

Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer, central Texas

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ABSTRACT

The Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer is a prolific karst aquifer system containing the fourth largest spring in Texas, Barton Springs. The Barton Springs segment of the Edwards Aquifer supplies drinking water for ~60,000 people, provides habitat for federally listed endangered salamanders, and sustains the iconic recreational Barton Springs pool. The aquifer is composed of Lower Cretaceous carbonate strata with porosity and permeability controlled by depositional facies, diagenesis, structure, and karstification creating a triple permeability system (matrix, fractures, and conduits). Groundwater flow is rapid within an integrated network of conduits discharging at the springs. Upgradient watersheds provide runoff to the recharge zone, and the majority of recharge occurs in the streams crossing the recharge zone. The remainder is direct recharge from precipitation and other minor sources (inflows from Trinity Group aquifers, the San Antonio segment, the bad-water zone, and anthropogenic sources). The long-term estimated mean water budget is 68 ft³/s (1.93 m³/s). The Barton Springs/Edwards Aquifer Conservation District developed rules to preserve groundwater supplies and maximize spring flow rates by preserving at least 6.5 ft³/s (0.18 m³/s) of spring flow during extreme drought. A paradox of the Barton Springs segment of the Edwards Aquifer is that rapid recharge allows the Barton Springs segment of the aquifer to be sustainable long term, but the aquifer is vulnerable and limited in droughts. The karstic nature of the aquifer makes the Barton Springs segment vulnerable to a variety of natural and anthropogenic contaminants. Future challenges will include maintaining the sustainability of the aquifer, considering climate change, population growth, and related land-use changes.

INTRODUCTION

The Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer is a prolific karst aquifer system primarily discharging at Barton Springs, the fourth largest spring in Texas (Fig. 1). The Barton Springs segment of the aquifer is the smallest of the Edwards (Balcones Fault Zone) Aquifer segments at ~20 mi (32 km) long north-south and 3–10 mi (5–16 km) wide east-west, for a freshwater area of ~166 mi² (30 km²; Table 1). The Barton Springs segment represents ~4% of the total Edwards (Balcones Fault Zone) Aquifer area, and ~6–9% of the total water budget (Fig. 2; Smith et al., 2005a; Anaya et al., 2016).

The Barton Springs segment of the Edwards Aquifer is a critical groundwater resource, and the majority of its area was designated as a sole source aquifer in 1988 by the Environmental Protection Agency (EPA, 2018). The Barton Springs segment is managed by the Barton Springs/Edwards Aquifer Conservation District (BSEACD). Presently, the aquifer supplies drinking water to ~60,000 people and is also used for industrial (aggregate, cement) and commercial purposes. It also contributes important flow to the Colorado River and therefore is considered a tributary aquifer (Anaya et al., 2016). The springs and aquifer also provide habitat for the federally listed Barton Springs (USFW, 1997) and Austin Blind salamanders (USFW, 2013; see also Krejca and Reddell, this volume; Devitt, this volume).

Barton Springs is located within Barton Creek near the confluence with the Colorado River (Lady Bird Lake) in Zilker Park near downtown Austin, Texas. The springs were an important water source for Native Americans and Spanish explorers (ca. A.D. 1730), and they were ultimately used in milling operations, water supply, and recreation by settlers starting in 1837 (Brune, 2002). In 1920, the City of Austin began construction of a large outdoor swimming pool by damming Barton Creek downstream of the main spring outlet. The pool is sustained by spring flow passing through the pool and over the dam. Barton Springs pool is often described as

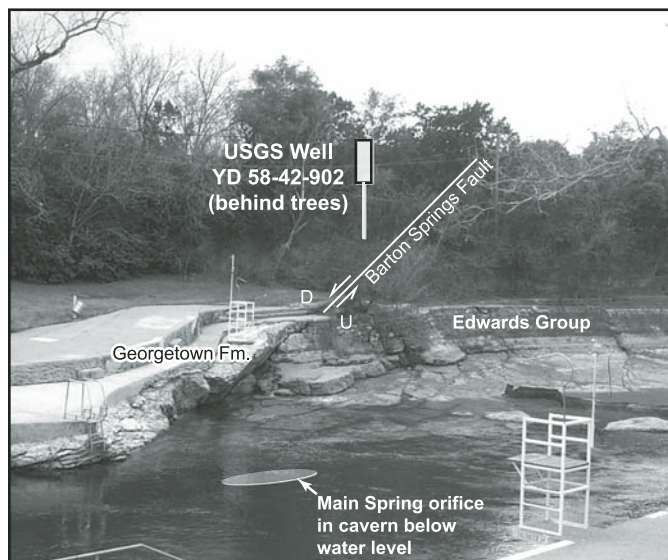


Figure 1. Photograph of Barton Springs during a lowering of the pool water level. Shown are the U.S. Geological Survey well (58-42-902) used for the spring flow rating curve (USGS, 2018), Main Spring within the pool, and the fault offsetting the Georgetown Formation from the Edwards Group. The fault has ~50 ft (15 m) of throw.

the “soul” of Austin, and the pool receives ~800,000 visitors annually (CoA, 2018).

The Barton Springs segment of the Edwards Aquifer is a mature karst aquifer system that is vulnerable to overpumping during drought (Smith and Hunt, 2004) and contamination (Mahler et al., 2006). The aquifer is in one of the fastest growing regions in the United States and is often the source of environmental, economic, social, and political conflict (Sharp and Banner, 1997). This chapter summarizes the current understanding of

TABLE 1. HYDROLOGIC ZONES OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER

| Hydrologic zone | Area (mi ²) | Area (km ²) | Description |
|-----------------------|-------------------------|-------------------------|--|
| Contributing | 671a 264b | 1738a 684b | Allogenic recharge source areas can change based on hydrologic conditions: (a) Blanco, Onion, and Barton Creek watersheds upstream of the recharge zone under low-flow conditions; (b) Onion and Barton Creek watersheds upstream of the recharge zone under average to high-flow conditions |
| Recharge | 107* | 277 | Edwards Group rocks exposed at surface where majority of (autogenic) recharge occurs. Source data: Texas Commission on Environmental Quality (TCEQ) Edwards Aquifer administrative boundary (TCEQ, 2008a) |
| Confined | 59 | 153 | Full thickness of the aquifer; confining units above aquifer, where most pumping occurs. Source data: Texas Water Development Board major aquifers (TWDB, 2017a) |
| Total freshwater area | 166 | 430 | |
| Saline | 470 | 1217 | Approximate area east of the freshwater–saline water interface (Hunt et al., 2014) to the edge of the Carrizo major aquifer boundary |

Note: Data from R. Gary, Barton Springs/Edwards Aquifer Conservation District (2013, personal commun.).

*Within the recharge zone there are sub-groundwater basins such as the Cold Springs springshed, which is about 12 mi² (31 km²; Hauwert, 2016).

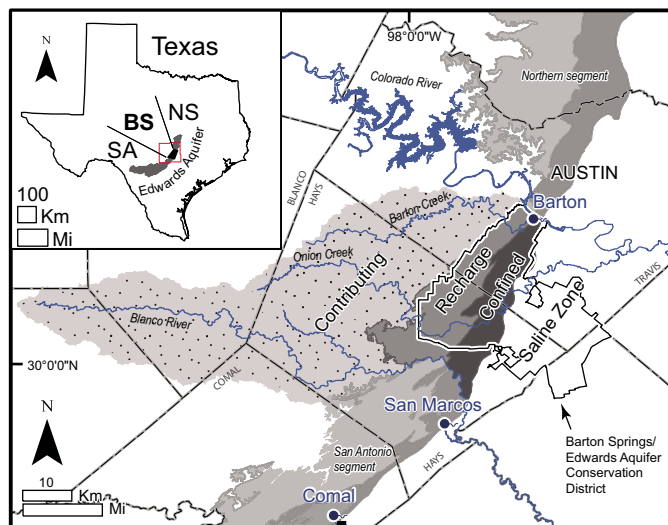


Figure 2. Map showing the three hydrologic zones of the Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer. The contributing zone is up to up to 670 mi² (1735 km²) and includes the Barton, Onion, and Blanco River watersheds upstream of the recharge zone. The Barton Springs segment of the Edwards Aquifer (BS in the inset) is ~166 mi² (430 km²). The boundary between unconfined (recharge zone) and confined conditions is dynamic. The Barton Springs segment of the Edwards Aquifer is generally contained within the indicated jurisdiction of the Barton Springs/Edwards Aquifer Conservation District (BSEACD). (Inset) Map of the three segments of the Edwards Aquifer (NS—Northern segment, BS—Barton Springs segment, SA—San Antonio segment).

the Barton Springs segment of the Edwards Aquifer and the basis for formulation of policies to preserve and protect the resource. We hope this chapter will serve as a guide for future research into this important groundwater resource.

HYDROGEOLOGIC SETTING

Segment Domain and Boundary Conditions

The boundary conditions for the aquifer are reasonably well constrained (Figs. 2 and 3). The northern boundary along the Colorado River is a regional hydrologic divide and base level, generally separating the Barton Springs segment of the Edwards Aquifer from the Northern segment of the Edwards Aquifer (Jones, this volume), and it is the location of the major springs of the Barton Springs segment of the Edwards Aquifer. To the south, the boundary between the San Antonio segment (Schindel, this volume; Green et al., this volume) and the Barton Springs segment of the Edwards Aquifer is a dynamic divide alternating between the Blanco River and Onion Creek (Fig. 3; Smith et al., 2012). The eastern boundary is the bad-water line (freshwater-saline-water interface; Sharp and Smith, this volume), characterized by an increase in dissolved constituents (>1000 mg/L total

dissolved solids [TDS]) and a decrease in permeability (Flores, 1990; Hunt et al., 2014). The western boundary of the Barton Springs segment is defined by the contiguous outcrop of the Edwards Group (Sharp, this volume), which is influenced by erosion and partly by faulting (Slagle et al., 1986). The Edwards Group units are generally unsaturated along this western boundary; however, the aquifer extends below the Edwards Group and into the Upper Glen Rose member (Wong et al., 2014). Upper Cretaceous shales and limestones that overlie the Georgetown Formation and Edwards Group provide vertical confining units, while evaporite-rich Glen Rose units provide the underlying aquitard boundary (Fig. 4; Wong et al., 2014).

Geologic History

The Barton Springs segment of the Edwards Aquifer units are mostly Lower Cretaceous (Middle and Upper Albian) carbonates that accumulated as a wedge of sediments on the broad shallow-marine, intertidal, and supratidal Comanche Shelf (Rose, 1972). The shelf's linear southeast-trending crest is defined as the San Marcos arch (Fig. 3, inset), which was a positive structural feature that influenced lithofacies, thicknesses, erosion, and diagenesis of the Edwards Group and associated units. The Georgetown Formation in the study area is an Upper Cretaceous (Cenomanian) unit that disconformably overlies the Edwards Group; it was deposited in a more openly circulated, shallow-marine environment (Rose, 2016a). Edwards Group units have undergone extensive diagenesis and speleogenesis, including dolomitization, calcification, silicification (chert), and dissolution (Rose, 1972; Abbott, 1975; Barker et al., 1994; Hovorka et al., 1996).

The Edwards Group has a maximum thickness of 450 ft (137 m) on the arch and thickens to the south into the Maverick Basin and northeastward into the East Texas Basin. Burial of the Edwards Group by Late Cretaceous clays and marls was likely never more than 2000 ft (610 m; Rose, 2016b).

Structure

Uplift of the Central Texas Platform during the late Oligocene (ca. 30 Ma) and early Miocene (ca. 15 Ma) culminated in the Balcones fault zone (Rose, 2016b). The Balcones fault zone defines the physiographic boundary (Balcones Escarpment) between the westerly elevated terrain (Hill Country and Edwards Plateau physiographic regions) and the easterly lower-elevation terrain (Blackland Prairie and Gulf Coastal Plain; Fig. 4).

In the study area, the Balcones fault zone is an en-echelon normal fault system of numerous faults with hanging walls generally down to the east. Faults and fractures generally trend northeast and dip steeply (45°–85°) to the southeast with ~1500 ft (460 m) of total displacement across the Barton Springs segment of the Edwards Aquifer. Faults are associated with other structures such as folds, horsts, grabens, and relay ramps (Grimshaw and Woodruff, 1986; Small et al., 1996; Collins and Hovorka, 1997; Collins, 1996, 2004; Ewing, 2004; Hunt et al., 2015).

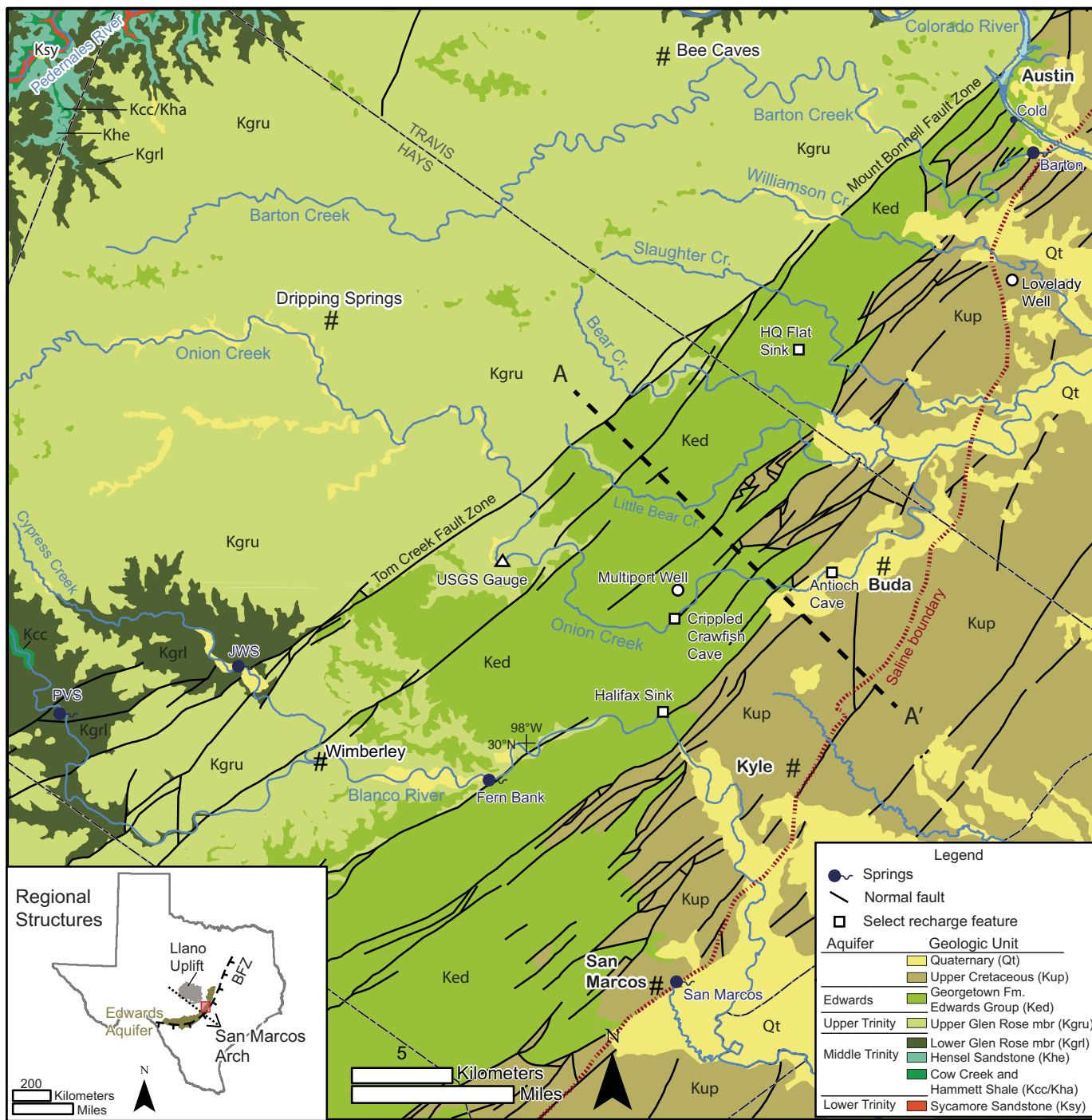


Figure 3. Study area geologic map (Barnes, 1992; Stoesser et al., 2005). Significant Edwards Aquifer springs and recharge features are indicated, as well as the eastern extent of the aquifer (saline-zone boundary). Middle Trinity Aquifer springs shown on the map include Pleasant Valley Spring (PVS) and Jacob’s Well Spring (JWS). Those springs contribute to the perennial flow on the Blanco River and ultimately to recharge of the Edwards Aquifer (both the San Antonio and Barton Springs segments of the Edwards Aquifer). Cross section A–A’ in Figure 4 is indicated. (Inset) Regional geologic and structural features of the study area. These include the Llano Uplift, San Marcos arch, and the Balcones fault zone (BFZ).

Barton Springs segment of the Edwards Aquifer, central Texas

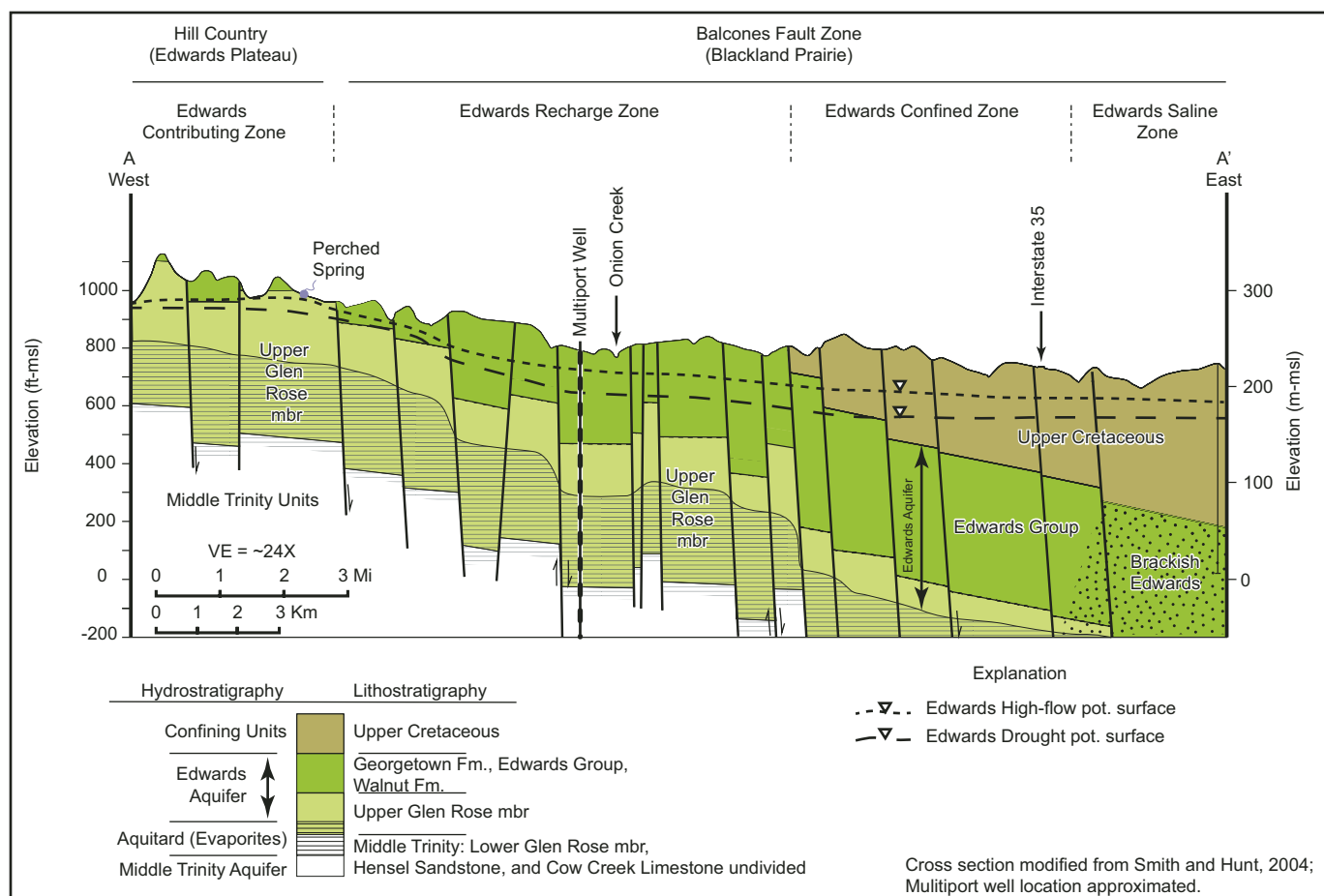


Figure 4. Cross section A–A' indicated in Figure 3. Section illustrates high- and low-flow potentiometric (pot.) surfaces and hydrologic and physiographic zones in relation to the hydrostratigraphy. VE—vertical exaggeration; m msl—meters relative to mean sea level.

Karst

The primary characteristic of karst aquifers is the rapid transport of water through interconnected conduits on a variety of scales. The Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer is considered a mature karst aquifer, characterized by an integrated network of conduits, losing streams, sinkholes, swallets, caves, and springs (Hauwert, 2009). Karstification occurred from a combination of multiple mechanisms. Dissolution of carbonate units by infiltrating meteoric water (epigenic speleogenesis) was the primary mechanism of karst formation (Abbott, 1975; Sharp, 1990; Hovorka et al., 1996, 1998; Schindel and Gary, 2018). Aquifer units were subject to subaerial exposure and early karst processes soon after deposition. However, the Balcones fault zone was most critical for the development of the karst aquifer, providing the geometry and initiation point for epigenic karst processes and the hydrologic connection between surface and groundwater (Abbott, 1975; Woodruff and Abbott, 1986; Ferrill et al., 2004). Dissolution originating from

deep fluid processes (hypogenic speleogenesis) began after the Late Cretaceous and also played an important role in the development of karst and permeability (Schindel et al., 2004, 2008; Schindel and Gary, 2018).

Based on hydrological and geochemical data, the Barton Springs segment of the Edwards Aquifer has been described as having two modes of karstic aquifer response (Wong et al., 2012). During flows less than 50 ft³/s (<1.5 m³/s) spring flow has a covariation to recharge, indicating low storage, similar to a teleogenetic karst system (Florea and Vacher, 2006). Above 50 ft³/s (>1.5 m³/s), spring flow has a lack of covariation with recharge and indicates greater storage of water during higher hydrologic conditions, similar to an eogenetic karst (Wong et al., 2012).

Hydrostratigraphy

The aquifer has historically been defined to include the Edwards Group and the overlying Georgetown Formation (Arnaw, 1963; Slade et al., 1986). The Edwards Group consists

of the Kainer and Person Formations as defined by Rose (1972). Informal hydrostratigraphic units of the Edwards Group were defined and mapped by Small et al. (1996). The Walnut Formation (equivalent to the basal nodular member of the Kainer Formation) in the Barton Springs segment of the Edwards Aquifer may be locally confining, but recent studies indicate a portion of the underlying Upper Glen Rose member is in hydrologic communication with the overlying Edwards Aquifer (Wong et al., 2014; Hunt et al., 2016). These studies have refined the hydrostratigraphy of the Barton Springs segment of the Edwards Aquifer to include the uppermost 100 to 150 ft (30–45 m) of the Upper Glen Rose member (Fig. 5). Evaporite-rich units near the contact between the Upper and Lower Glen Rose members serve as aquitards to varying degrees between the Edwards Aquifer and the middle Trinity Aquifer units (Wong et al., 2014).

CONCEPTUAL MODEL

The conceptual model of the Barton Springs segment of the Edwards Aquifer has been developed over the past 80 yr (Fig. 6; Tyson, 1924; Sayre and Bennett, 1942; Abbott, 1975). Slade et al. (1986) was the first to quantify the conceptual model and publish a water budget. Some of the changes to the conceptual model of the past 30 yr include: (1) expanding the potential recharge sources and contributing areas; (2) changes to the relative allocation of recharge; and (3) characterization and delineation of conduit flow pathways and velocities.

The aquifer is delineated into hydrologic zones (Slagle et al., 1986) that generally describe the hydrogeologic setting and hydrologic processes (Table 1; Figs. 3 and 4). The contributing zone is the watershed providing runoff and base flows to the streams that cross the recharge zone (allogenic recharge). Those contributing zone areas were historically thought to be only the Onion and Barton Creek watersheds, with an area of 264 mi² (684 km²; Slade et al., 1986; Scanlon et al., 2001). However, recent studies indicate that the contributing zone includes the Blanco River under low-flow conditions, effectively increasing the contributing zone area up to 671 mi² (1738 km²; Smith et al., 2012). Streams in the contributing zone also provide recharge to the Trinity aquifers (Smith et al., 2018), and they may provide some limited lateral recharge to the Edwards Aquifer, particularly via the Upper Glen Rose member. The Edwards Aquifer recharge zone is the exposed outcrop of the Edwards Group

and associated units and is the location where the majority of recharge occurs. The confined zone is the area where overlying impermeable units inhibit recharge and hydrologically confine the aquifer. The State of Texas (TCEQ, 2008a, 2008b) and the City of Austin regulate land use based on these zones (see “Land-Use Management” section).

Groundwater flow in the Barton Springs segment of the Edwards Aquifer occurs in a triple permeability system (matrix, fractures, and conduits). Conduit flow occurs within an integrated system that can provide rapid flow to wells and springs (Hauwert et al., 2004a; Mahler et al., 2006). Fractures, enlarged

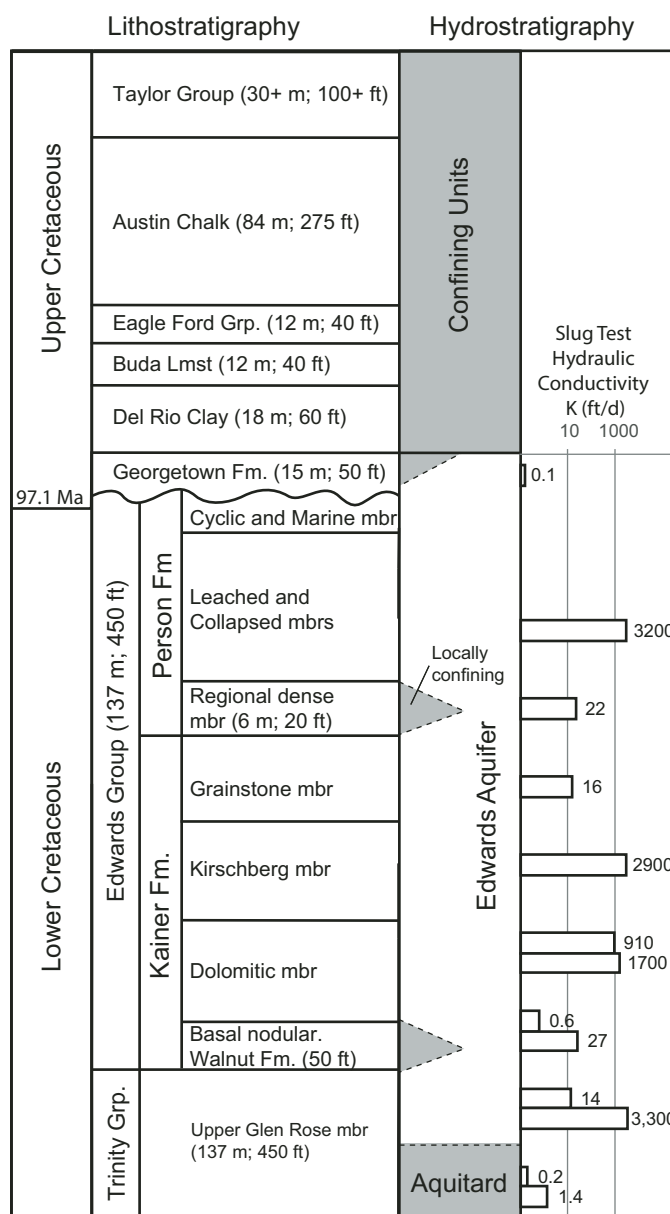


Figure 5. Stratigraphic column of the Barton Springs segment of the Edwards Aquifer. The Georgetown Formation and ~150 ft (45 m) of the uppermost Upper Glen Rose member are part of the Edwards Aquifer. Overlying clay units and underlying evaporite-rich sediments confine the aquifer. The regional dense and basal nodular (Walnut Formation [Fm.] members are locally semiconfining units within the aquifer. Note 1 ft/d = 3.5 × 10⁶ m/s. Lmst—Limestone; Grp.—Group; mbr—member.

Lithostratigraphy modified from Rose (1972) and Barker et al., (1994); Hydrostratigraphy modified Barker et al., (1994), and Hunt et al., (2017). Hydraulic conductivity data from Hunt et al. (2016).

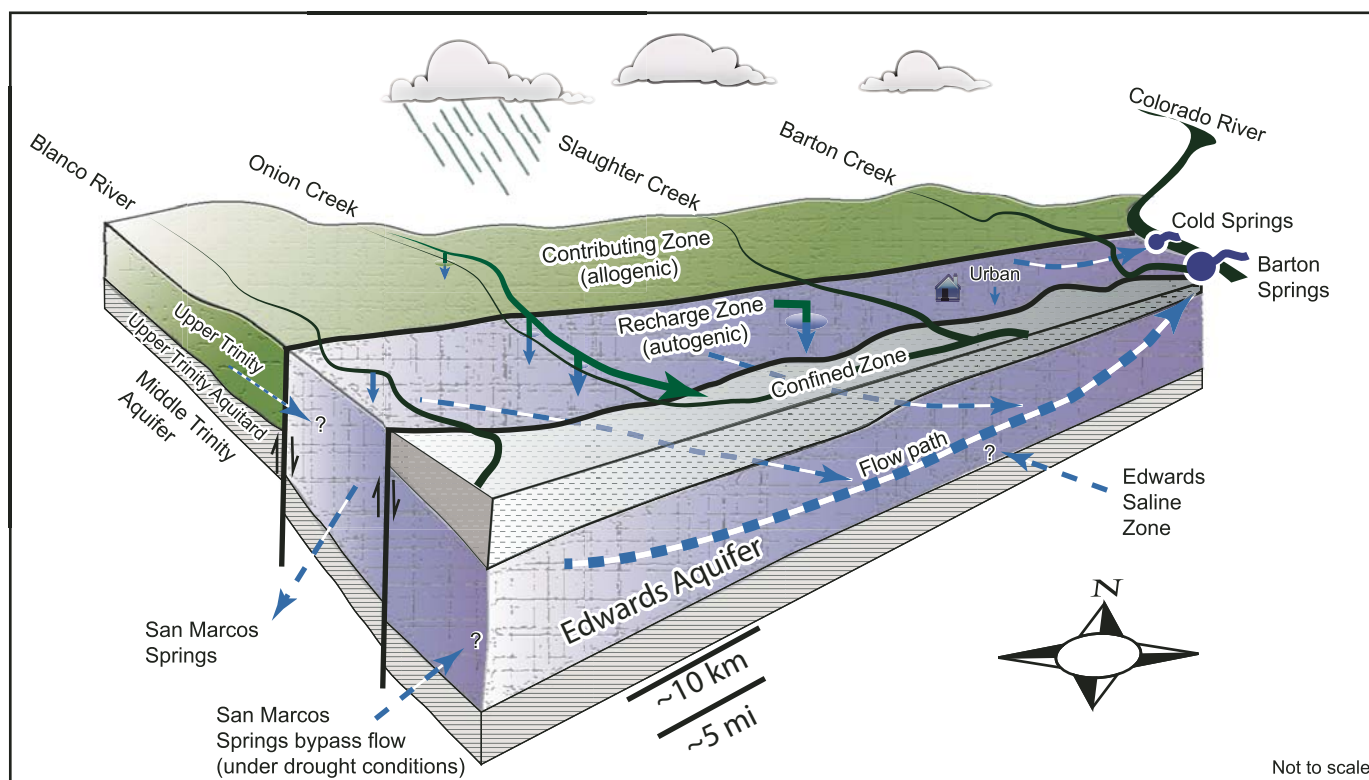


Figure 6. Schematic conceptual model of the Barton Springs segment illustrating the various sources of water, processes, and geographic relationships.

by solution, and bedding planes connect the matrix (storage) to the conduits (Fig. 7).

Climate, Recharge, Groundwater Flow, and Discharge

Climate

The amount of water within a mature karst aquifer is strongly influenced by climate and weather events. The region around the Barton Springs segment of the Edwards Aquifer is humid subtropical, characterized by hot summers and dry, mild winters (Larkin and Bomar, 1983). Annual average rainfall at Austin's Camp Mabry Station is 33.4 in. (85 cm; 1856–2010), with a range of 64.7 in. (164 cm; 1919) to 11.4 in. (29 cm; 1954). The maximum monthly average precipitation is bimodal, with highest precipitation occurring in May and a secondary peak in September (Hunt et al., 2012). Potential evaporation greatly exceeds precipitation. Evapotranspiration (ET) was calculated as 80%–85% of precipitation (Slade et al., 1986; Slade, 2014), and it was directly measured as 68% of precipitation (ranging from 55% to 70% during higher-than-average precipitation conditions, when most recharge occurs; Hauwert and Sharp, 2014).

Large rainstorms are often caused by warm and cold fronts encountering moisture-laden air from the Gulf of Mexico or the Pacific Ocean and less frequently from hurricanes. Large rainstorms can also be triggered by the orographic effect of the

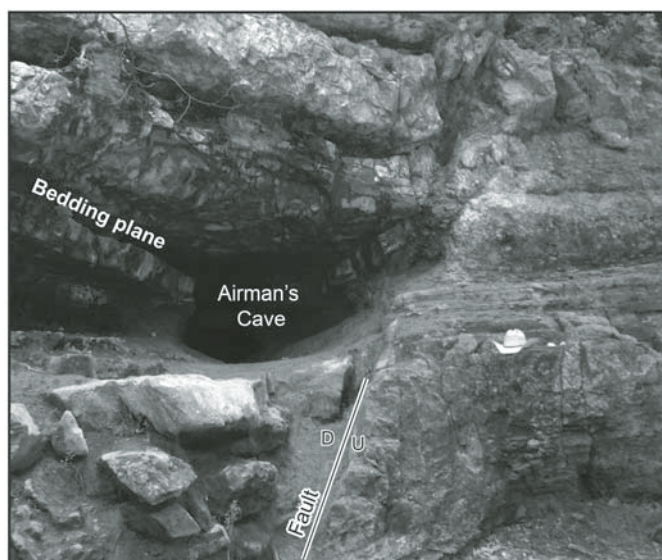


Figure 7. Photo of Airman's Cave within Barton Creek. The conduit is formed along the intersection of bedding planes and a fault. Cave diameter is ~3.5 ft (1 m). Cowboy hat for scale.

Balcones Escarpment. Consequently, the region has some of the most intense rainfall per drainage area in North America. Factors contributing to flooding include rapid runoff due to steep slopes, limited infiltration due to exposed bedrock, and relatively thin soils with sparse vegetation (Slade, 1986; Caran and Baker, 1986).

The region experiences protracted wet and dry periods (Diaz, 1983), resulting in climatic extremes. These periods are often influenced by global ocean-atmospheric circulation processes such as the El Niño–Southern Oscillation (Slade and Chow, 2011) and the Pacific Decadal Oscillation (Barlow et al., 2001; Schubert et al., 2004). The prolonged droughts of the 1930s and 1950s were the most severe of the twentieth century in the United States (Andreadis et al., 2005), and similarly the period from 1947 to 1957 was the worst drought on record in central Texas since records were kept, starting in the 1880s (Smith et al., 2013). While the 1950s drought is used for water planning purposes (Smith and Hunt, 2004), tree-ring studies document drought periods since 1500 that have exceeded the duration and intensity of the 1950s drought (Cleaveland et al., 2011). During the 1950s drought, water levels and spring flow reached historic lows at Barton Springs of 10 ft³/s (0.28 m³/s), and spring flow ceased altogether at Comal Springs in the San Antonio segment of the Edwards Aquifer (Guyton & Associates, 1979). An apparent climatic shift since ca. 1960 has resulted in shorter drought periods and increases in average rainfall (Hunt et al., 2012). However, the 2011 drought was more intense (drier and hotter) than any previous historic droughts (Nielsen-Gammon, 2012), with Barton Springs flow reaching a low of 16 ft³/s (0.45 m³/s). The 2009 drought was not as intense as the 2011 drought, but it lasted longer, and spring flow reached a low value of 13 ft³/s (0.37 m³/s; Smith and Hunt, 2010a).

Karst aquifers respond rapidly to changing hydrologic conditions and are likely to respond rapidly to climate change (Mace and Wade, 2008; Stamm et al., 2015; see also Loáiciga and Schofield, this volume). Anthropogenic climate change is predicted to increase mean temperatures, increase droughts, and increase extreme weather events (IPCC, 2014, 2018; USGCRP, 2018). Indeed, changes in historic long-term spring flow and stream-flow trends over the past 40 yr have already been attributed to climatic shifts, along with pumping. For example, Hunt et al.

(2012) described a climatic shift resulting in increased flows and variability since ca. 1960 to present. However, over that same time period, base flow and low spring flow percentiles have been decreasing. Similarly, Stamm et al. (2015) predicted decreasing low flow percentiles at Barton Springs from the impacts of climate change.

Recharge

The majority of recharge sources to the Barton Springs segment of the Edwards Aquifer are relatively local (Fig. 3) when compared to the more regional sources that contribute flow to San Marcos and Comal Springs in the San Antonio segment of the Edwards Aquifer (Musgrove and Crow, 2012). Water-balance and geochemical studies indicate that most recharge occurs within streams that cross the recharge zone (Slade et al., 1986; Slade, 2014, 2015; Wong et al., 2012; Hauwert and Sharp, 2014; Hauwert, 2016). A summary of the range of recharge as a percentage of discharge and precipitation is presented in Table 2. The studies summarized used different approaches and assumptions and were often conducted during different hydrologic conditions. Despite differences among the results, the overall conclusions and ranges of values are complementary, and all the studies conclude that most recharge occurs within streams. The reported range of recharge compared to discharge is 39%–75% from allogenic sources and 25%–61% from within the recharge zone (autogenic, and other minor sources).

Recharge is highly variable in space, time, and soil-moisture conditions, as demonstrated by the ranges in percentage of recharge in Table 2. In addition, discrete recharge features such as Antioch Cave in Onion Creek are significant and can recharge up to 100 ft³/s (2.83 m³/s; Smith and Hunt, 2013). During one flow event in Onion Creek, the unclogging of Crippled Crawfish Cave in Onion Creek increased recharge by 30 ft³/s (0.85 m³/s; Fig. 3; Hauwert, 2016).

Other sources of recharge to the Barton Springs segment of the Edwards Aquifer are thought to be relatively small on the basis of the mean water-budget analysis (Slade, 2014; Hauwert, 2016). However, during drought conditions, the relative contribution of recharge for a given source can change significantly (Passarello et al., 2012). For example, the Blanco River or other minor sources may contribute more and become significant sources of

TABLE 2. SUMMARY OF PUBLISHED RECHARGE ESTIMATES AS PERCENTAGE OF DISCHARGE AND PRECIPITATION

| Category | Percentage of total discharge (%) | Percentage of precipitation (%) | Comment |
|--|-----------------------------------|---|--|
| Total recharge | 100 | 8 (1) | |
| Stream recharge (mostly allogenic) | 56 to 67 (3) 75 (1) | N.D. | Includes 17% autogenic stream recharge (3) |
| Diffuse or upland recharge (autogenic) | 33 to 44 (3)* 25 (1) | 22–28 (30–45 during above average rainfall) (2, 3) 6.6 (1) | *Includes other minor sources |

Note: 1—Slade (2014, 2015); 2—Hauwert and Sharp (2014); 3—Hauwert (2016). N.D.—not determined.

recharge to the Barton Springs segment of the Edwards Aquifer during drought conditions.

Upper and middle Trinity Aquifer (interaquifer flow). Minor inflow from the upper Trinity Aquifer of the Hill Country into the Barton Springs segment of the Edwards Aquifer is suggested by potentiometric data and geochemistry (Senger and Kreitler, 1984; Slade et al., 1986; Garner and Mahler, 2007; Hunt et al., 2007; Wong et al., 2014).

Recent studies do not support substantial inflows from the middle Trinity Aquifer into the Barton Springs segment of the Edwards Aquifer as reported in the San Antonio segment (Mace et al., 2000; Anaya et al., 2016). The middle Trinity Aquifer is hydrologically separated from the overlying Barton Springs segment by a relatively thick evaporite-rich aquitard interval in the Upper Glen Rose member (Smith and Hunt, 2010b; Wong et al., 2014). Instead, a portion of groundwater flow within the middle Trinity Aquifer of the Hill Country is thought to remain within the middle Trinity units as it flows east into the Balcones fault zone and beneath the Barton Springs segment of the Edwards Aquifer (Hunt et al., 2015). Natural discharge from the deeply confined middle Trinity Aquifer beneath the Edwards Aquifer is unknown (Hunt et al., 2017).

Saline-water zone (interaquifer flow). Flow from the saline-water zone into the freshwater zone is relatively minor. Geochemical evaluations under low-flow conditions suggest a saline-water contribution of up to 3% for Old Mill Springs, but only 0.5% for Main and Eliza Springs when Barton Springs was discharging 17 ft³/s (0.48 m³/s; Hauwert et al., 2004b). Geochemical modeling by Wong et al. (2012) indicated a saline-zone contribution from <1% to 6% to Main Spring, with higher contributions during low-flow conditions. These estimates are similar to those of Johns (2006) and Garner and Mahler (2007). Similar studies in the San Antonio segment by Musgrove and Crow (2012) estimated that <1% of San Marcos Springs discharge is derived from the saline zone. Thus, saline groundwater is thought to be relatively isolated from the freshwater zone (Groschen and Buszka, 1997). Head data (Lambert et al., 2010; Thomas et al., 2012) and numerical modeling across the interface further suggest stability of the boundary over time (Brakefield et al., 2015).

San Antonio segment (intra-aquifer flow). Barton Springs occurs at the regional base level of the Edwards Aquifer and has the lowest elevation of the major Edwards Aquifer springs, such as San Marcos and Comal Springs. Accordingly, groundwater flow has the potential to bypass San Marcos Springs toward Barton Springs under extreme drought conditions. Land et al. (2011) estimated up to 5 ft³/s (0.14 m³/s) could bypass San Marcos Springs and flow to the Barton Springs segment of the Edwards Aquifer. Similarly, the majority of spring flow at San Marcos Springs is from regional flow that bypasses Comal Springs (Musgrove and Crow, 2012).

Anthropogenic sources. Recent numerical modeling studies have shown that urbanization increases recharge to the Barton Springs segment of the Edwards Aquifer (Passarello et al., 2012).

Sources of urban recharge include leaking water-supply and wastewater lines, stormwater basins, and irrigation return flow (Sharp, 2010). Anthropogenic recharge estimates range from 5% to 8% of mean flow but can be greater than natural recharge sources during dry periods (Passarello et al., 2012). Sources of anthropogenic recharge may be evidenced as contaminants within the aquifer and springs. However, as Wong et al. (2012) indicated, stream water is the dominant control on the quality of groundwater and spring discharge during storm and nonstorm conditions. Therefore, distinguishing anthropogenic recharge from surface-derived anthropogenic contaminants will likely be a challenge.

Groundwater Flow

The Barton Springs segment of the Edwards Aquifer contains heterogeneous and anisotropic groundwater flow through matrix, fracture, and conduit permeability (Hovorka et al., 1998, 2004; Halihan et al., 1999, 2000). Groundwater tracing and other types of studies demonstrate that a significant component of groundwater flow in the Edwards Aquifer is discrete, occurring in an integrated network of conduits, caves, and smaller dissolution features (Fig. 8; Hauwert et al., 2004a, 2004b; Johnson et al., 2012).

The influence of faulting on groundwater flow in the Barton Springs segment of the aquifer is complex. Dissolution along faults and fractures generally influences flow and increases permeability (Fig. 8, inset bottom). Bedding plane and joint-influenced conduits also transmit large amounts of water (Fig. 6). Groundwater tracing demonstrates that structural gradients can influence groundwater flow. Accordingly, groundwater flow can be directed perpendicular to the primary northeast-trending faults toward downdropped fault blocks (Hauwert et al., 2004a) or along relay ramps subparallel to fault trends (Hunt et al., 2015). However, faults can also be barriers to flow by juxtaposing rock units of different permeabilities (Ferrill et al., 2004; Hunt et al., 2015).

In the Barton Springs segment of the Edwards Aquifer, groundwater generally flows west to east within the recharge zone in secondary conduit systems that converge with NE-trending primary conduits defined by troughs in the potentiometric surface (Fig. 8; Hauwert, et al., 2004a; Hunt et al., 2007). Hauwert et al. (2004a) established two smaller groundwater subbasins within the larger Barton Springs segment of the Edwards Aquifer (Fig. 8). Groundwater within the Cold Springs basin primarily flows to Cold Springs along the Colorado River, while groundwater in the Sunset Valley basin flows to Upper Barton, Eliza, and Main Springs, but not Old Mill Spring. However, given the karstic and dynamic nature of the aquifer, groundwater can cross these groundwater divides or reverse direction under certain hydrologic conditions. For example, the southern groundwater divide shifts between Onion Creek and Blanco River depending on heads influenced by recharge in these streams (Smith et al., 2012).

Tracer studies show that conduit flow in the Barton Springs segment of the aquifer is very rapid from recharge features to

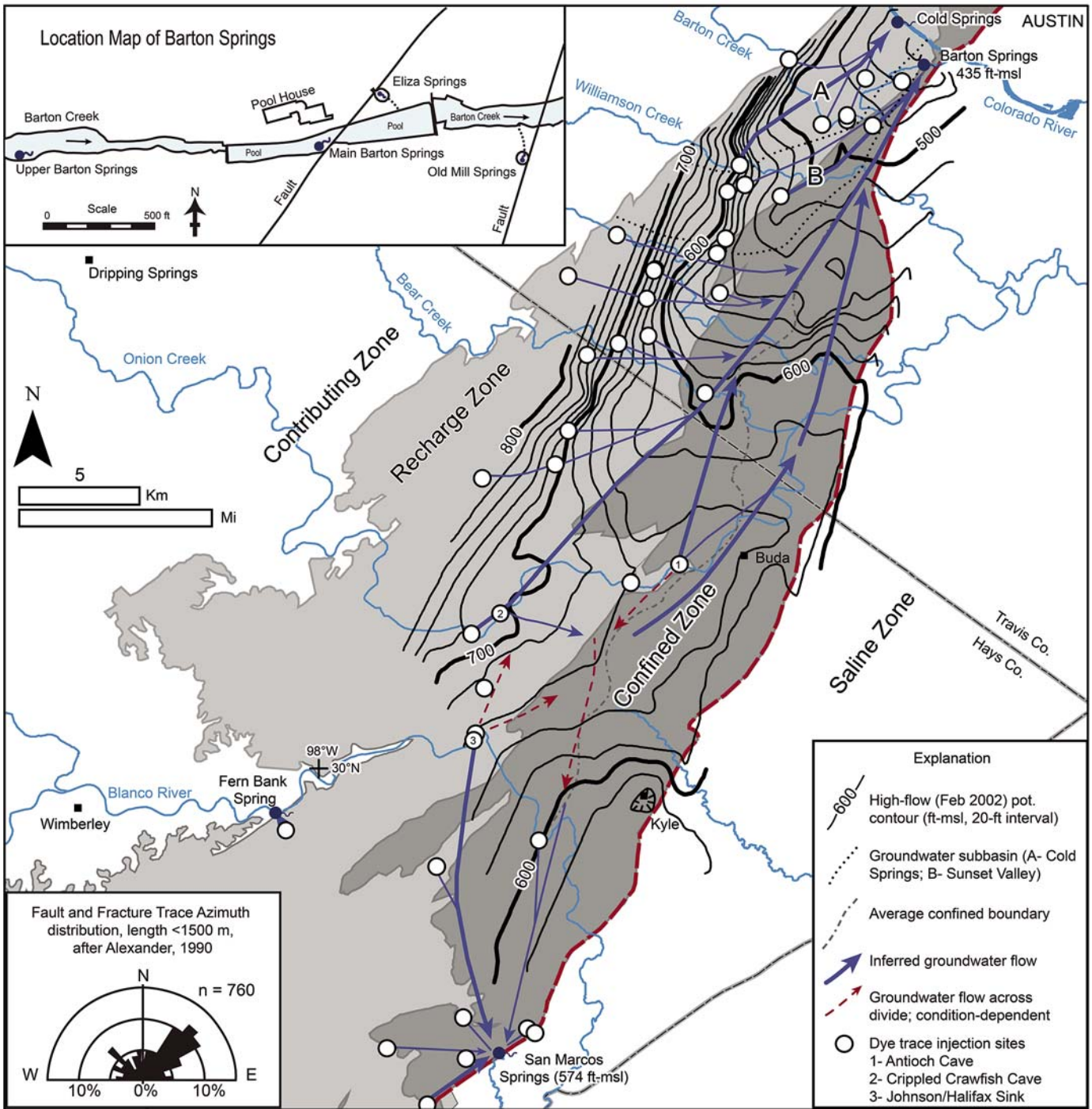


Figure 8. Generalized groundwater flow map based upon dye tracing (Hauwert et al., 2004a; Johnson et al., 2012; Smith et al., 2012; Zap-pitello and Johns, 2018). Potentiometric data are from high-flow conditions (Hunt et al., 2007). Contours are in ft above mean sea level (1 ft = 0.3048 m). (Inset top) Location map of the Barton Springs complex. (Inset bottom) Rose diagram showing the trend and relative proportion of faults and fractures, modified from Alexander (1990).

wells and springs, with velocities ranging from 1 to 7 mi/d (1.6–11.3 km/d) depending on hydrologic conditions (Hauwert et al., 2004a; Johnson et al., 2012). Near Barton Springs, groundwater velocities may be higher. In December 2018, boreholes drilled to a depth of 250 ft (75 m) and located ~4000 ft (1200 m) south-southwest of Barton Springs intersected a void connected to the primary conduit flowing to Barton Springs. A visible sediment plume (high turbidity) arrived within about 2 hr, for an estimated velocity of up to 9 mi/d (14.5 km/d) during relatively high-flow conditions (BSEACD, unpublished data, internal memo). Although flow is rapid within conduits, it is likely that a larger volume of the aquifer has relatively lower groundwater velocities, more similar to laminar flow through smaller fissures and rock matrix (Hovorka et al., 1998; Kresic, 2007, p. 67). Geochemical, water-level, and spring-flow data have been interpreted as evidence of the dual nature of conduit and diffuse flow in the Barton Springs segment of the Edwards Aquifer (Mahler et al., 2011; Wong et al., 2012). During wet periods, dye tracing and other studies indicate that stream recharge from allogenic and autogenic sources transmitted via conduits makes up the majority (up to 90%) of spring flow. During drought conditions, geochemical data have been interpreted to indicate that stream recharge comprises as little as 5% of spring flow (Mahler et al., 2006, 2011; Wong et al., 2012). Another interpretation, supported by dye tracing and other data, is that conduit flow is still dominant during drought conditions and is sustained, in part, by recharge from the Blanco River (Hauwert, 2016) and intra-aquifer flow from the San Antonio segment (Land et al., 2011). Casteel et al. (2013) reported a time-lagged increase in discharge and gauge height at Barton Springs in response to increases in recharge from the Blanco River during drought periods when all other contributing watersheds were dry. During drought, it is likely that spring flow is sustained by a combination of matrix storage, conduit flow, and the other recharge sources described above.

Discharge

Spring flow. The discharge and geochemistry at Barton Springs are the integrated measure of overall storage and water quality of the Barton Springs segment of the Edwards Aquifer. Barton Springs has four major outlets: Main, Eliza, Old Mill, and Upper Springs (Fig. 8, inset top). Barton Springs discharge is reported online by the U.S. Geological Survey (USGS, 2018) and is the combined discharge of Main (~82%), Eliza (~7%), and Old Mill (~11%) Springs, but it does not include flow from Upper Barton Springs (David Johns, 17 October 2018, personal commun.). Characteristics of the four springs in the complex are listed below:

- (1) Main (Parthenia) Spring is the largest outlet and discharges directly into Barton Springs pool (Fig. 1).
- (2) Eliza Spring occurs along strike of a fault at Main Barton Springs and has the largest population of salamanders (BSEACD, 2018).
- (3) Old Mill Spring is influenced by leakage from the saline zone and essentially ceases to flow when total Barton

Springs flow is near 15 ft³/s (0.42 m³/s). Old Mill is the least influenced by anthropogenic contaminants (Mahler et al., 2006).

- (4) Upper Barton Springs is an overflow spring and only flows when discharge at Barton Springs exceeds ~40 ft³/s (1.13 m³/s; Smith et al., 2013). Source waters partially originate from the urbanized Sunset Valley groundwater basin (Fig. 8), with strong anthropogenic influences (Mahler et al., 2006). Additional overflow springs (such as Airman's Cave; Fig. 7) are located upstream of Upper Barton Springs within Barton Creek and flow only during exceptionally wet periods.

Monthly mean data are available from 1917 to 1978 (Slade et al., 1986). Daily mean discharge data are available since 1978. Table 3 summarizes reported Barton Springs segment of the Edwards Aquifer spring-flow statistics. Note that the stage-discharge relationship derived to calculate flow for Barton Springs is very sensitive to lake- and pool-level fluctuations, and large errors in discharge are possible, especially during low-flow conditions (Hunt et al., 2012). Reported spring-flow data do not include discharge from springs upstream of the pool within Barton Creek such as Upper Barton Springs. Under high-flow conditions, up to 8 ft³/s (0.23 m³/s) of spring flow can occur within a reach ~3.5 mi (5.6 km) upstream of Barton Springs pool, including Upper Barton Springs (David Johns, 17 October 2018, personal commun.). Cold Springs and other minor springs along the Colorado River are also not included in reported Barton Springs discharge. Cold Springs is a significant karst spring complex and has a separate defined groundwater basin (Fig. 8; Hauwert et al., 2004a). Cold Spring discharges directly into the Colorado River and is partially submerged by Lady Bird Lake and thus has no direct discharge measurements. Accordingly, Cold Spring discharge is poorly constrained, with mean estimates reported from 3 to 35 ft³/s (0.08–0.99 m³/s; Table 3).

Pumping. The Barton Springs segment of the Edwards Aquifer has more than 1200 nonpermitted (exempt) wells and ~100 permittees, totaling ~12.5 ft³/s (0.35 m³/s or 8900 ac-ft/yr) of water that can potentially be pumped in a nondrought year. Table 4 summarizes permitted and estimated nonpermitted (exempt) pumping in the Barton Springs segment of the Edwards Aquifer in 2017. Most of the 1200 wells are used for domestic purposes and are exempt from most groundwater conservation district (GCD) rules. However, the 1200 wells only produce an estimated 5% of the permitted amount. Domestic pumping is distributed throughout the Barton Springs segment of the Edwards Aquifer and generally south of Austin City limits. About 95% of the total volume that can be pumped is from ~100 permittees from the BSEACD. About 75% of the permitted water is for public water-supply use, with the remainder for commercial, industrial, and nonagricultural irrigation uses. Permitted pumping generally occurs south of the city of Austin along the I-35 corridor in the confined portion of the aquifer near Manchaca, Buda, and Kyle, Texas (Fig. 3).

TABLE 3. SPRING FLOW STATISTICS

| Spring and statistic | Flow rate (cubic feet per second, ft ³ /s) | Flow rate (cubic meters per second, m ³ /s) | Source and notes |
|--|---|--|---|
| <u>Barton Springs daily</u> | | | |
| Daily mean (1978–2014) total discharge (includes pumping) | 68 | 1.93 | Hunt et al. (2012) |
| Daily mean (1978–2013) | 61 | 1.73 | Musgrove et al. (2016); Anaya et al. (2016); Johns (2015) |
| Highest daily mean (1991) | 130 | 3.68 | Johns (2015) |
| Lowest daily mean (Sept. 2009) | 13 | 0.37 | Johns (2015) |
| Lowest measured value (1956) | 9.6 | 0.27 | Brune (2002); Slade et al. (1986) |
| Highest measured value (1941) | 166 | 4.70 | Slade et al. (1986) |
| <u>Barton Springs monthly mean</u> | | | |
| Monthly mean spring flow (1917–2013) | 54 | 1.53 | Slade et al. (1986); Scanlon et al. (2001); Slade (2015) |
| Monthly mean total discharge (1917–2011; includes pumping) | 57 | 1.61 | Hunt et al. (2012) |
| Monthly mean total discharge (1958–2011; includes pumping) | 68 | 1.93 | Hunt et al. (2012) |
| Highest monthly mean (August 1961) | 135 | 3.82 | Slade et al. (1986) |
| Lowest monthly mean (July & August 1956) | 11 | 0.31 | Slade et al. (1986) |
| <u>Barton Springs mean annual</u> | | | |
| 1917–1957 | 41 | 1.16 | Hunt et al. (2012) |
| 1958–2010 | 65 | 1.84 | Hunt et al. (2012) |
| <u>Cold Springs</u> | | | |
| Mean | 3.1 | 0.09 | Scanlon et al. (2001); 5% of Barton Springs at 1.76 m ³ /s (62 ft ³ /s) |
| Estimated range of mean | 6 to 8 | 0.17–0.23 | Slade (2014, 2015) |
| Estimated range of mean | 15–35 | 0.42–0.99 | Hauwert (2016) |
| <u>Other springs</u> | | | |
| Lower Barton Creek (above Barton Springs) | 0.9 | 0.03 | Hauwert (2016) correlation; at 1.76 m ³ /s (62 ft ³ /s) at Barton Springs |
| Lower Barton Creek (above Barton Springs) | 0.8 | 0.02 | Slade (2014) correlation; when Barton springs is 1.76 m ³ /s (62 ft ³ /s) |
| Springs along Colorado River | <1.0 | <0.03 | Hauwert et al. (2004a) |
| Springs along Colorado River | 0.7 | 0.02 | Slade (2015) |

TABLE 4. ANNUAL 2017 PUMPING DATA

| Pumping type | Flow rate (cubic feet per second, cfs; ft ³ /s) | Flow rate (cubic meters per second, cms; m ³ /s) | Flow rate (acre-feet per year, ac-ft/yr) | Flow rate (million gallons per year, MG/ yr) | Flow rate (cubic meters per year, m ³ /yr) | Comment |
|-------------------------------|---|---|---|---|--|---|
| Exempt (domestic, stock etc.) | 0.58 | 0.02 | 417 | 136 | 515,000 | Estimated at 5% of permitted (BSEACD, 2017) |
| Historical permitted | 10.15 | 0.29 | 7,247 | 2,361 | 8,943,000 | Reduced up to 50%; considered firm yield |
| Conditional permitted | 1.72 | 0.05 | 1,230 | 401 | 1,519,000 | Reduces to zero below 38 ft ³ /s of spring flow (stage II drought) |
| Total | 12.45 | 0.35 | 8,894 | 2,898 | 10,977,000 | |

Note: Source data from BSEACD (2017).

Permitted pumping is reported on a monthly basis and reflects climatic and regulatory influences, ranging from 52% to 95% of the total annual permitted volume (Fig. 9). Maximum monthly pumpage was 13.6 ft³/s (0.39 m³/s) in August 2008. From 2007 to 2016, the monthly pumpage of wells with permits has ranged between 4.3 and 12.2 ft³/s (0.12–0.35 m³/s), averaging 7.5 ft³/s (0.21 m³/s; Fig. 9).

Hydraulic Parameters

Porosity and permeability are strongly influenced by depositional facies, diagenesis, structure, and karstification (Abbott, 1975; Sharp, 1990). The result is a highly anisotropic and heterogeneous aquifer with a broad range of aquifer parameters. Hydraulic conductivity values in Figure 10 range about eight orders of magnitude, reflecting matrix and conduit permeability in the Barton Springs segment of the Edwards Aquifer. Mace (1995) found that transmissivity and hydraulic conductivity values in the Edwards Aquifer are log-normally distributed. Fractures may control flow on the well scale, with conduits controlling flow on the regional scale (Halihan et al., 2000). Well yields range from less than 10 gallons per minute (gpm; 0.63 L/s) in the recharge zone to greater than 1000 gpm (63 L/s) in the confined zone (Smith and Hunt, 2004). However, well yields in the confined part of the Edwards Aquifer are often limited more by pump size than by aquifer properties (Schindel et al., 2004). Mean hydraulic conductivities are two orders of magnitude higher in the confined zone compared to the unconfined zone (Hovorka et al., 1998). Similarly, median specific capacity is higher within the confined zone compared to the unconfined zone (Smith and Hunt, 2004).

Faults and fractures create a strong anisotropy in the permeability of the Edwards Aquifer, with maximum permeability occurring at the intersections of bedding planes and fractures and faults (Fig. 7). Decreases in permeability perpendicular to faults are also reported (Maclay and Small, 1986; Hovorka et al., 1996; Ferrill et al., 2004).

Storativity values from aquifer tests reflect unconfined (0.02) to confined (mean 0.0006) aquifer conditions (Fig. 10). Average porosity of the Edward units varies from 16% to 28%, with an interpolated overall average of 18% (Hovorka et al., 1996). Mace et al. (2005) concluded that if fractal scaling is assumed, then fracture and secondary porosity could be twice as high as measured values. The saline portion of the Edwards Aquifer is reported to have higher average porosity than the freshwater aquifer (Maclay and Small, 1986; Smith et al., 2017a). Spring-flow hydrograph studies indicate elevated storage values above 50 ft³/s (1.42 m³/s) of flow at Barton Springs (Wong et al., 2012). Estimated total storage within the aquifer ranges from 306,000 ac-ft (3.77×10^8 m³; Slade et al., 1986) to 130,000 ac-ft (1.60×10^8 m³; Jones et al., 2013).

Water levels can vary more than 100 ft (30 m) from wet to dry conditions (Hunt et al., 2007), but they recover quickly from dry periods and pumping (Fig. 9). No long-term declines in storage have occurred from pumping in the Barton Springs segment

of the Edwards Aquifer, indicating its long-term sustainability as a water supply. However, wells in the unconfined aquifer and Barton Springs are vulnerable due to depletion of storage from high rates of pumping and severe drought conditions (Smith and Hunt, 2004).

Water Budget and Modeling

Basic physics and the conservation of mass require that the long-term mean recharge should approximately equal the long-term mean discharge. Previous studies utilized this principal for the purposes of water budget analyses and modeling (Scanlon et al., 2001; Smith and Hunt, 2004). The monthly mean discharge, which includes spring flow and pumping, is ~68 ft³/s (1.93 m³/s; Table 3; Fig. 11). However, this water budget may not apply to shorter periods of time, as changes in storage occur, or during hydrologic extremes.

The water budget for the Barton Springs segment of the Edwards Aquifer was first quantified by Slade et al. (1985, 1986), with subsequent refinements from Slade (2015) and Hauerwert (2016) (see also Table 2 herein). As part of the water budget analyses for numerical modeling, recharge from the uplands and streams within the recharge zone is considered to be the most significant source of recharge water. Thus, other inflows, such as the Trinity Aquifer, San Antonio segment, saline Edwards Aquifer water, or anthropogenic sources that are difficult to quantify, are not directly quantified in most numerical models (Scanlon et al., 2001; Smith and Hunt, 2004). Instead, all sources of recharge are assumed to be represented within the long-term mean discharge values that are very accurately measured.

The first published numerical models of the Barton Springs segment of the Edwards Aquifer concluded that the impact of high rates of pumping from the aquifer during periods of severe drought would be cessation of flow from the springs and dewatering of the aquifer (Slade et al., 1985; Barrett and Charbeneau, 1997; Wanakule, 1989). A groundwater availability model (GAM) was developed for water planning purposes that simulated high rates of pumping and a repeat of the drought of record (Scanlon et al., 2001; Smith and Hunt, 2004). GAM results indicated that Barton Springs would cease flowing and numerous water-supply wells would go dry under these conditions. A model developed by Hutchison and Hill (2011) produced probabilistic results with similar conclusions.

A key component of the conceptual and numerical modeling is the nearly one-to-one relationship between increases in pumping and decreases in spring flow under low-flow conditions (Brune and Duffin, 1983; Hunt et al., 2011). All of the numerical models showed that under extreme drought conditions with increased rates of pumping, flow at Barton Springs would periodically cease, and storage would be depleted. This would have serious consequences for groundwater availability, quality, and habitat of the endangered Barton Springs salamanders. As a result of these studies, the BSEACD put in place rules to manage existing and future permits by limiting the volume of

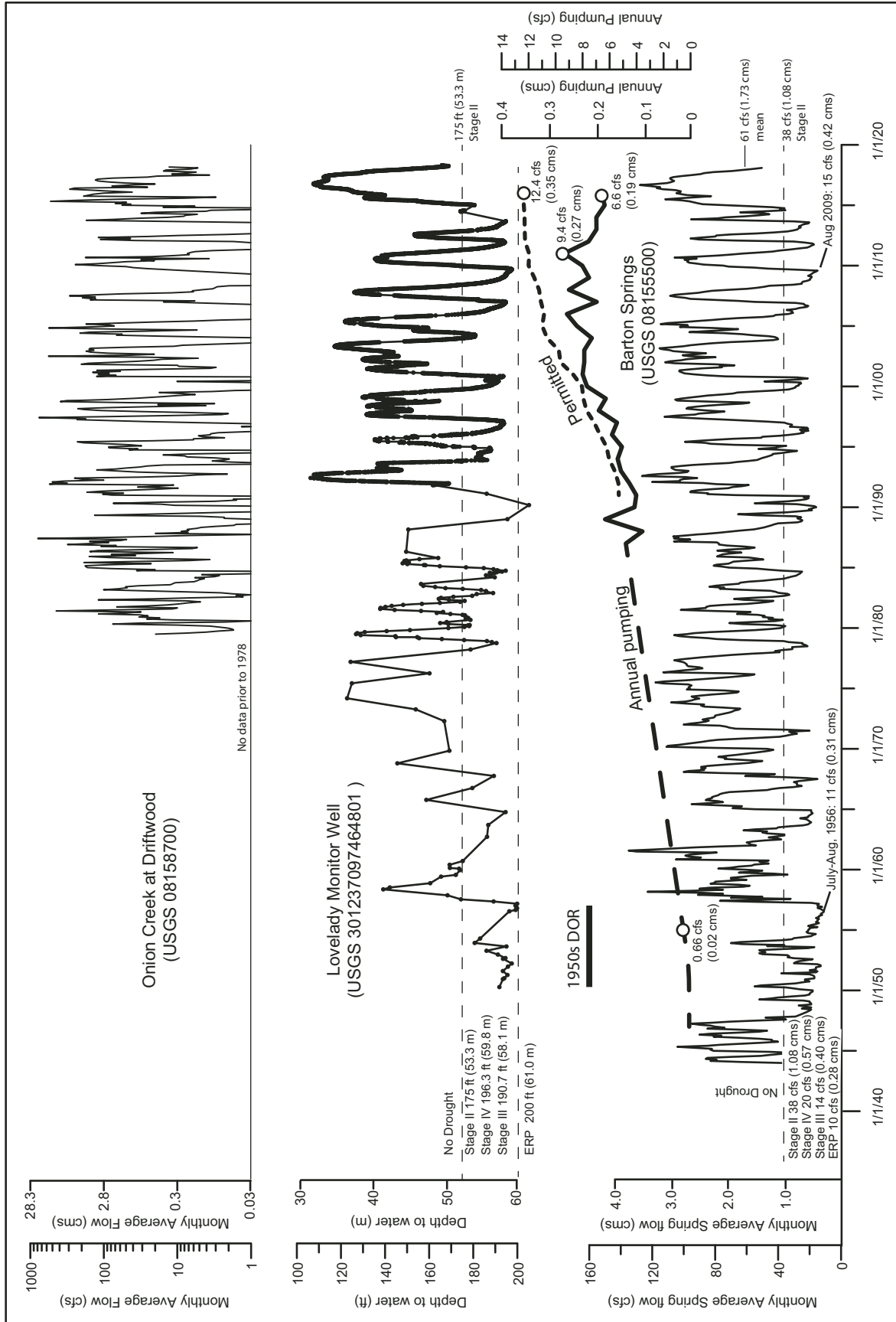


Figure 9. Hydrograph of Onion Creek (Driftwood), Lovelady monitor well, annual pumping, and Barton Springs flow. Records for annual pumping began in 1987. Values prior to 1987 are estimated. Note units (1 ft = 0.3048 m; 1 ft³/s = 0.0283 m³/s). USGS—U.S. Geological Survey; DOR—drought of record; cfs = ft³/s; cms = m³/s; ERP = Emergency Response Period.

Barton Springs segment of the Edwards Aquifer, central Texas

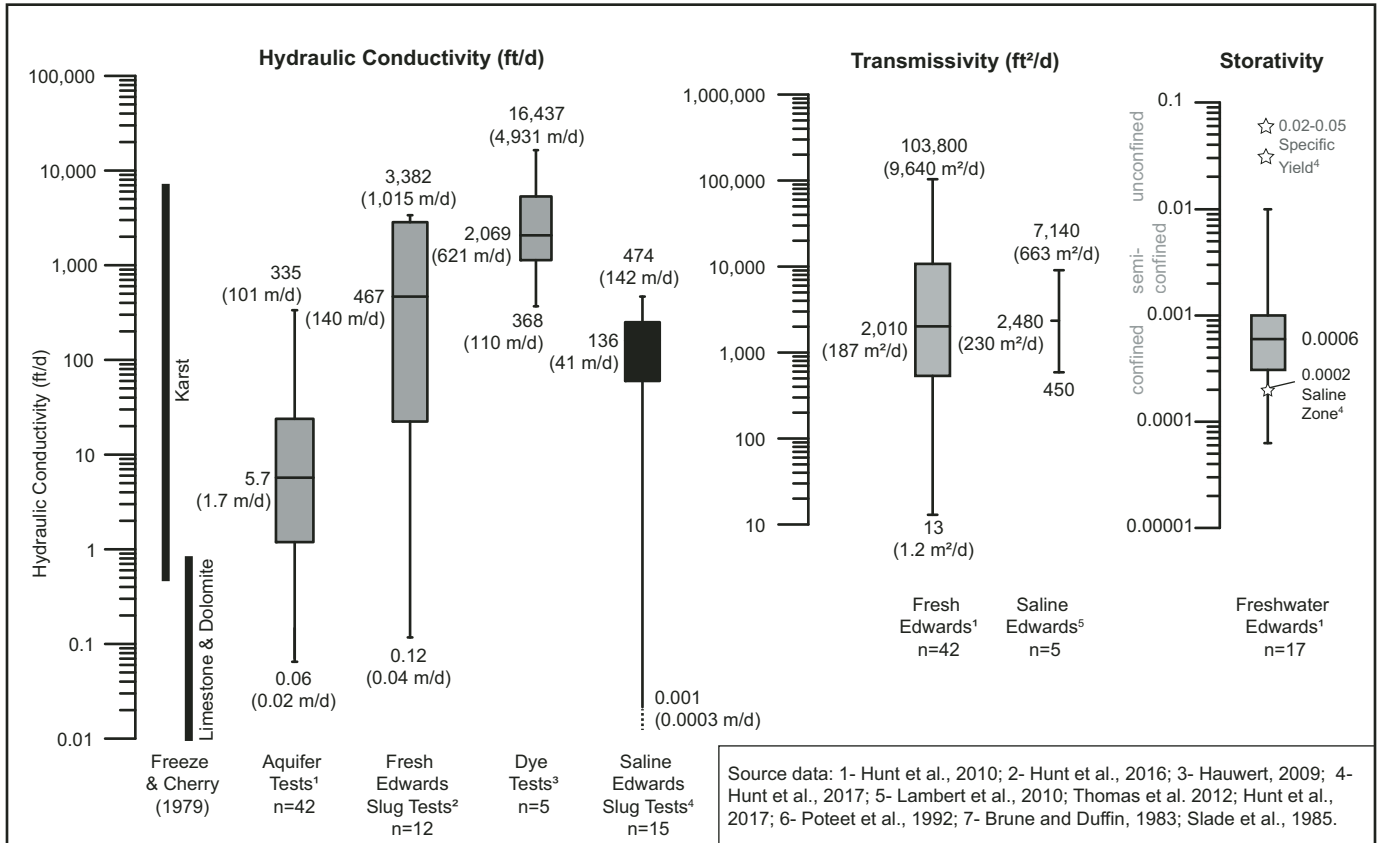


Figure 10. Whisker plot showing hydraulic parameters in the Barton Springs segment of the Edwards Aquifer. Permeability ranges eight orders of magnitude reflecting the triple permeability system. Note 1 ft/d = 3.5×10^6 m/s and 1 ft²/d = 0.93 m²/d.

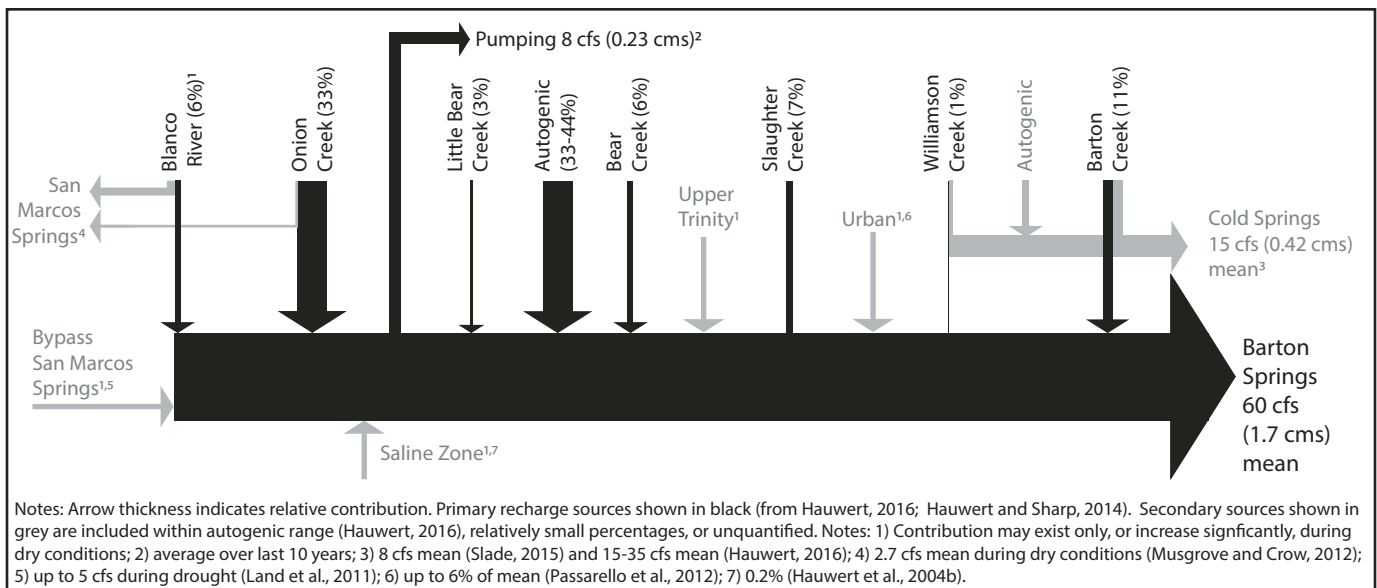


Figure 11. Schematic water balance of the Barton Springs segment of the Edwards Aquifer with an emphasis on Barton Springs. Arrow thickness indicates relative contribution. The primary budget is shown in black from Hauwert (2016). Secondary sources (unquantified or minor) are indicated in grey. Note 1 ft³/s = 0.0283 m³/s. BSEACD—Barton Springs/Edwards Aquifer Conservation District. cfs= ft³/s; cms = m³/s.

groundwater permitted from the Barton Springs segment of the Edwards Aquifer under drought conditions and by developing management zones, among other rules (see “Aquifer Management” section below).

Scanlon et al. (2003) demonstrated that the existing numerical (equivalent porous media) models are capable of simulating regional groundwater flow and spring discharge in a karst aquifer. These models are not capable of simulating travel times when compared to dye-trace results (Smith et al., 2005b; Lindgren et al., 2009). However, a dual continuum model of the Barton Springs segment of the Edwards Aquifer was able to simulate both conduit and diffuse flow and could yield better approximations of groundwater flow velocities (Sun et al., 2005).

Water Quality and Chemistry

Water quality of the Edwards Aquifer, and in the Barton Springs segment of the Edwards Aquifer, is very good, with few

samples approaching the U.S. Environmental Protection Agency’s (EPA) maximum concentration levels (MCLs) for drinking water (Slade et al., 1986; Smith et al., 2001; Anaya et al., 2016; Opsahl et al., 2018). The Barton Springs segment of the Edwards Aquifer groundwater generally has low TDS (<500 mg/L) calcium-bicarbonate (Ca-HCO₃) facies with trends toward high TDS (>1000 mg/L) and sodium-chloride (Na-Cl) in the saline part of the Edwards Aquifer (Fig. 12; Senger and Kreitler, 1984; Darling, 2017).

Geochemical data have demonstrated the dual nature (conduit and diffuse) of flow in the Barton Springs segment of the Edwards Aquifer. Hydrologic conditions, combined with the karstic nature (rapid conduit flow) of the aquifer, can dramatically influence water quality in portions of the aquifer and at Barton Springs (Mahler et al., 2006, 2011; Mahler and Massei, 2007; Wong et al., 2012). During recharge events, spring flow and conduit-influenced groundwater are dominated by surface-water geochemistry (Wong et al., 2012). The conduit-dominated

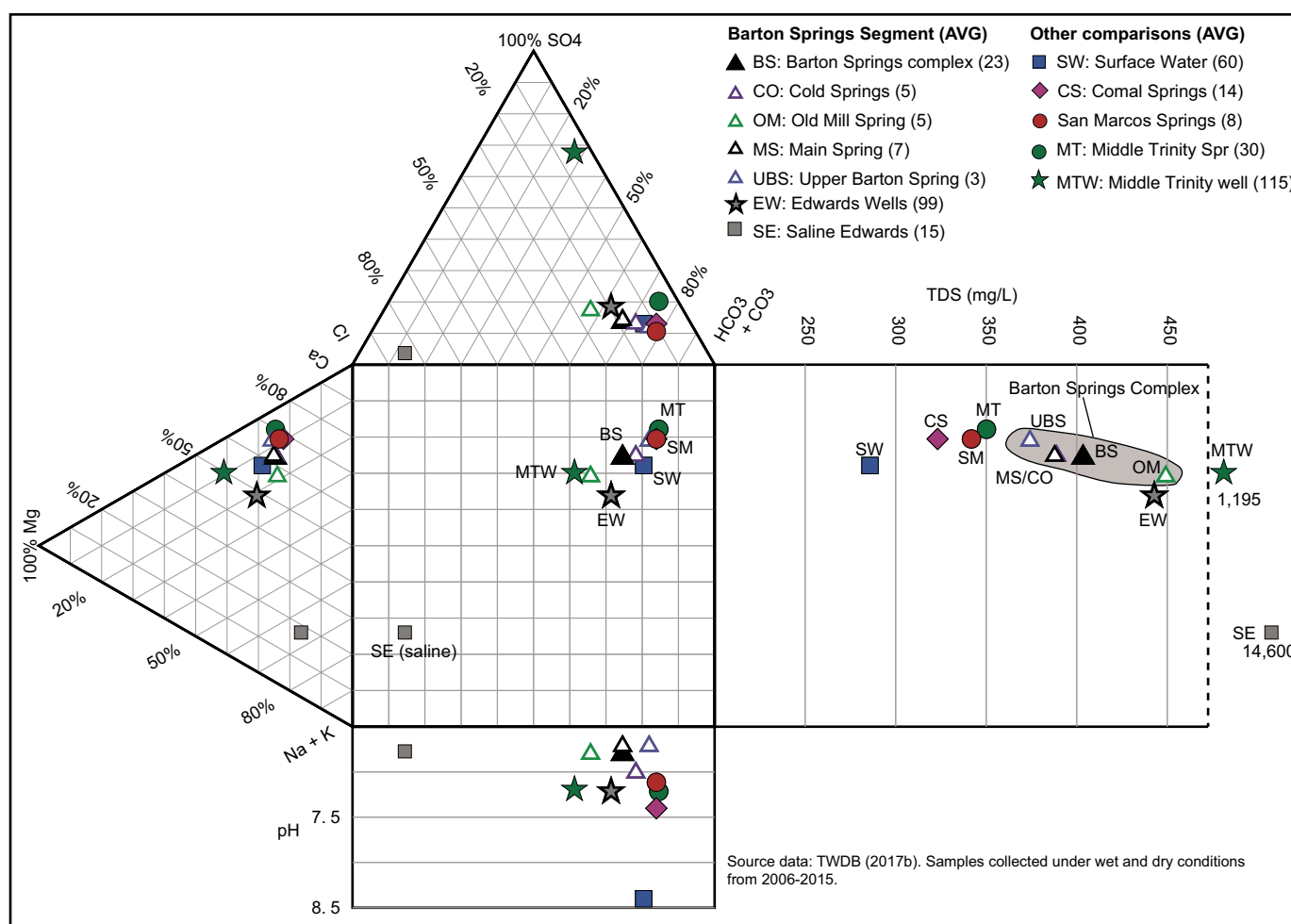


Figure 12. Durov diagram illustrating the geochemistry of the Barton Springs segment of the Edwards Aquifer relative to other waters. TDS—total dissolved solids; SM—San Marcos.

Barton Springs segment of the Edwards Aquifer, central Texas

nature of groundwater flow in the Barton Springs segment of the Edwards Aquifer is well illustrated by the physiochemical response of Barton Springs (Fig. 13). Conduit flow rapidly transports surface recharge water to wells and springs, resulting in discharge at Barton Springs that can rise quickly following

rain events. There is generally an inverse relationship between increased spring discharge and decreased concentrations of specific conductivity, nutrients, and major ions such as magnesium and strontium due to the dilution of the recharge water entering the aquifer. However, increasing discharge generally has a positive

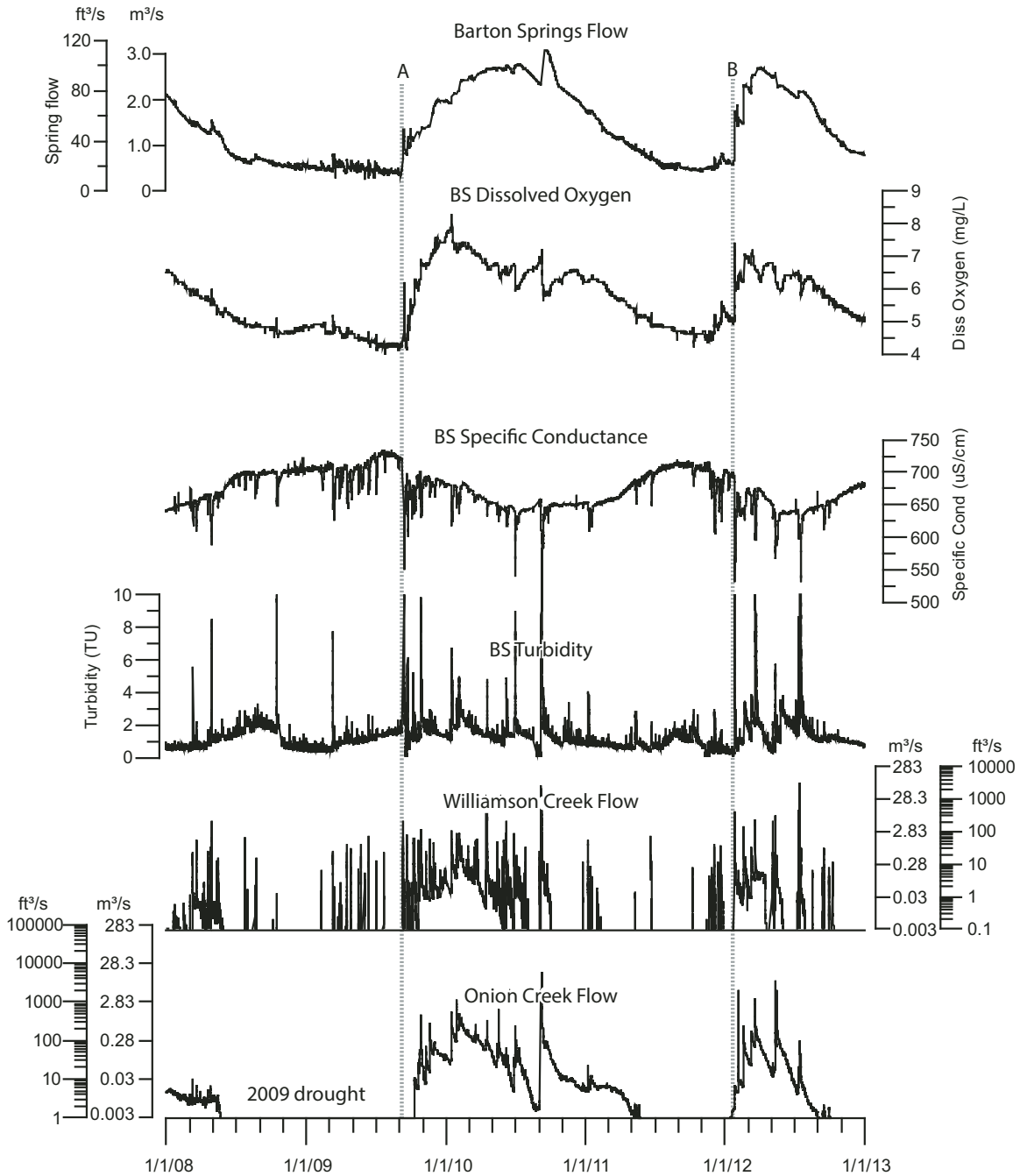


Figure 13. Hydrograph of Barton Springs (BS) and physiochemical parameters (turbidity, specific conductance, dissolved oxygen) compared to streamflow at Onion Creek (U.S. Geological Survey [USGS] Driftwood) and Williamson Creek (USGS, Hwy 71). Streamflow hydrographs are indicative of rainfall and recharge events. Dashed lines labeled A and B correlate parameters at the start of increased spring flow.

correlation to some major ions (sulfate), turbidity, and bacteria (Mahler and Lynch, 1999; Mahler et al., 2006). Geochemistry of the diffuse portion of groundwater flow is strongly influenced by mineral-solution reactions such as dissolution and precipitation of carbonates and gypsum, dedolomitization, and ion exchange (Chowdhury, 2008; Mahler et al., 2006; Wong et al., 2012). The geochemical composition of water from sites dominated by diffuse flow does not rapidly change from dry to recharge conditions (Wong et al., 2012).

Isotopic values reinforce the complexity and heterogeneity of the dual-porosity system within the Barton Springs segment of the aquifer. Carbon-14 (^{14}C ; expressed as percent modern carbon, pmC) and tritium (^3H) values are well correlated and can provide additional insight into source areas, flow paths, mixing, and groundwater residence time (Fig. 14A). Tritium values are generally greater than ~ 0.5 TU (tritium units), which is consistent with modern groundwater (younger than 1950). Low values of ^{14}C and tritium may reflect premodern water (older than 1950) or mixing between modern and premodern waters. Relatively old (premodern) groundwater samples generally occur from wells in the confined portion of the aquifer and the saline part of the Edwards Aquifer. These relatively older samples could reflect a change in the permeability field (diffuse flow) and longer regional flow paths, along with a corresponding higher carbon-13 ($\delta^{13}\text{C}/\text{C}12$ [‰]) value, suggesting longer interaction with carbonate rocks (Fig. 14B; Darling, 2017). In summary, the isotopic data are consistent with the conceptual model of the Barton Springs segment of the Edwards Aquifer showing bimodal flow systems of rapid conduit flow and slower diffuse flow.

Contaminants detected at Barton Springs since the 1970s include relatively low levels of pesticides, herbicides, petroleum hydrocarbons, and volatile organic compounds (VOCs; Hauwert and Vickers, 1994; Smith et al., 2001; Mahler et al., 2006; Hunt and Smith, 2014). The distribution of contaminants in the Barton Springs segment of the Edwards Aquifer is highly heterogeneous, reflecting the karstic and dynamic nature of the aquifer system, although more anthropogenic contaminants were detected within streams and wells in the northern urbanized portion of the aquifer (Mahler et al., 2006). Recent water-quality studies have provided valuable insight into the overall health and functioning of the Barton Springs segment of the aquifer (Mahler et al., 2006; Wong et al., 2012). Contaminants travel quickly through the conduit system during stormflow events. However, some contaminants remain stored within the aquifer matrix and less accessible fractures and voids, and these are released over time (Mahler et al., 2006; Hunt and Smith, 2014). Long-term storage and release of contaminants are illustrated by the VOC contaminant tetrachloroethene (TCE), which was detected intermittently in the past, but which was detected in every sample from Main Spring in a study in the early 2000s with a maximum value of $0.34 \mu\text{g/L}$. Additionally, Barton Springs is affected by chronic low levels of pesticides (atrazine, simazine, prometon) relative to drinking-water standards. A maximum value of atrazine was $0.45 \mu\text{g/L}$ at Upper Barton Springs during storm conditions, compared to an MCL of $3.0 \mu\text{g/L}$ (Mahler et al., 2006). Trace metals (copper, lead, nickel, arsenic) have been detected in the Barton Springs segment of the Edwards Aquifer and Barton Springs at very low levels, but all metals were well below MCLs for drinking water

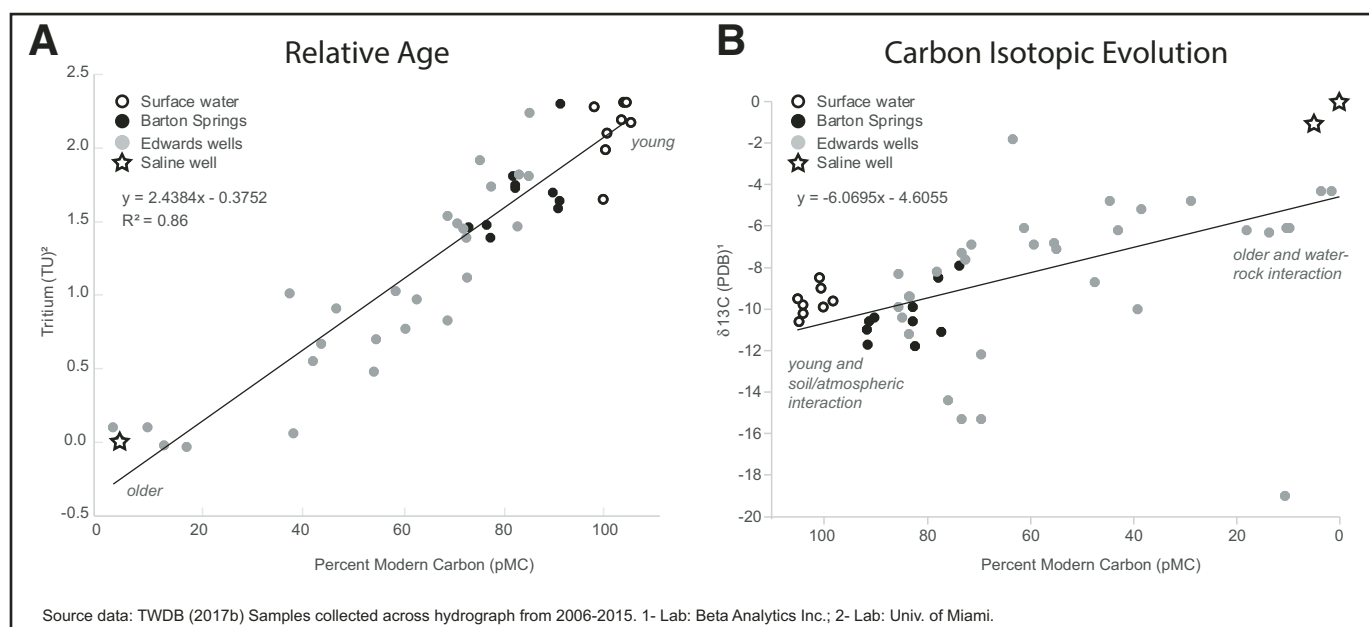


Figure 14. Environmental tracers using radiogenic and stable isotopes (tritium and carbon). (A) Carbon-14 (as percent modern carbon) vs. tritium. (B) Carbon-14 (as percent modern carbon) vs. $\delta^{13}\text{C}$ (‰, Pee Dee belemnite [PDB]).

(Smith et al., 2001; Mahler et al., 2006). Pharmaceutical compounds were detected in groundwater and spring water, including acetaminophen and caffeine (see Mahler et al., 2006; Mahler and Musgrove, this volume). Concentrations of some contaminants, such as pesticides, were higher during storm events such that routine sampling likely misses maximum concentrations of some contaminants (Mahler et al., 2006).

Detailed water-quality studies of the Barton Springs complex support the source-water basins defined by dye tracing (Hauwert et al., 2004b). Main, Eliza, and Old Mill Springs are generally geochemically similar and thus have related source areas. However, Old Mill Spring has slightly elevated TDS and ions (Na, K, and Cl) and attenuated contaminants compared to Main Spring, suggesting additional source water from distal unurbanized recharge and the saline zone, respectively (Mahler et al., 2006). Upper Barton Springs has the lowest TDS and ion concentration and is least affected by the saline-zone geochemistry. However, Upper Barton Spring is affected by anthropogenic contaminants (nutrients and pesticides) likely related to its highly urbanized watershed area. Similarly, in the San Antonio segment, wells completed in the unconfined urban areas had elevated nitrate and pesticide concentrations (Opsahl et al., 2018). Isotopes of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) can be used to identify anthropogenic sources of recharge for the Barton Springs segment of the Edwards Aquifer watersheds (Christian et al., 2011). Elevated values of $^{87}\text{Sr}/^{86}\text{Sr}$ from Upper Barton Springs (Mahler et al., 2006) could suggest a municipal water-supply source of recharge (Wong et al., 2012) possibly related to wastewater.

An estimated 140,000 people live on the contributing and recharge zones (excluding the Blanco watershed), and the population is projected to double by 2035. Impervious cover has increased 2.6 times from 2005 to 2010 in the Bear Creek watershed (Herrington et al., 2010). It is well established that concentrations of pollutants in stormflow increase with increasing impervious cover (Zhu and Glick, 2017). Accordingly, increasing urbanization in the contributing watersheds is a likely cause for impaired surface-water quality (TCEQ, 2015) and will likely affect the water quality of the Barton Springs segment of the Edwards Aquifer. The studies cited above have shown anthropogenic effects from the persistent presence of pesticides and VOCs. Other data and studies suggest an increasing trend of specific conductance, turbidity, suspended solids, sulfate, total organic carbon, and total nitrate attributed to anthropogenic effects on the Barton Springs segment of the Edwards Aquifer (Turner, 2000; Herrington et al., 2005; Herrington and Hiers, 2010).

Sediment (suspended particles) within water resources is one of the greatest pollutants by volume in the United States (Keller, 2008, p. 424). Suspended particles (measured as turbidity) after recharge are the most common water-quality problem in karst aquifers, with pathogens such as bacteria, viruses, and parasites being the highest concern for public health (Mahler et al., 2000; Kresic, 2013, p. 567). Sediments from urban areas often have high concentrations of hydrophobic contaminants, such as dichlorodiphenyltrichloroethane (DDT), polycyclic aro-

matic hydrocarbons (PAHs), and lead. Thus, influxes of sediment into karst aquifers have an impact on water quality. However, a study by Mahler (2003) indicated suspended particles in Barton Springs discharge showed minor effects from urbanization compared to stream samples, indicating some attenuation of the influx of sediment into the aquifer.

The karstic Edwards Aquifer is very vulnerable to wastewater contaminants that have a risk of pathogenic outbreaks (Hernandez, 2015), although, to date, the Barton Springs segment of the Edwards Aquifer has not had any known pathogenic outbreaks. Wastewater sources such as septic tanks, land application, and direct discharge of treated effluent are also potential sources of nutrients (including nitrate) to the Barton Springs segment of the Edwards Aquifer. Musgrove et al. (2016) documented increasing concentrations of nitrate in the Barton Springs segment of the Edwards Aquifer that have been attributed to anthropogenic wastewater sources such as septic tanks and land application of treated effluent. Recent approvals by the Texas Commission for Environmental Quality (TCEQ) allowing municipal utility districts and municipalities to directly discharge treated effluent into the contributing zone of the Barton Springs segment of the Edwards Aquifer will likely exacerbate this trend of degraded water quality within the contributing streams (Herrington and Richter, 2016).

The Barton Springs segment of the Edwards Aquifer provides a very good groundwater source for drinking water, recreational, and ecological purposes. However, the changes in water quality, and the inherent vulnerability to contaminants make resource protection for water supply paramount for its long-term sustainability. In addition, the changes in water quality are likely to have an impact on recreation at Barton Springs pool, on ecosystems, and on the endangered salamanders.

AQUIFER MANAGEMENT

The BSEACD was created in 1987 with a legislative mandate to conserve, protect, and enhance the groundwater resources located within its boundaries. Rules have been established to preserve groundwater supplies and maximize spring-flow rates during extreme drought. These include: (1) drought management; (2) capped firm-yield; (3) interruptible, conditional permits; and (4) management zones to protect vulnerable areas of the Barton Springs segment of the Edwards Aquifer and to foster alternative supplies (BSEACD, 2017).

The capped firm-yield production was supported by modeling studies (Smith and Hunt, 2004) and now relates to the joint groundwater planning process. Texas law (Title 31, Part 10, §356.10 [6] TAC) requires as part of the joint planning process the expression of a Desired Future Condition (DFC), which is a quantified condition of groundwater resources defined by participating groundwater conservation districts within a groundwater management area. The DFC for the Barton Springs segment of the Edwards Aquifer is: "Spring flow at Barton Springs during average recharge conditions shall be no less than

49.7 ft³/s (1.41 m³/s) averaged over an 84-month (7-year) period; and spring flow of Barton Springs during extreme drought conditions, including those as severe as a recurrence of the 1950s drought of record, shall be no less than 6.5 ft³/s (0.18 m³/s) average on a monthly basis” (BSEACD, 2017, p. 27). Modeling simulations indicate that to meet those quantitative criteria, the modeled available groundwater (MAG) is about 5.2 ft³/s (0.15 m³/s) of authorized pumping during severe drought (Hunt et al., 2011; Hutchison and Hill, 2011). This is approximately the amount of pumping allowed by BSEACD permits and rules under drought conditions.

Many of the strategies outlined above, among others, are part of the BSEACD’s Habitat Conservation Plan (HCP), designed to protect the Barton Springs (*Eurycea sosorum*) and Austin blind salamanders (*Eurycea waterlooensis*). The HCP outlines specific conservation measures to avoid, minimize, and mitigate the impacts of groundwater production on the endangered species (BSEACD, 2018). The measures are incorporated into the BSEACD’s Texas Water Development Board–approved management plan (BSEACD, 2017). The HCP was accepted by the U.S. Fish and Wildlife Service (USFW, 2018) with the issuance of an incidental take permit (ITP) for a 20 yr term (TE10607C-0). The BSEACD will work in coordination with the City of Austin, which received a 20 yr ITP in 2013 (TE839031-1) for its HCP related to the salamanders and operation of Barton Springs pool as a recreation area.

The BSEACD has developed strategies and rules to preserve groundwater supplies and maximize spring-flow rates. The BSEACD is approaching sustainable management of the Barton Springs segment of the Edwards Aquifer by balancing its use as a resource with preservation of spring flow during extreme drought. However, climate change will likely produce more severe droughts (USGCRP, 2018) and test current management strategies in the future. Thus, the paradox of the karstic Barton Springs segment of the Edwards Aquifer is that its rapid recharge allows the Barton Springs segment to be a sustainable long-term resource, but the aquifer is vulnerable and has limited groundwater availability during drought periods. Multiple integrated strategies will be needed to address the various impacts on the aquifer during drought, and these include increased supply (desalination, aquifer storage and recovery) and decreased demand (conservation, regulation; USGCRP, 2018).

LAND-USE MANAGEMENT

Limited regional protection of water quality specific to the Edwards Aquifer recharge zone has been addressed by the government of Texas (Chapter 213 Edwards Rules). Those rules provide some regional protections of water quality by prohibiting or limiting certain activities, such as landfills, wastewater discharge (over the recharge zone), and increases in total suspended sediments (TSS) in stormwater from developments and roadways. A recent study concluded that current highway stormwater treatment practices, such as sand filters, are an effective means of

preventing runoff of some common roadway contaminants over karstic aquifers (Barrett, 2018).

Municipalities generally have stricter land-use rules, such as the City of Austin’s Land Development Code and other ordinances that limit impervious cover and development to protect water quality. For example, in the city’s Save Our Springs (or “SOS”) ordinance, among other rules, impervious cover is limited to 15% in the recharge zone, and nondegradation standards are set for stormwater from land development.

One of the most effective strategies available today for protecting lands from urbanization and protecting water quality and quantity is the Water Quality Protection Lands (WQPL) program of the City of Austin. The WQPL program purchases lands or easements and has resulted in the preservation of 22% of the recharge zone and 7% of the contributing zone in the Onion and Barton Creek watersheds. In addition, the program enhances water quantity and quality through various land (vegetation restoration) and karst restoration (cleanout of caves) activities (Thuesen, 2015). Similarly, the BSEACD maintains an enhanced recharge facility at Antioch Cave that improves the quantity and quality of recharge entering the cave within Onion Creek. During a 1-yr study of the operation of the facility, more than 2400 lbs (1090 kg) of nitrogen (nitrate/nitrite), 295 lbs (134 kg) of phosphorus, and 190,000 lbs (86,180 kg) of sediment were prevented from entering the aquifer (Smith and Hunt, 2013).

FUTURE CHALLENGES

The Barton Springs segment of the Edwards Aquifer is vulnerable to contamination and pumping during drought conditions. Future challenges will include maintaining sustainability in the face of climate change and the additional threats related to population growth, such as contamination and increasing demand (USGCRP, 2018). Additional challenges will include understanding and preserving endangered species habitat, navigating a changing legal framework, and increasing alternative or conjunctive water supplies.

Increasing the supply, or strategic use of existing supplies, through aquifer storage and recovery (ASR) and desalination of the saline part of the Edwards Aquifer are potentially feasible strategies (Smith et al., 2017b; USGCRP, 2018). In addition, continued work on recharge enhancement and characterization of the sources of recharge and inter- and intra-aquifer flows will remain important areas for study as the water budget is refined. Demand reduction will need to be a component of any strategy for sustainability, given the likely impacts of a changing climate.

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