Chapter 4

Regional Groundwater Flow Systems in Trans-Pecos Texas

John M. Sharp, Jr.[1]

Introduction

Regional flow systems (Hubbert, 1940; Toth, 1963) are defined as groundwater flow systems that extend both from a regional topographic high to a regional topographic low and beneath overlying local watersheds (catchments) and local flow systems within those watersheds. Regional flow systems are an important aspect in the hydrogeology of Trans-Pecos Texas, which includes the Mesilla, Hueco, Presidio, and Redford Bolsons adjacent to the Rio Grande, the Diablo Plateau/Otero Mesa, the Salt Basin and its southern extensions, the Delaware and Apache Mountains, the Wylie Mountains, the Davis and Barilla Mountains, the Rustler Hills, the Cenozoic Pecos alluvial fill (including the Toyah Basin), and the Stockton Plateau. The area (fig. 4-1) is bordered on the north and east by the Pecos River and is transitional eastward to the Edwards Plateau; it is bordered on the south and west by the Rio Grande. Surface water is essentially nonexistent in this area; both the Pecos River and the Rio Grande are generally now too salty to use, and locally important springs are widely scattered. Consequently groundwater is of paramount importance; groundwater systems are both local and regional. Extensive irrigation districts have been established in the Dell City, Wildhorse Flat, Lobo Flat, Toyah Basin, Balmorhea, Coyanosa, Leon, and Belding areas and along the Rio Grande. As a consequence, there have been a number of hydrological studies of this area, but it is only in the last several decades that an understanding of the regional groundwater flow systems has begun to emerge.

Geological studies of the area are also numerous, and it is the geology (e.g., Barnes, 1976, 1979, 1995a, 1995b; Dickerson and Muehlberger, 1985), which varies from basin-and-range to stable platform and intracratonic basins, that gives the Trans-Pecos groundwater systems their flavor. Uplift, faulting, salt dissolution, and Tertiary volcanism were the significant geological processes in the evolution of this area. Isotopic data also indicate the importance of paleo-climatic processes. Some groundwater is probably Pleistocene in age (Lambert and Harvey, 1987; Kreitler and others, 1987; LaFave and Sharp, 1987; Uliana and Sharp, in press). Modern recharge is low and irregularly distributed both spatially and temporally.

---

[1] Department of Geological Sciences, The University of Texas at Austin

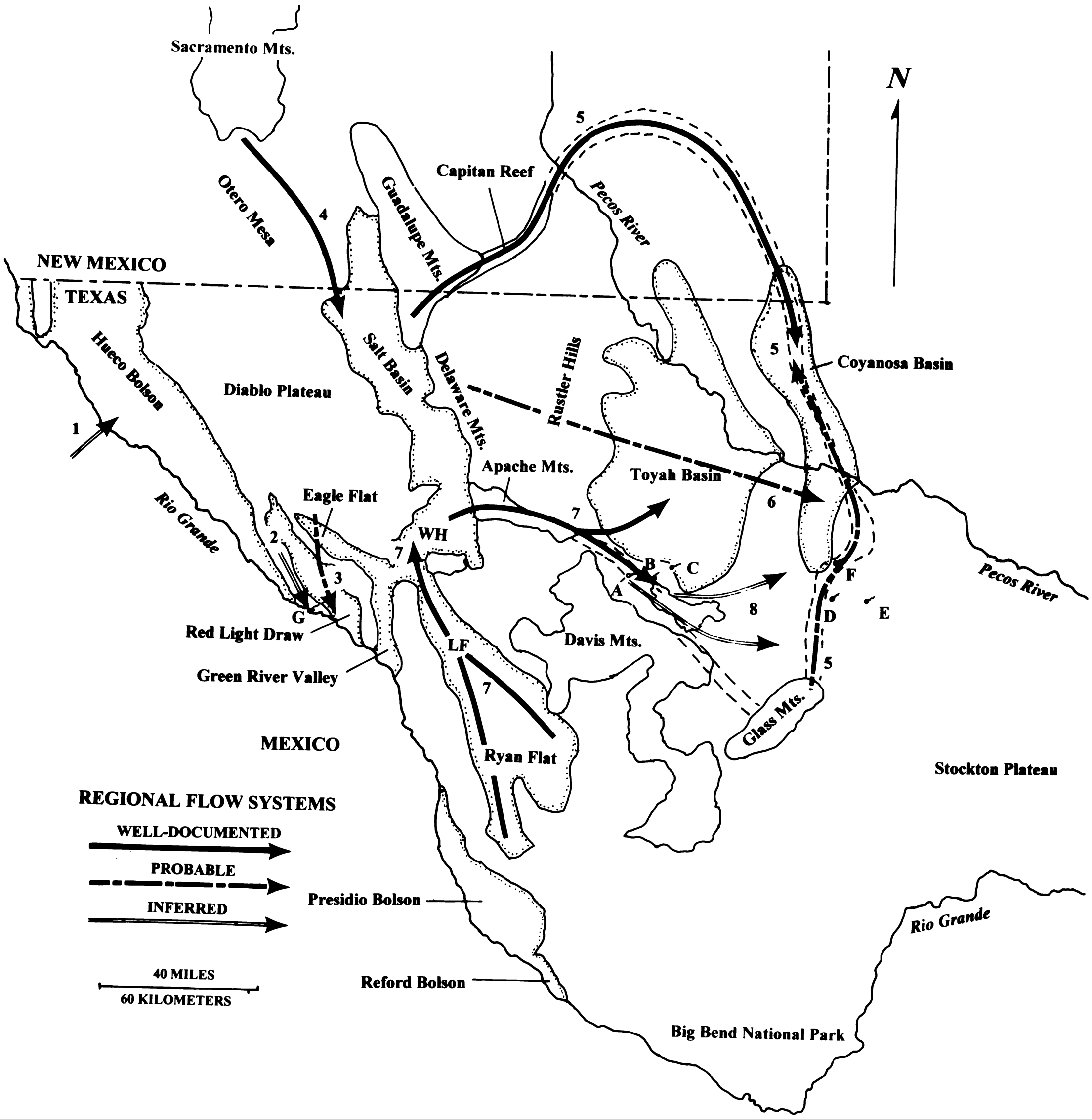

Figure 4-1: Regional flow systems of Trans-Pecos Texas. WH and LF denote Wild Horse Flat and Lobo Flat, respectively, of the Salt Basin. Springs are denoted by letters—A, Phantom Lake Spring; B, San Solomon and Giffin Springs; C, East and West Sandia Springs; D, Leon Springs; E, Comanche Springs; F, Diamond-Y Springs; and G, Indian Hot Springs. A, D, and E no longer flow. The regional flow systems are numbered—1 and 2, the inferred flow systems discharging 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 eastward extensions of this last flow system.

The most important aquifer systems are (1) the Cenozoic Pecos alluvial aquifer system (especially the Toyah Basin and Coyanosa Basin aquifers); (2) the Salt Basin bolson fill; (3) the bolson aquifers associated with the Rio Grande; and (4) the Permian-Cretaceous carbonate rock aquifers that supply Carlsbad, Dell City and Fort Stockton and that also feed (or fed) the major springs of Pecos (D and E on fig. 4-1) and Reeves (A, B, and C on fig. 4-1) Counties. All of these aquifer systems possess important regional flow components. Numerous other minor aquifers are in the area; they are mostly for domestic or livestock use. Among these, the volcanic rock aquifers of the Davis Mountains, designated the McCutcheon aquifer by Hart (1992), have become particularly important as that area has developed.

Regional flow systems become important in areas where recharge is limited, where there is a significant regional topographic gradient, and where high-permeability rocks exist at depth. These conditions are all met in Trans-Pecos Texas. In the following, the regional flow systems of Trans-Pecos Texas are discussed, with an emphasis on those that supply (or in the past supplied) the major springs of Pecos and Reeves Counties that also possess (or in the past possessed) unique biota, including Federally listed endangered species.

Hydrostratigraphy

The oldest hydrogeologically significant rocks are Permian, although Pennsylvanian through Precambrian rocks are present at depth (McMahon, 1977). Permian strata are divided into four series—Wolfcampian, Leonardian, Guadalupian, and Ochoan. In the area of the Delaware Basin, these units can be subdivided into three hydrogeologic facies (Hiss, 1980; Nielson and Sharp, 1985)—the high-permeability Guadalupian Series shelf margin/reef; the variably permeable (fracture-dependent) Leonardian and Wolfcampian Series shelf facies, which crop out in the Diablo Plateau and Otero Mesa (in New Mexico); and the low-permeability Guadalupian and Ochoan\Series basin facies rocks that fill the Delaware Basin. Shelfal facies rocks form the aquifer that serves the Dell City irrigation district and ranches throughout the Diablo Plateau and Otero Mesa. Overlying and east of the shelf is the Capitan Reef facies consisting of the Capitan and underlying Goat Seep limestones of Guadalupian age. Carlsbad Cavern is a prime example of this highly permeable reefal facies that extends circumferentially around the Delaware Basin (Adams, 1944; Hiss, 1980). The reefal facies exerts a major control on regional ground-water flow systems. The Guadalupian and Ochoan basinal facies, located east of the Guadalupe Mountains in the center of the Delaware Basin, are generally low in permeability, except where exposed at the surface. Water quality is also generally poor. Included in the Ochoan Series are the Castile, Salado, and Rustler Formations. The Castile Formation is composed of gypsum, calcareous anhydrite, halite, and subordinate limestone (Ogilbee and others, 1962); it possesses numerous karstic features (Olive, 1957). The Rustler Formation produces poor-quality water that is used for irrigation and livestock. However, basinal facies rocks form an eastward-flowing regional flow systems, and the Rustler probably discharges at Diamond-Y Springs in Pecos County (Boghici, 1997). Dissolution of these evaporite rocks also created swales in which the Cenozoic Pecos alluvial aquifers, such as the Toyah Basin aquifer, were deposited (LaFave, 1987; Ashworth, 1990).

Overlying the Permian is the Triassic Dockum Group that yields good-quality water in the southeastern part of the Toyah Basin. Overlying the Dockum are Cretaceous Comanchean and Gulfian carbonates and sandstones. Hydrogeologically important units include the Cox Sandstone and the Edwards, Georgetown, and Boquillas limestones. The Cox Sandstone is an aquifer on the southwestern flank of the Apache Mountains and just north of the Wylie Mountains in Wild Horse Flat, as well as along the Pecos River in the eastern part of the Trans-Pecos. The Cretaceous carbonates provide water to ranches north of the Davis Mountains and water for irrigation and municipal use in Pecos County. Paleokarst features are present in these formations. The regional flow systems of the Trans-Pecos Texas are either contained within or are strongly influenced by these fractured and karstified Cretaceous and Permian rocks.

Rocks of Tertiary age form the Davis Mountains and include the McCutcheon volcanics that consist of interbedded lava flows, tuffs, and nonmarine sedimentary rocks. Generally these yield minor quantities of water for domestic and livestock use. The Davis Mountains rest nonconformably over Cretaceous and, perhaps, Permian sedimentary rocks. The volcanic rocks have been undergoing slope retreat in the Cenozoic and were present originally farther to the north and east than at present (Halamicek, 1951).

Quaternary and Tertiary alluvial sediments that veneer much of the study area and attain thicknesses of over 2,400 ft in the Salt Basin (Gates and others, 1980) and over 1,500 ft in the Toyah Basin (Maley and Huffington, 1953) are of great hydrogeological significance. These sediments are dominantly clastic, although gypsum and caliche are probably present (Ogilbee and others, 1962). The alluvium provides water for irrigation in Hueco Bolson, Redford Bolson, Wild Horse Flat, Lobo Flat, and the Toyah and Coyanosa Basins, and the undifferentiated alluvium/Permian limestone system in Wild Horse Flat supplies water to the towns of Van Horn and Sierra Blanca (farther to the west). Ryan Flat has been considered as a potential water source for El Paso. In many parts of the region, including the vicinity of Balmorhea, some shallow wells produce small amounts of water from undifferentiated alluvium/limestone systems, but most of the water needs in Balmorhea are provided by spring flow, which issues from fractures and solution cavities in the Cretaceous units. The bolson aquifers, Hueco Bolson, Red Light Draw, Green River Valley, Eagle Flat, Presidio Bolson, and the Redford Bolson, provide fresh to brackish waters to municipalities and to the public for domestic, livestock, and irrigation uses.

Structural Setting

The northern Trans-Pecos is a transitional area from the Basin and Range province, exemplified by the Salt Basin graben, to the Permian Delaware Basin, a stable cratonic feature. The Delaware Basin contains more than 20,000 ft of Paleozoic sediments and is bounded by Capitan Reef rocks that are exposed in the Guadalupe Mountains, Apache, and Glass Mountains (fig. 4-1). The reef trend continues north-northeastward into New Mexico and southeastward in the subsurface. Basin-and-range style tectonics down-dropped the Salt Basin in the Cenozoic, and fault movement has continued to the present (Goetz, 1977, 1980, 1985). Important second-order structural features are the major fault and fracture sets in the carbonate units and the clastics-filled dissolution basins of the Cenozoic Pecos alluvial aquifer system and the bolson fills. For instance, LaFave and Sharp (1987) and Uliana and Sharp (in press) demonstrated how the regional flow system between the Salt and the Toyah Basins correlate with major fault/fractures systems in Permian/Cretaceous carbonates. Mayer and Sharp (1998) demonstrated a similar trend along Otero Break connecting the regional flow system between the Sacramento Mountains in New Mexico and the Dell City irrigation district. In the Salt Basin, major flexures/fracture systems correlate with groundwater divides (Neilson and Sharp, 1985). Finally, van Broekhoven and Sharp (1998) showed how recharge zones in Ryan/Lobo Flat correlate with fracture systems in the surrounding ranges. The Stocks Fault, which bounds the north-northeastern flank of the Apache Mountains, is one of a set of east-trending brittle fractures that are evident north of the Davis Mountains (LaFave and Sharp, 1987) and may, possibly, also be present beneath the Tertiary volcanics. DeFord (personal communication, 1986) and Wood (1965) stated that the large throw of the Stocks Fault, which abuts the Apache Mountains on the north, is the result of subsurface dissolution of Delaware Basin evaporites. The Rounsaville Syncline and Star Mountain Anticline parallel the Stocks Fault to the southeast. The large springs near Balmorhea are located near the syncline (A, B, C on fig. 4-1). The Toyah Basin and other units of the Cenozoic Pecos alluvial aquifer system (Ashworth, 1990) were created by late Tertiary and Quaternary dissolution of Permian evaporite-salts of the Castile and Salado Formations and anhydrite and gypsum from the Rustler Formation.

Regional Flow Systems

Although there was no comprehensive study of area groundwater systems prior to the large-scale municipal and agricultural development after World War II, it is possible to approximately infer some predevelopment potentiometric surfaces from a series of reports and unpublished data in the files of the Texas Water Commission. These include reports on the Rio Grande bolsons (Gates and others, 1980; White and others, 1941), the Toyah Basin in 1940 (Lang, 1943; see also LaFave and Sharp, 1987), the Salt Basin including Wild Horse, Lobo, and Michigan Flats in the late 1950's (Hood and Scalapino, 1951; White and others, 1980; Nielson and Sharp, 1985), and the Dell City area (Scalapino, 1950; Mayer, 1995). Data on the Diablo Plateau were compiled by Kreitler and others (1987) and Mullican and Senger (1992). The recent regional study by Richey and others (1985) presents potentiometric surfaces in the Cenozoic alluvium, the Santa Rosa aquifer, the Rustler Formation, and the Capitan Reef aquifer. Groundwater in the Diablo Plateau and Otero Mesa has not been extensively developed, except near Dell City, so its present potentiometric surface is probably similar to that of predevelopment conditions. Flow systems in the Rustler Formation are still not well delineated.

Figure 4-1 is a generalized depiction of the regional flow systems in Trans-Pecos Texas. Those flow systems have been designated as well documented because the flow systems are consistent with potentiometric, geologic, structural, geochemical, and isotopic data. Probable regional flow systems have fewer data sets confirming them. They are most consistent with available data, but other interpretations are possible. Inferred regional flow systems are more speculative. They feed artesian wells or hot springs and are inferred from limited data.

There are three regional predevelopment discharge areas—the Rio Grande, the northern and middle sections of the Salt Basin, and the Pecos River on the northeastern boundary of the study area. The Hueco, Presidio, and Redford Bolson groundwater systems discharge to the Rio Grande, as do those of Red Light Draw and the southern part of the Green River Valley. Most of the other systems discharge to the Pecos River. The Salt Basin is divided into three flow systems: the northern section, the middle section, and the southern section, including Wild Horse, Lobo, and Ryan Flats. There are playas in the northern and middle sections of the basin that demonstrate evaporative discharge. This inference is supported by water-chemistry studies (Gates and others, 1980; Boyd, 1982; Chapman, 1984; Mayer and Sharp, 1998) that show increasing salinity in the direction of flow. In the playas, gypsum and halite are precipitated from groundwater in the capillary fringe. On the eastern margin of the northern section and on the eastern and western margins of the middle section, ground-water recharge occurs by influent streams that cross alluvial fans and by precipitation on the permeable shelf margin carbonates. On the eastern flank of the Salt Basin, slightly brackish water can be found at depths of more than 2000 ft in Capitan Reef rocks (Reed, 1965). In contrast, near Dell City, on the western flank, there is little topographic relief on the western margin of the graben that merges gradually with the Diablo Plateau and Otero Mesa. Most of the other systems discharge to the Pecos River. These include the southern section of the Salt Basin, the Rustler Hills, Ryan and Lobo Flat, and the Stockton Plateau.

Rio Grande Bolsons

The flow systems in Hueco, Presidio, and Redford Bolson aquifers are (or were, prior to heavy groundwater pumpage) local flow systems that discharge to the Rio Grande. Recharge was concentrated on the basin margins, especially the proximal portions of alluvial fans, major fracture systems, and along the more perennial streams. However, the Fabens artesian zone and Indian Hot Springs (G on fig. 4-1) represent discharge from deeper artesian, regional flow systems (Kreitler and Sharp, 1990). These flow systems are designated as 1 and 2, respectively, on figure 4-1. The Fabens system is assumed to recharge in Mexico (Gates and others, 1980); the flow system at Indian Hot Springs could originate in either Texas (as suggested in fig. 4-1) or Mexico. Gabaldon (1991) suggested that deep brackish waters in the Presidio Bolson could arise from a similar regional system; an alternative explanation is that there are evaporite deposits at depth in this bolson.

Eagle Flat–Red Light Draw

Darling (1997) and Hibbs and others (1998) investigated the flow systems under Eagle Flat where a low-level radioactive waste repository had been proposed. There is no natural groundwater discharge in Eagle Flat, but there is flow into it. The water table is deep (>400 ft), and karstic/fractured carbonate rocks are present at depth. A deep flow system (3 on fig. 4-1) exists in the carbonate rocks from northwest Eagle Flat beneath the Devil Ridge to discharge into Red Light Draw and into the Rio Grande.

Diablo Plateau–Otero Mesa–Dell City

Scalapino (1950), the Groundwater Field Methods Class (1992b), Sharp and others (1993), Ashworth (1995), Mayer (1995), and Mayer and Sharp (1998) reported on the flow systems associated with the Dell City irrigation district. Irrigation pumpage near Dell City has created a cone of depression, and water quality has deteriorated from a TDS range of 1,100 to 1,800 mg/L to a range of 3,000 to 5,000 mg/L. It is unclear how much of the deterioration is due to irrigation return-flow and how much to a reversal of flow and salt-water intrusion from the basin, although return-flow is probably the major cause. Kreitler and others (1987) documented flow to the northeast in the Diablo Plateau, but hydrologic and geochemical data (Mayer and Sharp, 1998) indicate that the bulk of the flow comes from the area where the Sacramento River sinks and then flows southeastward along the Otero Break to Dell City. Mayer (1995) mapped fracture intensities and orientations in Otero Mesa. These are consistent with a zone of higher permeability rocks along the flow system (designated by 4 on fig. 4-1). A plume of relatively fresh water marks this path. Several paleolake basins exist along this regional flow path (Hawley, personal communication. 1996). In the southern margins of the Diablo Plateau, flow into the Hueco Bolson was documented by Mullican and Senger (1992) and shown as the proximal end (start) of flow path 3.

Delaware Basin and Capitan Reef

Hiss (1980) documented the regional flow system in the Capitan Reef aquifers that flows from its outcrops along the Texas-New Mexico border northeastward along its trends and southeastward from the Apache Mountains. The flow paths (5 on fig. 4-1) follow the high-permeability reef facies and are enhanced by fracture systems that subparallel the reef trends (Uliana, 2000). The uplift of the western side of the Delaware Basin created a regional topographic gradient, and a regional groundwater flow system from west to east was hypothesized by Hiss (1980), Mazzullo (1986) and Richey and others (1985). This regional flow has been suggested as a process for hydrocarbon migration and mineralization in the deeper sections of the Delaware Basin. This flow system is designated as 6 on figure 4-1. Boghici (1997) suggested that discharge from deep Rustler Formation waters along a fault system in Pecos County is responsible for the flows at Diamond-Y Springs (F on fig. 4-1). The southern part of the Capitan reef system (5) and the regional flow system (6) are designated as probable herein because of the potential effects of petroleum-production-related depressurization.

Ryan Flat–Lobo Flat–Salt Basin–Apache Mountains–Balmorhea–Toyah Basin–possible extension to Pecos County

The Ryan Flat–Lobo Flat–Salt Basin–Apache Mountains–Balmorhea–Toyah Basin is the longest regional flow system in Trans-Pecos Texas; it is designated as flow system 7 on figure 4-1. It extends from Ryan and Lobo Flats, which are southern extensions of the Salt Basin, and the groundwater boundaries are close to the Rio Grande. This flow system collects groundwater from the northern Green River Valley and southeastern Eagle Flat and flows into Wild Horse Flat in the Salt Basin near Van Horn, Texas. Recharge to the southern extensions occurs by infiltration at the proximal portions of alluvial fans and from subsurface flow in major fracture systems in Sierra Vieja on the western flank of Lobo and Ryan Flats (Darling and others, 1995; Darling, 1997, Hibbs and others, 1998; and van Broekhoven and Sharp, 1998). The magnitude of flow from Lobo Flat is uncertain, and a steepening of the water table gradient south of Van Horn is coincident with east-trending faults (Hay-Roe, 1958; Twiss, 1959; Sharp, 1989).

In Wild Horse Flat, additional recharge is gathered from the alluvial fans on the western side of the basin. This gathering is confirmed by isotopic analyses of the groundwater (Uliana and Sharp, in press) that show a Precambrian Sr-isotopic signature obtained from flow through these fans. The fans are largely derived from Precambrian rocks in the Carrizo Mountains, Beach Mountain, and the southern Sierra Diablo. Recharge also occurs from precipitation along ephemeral streams, such as Wild Horse Creek, and perhaps from irrigation return-flow. In Wild Horse Flat, the predevelopment water table was about 100 ft beneath the surface (Gates and others, 1980), in contrast to the evaporative-discharge playa systems in the northern portions of the Salt Basin. The main predevelopment, regional flow occurred eastward toward the Toyah Basin through shelf margin (reef) facies rocks of the Apache Mountains, which serve as a drain for Wild Horse Flat.

The structural setting is also conducive to interbasin flow not only because the rocks in the Apache Mountains are permeable but also because the trend of extensive, regional fractures is roughly east (LaFave and Sharp, 1987; Uliana, 2000). These rocks are highly anisotropic, and the direction of greatest permeability is subparallel to the Stocks Fault that is the northern border of the Apache Mountains. LaFave and Sharp (1987) concluded on the basis of regional geology and geochemistry that a significant portion of the flow of the Balmorhea Springs discharged from a regional aquifer system, recharged in part from interbasin flow through the Apache Mountains. This finding was reconfirmed by Uliana (2000), who used a much larger geochemical database augmented by Sr, ^{2}H (or D), and ^{18}O isotopic analyses. Balmorhea Springs (A, B, C on fig. 4-1) issue from orifices at elevations of about 3,300 ft. This elevation provides a reasonable hydraulic gradient of 10^{-3} to 10^{-4} between the springs and Wild Horse Flat. Spring flows enter Toyah Creek, which flows across the Toyah Basin but flows into the Pecos River only after major storms.

The regional flow system also discharges directly into the Toyah Basin aquifer, which produces groundwater for its extensive irrigation areas from the Cenozoic alluvium and, in the eastern section, from undifferentiated alluvium and Cretaceous limestones. In addition to the component of interbasin regional flow, recharge to the Toyah basin aquifer occurs in the Rustler Hills and from the ephemeral streams that drain the Davis and Barilla Mountains. LaFave (1987) noted that the aquifer produces Cl-dominated-facies water in the southwest and central portions of the Toyah Basin, whereas SO_4-dominated-facies water is produced from the western and northwestern portions. The Clfacies is virtually identical chemically to groundwaters produced from Capitan Reef aquifers and from Balmorhea Springs. This hypothesis is in concurrence with the reports of Hiss (1980), Mazzullo (1986), and Richey and others (1985), although these authors did not address the possibility that regional flow recharges the Toyah Basin aquifer. The SO_4 facies indicates its origin in the Ochoan rocks of the Rustler Hills. It is not known whether these waters recharge the Toyah Basin aquifer chiefly by subsurface flow or by infiltration along the many draws that drain eastward from the Rustler Hills. Finally, on the eastern margins of Toyah Basin, better-quality (>1,500 mg/L) water is obtained. Recharge in these areas is by precipitation and by infiltration from waters in draws draining the Barilla and Davis Mountains.

The effects of humans on the Toyah Basin aquifer have been significant. Irrigation pumpage increased rapidly after 1945. Many springs in the area have since ceased to flow (Brune, 1981). Irrigation pumpage from the Toyah Basin lowered water-table elevations and created a cone of depression. Thus, pumpage totally altered the regional-flow-system discharge zone from the Pecos River to irrigation wells within the Toyah Basin (LaFave and Sharp, 1987; Schuster, 1997; Boghici, 1999). Water quality has remained relatively constant, but a perched water table has developed about the City of Pecos, with salinities of over 8,000 mg/L (Groundwater Field Methods Class, 1990a, 1992a). The Groundwater Field Methods classes (1990b, 1992c, 1995, 1996) found water-level declines near Balmorhea Springs of about 20 ft with respect to the 1932 data (White and others, 1938). Recent declines of pumpage for irrigation because of economic conditions has allowed partial recovery of water levels, but it seems doubtful that predevelopment conditions will be achieved.

Eastward extensions of this regional flow system (designated by 8 on fig. 4-1) were suggested by Boghici (1997) and Uliana (2000). Boghici's numerical model of Pecos County flow systems required additional subsurface recharge from northwest of the Glass Mountains. Uliana found that chemical and isotopic data are consistent with continued geochemical evolution of waters along the trend of the Stocks Fault/Rounsaville syncline trend consistent with the eastward extension of the flow system. These extensions, however, are still somewhat speculative.

Other regional flow systems?

Other, yet-undocumented, regional flow systems may exist in Trans-Pecos Texas. For example, the flow systems in Mesozoic and Paleozoic units beneath the Davis Mountains may discharge to the Pecos River or, in part, south toward the Rio Grande. Permeable carbonate rocks are also present at depth toward the Big Bend area so that regional flow systems would be expected there, and transboundary (USA-Mexico) regional flow systems may exist. The delineation of these systems should be interesting.

Discussion

Regional groundwater flow systems are a major hydrogeologic characteristic of Trans-Pecos Texas. Geologic processes of faulting, folding, and dissolution in semiarid Trans-

Pecos Texas have created the controlling framework for regional groundwater flow systems. There exist three regional discharge areas—the Rio Grande, the northern and middle sections of the Salt Basin, and the Pecos River. The feature common to all eight flow systems depicted on figure 4-1, whether well-documented, probable, or inferred, is the presence of Permian carbonate rocks or Cretaceous carbonate rocks in close proximity to Permian units. The carbonate rocks have been fractured by a variety of tectonic episodes, including the Laramide orogeny, Basin-and-Range extension, and subsidence caused by dissolution of underlying evaporite deposits. The region remains tectonically active, as evidenced by recent seismic activity. In some areas, this was followed by very effective karstification—the Capitan reef aquifers may be some of the Earth's most permeable rocks. Coupled with the low rainfall and consequent groundwater recharge, regional flow systems have become an integral part of the regional hydrogeology. With greater recharge, local flow systems would be more dominant and, perhaps, they were in the past as is suggested by the old apparent ages of waters in some of these regional flow systems.

Yet unknown and apparently unstudied is the evolution of these regional flow systems and the effects on spring flows, desert ecosystems, and potential hydrocarbon and mineral deposits. Understanding of the regional flow systems is also critical to the development and sustainability of water resources in this region.

Acknowledgments

I acknowledge fruitful discussions with my past and present graduate students who studied various aspects of the hydrogeology of Trans-Pecos Texas. They are, alphabetically: Jeff Black, Radu Boghici, Bruce Darling, Pam Denney, Gil Gabaldon, Margaret Hart, Barry Hibbs, John LaFave, Rob Mace, Carla Matherne, Jim Mayer, Stefan Schuster, Becky Smyth, Matt Uliana, and Norm van Broekhoven. I also acknowledge the efforts of the 1990, 1992, 1995, and 1996 Groundwater Field Methods classes, whose reports provide key data. The Geology Foundation, The University of Texas at Austin, provided funds for manuscript preparation.

References

Adams, J. E., 1944, Upper Permian Ochoa Series of Delaware Basin, west Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 28, p. 1596-1625.

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 p.

Ashworth, J. B., 1995, Ground-water resources of the Bone Spring–Victorio Peak aquifer in the Dell Valley area, Texas: Texas Water Development Board Report 344, 42 p.

Barnes, V. E., 1976, Geologic atlas of Texas, Pecos Sheet: The University of Texas at Austin, Bureau of Economic Geology, map with explanation.

Barnes, V. E., 1979, Geologic atlas of Texas, Marfa Sheet: The University of Texas at Austin, Bureau of Economic Geology, map with explanation.

Barnes, V. E., 1995a, Geologic atlas of Texas, Fort Stockton Sheet: The University of Texas at Austin, Bureau of Economic Geology, map with explanation.

Barnes, V. E., 1995b, Geologic atlas of Texas, Van Horn–El Paso Sheet: The University of Texas at Austin, Bureau of Economic Geology, map with explanation.

Boghici, Radu, 1997, Hydrogeological investigations at Diamond Y Springs and surrounding area, Pecos County, Texas: The University of Texas at Austin, unpublished M.A. thesis, 120 p.

Boghici, Radu, 1999, Changes in groundwater conditions in parts of Trans-Pecos Texas, 1988–1998: Texas Water Development Board Report 348, 29 p.

Boyd, F. M., 1982, Hydrogeology of the northern salt basin of West Texas and New Mexico: The University of Texas at Austin, unpublished M.A. thesis, 135 p.

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

Chapman, J. B., 1984, Hydrogeochemistry of the unsaturated zone of a salt flat in Hudspeth County, Texas: The University of Texas at Austin, unpublished M.A. thesis, 132 p.

Darling, B. K., 1997, Delineation of the ground-water flow systems of the Eagle Flat and Red Light Basins of Trans-Pecos, Texas: The University of Texas at Austin, unpublished Ph.D. dissertation, 179 p.

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: *in* Hotchkiss, W. R., Downey, J. S., Gutentag, E. D., and Moore, J. E., eds., Water resources at risk: American Institute of Hydrology, Minneapolis, MN, p. SL12-SL24.

Dickerson, P. W., and Muehlberger, W. R., eds., 1985, Structure and tectonics of Trans-Pecos Texas: West Texas Geological Society Field Conference, Pub. 85-81, 278 p.

Gabaldon, Gilbert, 1991, A hydrogeologic characterization of the Presidio Bolson, Presidio County, Trans-Pecos Texas: The University of Texas at Austin, unpublished M.A. thesis, 100 p.

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 p.

Goetz, L. K., 1977, Quaternary faulting in Salt Basin Graben: The University of Texas at Austin, unpublished M.A. thesis, 136 p.

Goetz, L. K., 1980, Quaternary faulting in Salt Basin Graben, West Texas: *in* Dickerson, P. W., and Hotter, J. M., eds., New Mexico Geological Society, 31st Field Cent., Trans-Pecos Region, p. 83-92.

Goetz, L. K, 1985, Salt Basin Graben: a basin and range right-lateral transtensional fault zone—some speculations: *in* Dickerson, P. W., and Muehlberger, W. R., eds., Structure and tectonics of Trans-Pecos Texas: West Texas Geological Society Field Cent., Pub. 85-81, p. 165-168.

Groundwater Field Methods Class, 1990a, Hydrogeological investigations of a perched water table in Pecos, Texas: The University of Texas at Austin, unpublished report, 36 p.

Groundwater Field Methods Class, 1990b, Hydrology of springs and shallow ground water near Balmorhea, Texas: The University of Texas at Austin, unpublished report, 11 p. plus figures.

Groundwater Field Methods Class, 1992a, Perched aquifer project, Pecos, Texas: The University of Texas at Austin, unpublished report, variously paginated.

Groundwater Field Methods Class, 1992b, A groundwater investigation of Dell City, Texas: The University of Texas at Austin, unpublished report, variously paginated.

Groundwater Field Methods Class, 1992c, Water characteristics of springs and groundwater near Balmorhea, Texas: The University of Texas at Austin, unpublished report, variously paginated.

Groundwater Field Methods Class, 1995, Characterization of the ground-water resources in the Toyah Basin near Balmorhea, Texas: The University of Texas at Austin, unpublished report, 17 p. plus figures.

Groundwater Field Methods Class, 1996, Hydrologic investigation in the Toyah Basin, Balmorhea, Texas: The University of Texas at Austin, unpublished report, 31 p. plus figures.

Halamicek, W. A., 1951, Geology of the Toyah Field and Burchard Quadrangles, Reeves Co., Texas: The University of Texas at Austin, unpublished M.A. thesis, 55 p.

Hart, M. A., 1992, The hydrogeology of the Davis Mountains, Texas: The University of Texas at Austin, unpublished M.A. thesis, 158 p.

Hay-Roe, H., 1958, Geology of Wylie Mountains and vicinity: The University of Texas at Austin, unpublished Ph.D. dissertation, 226 p.

Hibbs, B. J., Darling, B. K., and Jones, I. C., 1998, Hydrogeologic regimes of arid-zone aquifer beneath low-level radioactive waste and other waste repositories in Trans-Pecos Texas and Chihuahua, Mexico: *in* Brahana, J. V., Eckstein, Y., Ongley, L. K., Schneider, R., and Moore, J. E., eds., Gambling with ground water–physical, chemical, and biological aspects of aquifer-stream relations: Proceedings, Joint Meeting of the American Institute of Hydrology and XXVIII Congress of the International Association of Hydrogeologists, Las Vegas, p. 311-322.

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

Hood, J. W., and Scalapino, R. A., 1951, Summary of the development of ground water for irrigation in the Lobo Flats area, Culberson and Jeff Davis Counties, Texas: Texas Board of Water Engineers, Bulletin 5102, 25 p.

Hubbert, M. K., 1940, The theory of groundwater motion: Journal of Geology, v. 48, p. 785-944.

Kreitler, C. W., Raney, J., A., Nativ, R., Collins, E. W., Mullican, W. F., III, Gustavson, T. C., and Henry, C. D., 1987, Siting of a low-level radioactive facility in Texas, volume 4—geologic and hydrologic investigations in the State of Texas and University of Texas Lands: The University of Texas at Austin, Bureau of Economic Geology, report to Texas Low-Level Radioactive Waste Disposal Authority, 330 p.

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

LaFave, J. I., 1987, Groundwater flow delineation in the Toyah Basin of Trans-Pecos Texas: The University of Texas at Austin, unpublished M.A. thesis, 159 p.

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

Lambert, S. J., and Harvey, D. M., 1987, Stable-isotope geochemistry of groundwaters in the Delaware Basin of southeastern New Mexico: Sandia National Laboratory Report, SAND 87-0138, 259 p.

Lang, J. W., 1943, Ground-water resources in the Toyah area, Reeves County, Texas: Texas Board of Water Engineers Report, 19 p.

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, v. 64, p. 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: The University of Texas at Austin, unpublished Ph.D. dissertation, 221 p.

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

Mazzullo, S. J., 1986, Mississippi Valley-type sulfides in Lower Permian dolomites, Delaware Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 70, p. 943-952.

McMahon, D. A., Jr., 1977, Deep subsurface structural geology of Reeves County, Texas: The University of Texas at Austin, unpublished M.A. thesis, 144 p.

Mullican, W. F., III, and Senger, R. K., 1992, Hydrogeologic investigations of deep ground-water flow in the Chihuahuan Desert, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 205, 60 p.

Nielson, P. D., and Sharp, J. M., Jr., 1985, Tectonic controls on the hydrogeology of the Salt Basin, Trans-Pecos Texas: *in* Dickerson, P. W., and Muehlberger, W. R., eds., structure and tectonics of Trans-Pecos Texas: West Texas Geological Society Field Conf., Pub. 85-81, p. 231-235.

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

Olive, W. W., 1957, Solution-subsidence troughs, Castile Formation of Gypsum Plain, Texas and New Mexico: Geological Society of America Bulletin, v. 68, p. 351-358.

Reed, E. L , 1965, A study of ground water resources: Capitan Reef reservoir, Hudspeth and Culberson counties, Texas: unpublished report.

Richey, S. F., Wells, J. G., and Stephens, K.T., 1985, Geohydrology of the Delaware Basin and vicinity: U.S. Geological Survey, Water Resources Investigation Report 84-4077, 99 p.

Scalapino, R. A,, 1950, Development of ground water for irrigation in the Dell City area, Hudspeth County, Texas: Texas Board of Water Engineers, Bulletin No. 6004, 41 p.

Schuster, S. K., 1997, Hydrogeology and local recharge analysis in the Toyah Basin aquifer: The University of Texas at Austin, unpublished M.A. thesis, 102 p.

Sharp, J. M., Jr., 1989, Regional ground-water systems in northern Trans-Pecos Texas: *in* Muehlberger, W. R., and Dickerson, P. W., eds., Structure and stratigraphy of Trans-Pecos Texas: 28th Int. Geol. Congress Field Trip Guidebook T317, p. 123-130.

Sharp, J. M., Jr., Mayer, J. R., and McCutcheon, E., 1993, Hydrogeologic trends in the Dell City area, Hudspeth County, Texas: *in* Love, D. W., Hawley, J. W., Kues, B. S., Adams, J. W., Austin, G. S., and Barker, J. M., eds., Carlsbad region, New Mexico and Texas: New Mexico Geological Society Forty-Fourth Annual Field Conference, p. 327-330.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, p. 4795-4812.

Twiss, P. C., 1959, Geology of the Van Horn Mountains, Trans-Pecos Texas: The University of Texas at Austin, unpublished M.A. thesis, 234 p.

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

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

van Broekhoven, N. G., and Sharp, J. M., Jr., 1998, Recharge in a semi-arid basin aquifer: Ryan Flat and Lobo Flat, Trans-Pecos, Texas [abs.]: *in* Brahana, J. V., Eckstein, Y., Ongley, L. K., Schneider, R., and Moore, J. E., eds., Gambling with Ground Water–Physical, Chemical, and Biological Aspects of Aquifer-Stream Relations: Proceedings, Joint Meeting of the American Institute of Hydrology and XXVIII Congress of the International Association of Hydrogeologists, Las Vegas, p. 62.

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

Wood, J., 1965, Geology of the Apache Mountains, Trans-Pecos Texas: The University of Texas at Austin, unpublished Ph.D. dissertation, 241 p.

Chapter 5

Regional Ecology and Environmental Issues in West Texas

Gary P. Garrett[1] and Robert J. Edwards[2]

Introduction

The Chihuahuan Desert of Mexico, Texas, and New Mexico contains a wide variety of habitats and many uniquely adapted plants and animals. The limited aquatic habitats of this ecosystem have undergone substantial modifications in the last hundred years, including: reduced water quality, diversion of surface water, overdrafting of groundwater, channelization, impoundment, and extensive introduction of nonnative species (Miller and Chernoff, 1979; IBWC, 1994; Propst and Stefferud, 1994; TNRCC, 1994; Lee and Wilson, 1997; Propst 1999; Edwards and others, in press).

One of the most heavily impacted habitats is the desert springs and their associated wetland habitats. In the American Southwest and northern Mexico these are known as *ciénegas*. These ecosystems were seldom damaged on purpose; put simply, water is rare in the desert and people want it for a variety of uses. The ways in which ecosystems have been destroyed include grazing and watering livestock, draining to move water more efficiently to agricultural fields, and over-pumping of aquifers. Impacts from these modifications are only now being documented, and few baseline data exist concerning the ecological requirements for most of the aquatic species.

Approximately half of the native fishes of the Chihuahuan Desert are threatened with extinction or are already extinct (Hubbs, 1990). Documented extinctions from this area include the Maravillas red shiner (*Cyprinella lutrensis blairi*), the phantom shiner (*Notropis orca*), the Rio Grande bluntnose shiner (*Notropis simus simus*), and the Amistad gambusia (*Gambusia amistadensis*) (Miller and others, 1989). Extirpations include the Rio Grande shiner (*Notropis jemezanus*) from the New Mexico portion of the Rio Grande (Propst and others, 1987) and the Rio Grande silvery minnow (*Hybognathus amarus*) and the Rio Grande cutthroat trout (*Oncorhynchus clarki virginalis*) and blotched gambusia (*Gambusia senilis*) in Texas (Bestgen and Platania, 1988, 1990; Hubbs and others, 1991). Endemic species other than fishes are also being lost from this area (Howells and Garrett, 1995).

[1] Texas Parks and Wildlife Department
[2] The University of Texas-Pan American

A number of species inhabiting the area have insufficient information about their status, but enough is known to raise concern among biologists. Not all have legal status (yet), and ideally we can find solutions before legal protection is needed. All serve as indicators of ecosystem integrity and for the quality of our lives.

Extirpated Species

Rio Grande silvery minnow (*Hybognathus amarus*) is a federally endangered species that once occurred throughout the Rio Grande basin from northern New Mexico to Brownsville. There is now only a small population in the middle Rio Grande of New Mexico. This sort of range reduction, from common to near extinction, is indicative of much larger problems in the watershed. Recovery efforts include attempts to insure flow and water quality, as well as possible reintroductions into selected sites.

Rio Grande cutthroat trout (*Oncorhynchus clarki virginalis*) was apparently a Texas inhabitant until the late 1800's (Garrett and Matlock, 1991). Remnant populations were reported in the Guadalupe and Davis Mountains, and officers at Fort Hudson reported them in San Felipe Springs. Reduced water flows and introduction of rainbow trout (*O. mykiss*) led to their ultimate extirpation from Texas.

Blotched gambusia (*Gambusia senilis*) is listed as threatened by Texas, although it has apparently been extirpated since the filling of Amistad Reservoir. It originally occurred in springs of the Devils River arm of the reservoir but was wiped out when this habitat was inundated. The species is still found in Río Conchos and is a protected species in Mexico.

Species of Concern

Sturgeon (*Scaphirhynchus platorynchus*) is known to occur in the Red River below Lake Texoma Reservoir. There are also historic records from the Rio Grande at Albuquerque, New Mexico (Cope and Yarrow, 1875). There are anecdotal accounts of occurrence in the Rio Grande in the vicinity of Big Bend National Park, but numerous collections have not yielded specimens. Some think that this animal may actually be an Atlantic sturgeon (*Acipenser oxyrhynchus*). Further surveys of the Rio Grande are planned, but, even if it is found, many questions will remain. Conservation decisions will hinge upon whether a viable population exists or whether there are simply some very old "relict" sturgeon cut off from the Gulf of Mexico by dams.

Mexican stoneroller (*Campostoma ornatum*) occurs throughout the Chihuahuan Desert, but populations are fractured and appear to be reduced in abundance. This reduction is primarily due to pollution and overpumping from aquifers. Determining solutions to problems for this species will also be beneficial to water issues for all organisms in this ecosystem. An ongoing survey of Chihuahuan Desert fishes may provide needed information to help conserve this species. A small, but secure population exists in Cienega Creek in the Big Bend Ranch State Park.

Proserpine shiner (*Cyprinella proserpina*) is a State threatened species. It is closely related to the more common red shiner (*C. lutrensis*) but has a range restricted to the Pecos and Devils Rivers; the San Felipe, Las Moras and Pinto Creeks; and the Río San Carlos in Mexico.

Devils River minnow (*Dionda diaboli*) is a Federally threatened species. It is now only found in the Devils River and San Felipe and Sycamore Creeks. The geographic location and historic stability of the Devils River have sustained a number of indigenous organisms. Because of limited access, the river has not been well studied. However, collections in the past decade by Garrett and others (1992) and others indicate a diminution in abundance of several flowing-water species, particularly the Devils River minnow. In 1953, a collection at Baker's Crossing showed the Devils River minnow to be the fifth-most-abundant fish species there. In the mid-1970's Harrell (1978) found it to be the sixth-most-abundant fish in the river. By 1989, collections from 24 locations throughout the range of the minnow yielded a total of only 7 individuals. Only one fish was obtained from Baker's Crossing, and no more than two were obtained at any site. In 1979, the Devils River minnow made up 6 to 18 percent of the *Dionda* population at the Headsprings area of San Felipe Creek. In 1989, none were present. Very little is known of the Devils River minnow, but some problem areas are apparent. Habitat loss has occurred by extirpation of the Las Moras Creek population, minimal flows in Sycamore Creek, and inundation of the lower Devils River by Lakes Walk and Devils and, ultimately, Amistad Reservoir. Many springs in the area have diminished flows, and some have totally stopped (e.g., Willow Springs, Beaver Springs, Juno Springs, and Dead Man's Hole), thus reducing the overall length of the Devils River, as well as the quantity of water flowing in it. Many of the perennial streams (Gray, 1919) of the area no longer flow. USGS data from the Pafford Crossing gauging station reveal a general decrease in daily mean discharge for the period between the study by Harrell (1978) and that of Garrett and others (1992). Brune (1981) attributed the reduced spring flows in this area to heavy pumping from wells and overgrazed soils with lowered capacity to absorb water and thus recharge aquifers.

Manantial roundnose minnow (*Dionda argentosa*) is a species closely related to the Devils River minnow. It is limited to the Devils River and San Felipe and Sycamore Creeks. It is not legally protected, and hopefully efforts to recover the Devils River minnow will also benefit the manantial roundnose minnow.

Blue sucker (*Cycleptus elongatus*) is a State threatened species. It is a big river fish found throughout the Mississippi Basin and large streams of Texas. Because these systems suffer from impoundment, pollution, and reduced water flows, abundances have decreased. Those in the Rio Grande may be a different, as yet undescribed, species.

West Mexican redhorse (*Scartomyzon austrinus*) is closely related to the common gray redhorse (*S. congestus*). It occurs from Pacific coast drainages in Mexico to the mid-Rio Grande in Texas. Those in the Rio Grande may also be a new, undescribed species.

Rio Grande blue catfish (*Ictalurus furcatus* ssp.) is very likely a unique subspecies of blue catfish. We have taken it only in the Rio Grande from Presidio to Laredo. The unique spotting pattern and head shape of this fish make it different from other blue catfish. Unfortunately very little else is known of this creature.

Headwater catfish (*Ictalurus lupus*) originally ranged throughout the streams of the Edwards Plateau and Pecos River and Rio Grande. It is now uncommon and can now be found only in subsegments of the Pecos River and Rio Grande.

Leon Springs pupfish (*C. bovinus*) were first collected in 1851 by the U.S. and Mexican Boundary Survey at Leon Springs (Baird and Girard, 1853). Leon Springs no longer exists because of impounding, inundation, and groundwater pumping (Hubbs, 1980). *Cyprinodon bovinus* was extirpated from Leon Springs as early as 1938 (Hubbs, 1980) and presumed extinct (Hubbs, 1957). In the early 1900's Leon Springs flowed at approximately 20 cfs, but heavy groundwater pumping reduced the flow to 0 by 1962 (Echelle and Miller, 1974). Today the only water source for the species is the Diamond-Y Springs and outflows north of Fort Stockton, Pecos County, Texas.

Conchos pupfish (*Cyprinodon eximius*) is a State threatened species occurring in the Conchos basin of Mexico and Rio Grande from Alamito Creek to the Devils River. Populations in the Devils River were nearly eliminated in the 1950's, but recovery efforts have led to a thriving population in the Devils River State Natural Area. Although the reestablished population in Dolan Creek is thriving (Hubbs and Garrett, 1990), most of the other Rio Grande tributary populations are sparse.

Comanche Springs pupfish (*C. elegans*) originally inhabited two isolated spring systems approximately 90 km apart in the Pecos River drainage of western Texas (Baird and Girard, 1853). The type locality, Comanche Springs inside the city limits of Fort Stockton, is now dry, and the population at this locality is extinct. The other population is restricted to a small series of springs, their outflows, and a system of irrigation canals interconnecting Phantom Lake Springs (located in easternmost Jeff Davis County, Texas), San Solomon Springs, Giffin Springs, and Toyah Creek near Balmorhea, Reeves County, Texas. The habitat of Comanche Springs pupfish has been markedly altered into an irrigation network of concrete-lined canals with swiftly flowing water and dredged, earth-lined laterals. Waters from Phantom Lake Springs originally emerged from a cave and formed a ciénega that drained back into a cave. Water is now captured in an irrigation canal as it emanates from the cave. Water from San Solomon and Giffin Springs flows into additional irrigation systems, some of which is stored in an irrigation supply lake known as Lake Balmorhea. This habitat is highly impacted, ephemeral, and very dependent upon local irrigation practices and other water-use patterns. For the most part, the irrigation canals provide little suitable habitat for *C. elegans*. The species is wholly dependent upon failing spring flows in the area and suffers as well from threats of hybridization and competition with introduced sheepshead minnow (*C. variegatus*).

Pecos pupfish (*C. pecosensis*) once occurred throughout the Pecos River in New Mexico and Texas. It now suffers from habitat degradation and hybridization with the introduced *C. variegatus*.

Big Bend gambusia (*Gambusia gaigei*) was described in 1929 (Hubbs, 1929) on the basis of specimens taken from a spring-fed slough across from Boquillas, Mexico, in Brewster County, Texas (now Big Bend National Park). Big Bend gambusia went under an extreme genetic bottleneck approximately 50 yr ago, when their only habitat was contaminated with *G. affinis*. All *G. gaigei* are descendents of three individuals taken in 1956 (Hubbs and Broderick, 1963). At present, several thousand Big Bend gambusia inhabit two spring-pool refugia and a spring-fed drainage ditch. Smaller populations also occur in the presumed original habitat and the spring's outflow channel. The limited quantities of warm spring waters available, park campground development in the area, and the loss of the species' natural habitats in Boquillas Spring and Graham Ranch Warm Springs further limit this species' recovery.

Pecos gambusia (*Gambusia nobilis*) was described by Baird and Girard (1853) from Leon and Comanche Springs, Pecos County, Texas. Leon Springs was later designated the type locality (Hubbs and Springer, 1957). The species is endemic to the Pecos River basin in southeastern New Mexico and western Texas. At present, the species is restricted to four main areas, two in New Mexico and two in Texas. Where suitable habitats exist, Pecos gambusia populations can be dense, ranging from 27,000 to 900,000 individuals in the isolated environments in which they occur (Bednarz, 1975). Pecos gambusia face severe threats from spring-flow declines and habitat modifications throughout their range and from competition with *G. geiseri*.

Rio Grande darter (*Etheostoma grahami*) is a State threatened species. It is found in the lower Pecos and Devils Rivers, San Felipe and Sycamore Creeks, and the intervening Rio Grande. It is also part of the unique fauna of the region, and efforts to protect the Devils River minnow should also help this species.

Hope for the future

The Texas Parks and Wildlife Department is working with Federal, State, local agencies, and especially private landowners to resolve endangered species problems. With 97 percent of the land in Texas being privately owned, this is the only way we can achieve long-term benefits.

San Solomon Ciénega

A cooperative project in West Texas has recreated a unique and valuable type of aquatic habitat that is rapidly vanishing from the desert Southwest. The main purpose of the restoration project was to create vital habitat, not only for the two endangered fishes, Comanche Springs pupfish and Pecos gambusia, but also for all of the plants and animals that lived in these fragile desert wetlands. Additional benefits include educational opportunities, boost to a local economy, and protection of an agricultural lifestyle.

Few ciénegas, or desert wetlands, have survived intact to this day. San Solomon Springs continues to flow at Balmorhea State Park, but its associated ciénega was destroyed long ago, along with its great diversity of wildlife. San Solomon Springs is currently the largest spring in the Trans-Pecos and the sixth largest in the state. Comanche Springs, in nearby Fort Stockton, used to be able to claim that title, but groundwater pumping caused its perennial flow to cease entirely in 1961.

The native inhabitants of the San Solomon ciénega ecosystem have suffered greatly. When the original wetlands were modified and for the most part destroyed, the only aquatic habitat remaining was in concrete irrigation canals. Although better than no habitat at all, the irrigation canals, at best, provided a tenuous existence for many of the aquatic species.

People also suffer when their water sources vanish. Farmers who depended on surface irrigation from Comanche Springs lost everything when the springs went dry. Farmers in the Balmorhea area also rely on surface irrigation from springs, and if serious conflicts on groundwater use were to occur, local agriculture would suffer. The effects on the community of Balmorhea also would be catastrophic because the community depends on the aquifer and the spring flows for everything from drinking water to tourist dollars.

Somewhat ironically, the one thing that can prevent over-pumping of this aquifer is the Federal Endangered Species Act. The Endangered Species Act protects the fish, the fish need the water, and as long as the water is flowing from the springs, it is also available to humans downstream. Through a pragmatic understanding of the basic relationship between the natural and human communities, biologists and Balmorhea community leaders chose to come together to work out a solution that would benefit all concerned, rather than adopt adversarial roles, which so often occurs today.

A plan was formulated to create a ciénega that would look and function like a natural ecosystem. In this way, the survival of the fishes and a dependable water supply could be assured. Water, of course, was the most important element of the whole plan. The Reeves County Water Improvement District and the agricultural community it represents agreed to provide the essential water needed to create a secure environment for the endangered species. Water is a rare and precious commodity in far West Texas, particularly for farmers, but by each of the users giving up a small amount, they could ensure that they all would have water for the future.

An additional benefit for the farmers was that, because of their help in creating a permanent habitat for the endangered fishes, the Texas Department of Agriculture, the U.S. Fish and Wildlife Service, and the U.S. Environmental Protection Agency worked out a plan to reduce some the extra pesticide restrictions that had been in place to protect the endangered species in the irrigation canals. The fish have a better place to live, and the farmers can continue to raise their crops economically.

Biologists, engineers, and resource managers from universities and government agencies joined forces to make the project work. The USDA Natural Resource Conservation Service provided soil analysis and, along with the Texas Agricultural Extension Service and the Texas Department of Agriculture, gave expert advice on some of the intricacies of the project. The expertise of the Texas Department of Transportation also was crucial. Their surveyors, design engineers, and equipment operators transformed biological ideas into reality. The Texas Department of Criminal Justice provided inmate manpower to do such things as build the observation deck and retaining walls, as well as install the plant materials selected for the initial ciénega vegetation restoration. Botanists at Sul Ross State University provided container-grown native plants for the project.

Devils River Minnow Conservation Agreement

Dionda diaboli was recommended for listing as endangered by the U.S. Fish and Wildlife Service because of its extremely low numbers and reduced habitat. It is somewhat of a mystery why this fish almost disappeared after being one of the more abundant species present. Certainly the mere act of putting it on the Endangered Species list would not do much for the species. Something needed to be done to determine the causal factors and protect not only the fish, but also the health of the rivers and creeks in which it occurred. Private landowners and the city of Del Rio were extremely interested in working with the Texas Parks and Wildlife Department to determine and resolve these problems. As a result, the species was listed as threatened and a Conservation Agreement was developed.

In formulating the Conservation Agreement, the Texas Parks and Wildlife Department and the U.S. Fish and Wildlife Service agreed to work closely with landowners and the City of Del Rio to determine and resolve life-history requirements and restore populations to natural levels. As a result, there will also be additional protection for the quality of the Devils River and associated streams.

Specifically, the conservation actions outlined in the agreement are designed to (1) assess the current status of wild populations, (2) provide immediate security for the Devils River minnow, (3) implement actions needed for long-term conservation of the Devils River minnow, and (4) fill in gaps in pertinent information.

Pecos Pupfish Conservation Agreement

Cyprinodon pecosensis was recommended for listing by the U.S. Fish and Wildlife Service because of its loss of habitat and massive hybridization with *C. variegatus*. In this situation, the rationale of the Texas Parks and Wildlife Department was to fix the problem and preclude the need to list. If the State were to fail, the species would be listed.

The approach has three components: (1) amend baitfish regulations to prevent further introductions of nuisance fishes; (2) protect the existing natural population, and (3) create new habitat through a landowner-incentive program that turns stock ponds into ciénegas, thus creating alternate habitat on private land. To date, baitfish regulations have been changed, progress in habitat protection has been made, and, perhaps most importantly, two wetlands on private land have been created that have thriving populations of Pecos pupfish.

Summary

Exploitation of limited resources, particularly groundwater pumping, has degraded the West Texas environment, caused extirpation and extinction of species, and, ultimately, loss of habitat and ecosystems. Many of the fishes of this region could serve well as biological indicators of the overall integrity of the ecosystem. The few remaining relatively intact faunas and unmodified localities need careful management if they are to be preserved. In addition, information gained by studying aquatic communities can be used to provide useful baseline data for future actions and decisions affecting the management of the Chihuahuan Desert ecosystem within the larger bi-national border region. By involving individuals and local governments, we are more likely to achieve long-term benefits for natural resources, as well as public health and quality of life.

References

Baird, S. F., and Girard, C., 1853, Descriptions of new species of fishes collected by Mr. John H. Clark, on the U.S. and Mexican Boundary Survey, under Lt. Col. Jas. D. Graham: Proceedings of the Academy of Natural Sciences, Philadelphia, v. 6, p. 387-390.

Bednarz, J., 1975, A study of the Pecos gambusia: Endangered Species Program, New Mexico Department of Game and Fish, Santa Fe, New Mexico, p. 1-30.

Bestgen, K. R., and Platania, S. P., 1988, The ichthyofauna and aquatic habitats of the Rio Grande from the New Mexico-Texas border to Big Bend National Park: final report to the U.S. Fish and Wildlife Service, Office of Endangered Species, Albuquerque, New Mexico, 55 p.

Bestgen, K. R., and Platania, S. P., 1990, Extirpation of *Notropis simus simus* (Cope) and *Notropis orca* Woolman (Pisces: Cyprinidae) from the Rio Grande in New Mexico, with notes on their life history: Occasional Papers, Museum of Southwestern Biology, v. 6, p. 1-8.

Brune, G., 1981, Springs of Texas: Branch-Smith, Inc., Fort Worth, 566 p.

Cope, E. D., and Yarrow, H. C., 1875, Report upon the collections of fishes made in portions of Nevada, Utah, California, Colorado, New Mexico, and Arizona during the years 1871-1874: *in* United States Army Engineers Department Report, in charge of George M. Wheeler, Geography and geology of the explorations and surveys west of 100th meridian, v. 5, p. 645-703.

Echelle, A. A., and Miller, R. R., 1974, Rediscovery and redescription of the Leon Springs pupfish, *Cyprinodon bovinus*, from Pecos County, Texas: Southwestern Naturalist, v. 19, p. 179-190.

Edwards, R. J., Garrett, G. P., and Marsh-Matthews, E., in press, Conservation and status of the fish communities inhabiting the Río Conchos Basin and Middle Rio Grande, México and U.S.A.: Reviews in Fish Biology and Fisheries, v. XX, p. 1-13.

Garrett, G. P., Edwards, R. J., and Price, A. H., 1992, Distribution and status of the Devils River minnow, *Dionda diaboli*: Southwestern Naturalist v. 37, p. 259-267.

Garrett, G. P., and Matlock, G. C., 1991, Rio Grande cutthroat trout in Texas: Texas Journal of Science, v. 43, p. 405-410.

Gray, G. A., 1919, Gazetteer of streams of Texas: U.S. Geological Survey, Water-Supply Paper 448, 267 p.

Harrell, H. L., 1978, Response of the Devil's River (Texas) fish community to flooding: Copeia, v. 1, p. 60-68.

Howells, R. G., and Garrett, G. P., 1995, Freshwater mussel surveys of Rio Grande tributaries in Chihuahua, Mexico: Triannual Unionid Report, v. 8, p. 10.

Hubbs, C. L., 1929, Studies of the fishes of the order Cyprinodontes VIII: *Gambusia gaigei*, a new species from the Rio Grande: Occasional Papers of the Museum of Zoology, University of Michigan, v. 198, p. 1-11.

Hubbs, C., 1957, Distributional patterns of Texas fresh-water fishes: Southwestern Naturalist, v. 2, p. 89-104.

Hubbs, C., 1980, Solution to the *C. bovinus* problem—eradication of a pupfish genome: Proceedings of the Desert Fishes Council, v. 10, p. 9-18.

Hubbs, C., 1990, Declining fishes of the Chihuahuan Desert: *in* Third Symposium on resources of the Chihuahuan Desert Region, United States and Mexico: Chihuahuan Desert Research Institute, Alpine, Texas, p. 89-96.

Hubbs, C., and Broderick, H. J., 1963, Current abundance of *Gambusia gaigei*, an endangered fish species: Southwestern Naturalist, v. 8, p. 46-48.

Hubbs, C., Edwards, R. J., and Garrett, G. P., 1991, An annotated checklist of the freshwater fishes of Texas, with keys to identification of species: Texas Journal of Science, Supplement, v. 43, p. 1-56.

Hubbs, C., and Garrett, G. P., 1990, Reestablishment of *Cyprinodon eximius* (Cyprinodontidae) and status of *Dionda diaboli* (Cyprinidae) in the vicinity of Dolan Creek, Val Verde Co., Texas: Southwestern Naturalist, v. 35, p. 446-478.

Hubbs, C., and Springer, V. G., 1957, A revision of the *Gambusia nobilis* species group, with descriptions of three new species, and notes on their variation, ecology, and evolution: Texas Journal of Science, v. 9, p. 279-327.

IBWC, 1994, Binational study regarding the presence of toxic substances in the Rio Grande/Río Bravo and its tributaries along the boundary portion between the United States and Mexico: final report by the International Boundary and Water Commission, September, 250 p.

Lee, R. W., and Wilson, J. T., 1997, Trace elements and organic compounds associated with riverbed sediments in the Rio Grande/Río Bravo basin, Mexico and Texas: U.S. Geological Survey Fact Sheet, FS-098-97, 6 p.

Miller, R. R., and Chernoff, B., 1979, Status of populations of the endangered Chihuahua chub, *Gila nigrescens*, in New Mexico and Mexico: Proceedings of the Desert Fishes Council, v. 11, p. 74-84.

Miller, R. R., Williams, J. D., and Williams, J. E., 1989, Extinctions of North American fishes during the past century: Fisheries, v. 14, p. 22-39.

Propst, D. L., Burton, G. L., and Pridgeon, B. H., 1987, Fishes of the Rio Grande between Elephant Butte and Caballo reservoirs, New Mexico: Southwestern Naturalist, v. 32, p. 408-411.

Propst, D. L., 1999, Threatened and endangered fishes of New Mexico: New Mexico Department of Game and Fish, Technical Report No. 1, 84 p.

Propst, D. L., and Stefferud, J. A., 1994, Distribution and status of the Chihuahua chub (Teleostei: Cyprinidae: *Gila nigrescens*), with notes on its ecology and associated species: Southwestern Naturalist, v. 39, p. 224-234.

TNRCC, 1994, Regional assessment of water quality in the Rio Grande basin including the Pecos River, the Devils River, the Arroyo Colorado and the Lower Laguna Madre: Texas Natural Resource Conservation Commission, AS-34, 377 p. + appendices.

Chapter 6

The Hueco Bolson: An Aquifer at the Crossroads

Zhuping Sheng[1], Robert E. Mace[2], and Michael P. Fahy[3]

Introduction

The Hueco Bolson is a thick pocket of sediments derived from nearby mountains that extends from New Mexico, through Texas, and into Mexico in the El Paso and Ciudad Juarez area. Over time, these sediments filled with water and became the Hueco Bolson aquifer: an oasis of plentiful water in the northern part of the Chihuahuan Desert. El Paso and Ciudad Juarez have relied on the Hueco Bolson aquifer as a primary source of drinking water for several decades (Sayre and Penn, 1945; White and others, 1997). Ciudad Juarez, several communities in New Mexico, and the Fort Bliss Military Reservation currently depend on the Hueco Bolson aquifer as their sole source of drinking water (Sheng and others, 2001). Because of the desert climate and the local geology, the aquifer is not easily replenished, and recharge is low. Low recharge and high pumping rates have caused large water-level declines and large decreases in fresh-water volumes in the aquifer.

The aquifer and the El Paso-Ciudad Juarez area are at the crossroads. With current trends, groundwater models predict that El Paso will pump the last of its fresh water by 2025, and Ciudad Juarez will pump the last of its fresh water by 2005 (Sheng and others, 2001). The El Paso Water Utilities/Public Service Board (EPWU) has recognized the nature of limited groundwater resources in the area and has investigated and invested in several strategies to increase the longevity and usefulness of the aquifer. The purpose of this paper is to briefly summarize the hydrogeology of the Hueco Bolson aquifer and discuss several of the management strategies to protect and responsibly use the aquifer.

Hydrogeology

The Hueco Bolson aquifer is coincident with the Hueco Bolson, a long, sediment-filled trough that lies between the Franklin, Organ, and San Andres Mountain ranges and the Quitman, Malone, Finlay, Hueco, and Sacramento Mountain ranges (fig. 6-1). Hill (1900) defined the Hueco Bolson as including the Tularosa Basin (as shown in fig. 6-1).

[1] Texas A&M University System, El Paso Research and Extension Center
[2] Texas Water Development Board
[3] El Paso Water Utilities

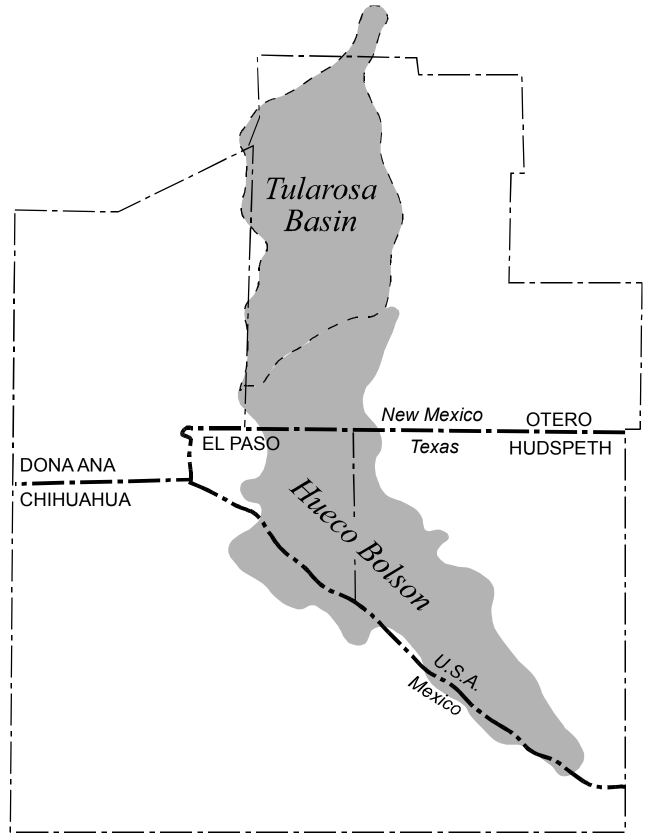

Figure 6-1: Location of the Hueco Bolson aquifer in Texas, New Mexico, and Mexico.

However, Richardson (1909) divided the bolson into two parts: the Tularosa Basin to the north and the Hueco Bolson to the south. The topographic divide between these two basins is about 7 mi north of the Texas–New Mexico border. However, the Hueco Bolson and the Tularosa Basin are hydraulically connected to each other (Wilkins, 1986) and have been combined into the Hueco-Tularosa aquifer (Hibbs and others, 1997).

The Hueco Bolson is about 200 mi long and 25 mi wide. The Hueco Bolson aquifer consists of unconsolidated to slightly consolidated deposits composed of fine- to medium-grained sand with interbedded lenses of clay, silt, gravel, and caliche. Sediments in the bolson are fluvial, evaporitic, alluvial fan, and aeolian in origin and have a maximum thickness of 9,000 ft (Mattick, 1967; Cliett, 1969; Abeyta and Thomas, 1996). The bottom part of the Hueco Bolson is primarily clay and silt. Therefore, only the top several hundred feet produce good-quality water.

Recharge

The Hueco Bolson aquifer is recharged by mountain-front recharge; seepage from the Rio Grande, canals, and agricultural drains; and deep-well injection (Knorr and Cliett, 1985;

Land and Armstrong, 1985; White and others, 1997). Mountain-front recharge is the seepage of surface run-off after rainfalls into the aquifer where the bolson laps up against bordering mountains. Before the aquifer was heavily pumped, water in the aquifer naturally discharged to the Rio Grande. After pumping caused water levels to decline, the Rio Grande began to lose water into the aquifer, so much so that a part of the river through El Paso-Ciudad Juarez has been lined with concrete to minimize leakage. Unlined irrigation canals and drains also leak water into the aquifer, although the water is usually of poor quality. EPWU has taken treated wastewater and injected it up-gradient of one of El Paso's well fields to increase recharge to the aquifer.

Meyer (1976) estimated that mountain-front recharge (from the Organ and Franklin Mountains in New Mexico and Texas and the Sierra de Juarez in Mexico) to the aquifer in El Paso County is 5,640 acre-ft/yr. White (1987) estimated that about 33,000 acre-ft/yr of water is recharged into the Rio Grande alluvium overlying the bolson aquifer. Recharge from the Rio Grande was reduced significantly when the bottom of the Rio Grande was lined in 1973 and 1998 in the El Paso-Ciudad Juarez area (Hibbs and others, 1997; Heywood and Yager, in review).

Treated wastewater is injected at the Fred Harvey Wastewater Treatment Plant in El Paso and provided about 3,800 acre-ft of water per year in 1995 (USEPA, 1995) and about 1,800 acre-ft in 1999 (Sheng and others, 2001).

Well Yields

Well yields in the Texas part of the Hueco Bolson aquifer are as much as 1,800 gpm (Hibbs and others, 1997). In New Mexico, yields are higher in alluvial fans that flank the basin (~1,400 gpm) and lower in the interior of the basin (300 to 700 gpm) (Hibbs and others, 1997). In the well field for Ciudad Juarez in Mexico, yields range between 300 and 1,500 gpm (Hibbs and others, 1997). Hydraulic conductivity in the Hueco Bolson, as determined with 73 aquifer tests, varies from 6.4 to 98.9 ft/day (Hibbs and others, 1997).

Pumping

The Hueco Bolson aquifer is pumped at a much greater rate than the aquifer is recharged. Groundwater withdrawals from the aquifer in Texas amounted to about 69,000 acre-ft in 1999 (Sheng and others, 2001): about nine times greater than the amount of recharge in El Paso County. Over the past 20 yr, pumping from the Hueco and Mesilla Bolsons in Texas has ranged from 96,000 to 138,000 acre-ft/yr (Mace, this volume).

Water Quality

Water quality in the Hueco Bolson varies depending on location and depth. Water quality in the Texas part of the Hueco Bolson tends to be better to the west than to the east, although there are pockets of good-quality water in the eastern part of the bolson (Gates and others, 1980). North of the Texas-New Mexico border, water tends to have total dissolved solids (TDS) greater than 1,000 mg/L except near mountain fronts where there is active recharge (Hibbs and others, 1997). The upper part of the aquifer tends to be fresher with TDS ranging between 500 and 1,500 mg/L, with an average of about 640 mg/L (Ashworth and Hopkins, 1995). Water quality has been affected by the large water-level declines in the aquifer, which have induced flow of poor-quality water into areas of fresh water. Water quality in the shallow part of the aquifer along the Rio Grande in the alluvium has degraded because of leakage of poor-quality irrigation return-flow into the aquifer (Sheng and others, 2001). Water quality beneath Ciudad Juarez is generally less than 1,000 mg/L TDS (Hibbs and others, 1997), however, water-quality deterioration has been observed in wells along the border and in the downtown area.

Water Levels and Groundwater Flow

Depth to water in the Hueco Bolson aquifer ranges from very shallow to very deep. Depth to groundwater near the Cities of Tularosa and Alamogordo is between 20 and 150 ft, whereas depth to water below El Paso ranges from 250 to 400 ft in depth, and depth to water below Ciudad Juarez ranges between 100 and 250 ft (Hibbs and others, 1997). Depth to water below the Rio Grande is less than 70 ft. Groundwater flows from the Tularosa Basin southward into the Hueco Bolson and into Texas (Hibbs and others, 1997, their fig. 3.8). Little drawdown has been recorded in the northern part of the aquifer. The drawdown in Hueco Bolson along the Texas-New Mexico border has been relatively small, not exceeding 30 ft (Hibbs and other 1997). In heavily developed parts of the Hueco Bolson aquifer, drawdowns since predevelopment in 1903 are up to 170 ft. Focal points of drawdown are beneath the City of El Paso and Ciudad Juarez (Hibbs and others, 1997).

The model by Heywood and Yager (in review) suggests that about 6,000 acre-ft/yr of groundwater flowed in the Hueco Bolson aquifer from New Mexico into Texas before large-scale pumping by El Paso in the 1960's. Since then, the amount of flow has increased to about 18,000 acre-ft/yr. In the El Paso-Ciudad Juarez area, groundwater flows toward cones of depression. Between 1910 and 1960, groundwater flowed from Mexico into Texas toward pumping centers in El Paso (Sheng and others, 2001). Since 1960, groundwater, generally of poor quality, has flowed from Texas into Mexico (Sheng and others, 2001).

Groundwater Models

Several groundwater flow models have been constructed for the Hueco Bolson aquifer system. These models include an early electric-analog model of the El Paso area (Leggat and Davis, 1966) and three numerical models developed by the U.S. Geological Survey, including (1) Meyer and Gordon (1973) and Meyer (1975, 1976) (later updated by Knowles and Alvarez, 1979), (2) Groschen (1994), and (3) an as yet unpublished model (Heywood and Yager, in review). Mullican and Senger (1990, 1992) developed a model of the southeastern part of the Hueco Bolson. Mexico has also developed a groundwater flow model for part of the area. Wilson and others (1986) used a preexisting model to predict water resources through 2060.

Models by Groschen (1994) and Heywood and Yager (in review) simulate potential water-level declines, as well as changes in water quality due to pumping. Groschen (1994) showed that water quality in the bolson is most likely affected by horizontal movement of saline water in response to pumping.

The integrated flow and water-quality model by Heywood and Yager (in review) represents the cooperation of EPWU, the USGS, the International Boundary and Water Commission (IBWC), Fort Bliss Military Reservation, JMAS (Junta Municipal de Agua y Saneamiento de Ciudad Juarez), and CILA (Comision Internacional de Limites y Aguas). Binational coordination has included the exchange of aquifer information and comparison of water-resource management plans. The model is being used to assess (1) water storage in the aquifer, (2) the optimization of pumping for fresh and brackish water, (3) the location of new production wells, (4) the control of brackish-water intrusion, (5) the design of an aquifer storage and recovery program, and (6) the planning of water resources among Texas, New Mexico, and Mexico (Sheng and others, 2001).

Groundwater Availability

Groundwater availability represents the amount of water that can be used from an aquifer. Groundwater availability can be defined in many different ways depending on the local socioeconomic needs (Mace and others, 2001). In the El Paso area, groundwater availability has been defined using a systematic depletion approach, where the total amount of recoverable water is considered the amount of water available for use. In general, groundwater availability is assessed for the fresh-water part of the aquifer. However, as water resources become scarcer in the state, more and more areas, including El Paso, are also evaluating the usable amounts of slightly saline water for ongoing or potential desalination projects.

Fresh Water

The approximate volume of recoverable freshwater in the entire Hueco Bolson aquifer is about 7.5 million acre-ft, with 3 million acre-ft in Texas, 3.9 million acre-ft in New Mexico, and 600,000 acre-ft in Mexico (Sheng and others, 2001, on the basis of a review of USGS publications). The Far West Texas Planning Group estimated that there were about 3 million acre-ft of fresh water in the Hueco Bolson and 2.5 million acre-ft of slightly saline water for desalination (FWTPG, 2001). Recoverable fresh water accounts for economic and geologic constraints and does not represent all of the fresh water in the aquifer.

Other studies have suggested differing volumes of fresh water. Knowles and Kennedy (1956) estimated that the Hueco Bolson in Texas had about 7.4 million acre-ft of recoverable water, with less than 250 mg/L chloride (~750 mg/L TDS). Meyer (1976) estimated the recoverable amount of fresh water in the Texas part of the Hueco Bolson to hold 10.64 million acre-ft. White (1987) estimated that the Hueco Bolson aquifer in Texas holds about 9.95 million acre-ft of recoverable fresh water. The TWDB (1997) estimated that there was about 9 million acre-feet of fresh water in the Texas part of the Hueco Bolson.

Slightly Saline Water

Slightly saline water may be a large potential water resource in the El Paso area. There is an estimated 20 million acre-ft of slightly saline water (TDS between 1,000 and 3,000 mg/L) in the Hueco Bolson aquifer in El Paso County (Sheng and others, 2001). Similar volumes of slightly saline water may also exist in New Mexico and Mexico (Sheng and others, 2001). Sheng and others (2001) recommended additional studies to quantify a more exact volume of poor-quality water in the aquifer.

Strategies to Increase Groundwater Availability

Although recent modeling work suggests that the Hueco Bolson in the El Paso area will run out of fresh water by 2025, it is not a forgone conclusion. For prediction purposes, the model assumes that current trends and practices will remain the same. However, the life of the fresh groundwater resource can be extended by implementing strategies to increase the availability of groundwater.

Increase Surface-Water Use

By increasing the use of surface water, groundwater use can be minimized, thus extending the useful life of the fresh-water part of the aquifer. In this case, surface water is relied upon when plentiful, and groundwater is relied upon when surface water is not plentiful. Regional water providers are pursuing this strategy by the implementation of the Regional Sustainable Water Project (IBWC and EPWU, 2000). The Far West Texas Planning Group also identifies the pursuit of additional surface-water supplies as a recommended water management strategy for the area (FWTPG, 2001). However, the planning group noted that El Paso cannot rely on the Rio Grande for water during times of severe drought (FWTPG, 2001).

Hydraulic Control and Desalination

To reduce the degradation of groundwater quality due to laterally flowing poorer quality water, wells can be installed to hydraulically control the migration of poorer quality water by capturing the poorer quality water before it mixes with fresher water. The produced water can then be desalinated. EPWU and the Department of Defense at the Fort Bliss Military Reservation are investigating this approach in existing wells in the Airport/Montana well field (Sheng and others, 2001). To maximize the water supply, the desalinated water (~200 mg/L TDS) can then be blended with slightly saline water (~1,500 mg/L TDS) to produce a water with a TDS of about 900 mg/L TDS. Hydraulic control and desalination extend the life of the fresh-water part of the aquifer by protecting existing fresh-water resources from further intrusions of poor-quality water and decreasing the reliance on the fresh-water part of the aquifer. Hydraulic control and desalination are also being considered in other El Paso wellfields (Sheng and others, 2001).

Pumping Optimization

Pumping of wells can be optimized to minimize the migration of poor-quality water and the depth of cones of depression around pumping centers. Pumping of water-supply wells should be optimized aquiferwide to minimize the effects of pumping on the migration of poor-quality water into areas of fresh water. An operational priority list for the Hueco well fields has been developed and used in well-field operation for over a year (Sheng and others, 2001). Results of the optimization program will be evaluated to further improve operation of the well fields. Pumping optimization extends the life of the fresh-water resource by minimizing the impacts of poor-quality water intrusions.

Aquifer Storage and Recovery

Aquifer Storage and Recovery (ASR) is when treated surface water is injected into an aquifer when it is plentiful and demand is low, and then recovered the stored water from the aquifer when demand is high or during times of drought. ASR extends the life of the aquifer by maximizing the use of surface water and recharging the aquifer. In addition, it will also prevent brackish water intrusion if injection wells are located along the transition zone of marginal quality groundwater.

Blending high-grade water with poor-quality water

Using the best quality water first has often been the preferred method of groundwater production. However, by blending good quality water with poorer quality water up to the Safe Drinking Water Act standards for TDS, chloride, and sulfate secondary maximum contamination levels, water providers can enhance their production capacity. The blending method extends the life of the aquifer by maximizing the use of the freshwater resource. When combined with hydraulic control, existing freshwater resources can also be additionally protected.

Conclusions

The Hueco Bolson aquifer and the El Paso-Ciudad Juarez area are at the crossroads. Several scientific studies and recent modeling projects suggest that, under current trends, fresh water from the Hueco Bolson aquifer in Texas will be depleted by 2025. However, using groundwater more strategically can extend the longevity of fresh-water resources in the aquifer. EPWU and FWTPG are actively researching and implementing a number of strategies to do just this, including increased surface-water use, hydraulic control and desalination, pumping optimization, aquifer storage and recovery, and blending to increase freshwater supplies. The area will need to continue to follow this path to ensure that future water needs of El Paso are met.

Acknowledgments

Authors would like to thank Mr. Edmund G. Archuleta, General Manager of EPWU, and John Burkstaller, Chief Technical Officer of EPWU, for their valuable discussions with the authors. Authors also thank Mr. Charles Heywood of USGS, Jeff Devere of Rio Blanco County Development Department of Colorado, and Mr. Roger Sperka and Mr. Scott Reinert of EPWU for their assistance. The opinions and results presented are those of the authors and do not represent those of EPWU.

References

Abeyta, C., and Thomas, C. L., 1996, Hydrogeology and groundwater quality of the chromic acid pit site, U.S. Army Air Defense Artillery Center and Fort Bliss, El Paso, Texas: U.S. Geological Survey Water Resource Investigations Report 96-4035.

Ashworth, J. B., and Hopkins, J., 1995, Aquifers of Texas: Texas Water Development Board Report 345, 69 p.

Cliett, T. E., 1969, Groundwater occurrence of the El Paso area and its related geology: *in* New Mexico Geological Society, Border Region, Chihuahua, Mexico, and United States, Guidebook, 20th Field Conference, p. 209-214.

FWTPG, 2001, Far West Texas Regional Water Plan: Far West Texas Planning Group, report submitted to the Texas Water Development Board, variously paginated.

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

Groschen, G. E., 1994, Simulation of ground-water flow and the movement of saline water in the Hueco Bolson aquifer, El Paso, Texas, and adjacent areas: U.S. Geological Survey Open-File Report 92-171.

Heywood, C. E., and Yager, R. M., in review, Ground-water flow and chloride-transport simulation of the Hueco Basin, El Paso, Texas, and adjacent areas: U.S. Geological Survey.

Hibbs, B. J., Ashworth, J. B., Boghici, R. N., Hayes, M. E., Creel, B. J., Hanson, A. T., Samani, B. A., and Kennedy, J. F., 1997, Trans-boundary aquifers of the El Paso/Ciudad Juarez/Las Cruces region: report prepared by the Texas Water Development Board and New Mexico Water Resources Research Institute for the U.S. Environmental Protection Agency, Region VI, under contract X 996343-01-0 and X 996350-01-0, 156 p.

Hill, R. T., 1900, Physical geography of the Texas region: U.S. Geological Survey Topographic Atlas, Folio No. 3.

IBWC (International Boundary and Water Commission) and EPWU, 2000, Draft environmental impact statement, El Paso–Las Cruces regional sustainable water project, volume I.

Knorr, D. and Cliett, T., 1985, Proposed groundwater recharge at El Paso, Texas: *in* Asano, T., ed., Artificial recharge of groundwater Butterworth Publishers, p. 425-480.

Knowles, D. B., and Kennedy, R. A., 1956, Groundwater resources of the Hueco Bolson, northeast of El Paso, Texas: Texas Board of Water Engineers Bulletin 5615, 265 p.

Knowles, T. R., and Alvarez, H. J., 1979, Simulated effects of ground-water pumping in portions of the Hueco Bolson in Texas and Mexico during the period 1973 through 2029: Texas Department of Water Resources Report LP-104.

Land, L. F., and Armstrong, C. A., 1985, A preliminary assessment of land-surface subsidence in the El Paso area, Texas: U.S. Geological Survey Water Resource Investigations Report 85-4155.

Leggat, E. R., and Davis, M. E., 1966, Analog model study of the Hueco bolson near El Paso, Texas: Texas Water Development Board, 26 p.

Mace, R. E., Mullican, W. F., III, and Way, T. (S.-C.), 2001, Estimating groundwater availability in Texas: *in* the proceedings of the 1st annual Texas Rural Water Association and Texas Water Conservation Association Water Law Seminar: Water Allocation in Texas: The Legal Issues. Austin, Texas, January 25-26, 2001. Section 1, 16 p.

Mattick, R. E., 1967, A seismic and gravity profile across the Hueco Bolson, Texas: *in* U.S. Geological Survey Professional Paper 575-D, p. 85-91

Meyer, W. R., 1975, Digital model studies of the hydrology of the Hueco Bolson, El Paso area, Texas: *in* Hills, J. M., ed., Exploration from the mountains to the basin, p. 141.

Meyer, W. R., 1976, Digital model for simulated effects of ground water pumping in the Hueco Bolson, El Paso area, Texas, New Mexico, and Mexico: U.S. Geological Survey Water-Resources Investigations Report 58-75.

Meyer, W. R., and Gordon, J. D., 1973, Water-budget studies of lower Mesilla Valley and El Paso Valley, El Paso County, Texas: U.S. Geological Survey, Open-File Report OF 73-0185, 41 p.

Mullican, W. F., III, and Senger, R. K., 1990, Saturated-zone hydrology of south-central Hudspeth County, Texas, *in* Hydrogeology of Trans-Pecos Texas: Kreitler, C.W., and Sharp, J. .M., Jr., eds., The University of Texas at Austin, Bureau of Economic Geology Guidebook 25, p. 37-42.

Mullican, W. F., III, and Senger, R. K., 1992, Hydrogeologic investigations of deep ground-water flow in the Chihuahuan Desert, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 205, 60 p.

Richardson, G. B., 1909, Geological atlas, U.S. Geological Survey, El Paso Folio (No. 166).

Sayre, A. N., and Penn, L., 1945, Groundwater resources of the El Paso area, Texas: U.S. Geological Survey Water Supply Paper 919.

Sheng, Z., Fahy, M. P., and Devere, J., 2001, Management strategies for the Hueco Bolson in the El Paso, Texas, USA, and Ciudad Juarez, Mexico, region: *in* Bridging the gap–Proceedings of the World Water and Environmental Resources Congress, Orlando, Florida, May 20–24, CD ROM, ASCE.

TWDB, 1997, Water for Texas: Texas Water Development Board, Document No. GP-6-2, variously paginated.

USEPA , 1995, Hueco Bolson ground water recharge demonstration project, El Paso Texas, Part II, Water quality analysis: U.S. Environmental Protection Agency.

White, D. E., 1987, Summary of hydrologic information in the El Paso, Texas, area, with emphasis on ground-water studies, 1908-1980: Texas Water Development Board Report 300, 75 p.

White, D. E., Baker, E. T., and Sperka, R., 1997, Hydrology of the shallow aquifer and uppermost semi-confined aquifer near El Paso, Texas: U.S. Geological Survey, Water-Resources Investigations Report 97-4263.

Wilkins, D. W., 1986, Geohydrology of the southwest alluvial basins regional aquifer-systems analysis, parts of Colorado, New Mexico, and Texas: U.S. Geological Survey.

Wilson, L., and Associates, 1986, Technical Report for the Hueco Bolson Hearing, Prepared for El Paso Water Utilities/Public Service Board.