled cave formed along a N60-65W trending joints (Boghici, 1997; Veni, 1991). Dye tracer tests conducted in the 1950's demonstrated that groundwater was flowing to Comanche Springs at rates of up to 3.2 km/day (Sparks, cited in Veni, 1991). A structural low in the permeable Cretaceous limestones (the Belding-Coyanosa trough) extends some 64 km to the southwest of Comanche Springs connecting them with the recharge areas in the vicinity of the Glass Mountains (Boghici, 1997; Boghici and Van Broekhoven, 2001).

Darling (1997), Darling et al. (1995), and Darling and Hibbs (2001) examined oxygen, deuterium, and carbon isotopes in the groundwater in the western portions of the study area (in particular, in flow systems 2 and 3 on Figure 3). These data suggest recharge during a cooler and wetter Pleistocene climate. Groundwater ages of 8,000 to 50,000 years are indicated. Balmorhea springs show little seasonal variation. Their waters are brackish and slightly higher than mean annual surface temperature. Isotopic data, although sparse, support Darling's results, indicating long residence times (Uliana, 2000;

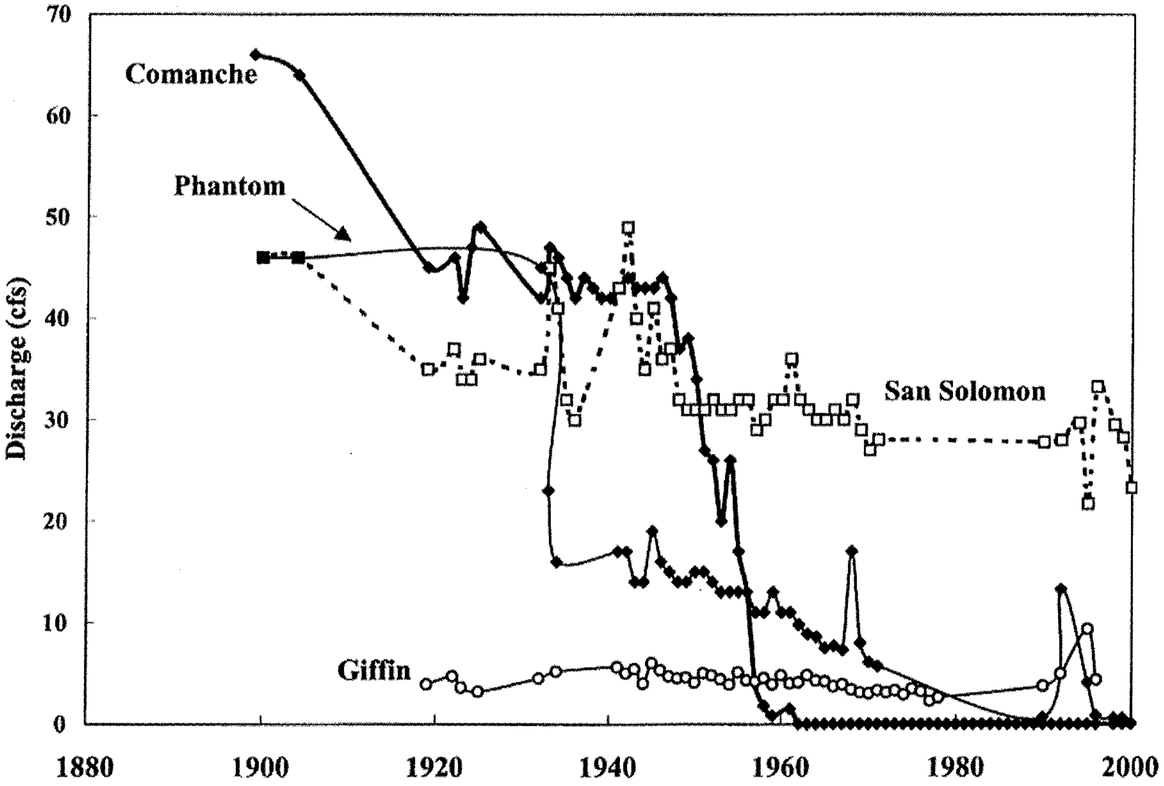


Figure 4. Spring flow hydrographs of Comanche, Phantom Lake, San Solomon, and Giffin Springs. Data are from U. S. Geological Survey, U. S. Bureau of Reclamation, and Groundwater Field Methods Class (1990, 1992, 1995, and 1996).

Uliana and Sharp, 2001). In addition, the unique spring ecosystems suggest that spring flow and spring chemistry have remained relatively stable for extended periods of time. Such stability in a semi-arid zone implies a regional flow system because local flow systems show greater seasonal variations. Consequently, a few years of drought would not be suspected to impact spring flows significantly.

SPRING DISCHARGE AND WATER RESOURCE MANAGEMENT

Figure 4 shows the discharge of the four of the largest springs in the area. Early (before 1920) data are less reliable, but several trends are evident. First, springflows appear to have been declining prior to the development of extensive irrigation in the 1940's. This is consistent with longer-term climatic studies that suggest a drying of the region (cited in Kreitler and Sharp, 1990). Second, there is variability in discharge, particularly, when average annual discharges are low. This is caused by normal climatic variability and may not be indicative of long-term sustained trends. The variations probably reflect short-term variability in groundwater recharge. Some later data on San Solomon, Giffin, and Phantom Lake Springs are point (in time) measurements taken by the Groundwater Field Methods Classes (1990, 1992, 1995, and 1996). These are not annual averages, but reflect the short term variability. Third, San Solomon and Giffin Springs show a remarkably steady annual flow regardless of climatic variability. Flow has been relatively constant since the 1930's even through the major drought of 1947-1955. Four, Comanche and Phantom Lake spring discharges began to decline at greater rates when groundwater pumpage for irrigation commenced. Comanche Springs ceased to flow about 1961, and Phantom Lake Springs largely ceased to flow in January 1999.

Balmorhea Springs.—San Solomon, Giffin, and Phantom Lake springs are in close proximity and are probably fed from the same fractured, karstic conduit (Uliana and Sharp, 2001). The conduit system, which is accessed at the Phantom Lake Spring orifice, was gauged in 1997 by Tucker (2000). His preliminary data showed that, at that time, only a small percentage of the flow in the conduit discharged at Phantom Lake Springs. The bulk presumably discharges to San Solomon and Giffin springs, but this is not yet documented. Phantom Lake Spring fed a ciénega and canal system that harbored endangered fish species. Inconsistencies in spring discharges fed from the fractured, karstic conduit trend are typical of karstic systems.

The decline in Phantom Lake springflow may be caused by several factors. First, a regional lowering of the water table is documented by comparing recent data from The University of Texas Groundwater Field Methods classes (1990, 1992, 1995, and 1996) and the U. S. Bureau of Reclamation with the earliest known data (White et al., 1941). These show that the water table near Balmorhea has been lowered by some combination of long-term climatic change and, probably more importantly, regional pumping for irrigation and municipal uses. This pumping could include both local well effects and the regional lowering of heads in the Toyah Basin. A second possibility is that the "plumbing" itself has changed because of either opening of fractures/conduits because of dissolution, tectonic activity, or changing sediment storage in the conduits that could increase or decrease the permeability of various branches of the conduit. Major pulses in turbidity of spring discharge have been observed (White et al., 1941; Kreitler and Sharp, 1990). Loss of recharge because of domestic wells in the Davis Mountains is another potential, but probably secondary, effect. Finally, the beheading of the regional flow system because of pumping in Wildhorse Flat may have an effect. Water recharging Wildhorse Flat now supplies the communities of Van Horn and Sierra Blanca, as well as local irrigators of cotton, pecans, hay, and vegetables (Nielson and Sharp, 1985; Kreitler and Sharp, 1990) so that discharge from Wildhorse Flat via interbasin flow has been diminished, if not stopped. At present, there are insufficient data to differentiate between these hypotheses or eliminate any of them.

Pecos County Springs.—The cessation of flow at Comanche and Leon Springs is closely correlated in time with the onset of irrigation pumpage, although, quality long-term discharge data are not available for Leon Springs. Diamond Y Springs, however, continue to flow. The discharge data for the Diamond Y Springs are sparse: only four measurements between 1943 and 1987, and only the main spring was gauged. Based on their response to rainfall, Veni (1992) indicated the existence of two distinct groups of springs and seeps. The springs' response suggests slight to moderately extensive flow conduits feeding the Diamond Y Springs system. Diamond Y Springs discharge a low to moderately saline Na-Ca-Cl-SO_4 type of water that is similar in composition to waters from the Rustler aquifer near Fort Stockton. The main processes affecting the water chemistry are: calcite, dolomite, halite, and gypsum dissolution and/or precipitation, and ion exchange between calcium, magnesium, and sodium (Boghici, 1997, 1999).

Stable and radiogenic isotope analyses in the Diamond Y Springs suggest that evaporation and water mixing processes are important controls on the spring water chemistry. Oxygen-18 and deuterium data indicate that Diamond Y waters are meteoric in origin; the data are distributed along an evaporation line according to spring discharge and pool size - the larger the discharge and the pool, the closer they resemble the main spring composition. The two main springs, Diamond Y main spring and Euphrasia spring, show tritium and ^{14}C data indicative of a mixing of older and recent waters (Boghici, 1997, 1999). This occurs elsewhere in the study region (e.g., LaFave and Sharp, 1987; Uliana, 2000; Darling, 1997; Darling et al., 1995) and is supported by geochemical mass-balance modeling (Boghici, 1997). These are all consistent with the model of Diamond Y spring water being the product of mixing between Rustler Formation waters and recent local rain falling directly on the springs' pools. There is apparently discharge of older waters from the Rustler Formation, perhaps up along a fault trend, into Diamond Y Draw (Figures 1 and 3). Regional discharge, coupled with limited pumping from nearby wells to lower water tables, can explain the steadiness of these springs discharge. The spring flows then sink in the streambed and may reappear at downstream as seeps after undergoing various levels of evaporative concentration.

DISCUSSION AND CONCLUSIONS

All data and existing models support the hypothesis of extensive regional flow systems in Trans-Pecos Texas. Analyses of the fracture zones and the regional structural trends indicate that those trends influence, and probably control, the flow paths in this regional system. We also observe extensive structural features that connect recharge and discharge areas over great distances. Analyses of the fracture zones indicate that their orientations are controlled by pre-existing structural trends that have been reactivated over the history of this area. These demonstrate a pattern where ancient structural trends create the templates for fractures and karst patterns that control the development of a regional groundwater system. We hypothesize that this pattern may be repeated in carbonate systems in other semi-arid parts of the world. This has implications for our understanding of groundwater flow systems in regions that are usually dependent on groundwater for irrigation and municipal needs.

Regional flow systems connect individual groundwater basins. Fractures and subsequent karstification follow the structural trends and control the location of the major natural recharge and discharge areas (springs). At least 5 tectonic events and physical stratigraphic variability have led to a complex set of fracture domains. Mapping of these domains demonstrates how they have controlled the development of the regional hydrogeologic system, including the karstification. Furthermore, the fractured (and karstic) systems inherent variability makes it difficult to predict the response of the groundwater systems to anthropogenic stresses and climatic variability. Detailed hydrogeologic assessments are required to utilize the region's groundwater resources and yet maintain critical environmental habitat. Natural tracer tests using strontium isotopes ($^{87}Sr/^{86}Sr$ ratios) and fracture trace/intensity mapping are demonstrated to be promising assessment techniques of regional flow systems in this area or similar hydrogeological settings.

Diminishing spring flows or their cessation demonstrates the potential threats to remaining spring systems and their unique biota. Cessation is caused by a combination of climatic and regional factors. Increased groundwater extraction for irrigation and municipal use is the obvious cause, but other factors may also be important. These include the long-term pattern of increasing aridity in the region, possible alterations in the carbonate system permeability by either tectonic or sedimentation effects, localized pumping effects, reduction of recharge to the regional flow systems, and changes in the regional flow system boundaries, such as the beheading of the Wildhorse Flat - Toyah Basin flow system. However, it seems clear in general that rates of springflow decline have increased with groundwater extractions for agricultural, municipal, and domestic use during the past century.

Municipalities (e.g., El Paso, Pecos, Fort Stockton, and Midland-Odessa) may need increased water resources. Irrigated agriculture is an economic mainstay for the area, and although the trends for irrigated agriculture are highly dependent upon economic conditions, the long-term needs for agricultural products are inferred to remain steady or increase. Increased utilization of groundwater will draw upon groundwater in storage both on a cyclical basis depending upon normal climatic variability and on a long term trend that could lead to overexploitation. Increased understanding of the regional flow systems, including fracture controls, the nature of the recharge, and the flow paths, is needed to manage these resources. It may be possible to design pumping strategies that minimize the effects on natural springflows and yet meet projected demands. In addition, identification of key recharge areas and *a priori* analysis of fracture systems to identify fracture hydraulic domains may make it possible to maintain the springflows in the face of present or increased levels pumping (White et al., 1941; Mayer and Sharp, 1996; Uliana, 2000). We suggest that similar analyses and methodologies may prove of value in studies of spring systems in other areas of the southwestern United States and northern Mexico or other areas where regional flow systems exist in carbonate aquifers in semi-arid and arid zones.

ACKNOWLEDGEMENTS

This research was partially supported by the Chevron Centennial Professorship and the Owen-Coates Fund of the Geology Foundation of The University of Texas.

LITERATURE CITED

Anaya, R. 2001. An overview of the Edwards-Trinity aquifer system, central-west Texas. Pp. 100-119, *in* Aquifers of West Texas (R. E. Mace, W. F. Mullican, III, and E. S. Angle, eds.), Texas Water Development Board, Austin, Texas, Report 356, 272 pp.

Ashworth, J. B. 1990. Evaluation of ground-water resources in parts of Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas. Texas Water Development Board Report 317, 51 pp.

Ashworth, J. B. 2001. Bone Spring B Victorio Peak aquifer of the Dell Valley region of Texas. Pp.135-152, *in* Aquifers of West Texas (R. E. Mace, W. F. Mullican, III, and E. S. Angle, eds.), Texas Water Development Board, Austin, Texas, Report 356, 272 pp.

Boghici, R. 1997. Hydrogeological investigations at Diamond Y Springs and surrounding area, Pecos County, Texas. Unpublished Master's Thesis, University of Texas at Austin, 120 pp.

Boghici, R. 1999. Changes in groundwater conditions in parts of Trans-Pecos Texas, 1988-1998. Texas Water Development Board, Austin, Texas, Report 348, 29 pp.

Boghici, R. and Van Broekhoven, N. G. 2001. Hydrogeology of the Rustler Aquifer, Trans-Pecos Texas. Pp. 207-225, *in* Aquifers of West Texas (R. E. Mace, W. F. Mullican, III, and E. S. Angle, eds.), Texas Water Development Board, Austin, Texas, Report 356, 272 pp.

Boyd, F. M., 1982, Hydrogeology of the Northern Salt Basin of West Texas and New Mexico. Unpublished Master's Thesis, University of Texas at Austin, 135 pp.

Brune, G. 1981. Springs of Texas (vol. 1). Branch-Smith, Inc., Fort Worth, Texas, 565 pp.

Chastain-Howley, A.. 2001. Igneous aquifers of far West Texas. Pp. 175-189, *in* Aquifers of West Texas (R. E. Mace, W. F. Mullican, III, and E. S. Angle, eds.), Texas Water Development Board, Austin, Texas, Report 356, 272 pp.

Couch, H. E. 1978. Study of the lower Cretaceous and associated aquifers in the Balmorhea district of Trans-Pecos, Texas. Texas Department of Water Resources, Unpublished Report, 97 pp.

Darling, B. K. 1997. Delineation of the Ground-Water Flow Systems of the Eagle Flat and Red Light Basins of Trans-Pecos, Texas. Unpublished Ph.D. Dissertation, University of Texas at Austin, 179 pp.

Darling, B. K. and Hibbs, B. J. 2001. The aquifers of Red Light Draw, Green River Valley and Eagle Flat. Pp. 226-240, *in* Aquifers of West Texas (R. E. Mace, W. F. Mullican, III, and E. S. Angle, eds.), Texas Water Development Board, Austin, Texas, Report 356, 272 pp.

Darling, B. K., Hibbs, B. J., Dutton, A. R., and Sharp, J. M., Jr. 1995. Isotope hydrology of the Eagle Mountains area, Hudspeth County, Texas: Implications for development of ground-water resources. Pp. SL12-SL24 *in* Water Resources at Risk (W. R. Hotchkiss, J. S. Downey, E. D. Gutentag, and J. E. Moore, eds.). American Institute of Hydrology, Minneapolis, Minnesota.

Davis, M. E. and Leggat, E. R. 1965. Reconnaissance investigation of the ground-water resources of the Rio Grande Basin, Texas. Texas Water Commission Bulletin 6502, 199 pp.

Dickerson, P. W. and Muehlberger, W. R. (eds.). 1985. Structure and Tectonics of Trans-Pecos Texas. West Texas Geological Society Field Conference, Publication 85-81, 278 pp.

Gates, J. S., White, D. E. Stanley, W. D., and Ackermann, H. D. 1980. Availability of fresh and slightly saline ground water in the basins of westernmost Texas. Texas Department of Water Resources, Report 256, 108 pp.

Goetz, L. K. 1977. Quaternary Faulting in Salt Basin Graben. Unpublished Master's Thesis. University of Texas at Austin, 136 pp.

Groundwater Field Methods Class. 1990. Hydrology of springs and shallow ground water near Balmorhea, Texas. Unpublished Report, University of Texas at Austin, 11 pp+.

Groundwater Field Methods Class. 1992. Water characteristics of springs and groundwater near Balmorhea, Texas. Unpublished Report, University of Texas at Austin.

Groundwater Field Methods Class. 1995. Characterization of the ground-water resources in the Toyah Basin near Balmorhea, Texas. Unpublished Report, University of Texas at Austin, 17+ pp.

Groundwater Field Methods Class. 1996. Hydrologic investigation in the Toyah Basin, Balmorhea, Texas. Unpublished Report, University of Texas at Austin, 31+ pp.

Hall, S. A. 1990. Channel trenching and climatic change in the southern U. S. Great Plains. Geology, 18:342-345.

Hart, M. A. 1992. The hydrogeology of the Davis Mountains, Texas. Unpublished Master's Thesis, University of Texas at Austin, 158 pp.

Hiss, W. L. 1980. Movement of ground waters in Permian Guadalupian aquifer systems, southeastern New Mexico and western Texas. Pp. 289-294, *in* Trans-Pecos Region: New Mexico Geological Society 31st Field Trip Guidebook, (P. W. Dickerson and J. M. Hotter, eds.).

Kreitler, C. W., and Sharp, J. M., Jr. 1990. Hydrogeology of Trans-Pecos Texas. University of Texas at Austin, Bureau Economic Geology, Guidebook No. 25, 120 pp.

LaFave, J. I., 1987. Groundwater flow delineation in the Toyah Basin of Trans-Pecos Texas. Unpublished Master's Thesis, University of Texas at Austin, 159 pp.

LaFave, J. I., and Sharp, J. M. Jr. 1987. Origins of ground water discharging at the springs of Balmorhea. West Texas Geological Society Bulletin, 26:5-14.

Maley, V. C. and Huffington, R. M. 1953. Cenozoic fill and evaporite solution in the Delaware Basin, Texas and New Mexico. Geological Society of America Bulletin, 64:539-546.

Mayer, J. R. 1995. The role of fractures in regional groundwater flow: field evidence and model results from the basin and range of Texas and New Mexico. Unpublished Ph. D. dissertation, University of Texas at Austin, 221 pp.

Mayer, J. R. and Sharp, J. M., Jr. 1998. Fracture control of regional ground-water flow in a carbonate aquifer in a semi-arid region. Geological Society America Bulletin, 110:269-283.

Muehlberger, W. R. and Dickerson, P. W. 1989. Structure and Stratigraphy of Trans-Pecos Texas. American Geophysical Union Field Trip Guidebook, T317, 199 pp.

Musgrove, M. 2000. Temporal links between climate and hydrology: insights from central Texas cave deposits. Unpublished Ph. D. dissertation, University of Texas at Austin, 432 pp.

Nielson, P. D. and Sharp, J. M., Jr. 1985. Tectonic controls on the hydrogeology of the Salt Basin, Trans-Pecos Texas. Pp. 231-235, *in* Structure and Tectonics of Trans-Pecos Texas (P. W. Dickerson and W. R. Muehlberger, eds.), West Texas Geological Society Field Conference, Publication 85-81.

Ogilbee, W., Wesselman, J. B., and Ireland, B. 1962. Geology and ground-water resources of Reeves County, Texas. Texas Water Commission Bulletin 6214, 1:193 and 2:245.

Scalapino, R. A. 1950. Development of ground water for irrigation in the Dell City area, Hudspeth County, Texas. Texas Board Water Engineers Bulletin, No. 5004, 41 pp.

Schuster, S. K. 1996. Water resource and planning assessment in San Solomon Springs and associated spring systems surrounding Balmorhea, Texas. Unpublished Master's Thesis, University of Texas at Austin, 102 pp.

Sharp, J. M., Jr. 1989. Regional ground-water systems in northern Trans-Pecos Texas. Pp. 123-130 *in* Structure and Stratigraphy of Trans-Pecos Texas (W. R. Muehlberger and P. W. Dickerson, eds.), 28th International Geological Congress Field Trip Guidebook T317.

_____. 2001. Regional groundwater flow systems in Trans-Pecos Texas. Pp. 41-55, *in* Aquifers of West Texas (R. E. Mace, W. F. Mullican, III, and E. S. Angle, eds.), Texas Water Development Board, Austin, Texas, Report 356, 272 pp.

Sharp, J. M., Jr., Uliana, M. M., and Boghici, R.. 1999. Fracture controls on regional groundwater flow in a semiarid environment and implications for long-term maintenance of spring flows. Water 99 Joint Congress, Institute of Engineers, Brisbane, Australia, 2:1212-1217.

Tucker, A. W. 2000. Phantom Lake Cave. The Texas Caver, Texas Speleological Association, p. 4-7.

Uliana, M. M.. 2000. Delineation of regional groundwater flow paths and their relation to regional structural features in the Salt and Toyah Basins, Trans-Pecos Texas. Unpublished Ph. D. dissertation, University of Texas at Austin, 215 pp.

Uliana, M. M., and Sharp, J. M., Jr. 2001. Tracing regional flow paths to major springs in Trans-Pecos Texas using historical geochemical data. Chemical Geology, 179: 53-72.

Veni. G. 1991. Delineation and preliminary hydrogeologic investigation of the Diamond Y Spring, Pecos County, Texas. Unpublished Report, The Nature Conservancy of Texas, San Antonio, Texas, 110 pp.

White, W. N., Gale, H. S., and Nye, S. S. 1941. Geology and ground-water resources of the Balmorhea area, western Texas. U. S. Geological Survey Water-Supply Paper, 849-C:83-146.

Addresses of Authors:

JOHN M. SHARP, JR.

Department of Geological Sciences [C1100]
Jackson School of Geosciences
The University of Texas
Austin, TX 78712-1101

RADU BOGHICI

Texas Water Development Board
P. O. Box 13231
Austin, TX 78711-3231

MATTHEW M. ULIANA

Department of Biology
Southwest Texas State University
601 University Drive
San Marcos, TX 78666