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INSIDE

The Edwards Aquifer: A Resource in Conflict

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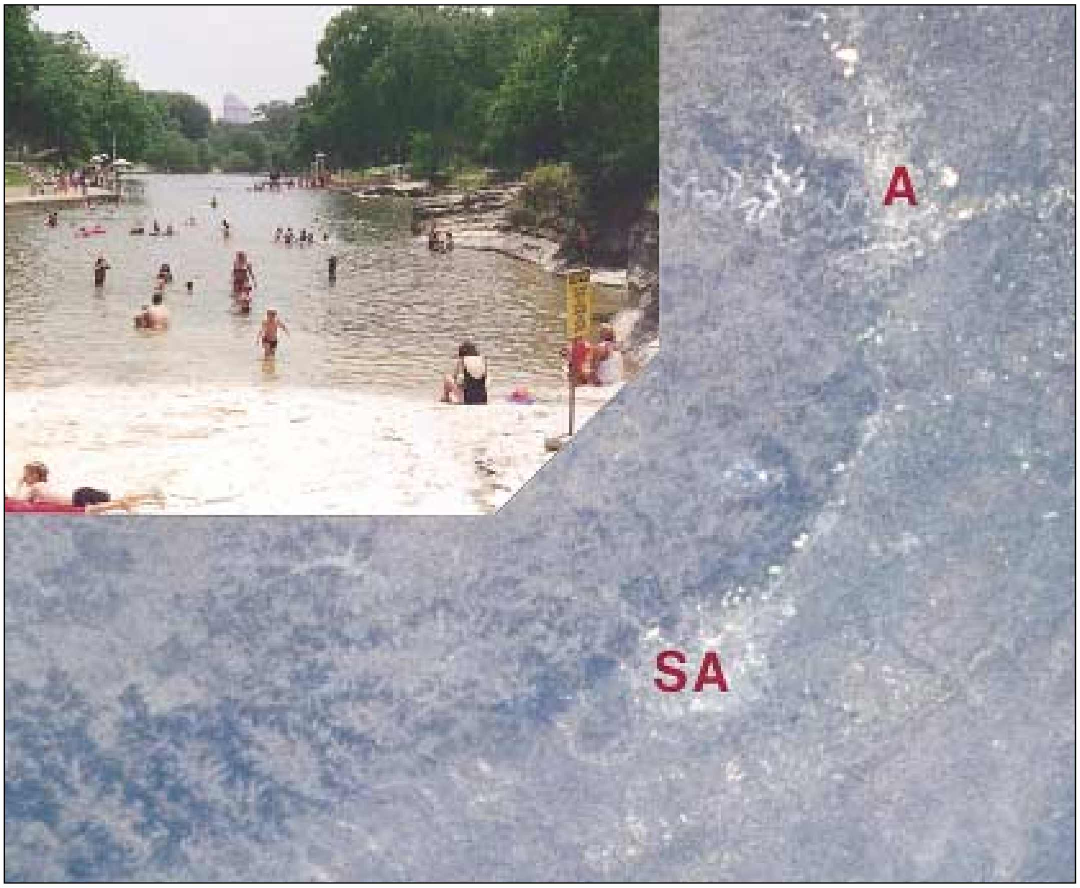

Figure 1. Space shuttle photograph of central Texas showing prominent physiographic features (see also Figs. 2, 3, and 5) that dictate patterns of recharge and flow in the Edwards aquifer. The landscape break shown by the color change across a southwest-northeast arc from San Antonio (SA) to Austin (A) formed as a consequence of en echelon, down-to-the-southeast normal faults of the Balcones fault zone. Urbanization of land (indicated by the light gray colors) around Austin, San Antonio, and the area in between has increased rapidly in the previous decade. North is to the top of the photograph. Austin–San Antonio distance is 120 km. Shuttle photo #NASA STS-62-97-143 (March 1994). Inset: The Barton Springs swimming pool in Austin, Texas, exemplifies the conflicting interests regarding the aquifer's waters. The pool is supplied by springs that discharge from submerged orifices in fractured limestone, which is visible on the right bank. The pool and surrounding park are important recreational resources. This spring system is the sole environment for the rare Barton Springs salamander, which is a federally listed endangered species. The rising skyline of the City of Austin is visible in the background. Water demands and conflicts will increase with increasing urbanization.

ABSTRACT

The Edwards aquifer of central Texas is an extensive, karstified flow system developed in rocks deposited on a Cretaceous limestone platform. Development of the aquifer was controlled by changes in sea level, large-scale hydrodynamic and tectonic processes in the Gulf of Mexico, and local climatic and geomorphic processes. The aquifer is a vital water resource and provides a diverse set of habitats, including those for several endangered species that live in its major spring systems. Because of its unique stratigraphic, hydraulic, and hydrochemical properties, the Edwards aquifer is a natural laboratory that is well suited for hydrogeologic studies. Because of numerous economic, social, and political interests in the use of the water and because of the rapid rate of population growth (and urbanization) of its watersheds, the aquifer is also a source of political conflict. Competing interests for its waters have stimulated an ongoing debate over how the aquifer would best be utilized. Historical water-balance analysis demonstrates that major water shortages will develop with the recurrence of historic decadal droughts. Future decisions regarding the aquifer's use will therefore have significant socioeconomic and environmental ramifications. These decisions should be based upon accurate hydrogeological data. The general nature of how the aquifer functions is understood, but more detailed interpretations are needed. Application of ground-water flow models based on field data and natural geochemical tracers have the potential to reduce uncertainties in the details of how the aquifer functions now and will function in response to potential future developments.

INTRODUCTION

There is a saying in Texas—"whiskey is for drinking, water is for fighting." Fighting over water resources involves legal, political, and economic interests. Much attention is focused on the Edwards aquifer, which is one of the most prolific aquifers in North America, providing water for more than two million people. It provides all the water used by the City of San Antonio and by numerous smaller municipalities, industry, and agriculture. Individual well yields can be tremendous; a City of San Antonio well drilled in 1941 had a natural flow of 16,800 gallons/minute (1.06 m^3/s; Livingston, 1942), and a well drilled in 1991 is reportedly the world's greatest flowing well, with a natural discharge of 25,000 gallons/minute

Edwards Aquifer *continued on p. 2*

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IN THIS ISSUE

In Memoriam

George M. Brown
Oxford, England
March 27, 1997

Nikolaus H. Heine
Germany
June 24, 1997

Dorothy Lewis
Queensland, Australia
April 23, 1997

Joseph R. Chelikowsky
Manhattan, Kansas
March 31, 1997

Ralph H. Howe
Bluff, Utah
June 1997

Henry G. Thode
Hamilton, Ontario
June 1997

Notice of Council Meeting

Meetings of the GSA Council are open to Fellows, Members, and Associates of the Society, who may attend as observers, except during executive sessions. Only councilors, officers, and section representatives may speak to agenda items, except by invitation of the chair. Because of space and seating limitations, notification of attendance must be received by the Executive Director prior to the meeting. The next meeting of the Council will be Tuesday afternoon, October 21, 1997, at the Annual Meeting in Salt Lake City.

Edwards Aquifer *continued from p. 1*

(1.58 m^3/s; Swanson, 1991). The Edwards aquifer also provides important recreational resources in stream waters and in the parks that surround major spring orifices that discharge the aquifer's water. The streams that flow over the aquifer and are fed by its springs provide needed fresh water to the south Texas Gulf Coast bays and estuaries, which are the nurseries for shrimp, redfish, and other species of coastal and marine wildlife.

The aquifer has been the subject of recent litigation, notably regarding the maintenance of natural flow to certain spring systems and the preservation of the threatened and endangered species that dwell in them. This conflict has developed because the communities and region that overlie and rely upon the Edwards constitute one of the fastest growing urban corridors in the United States (Fig. 1). During 1996, undeveloped land in Williamson County, north of Austin, was being subdivided for homes and businesses at the rate of one acre every three hours (*Austin-American Statesman,* 1996). Significant decisions will have to be made about these water resources in the coming decades. These decisions should be based more on accurate scientific data and less on political exigencies. Hydrogeological facts about the Edwards aquifer and related natural (including biological) resources must be effectively conveyed to those drafting policy and making decisions about future resource utilization.

The Cretaceous rocks that form the aquifer are present over much of Texas, either in outcrop or in the subsurface. These units also extend into northern Mexico (Lesser and Lesser, 1988). There are three aquifers in these rocks (Fig. 2): the Edwards-Trinity (Plateau) aquifer, the Edwards (Washita Prairie) aquifer, and the Edwards (Balcones fault zone) aquifer. The last is the most prolific and is what most people consider the Edwards aquifer (and that to which we refer in this paper). It stretches in a band (usually <64 km wide) from the Rio Grande river near Del Rio east through San Antonio, then northeast through Austin, and ends near

Edwards Aquifer *continued on p. 3*

Legislative Alert: House Moves To Eliminate Tax Exemption for Graduate Student Tuition Waivers

The U.S. House of Representatives recently passed H.R. 2014, which modifies the federal tax code. One provision of this bill would eliminate the current tax exemption for graduate students who receive tuition waivers from their universities. If this provision becomes law, graduate teaching and research assistants would have to pay taxes on the value of their tuition waivers, starting with 20% of the waivers' value in 1998, and rising incrementally to 100% in 2002. The tuition waivers, in other words, would be treated as taxable income.

Senate tax legislation, S. 949, does not eliminate the tuition waiver exemption. This and other differences between House- and Senate-passed tax bills must be ironed out in a conference committee meeting. For updated information on the status of the tax legislation, visit the American Geological Institute's Web site: www.agiweb.org and click on "Government Affairs."

In response to passage of H.R. 2014, GSA President George A. Thompson has written the following letter to House Ways and Means Committee Chairman William Archer:

The Honorable William Archer,
Chairman, Committee on Ways and Means,
United States House of Representatives, Washington, DC 20515

Dear Chairman Archer:

For the past 50 years, the U.S. Congress has been a steadfast supporter of the nation's system of scientific research and education. This system is the envy of the world, and the source of the talent and innovation that will fuel our nation's welfare in the coming century. Congress is to be commended for maintaining its historical commitment to research and education even while struggling to get the nation's fiscal house in order. In this light, I want to point out that recent provisions of House-passed tax reform legislation, H.R. 2014, threaten to undermine this commitment and our investment in training the nation's next generation of scientists and engineers. In specific, the provision that would eliminate Section 117(d) of the tax code—the exclusion of tuition waivers or reductions from taxable gross income—could have a serious negative impact on the nation's ability to attract the best and brightest students into our graduate science programs. I write to strongly urge that Section 117(d) be restored to the final tax bill during House-Senate conference.

As President of the Geological Society of America, a 15,000 member organization dedicated to the pursuit of world class scientific knowledge about the Earth, I am acutely aware of the challenge that we face in striving to maintain the preeminent status of the nation's research effort. The key element to meeting this challenge is the quality of our next generation of scientists. Ability in science—not ability to pay—must remain the prime criterion for entry into our graduate programs. Elimination of the tuition waiver exclusion could seriously compromise our capacity to fulfill this criterion.

In considering this issue, I urge you to keep in mind some very special aspects of our graduate science education system. Graduate education in science is a process that requires deep personal commitment over many years of hard work and meager pay. Our best graduate students typically receive stipends of less than $15,000, and they are often in their late twenties or early thirties when they complete their studies. If these students must accept an additional tax burden on tuition waivers—which may be worth as much as $20,000 per year—the economics of graduate training in science may become untenable for those without independent financial means. This is particularly the case because the salaries that scientists receive after finishing graduate school are far less than those for graduates of law, business, and medical schools. While a future doctor, lawyer, or corporate executive can justify the high cost of professional training based on anticipated future earnings, scientists do not have this luxury. Thus, if we ask our graduate students to accept a considerable real increase in tax burden (and, in many cases, an increase in personal debt, as well), we may well find that our most promising future scientists opt for more economically viable careers in the professions.

In the coming century, every aspect of the nation's well being—from economic competitiveness in the global marketplace, to the preservation of health in an aging population, to the development of energy resources and protection of the environment—will depend on the ability and ingenuity of our scientists. Short-term revenue losses resulting from the tax exclusion for tuition waivers will be paid back in spades by the long-term benefits of our investment in the next generation of world class scientists.

Sincerely,
George A. Thompson, President
[Geological Society of America]

Edwards Aquifer *continued from p. 2*

the town of Salado in Bell County. The boundaries of the Edwards aquifer (Fig. 3) are (1) the northern and western limits of the outcrops (except in the west, where it is continuous with the Edwards-Trinity Plateau aquifer; (2) the Rio Grande; and (3) the bad-water line, which separates the fresh-water zone (potable waters) from the bad-water zone (brackish or saline waters with >1000 mg/l total dissolved solids). Of particular interest is the aquifer between the ground-water divides near Brackettville (east of Del Rio) and Kyle (just north of San Marcos) because this is the largest segment of the aquifer and includes San Antonio.

There have been many studies of the Edwards aquifer. The aquifer's water balance and how it functions are basically known, but the lack of knowledge about many details disturbs those who need to make decisions and wish to maintain a broad consensus of support. As stated by Tilford (1994), "geological facts and fantasies will be called on to support both proponents and critics" of any water resources project, and "unknowns are powerful tools," whether or not warranted, in the hands of these groups. In this paper, we review the hydrogeology of the aquifer (its stratigraphy, structure, and relatively unique hydraulic parameters) and major issues facing the many users of the aquifer, and we suggest some areas where hydrogeological research should have both practical and scientific implications.

STRATIGRAPHY AND STRUCTURE

The aquifer is in carbonate rocks that were deposited in shallow subtidal to tidal-flat facies on an extensive marine platform approximately 100 m.y. ago. This stratigraphic package formed as part of an extensive series of shallow-water carbonate-evaporite platforms that encircled the margin of the ancestral Gulf of Mexico during a major marine transgression in the Early Cretaceous. Subsequent lowering of sea level, rapid burial of the deep sections of the Gulf of Mexico basin, tectonic uplift along the margins, and erosion and karstification have played important roles in the development of the aquifer (see Fig. 4 for representative stratigraphic sections). Detailed hydrostratigraphic relationships

Edwards Aquifer *continued on p. 4*

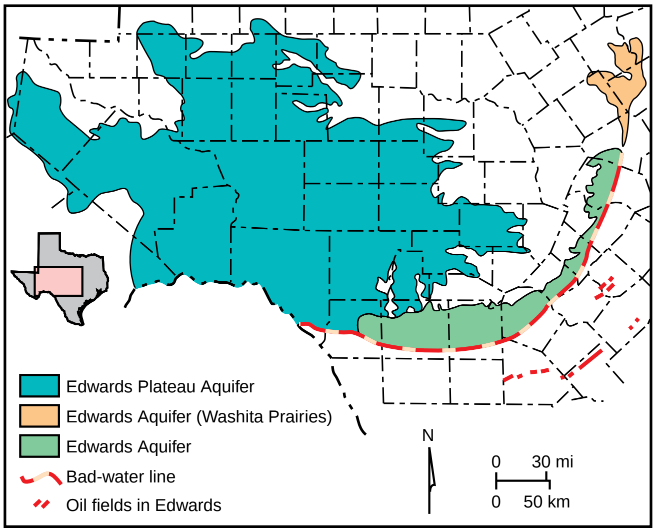


Figure 2. Edwards aquifers of Texas.

Edwards Aquifer *continued from p. 3*

are given in Rose (1972), Maclay and Small (1986), and Pavlicek et al. (1987), among many others.

Some confusion still persists over differences between hydrostratigraphic and stratigraphic nomenclature. It is not always recognized, for instance, that although the Edwards aquifer is present in the San Antonio area, the Edwards Limestone is not! The Edwards aquifer is a hydrostratigraphic unit that generally includes all rocks above the Glen Rose Limestone and beneath the Del Rio Clay, except where the latter has been eroded and aquifer crops out. The aquifer thickens to the south and southwest from about 60 to 275 m.

Both the upper and lower confining units are continuous and widespread. In the Glen Rose, layers of limestone and marl alternate and form a local aquifer with a low vertical permeability. The Del Rio Clay is a very efficient confining layer. It consists of low-permeability smectitic shales with occasional shell-fragment beds. Where exposed at the surface, the Del Rio Clay is a gray, sticky, expansive clay and is well known for causing foundation and slope-stability problems. The geologic formations of the aquifer (Fig. 4) have highly variable hydrogeologic properties. Organic, reeflike buildups of an unusual suborder of bivalves called rudistids are common in the aquifer unit. These provide significant primary porosity. The Regional Dense Member of the Person Formation is relatively unkarstified and functions as a semiconfining unit. The Leached and Collapsed members of the Person Formation and the Kirschberg Evaporite Member of the Kainer Formations tend to be the most permeable units because of secondary permeability caused by dissolution.

The structure is simple regionally, but it can be quite complex locally. Subdued arches and synclines are oriented nearly normal to the strike of the aquifer. The early Miocene, en echelon normal faults of the Balcones fault zone dip toward the Gulf of Mexico. Throws vary, reaching a maximum total displacement of >500 m along the San Marcos Arch (Fig. 5). The result is a series of blocks of Edwards aquifer rocks that are partly to completely offset. Some of these blocks are unconfined and some are confined. The San Marcos Arch has been a persistent high during the late Mesozoic and Cenozoic, and the carbonates that lie above it are more highly dolomitized. Finally, the aquifer has been affected by several uplifts. The first, in the Cretaceous, resulted in karstification before deposition of the Georgetown Formation (Fig. 4); this was followed by several episodes of erosion and karstification. The major uplift, in the early Miocene, led to both major faulting and modern karstification.

The stratigraphic and structural features serve to (1) control the distribution of recharge features, primary and secondary porosity, permeability, and water chemistry and (2) make the Edwards one of the most highly productive aquifers in North America. Even though the aquifer is commonly treated as a single hydrostratigraphic unit, its properties are highly variable both laterally and vertically. This variability, coupled with the intricacies and variability created by karstification, leads to considerable complexity within the aquifer.

HYDROGEOLOGY

The Edwards aquifer receives approximately 80% of its recharge through losing (influent) streams that flow over its unconfined parts. Most of the remaining recharge is from direct precipitation on aquifer outcrops. Minor amounts of recharge come from the movement of saline ground waters across the bad-water line, from leaky water mains and sewage lines in urbanized areas, and from cross-formational flow from underlying units. A cross-formational flow component is locally important especially to the north, where the aquifer thins, and it may be identified by chemical and isotopic signatures (Clement and Sharp, 1988; Oetting et al., 1996). Recharge from streams is highly variable because it depends primarily upon the duration and intensity of stream flows. Figure 6 shows historical trends in recharge to and discharge from the aquifer. Average recharge over the period of record has been 682,800 acre-feet/year (26.63 m^3/s), but the highest recorded recharge was 2,486,000 acre-feet/year (96.95 m^3/s) in 1992, and the lowest recorded was 43,700 (1.70 m^3/s) in 1956 (Edwards Underground Water District, 1993). Discharge is by springs and wells, and well discharge has increased in the 60 years of record to meet the growing needs of the population and irrigation. Well discharge is inversely correlated with years of high recharge (and precipitation).

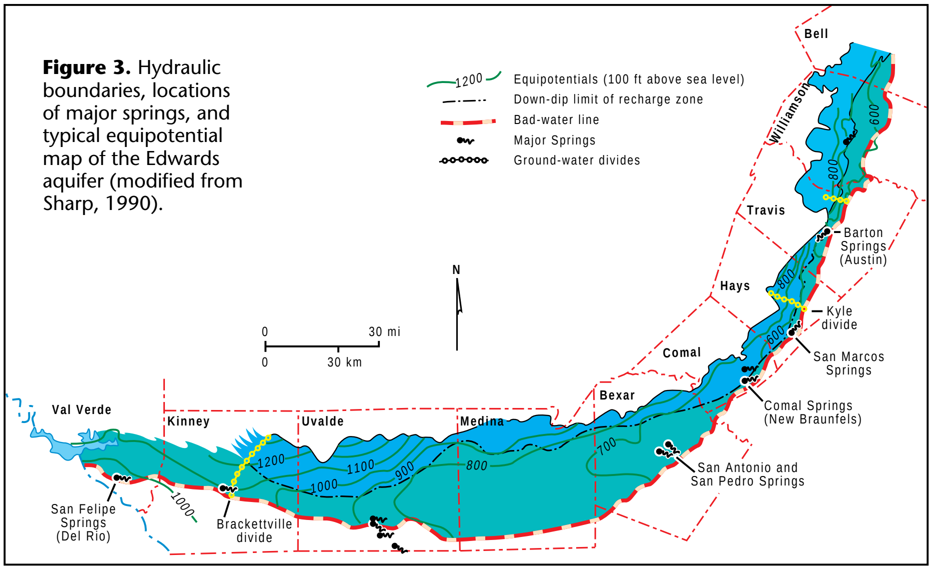


Figure 3. Hydraulic boundaries, locations of major springs, and typical equipotential map of the Edwards aquifer (modified from Sharp, 1990).

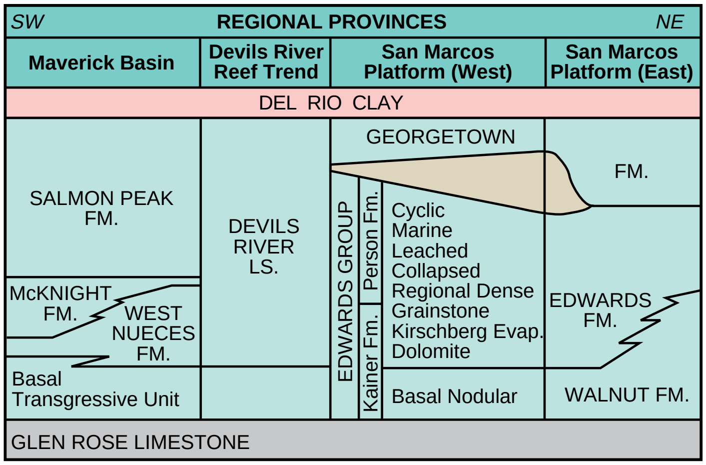


Figure 4. Stratigraphic formations that make up the Edwards–Balcones fault zone aquifer. Member names are shown for the Person and Kainer Formations.

Nevertheless, the current needs of the regions that depend upon the aquifer exceed the historical water availability during the drought of 1947–1956. When a similar decadal drought occurs, it will be a considerable hardship to the region. In order to plan for the combination of an extended period of low recharge with the rapid urbanization of the area, authorities must consider use restrictions and water-supply plans, as discussed below, and ways to raise revenue to institute them, including (unpopular) higher water rates or (equally unpopular) higher taxes.

The general flow systems are understood, but local hydrogeological details are complex. Faulting and subsequent dissolution along fractures create a very heterogeneous and anisotropic permeability distribution. The orientation of the maximum permeability is subparallel to the strike of the rocks and fracture trends. All waters recharged east of the ground-water divide near Brackettville flow east, where they discharge to wells or at the large springs. These include San Pedro and San Antonio springs in San Antonio, Comal Springs and Hueco Springs, near New Braunfels, and San Marcos Springs in San Marcos. In the confined part of the Edwards, the flow is nearly parallel to the strike of the aquifer. San Marcos Springs is the lowest natural discharge point of the aquifer (570 ft/174 m above mean sea level). Just north of San Marcos, a ground-water divide near Kyle separates the San Antonio system of the aquifer from the Barton Springs system, which ultimately discharges to the Colorado River in Austin.

Maclay and Small (1986) and Maclay and Land (1988) recognized several domains of highly variable transmissivity. Faulting has juxtaposed different hydrostratigraphic units in the aquifer, so that some fault blocks are almost isolated. Other blocks are connected, to varying degrees, with the adjacent ones, because of the variable hydraulic characteristics of the different members within the aquifer and variation in the throw of faults. The faults may serve as barriers to flow between blocks and simultaneously serve as conduits to flow along the fracture planes. Only guesses can be made regarding the detailed hydraulic characteristics of the fracture systems. There are extensive cave systems that support a strikingly diverse subsurface ecosystem that includes two species of blind catfish (Longley, 1981). Flow-system delineation by tracer tests demonstrated complexities unusual even in karst systems (N. Hauwert, 1996, personal commun.). Consequently, even though several numerical models have been developed, they only simulate the general characteristics of the system. It is often proposed at public hearings that the aquifer can be overdrafted during drought because large recharge events will replenish the aquifer. This would avoid both the costs of a huge regional water distribution system and use restrictions, and would allow the current users of the aquifer to continue to use this very high quality, cheaply produced water for current and projected needs. However, this scenario is rendered tenuous by unknown potential effects of severe overdrafting on water quality, water availability, and habitats (especially those of endangered species living in the two largest spring systems).

GEOCHEMISTRY: BAD WATER, FRESH WATER, AND EFFECTS OF URBANIZATION

Major and trace element concentrations and isotopic variations in Edwards ground waters provide clues to the sources of dissolved ions in the waters and the

Edwards Aquifer *continued on p. 6*

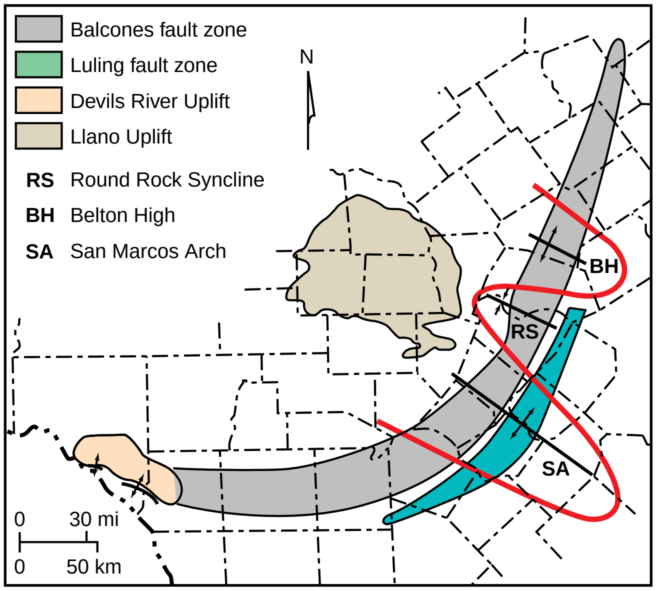


Figure 5. Structural trends in the Edwards aquifer (modified from Sharp, 1990).

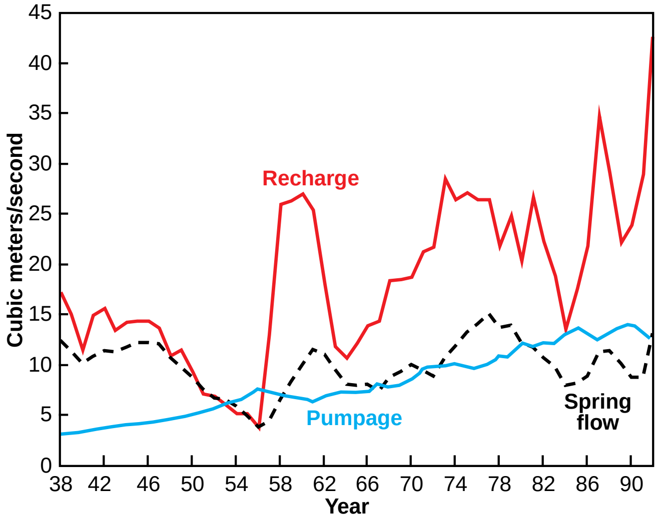


Figure 6. Water budget for the San Antonio part of the Edwards aquifer. Five-year linearly weighted averages of recharge and discharge from wells and springs (data from Edwards Underground Water Conservation District, 1992, written commun.). Note: 1,000 acre feet per year = 1.38 cfs = 0.039 m^3/s.

Edwards Aquifer *continued from p. 5*

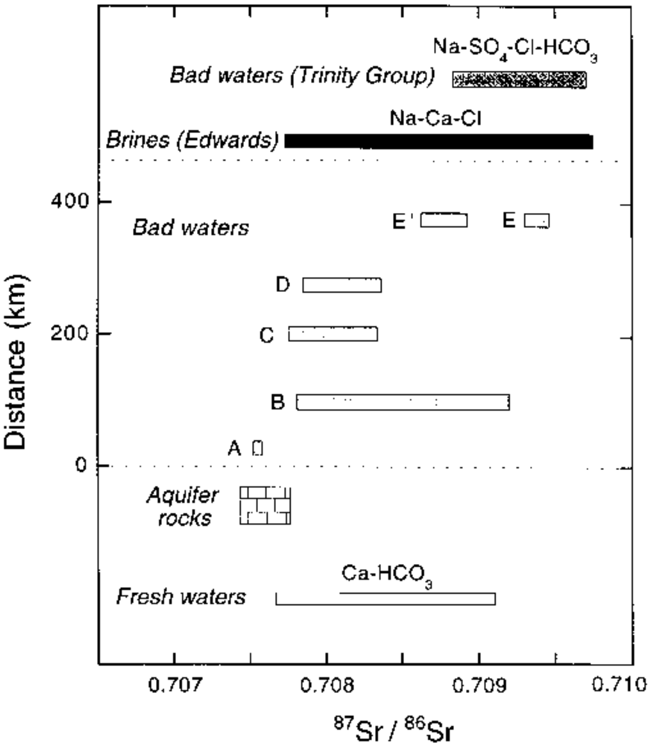


Figure 7. Strontium isotope variations in the Edwards aquifer system. All ^{87}Sr/^{86}Sr values are for waters and rocks from the Edwards, except for those of the Trinity Group bad waters, which are from underlying stratigraphic units. Low ^{87}Sr/^{86}Sr values of aquifer carbonate and evaporite rocks reflect their Lower Cretaceous marine origin. Major ion compositions are used to define six Edwards bad-water hydrochemical facies, A through E', that are also geographically distinct, as represented by distance along a southwest-northeast transect along the bad-water line from Kinney to Bell County. These bad waters change in the southwest-northeast sequence: facies (A) Ca-SO$_4$ waters; (B) Ca-Mg-SO$_4$ (low Na-Cl); (C) Ca-Mg-SO$_4$ (high Na-Cl); (D) Na-Cl; (E) Na-SO$_4$-Cl; (E') Na-Cl-SO$_4$-HCO$_3$. The geochemistry of Edwards bad waters portray regional controls on ground-water evolution, as discussed in the text. Only Edwards bad-water samples are referenced to the ordinate. Although fresh waters in the Edwards aquifer (ground water, surface water, and precipitation) have a wide range in ^{87}Sr/^{86}Sr similar to bad waters and brines, fresh-water isotopic variations appear to reflect more local controls such as flow paths and residence time in the aquifer. Data are from Oetting (1995), Oetting et al. (1996), and sources cited by them.

processes that govern the chemical evolution of the waters. As demonstrated by Sharp and Clement (1988), the bad-water line marks the convergence of two flow systems (Fig. 3). The first is characterized by very high permeabilities and flow rates and by low-salinity, oxidizing Ca-HCO$_3$ waters. The second flow system is relatively stagnant and is characterized by higher salinity, reducing waters of several hydrochemical facies. Consequently, this chemical boundary (the bad-water line) also reflects a physical change in the hydrogeological regime. Downdip from the aquifer toward the Gulf of Mexico, Edwards aquifer–equivalent rocks are important oil reservoirs. Natural oil seeps occur in outcrops of aquifer rocks along the Balcones fault zone. Hydrocarbons and associated oil-field brines influence bad-water zone chemistry in the central part of the Edwards aquifer. Integrated Sr isotopic and major and trace element variations indicate that a wide range of processes are involved in the origin and evolution of different bad-water hydrochemical facies in the Edwards (Fig. 7; Clement and Sharp, 1988; Oetting et al., 1996). These processes include (1) incongruent dissolution of gypsum, (2) recrystallization of calcite, (3) ion exchange with clays, (4) sulfate reduction, (5) fluid mixing involving at least five end-member ground-water compositions, and (6) interaction with igneous intrusions. Regional and local variations in hydrogeologic parameters that may govern the extent to which these processes occur include the mineralogy and thickness of the aquifer, the extent of flow along fractures, and the composition of saline ground waters in Edwards rocks downdip and in underlying hydrostratigraphic units.

Strontium isotope values in Edwards aquifer bad waters vary regionally, from lower values in the southwest part of the aquifer, where it is relatively thick and evaporite-rich, to higher values in the northeast, where the aquifer is thinner and evaporite-poor. This can be accounted for by the enhanced effect of mineral-solution reactions between bad-water and host-aquifer minerals in the southwest aquifer region (i.e., facies A in Fig. 7) and the increased mixing of saline waters from downdip Edwards units and underlying hydrostratigraphic units in the northeastern part of the aquifer (i.e., facies E and E'). The geochemical and isotopic signatures of bad waters may be useful in monitoring the encroachment and source of Edwards brines or cross-formational flow from underlying hydrostratigraphic units into the aquifer in response to drought or increased pumpage. The saline water encroachment problem is particularly pertinent in densely populated areas that rely solely on the Edwards, such as San Antonio, where fresh ground water is withdrawn from wells near the bad-water line.

In contrast to the regional bad-water compositional patterns, geochemical and Sr isotope variability in the fresh-water aquifer appears to be a function of variations in smaller scale factors such as flow routes and ground-water residence times in the karst aquifer, soil type and thickness, and land use (e.g., Banner et al., 1996). Studies of local fresh-water flow systems within the Edwards, such as the Barton Springs segment in the Austin area (Fig. 3), indicate that ground water and surface water in some parts of the aquifer contain higher than normal concentrations of sediment, hydrocarbons, pesticides, bacteria, nitrate, and heavy metals. The spatial distribution of elevated contaminant levels in ground water relative to land use indicate some correspondence between contamination and those parts of the aquifer where urban development has been heaviest (Slade et al., 1986; Veenhius and Slade, 1990; Hauwert and Vickers, 1994). This correspondence is enhanced in surface waters during periods of increased runoff and flow resulting from storms (Veenhius and Slade, 1990). Conflicting interests regarding the development of the aquifer's watersheds has led to intense scrutiny of the scientific methods used in such water-quality studies (see Addendum to Hauwert and Vickers, 1994). Future studies of the effects of development on water quality in the Edwards will need to constrain natural compositional variability and flow paths (using tracers), as well as changes in land use and impervious surface coverage. The amount and distribution of impervious cover are key measures for assessing and predicting the effects of urbanization on water quality in watersheds in Austin and other metropolitan areas (Veenhius and Slade, 1990; Schueler, 1994).

On the basis of regional geochemical studies, it is clear that more focused studies of surface water and ground water within individual watersheds in the Edwards aquifer will improve our understanding of the sources and transmission of water, sediment, and dissolved material through the aquifer. Mineralogical and chemical studies of sediment sampled from recharge and discharge sites and from within the aquifer demonstrate the potential for allochthonous sediments to introduce and transport surface contaminants into the aquifer (Mahler and Lynch, 1996). Integration of hydrogeological, geochemical, and biological studies may reveal critical habitat controls, such as solute sources, on biota that occupy surface and ground-water ecosystems (e.g., Carney et al., 1996). Geochemical and geochronological studies of calcite deposits in Edwards caves can provide insight about the relation between climate variability and ground-water flow and composition on a range of temporal scales (e.g., Banner et al., 1996).

ENDANGERED SPECIES

A significant drop in natural (spring) discharge occurred during the period from 1947 to 1956 (see Fig. 6). The two largest spring systems are Comal and San Marcos springs. Comal Springs ceased flow for more than four months in 1956, and San Marcos Springs discharge dropped to about 50 cubic feet per second (cfs) (1.42 m^3/s). Since then, several organisms living in these springs have been listed under the Endangered Species Act of 1973. At San Marcos Springs, these are (1) the San Marcos salamander *(Eurycea nana),* (2), a fish, the fountain darter *(Etheostoma fonticola),* and (3) the Texas wild rice *(Zizania texana)*. A fourth species, the San Marcos gambusia *(Gambusia georgei)* has not been observed for several years. This fish may be extinct, but it is still listed. At Comal Springs, fountain darters had been present before 1956, but they could not be found in 1974 (Schenck, 1975). Fountain darters from San Marcos Springs were reintroduced to the Comal Springs system between February 1975 and March 1976 (U.S. Fish and Wildlife Service, 1984). There is now a significant population of the darters at Comal Springs (Crowe and Sharp, 1997). Several other species at Comal Springs may be candidates for listing as endangered species. These include the Comal Springs salamander (*Eurycea* sp.) and the Comal Springs riffle beetle *(Heterelnis comalensis)*.

A lawsuit was filed in 1991 by the Sierra Club against the U.S. Fish and Wildlife Service and other agencies in order to maintain adequate spring flows for the preservation of these species. This has resulted in the establishment of minimum springs flows required for the preservation of the species. These minima are 100 cfs (2.83 m^3/s) at San Marcos Springs and 200 cfs (5.66 m^3/s) at Comal Springs. The latter limit may be reduced to 150 cfs (4.25 m^3/s) if the ramshorn snail, an introduced tropical species, can be controlled. This snail is a voracious herbivore and can significantly alter the ecosystem of the Comal Springs system. A review of these requirements can be found in McKinney and Sharp (1995). Historical data, however, clearly demonstrate that spring flows in the Edwards (not just at these two largest springs) cannot be maintained under the drought conditions similar to those of the mid-1940s to mid-1950s, even if the demand for water was still that low.

The Barton Springs salamander *(Eurycea sosorum)* was recently listed by the federal government as an endangered species. This salamander has been found only in Barton Springs in Austin (Fig. 1), and its population is smaller than that of the San Marcos salamander. Protection of endangered species requires protection of the spring system environments against contamination and loss of flow—a difficult task in a region of increasing urbanization.

LEGAL-POLITICAL-ECONOMIC MANAGEMENT PROBLEMS

Texas has an intriguing system of water law. Surface waters are owned and allocated by the state. Any extraction of water from a stream or its underflow (Meinzer, 1923; Larkin and Sharp, 1992), except for domestic or livestock use, must be approved by the state. On the other hand, ground water belongs to the land owner who can produce it by the "rule of capture." The owners of the land above the Edwards aquifer consequently have a legal right to pump as much water as they can as long as they use it beneficially, don't use it in a malicious manner, or negligently cause subsidence. However, continued pumping during times of drought will reduce spring flows and violate the Endangered Species Act. In addition, the communities of New Braunfels and San Marcos gain considerable revenues from the recreational users of the Comal and San Marcos rivers, which are fed almost solely by the springs. The Edwards Aquifer Authority was created by the Texas legislature in January 1993, to regulate withdrawals in order to protect spring flows and thereby protect the endangered species of Comal and San Marcos springs. However, resolutions to the conflicts are not cheap, readily available, or agreeable to all parties.

First, population growth is intensifying water demands. Second, there are no potential alternative water resources that can provide high-quality, abundant water as cheaply as the Edwards aquifer. Third, there are few, if any, sites for potential high-yield reservoirs in the area, and downstream users of streamflow, such as the city of Corpus Christi, object to actions that will diminish the flows that replenish their reservoirs. In addition, some levels of fresh-water flow to the coast are required to maintain the ecological health of the estuaries of the south Texas Gulf Coast. The state of Texas and the users of the Edwards aquifer waters are not immune to the financial consequences of who will be allocated or supplied with water. Coupling these considerations with the complexities of interbasin or interstate regional water transfer makes clear the difficulties associated with future water-resource development in this area, even though it overlies one of the most prolific aquifers in the world.

Solutions to all water shortages involve one or more of the following types of actions: (1) increasing water supplies, (2) decreasing water demands, or (3) better management and more efficient use of existing resources. How much water is stored in, discharges from, and recharges the aquifer is generally known, as is how the water is being used (53% municipal, 36% agricultural, 3% industrial, 8% rural domestic and livestock; Technical Advisory Panel, 1990). Potential management actions will benefit from a better understanding of the hydrogeology of the Edwards aquifer. If the detailed hydrogeology were better understood, for instance, then we should be better able to: (1) target well-field locations to maximize production and minimize adverse effects; (2) manage well production with respect to which river basin is contributing recharge; (3) evaluate more precisely methods of spring-flow augmentation which could be used to maintain minimal flows during drought; (4) predict more accurately how waste water recovery (and injection?) systems will function in the aquifer; and (5) predict more accurately the effects of urban development, construction, and point-source pollution. In particular, as the watersheds in the urban areas increase the amount of impervious cover and sewage lines (which inevitably leak), what will be the eventual effects on water quality?

PROMISING RESEARCH

Analysis of the Edwards aquifer situation suggests that detailed hydrogeological studies could have significant economic applications as well as providing new insights into the processes that form the aquifer, the processes now occurring in the aquifer, and how to develop more meaningful numerical simulations. Detailed precise answers are sought by the various groups contesting uses of the Edwards waters, but our hydrogeological and hydrostratigraphic knowledge is of a regional and conceptual nature. Significant financial decisions will be based upon our current knowledge, or lack thereof. The scientific questions include: What are the details of the aquifer's hydrogeologic property distribution?; What is the extent of flow between various fault blocks?; Can we predict travel paths and times within the aquifer?; and What flow equations are suitable? For instance, is Darcy's Law applicable, or is the flow better described by turbulent flow models? Can we quantify with any reasonable degree of certainty how siting of the pumping wells would affect spring flows?

Uncertainties exist in the analysis for methods of springflow augmentation and artificial recharge. Artificial recharge structures have been proposed, and some have been constructed with some success (HDR, 1993). Not all sites or areas are

Edwards Aquifer *continued on p. 8*

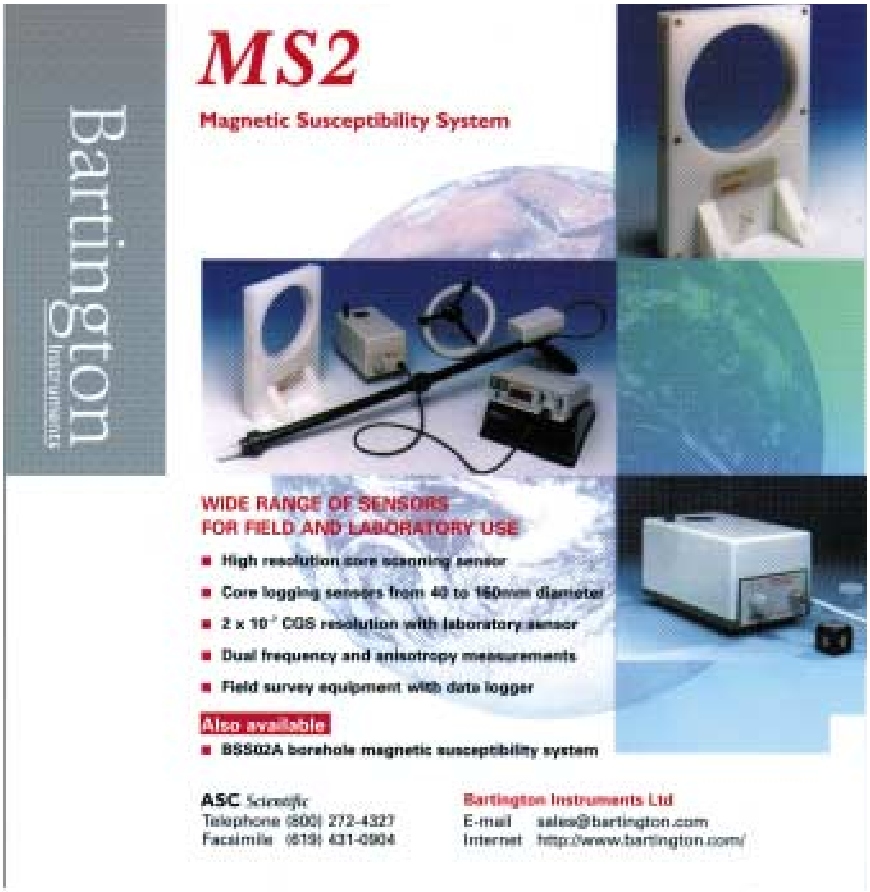
Edwards Aquifer *continued from p. 7*

equally conducive, because the permeabilities and the connections between various faulted blocks are irregular. What are the best mechanisms and where are the best sites for enhanced or artificial recharge? Uliana and Sharp (1996) and McKinney and Sharp (1995) examined potential methods for spring-flow augmentation. They noted that geological mapping and tracer tests are required near the large springs before the feasibility of these methods can be assessed with confidence. Detailed hydrogeological mapping of the aquifer has not been accomplished despite numerous previous studies (Menard, 1995), but recent studies by Hovorka et al. (1993, 1995), Stein and Ozuna (1995), Small et al. (1996), and Hauwert (1997) are encouraging because they provide high quality conceptual and numerical data. Determining the effects of both natural processes and changing land use on water quality will require studies that cover a range of spatial and temporal scales.

Another important question requiring quantification is the effect on the downstream users of the proposed water resource developments relating to the aquifer. For instance, it is commonly assumed by the general public that all the water that issues from the springs flows into the Gulf of Mexico. The other extreme position is that even if all discharge from the springs were diverted, there would be very little effect on fresh water reaching the Gulf Coast. Water balance studies should be conducted to analyze these possibilities.

Scientific analyses are needed for the evaluation of water-supply proposals, which range from the simple to the grandiose, such as a massive regional transfer of water from east Texas or Louisiana to Houston, Austin, and San Antonio. For instance, would the environmental consequences of such a scheme be greater than those from periodic diminution of spring discharges below the take limit flows for endangered species? (Take limit flows are the established minima below which we cannot maintain the species' critical habitat.) What would be the effects of such transfers on the coastal systems or on river systems such as the Sabine, the Trinity, or the Brazos? Finally, political and economic studies are also required. For instance, curtailment of irrigated agriculture during droughts would reduce spring-flow diminution. What would be the legal, economic, social, and hydrologic effects of such an action?

The Edwards aquifer represents an important natural resource where geologic, hydrologic, biologic, legal, political, and socioeconomic factors are intertwined. The region will be developed and the aquifer will be stressed. A greater understanding of the aquifer's and the region's hydrogeology is required to use these precious water resources more efficiently in response to the changing combination of demands and constraints.



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REFERENCES CITED

Austin-American Statesman, 1996, Houses sprouting in Williamson: September 9, p. 1.

Bader, R. W., Walthour, S. D., and Waugh, J. R., 1993, Edwards aquifer hydrogeologic status report for 1992: Edwards Underground Water District (now Edwards Aquifer Authority) Report No. 93-05, San Antonio, Texas, 71 p.

Banner, J. L., Musgrove, M., Edwards, R. L., Asmerom, Y., and Hoff, J. A., 1996, High-resolution temporal record of Holocene groundwater chemistry: Tracing links between climate and hydrology: Geology, v. 24, p. 1049–1052.

Carney, J., Smith, A. J., and Forester, R. M., 1996, Identifying modern analogs of Holocene recharge history for the Edwards aquifer, Central Texas, using ostracodes: AMQUA Proceedings with Abstracts, p. 70.

Clement, T. J., and Sharp, J. M., Jr., 1988, Hydrochemical facies in the bad-water zone of the Edwards aquifer, Central Texas, *in* Proceedings of the Ground Water Geochemistry Conference: Dublin, Ohio, National Water Well Association, p. 127–149.

Crowe, J., and Sharp, J. M., Jr., 1997, Hydrogeologic delineation of habitats for endangered species: The Comal Springs/River system: Environmental Geology, v. 30, p. 17–28.

Hauwert, N., and Vickers, S., 1994, Barton Springs/Edwards aquifer hydrogeology and groundwater quality: Barton Springs/Edwards Aquifer Conservation District, Austin, TX, Contract 93483-346 Report to Texas Water Development Board, 92 p.

Hauwert, N., 1997, Geological map of the Barton Springs segment of the Edwards aquifer: Austin, Texas, Barton Springs/Edwards Aquifer Underground Water Conservation District, 1 sheet.

HDR Engineering, Inc., 1993, Recharge enhancement study: Guadalupe–San Antonio River Basin: San Antonio, Texas, Volume 1, Executive Summary, 44 p.

Hovorka, S. D., Ruppel, S. C., Dutton, A. R., and Yeh, J., 1993, Edwards aquifer storage assessment, Kinney County to Hays County, Texas: San Antonio, Texas, Edwards Aquifer Underground Water Conservation District Report No. 93-04-F0, 101 p.

Hovorka, S. D., Mace, R. E., and Collins, E. W., 1995, Regional distribution of permeability in the Edwards aquifer: San Antonio, Texas, Edwards Aquifer Underground Water Conservation District Report No. 93-17-F0, 128 p.

Larkin, R. G., and Sharp, J. M., Jr., 1992, On the relationship between river basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial

Edwards Aquifer *continued on p. 9*

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Edwards Aquifer *continued from p. 8*

aquifers: Geological Society of America Bulletin, v. 104, p. 1608–1620.

Lesser, J. M., and Lesser, G., 1988, Region 9, Sierra Madre Oriental, *in* Back, W., et al., eds., Hydrogeology: Boulder, Colorado, Geological Society of America, Geology of North America, v. O-2, p. 89–92.

Livingston, p., 1942, A few interesting facts regarding natural flow from artesian well 4, owned by the San Antonio Public Service Company, San Antonio, Texas: U.S. Geological Survey Open-File Report, 7 p.

Longley, G. 1981, The Edwards aquifer—Earth's most diverse groundwater ecosystem?: International Journal of Speleology, no. 11, p. 123–128.

Maclay, R. W., and Land, L. F., 1988, Simulation of flow in the Edwards aquifer, San Antonio region, Texas, and refinements of storage and flow concepts: U.S. Geological Survey Water-Supply Paper 2336-A, 48 p.

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

Mahler, B. J., and Lynch, F. L., 1996, Characteristics of mobile sediment in a karst aquifer: Geological Society of America, Abstracts with Programs, v. 28, no. 7, p. A-479.

McKinney, D. C., and Sharp, J. M., Jr., 1995, Springflow augmentation of Comal and San Marcos Springs, Texas: Phase I—Feasibility study: Austin, Texas, Center for Research in Water Resources, University of Texas, Technical Report CRWR 247.

Meinzer, O. E., 1923, Outline of ground-water hydrology with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p.

Menard, J. A., 1995, Bibliography of the Edwards aquifer, Texas, through 1993: U.S. Geological Survey Open-file Report 95-336, 75 p.

Oetting, G. C., 1995, Evolution of fresh and saline waters in the Edwards aquifer, central Texas: Geochemical and isotopic constraints on processes of fluid-rock interaction and fluid mixing [M.A. thesis]: Austin, University of Texas, 204 p.

Oetting, G. C., Banner, J. L., and Sharp, J. M., Jr., 1996, Geochemical evolution of saline groundwaters in the Edwards aquifer, central Texas: Regional stratigraphic, tectonic, and hydrodynamic controls: Journal of Hydrology, v. 181, p. 251–283.

Pavlicek, D. L., Small, T. A., and Rettman, P. L., 1987, Hydrogeologic data from a study of the freshwater zone/saline water zone interface in the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Open-File Report 87-389, 108 p.

Rose, P. R., 1972, Edwards group, surface and subsurface, central Texas: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 74, 198 p.

Schenck, J. R., 1975, Ecology of the fountain darter, *Etheostoma fonticola (Osteichthyes: Percidae)* [M.S. thesis]: San Marcos, University of Southwest Texas, 100 p.

Schueler, T., 1994, The importance of imperviousness: Watershed Protection Techniques, v. 1, p. 100–111.

Sharp, J. M., Jr., 1990, Stratigraphic, geomorphic and structural controls of the Edwards aquifer, Texas, U.S.A., *in* Simpson, E. S., and Sharp, J. M., Jr., Selected papers on hydrogeology: Hannover Germany, International Association of Hydrogeologists, v. 1, p. 67–82.

Sharp, J. M., Jr., and Clement, T. J., 1988, Hydrochemical facies as hydraulic boundaries in karstic aquifers—The Edwards aquifer, U.S.A., *in* Proceedings of the 21st I.A.H. Congress, Karst Hydrogeology and Karst Environment Protection, Guilin, People's Republic of China: Beijing, Geological Publishing House, v. 2, p. 841–845.

Slade, R. M. Jr., Dorsey, M. E., and Stewart, S. L., 1986, Hydrology and water quality of the Edwards aquifer associated with Barton Springs in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 86-4036, 117 p.

Small, T. A., Hanson, J. A., and Hauwert, N. M., 1996, Geologic framework and hydrogeologic characteristics of the Edwards aquifer outcrop (Barton Springs segment), northeastern Hays and southwestern Travis Counties, Texas: U.S. Geological Survey Water-Resources Investigations Report 96-4306, 15 p.

Stein, W. G., and Ozuna, G. B., 1995, Geologic framework and hydrogeologic characteristics of the Edwards aquifer recharge zone, Bexar County, Texas: U.S. Geological Survey Water- Resources Investigations Report 95-4030, 8 p.

Swanson, G. J., 1991, Super well is deep in the heart of Texas: Water Well Journal, no. 7 (July), p. 56–58.

Technical Advisory Panel, 1990, Technical factors in Edwards aquifer use and management: Report to Special Committee on the Edwards Aquifer (Joint Committee of Texas Senate and House of Representatives), 57 p.

Tilford, N. E., 1994, Site selection: Past and present: Association of Engineering Geologists Bulletin, v. 31, p. 157–169.

Uliana, M., and Sharp, J. M., Jr., 1996, Springflow augmentation possibilities at Comal and San Marcos springs, Edwards aquifer: Gulf Coast Association of Geological Societies Transactions, v. 46, p. 423–432.

U.S. Fish and Wildlife Service, 1984, San Marcos River recovery plan for San Marcos River endangered and threatened species—San Marcos gambusia (*Gambusia georgei* Hubbs and Peden), fountain darter (*Etheostoma fonticola* Jordan and Gilbert), San Marcos salamander (*Eurycea nana* Bishop), and Texas wild rice (*Zizania texana* Hitchcock): Albuquerque, New Mexico, 109 p.

Veenhuis, J. E., and Slade, R. M., Jr., 1990, Relation between urbanization and water quality of streams in the Austin area, Texas: U.S. Geological Survey Water-Resources Investigations Report 90-4107, 64 p.

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