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THE EDWARDS AQUIFER AND CHANGES IN THE SAN ANTONIO, TEXAS WATER SUPPLY, 1993-2013

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1. INTRODUCTION

San Antonio, Texas with a 2012 population of 2.2 million, is the sixth fastest growing Metropolitan Statistical Area in the U.S. with a population of over 1 million (USCB, 2012). It owes its location to San Pedro Springs of the Edwards Aquifer that form the headwaters of the San Antonio River. Its continued growth has been sustained by the aquifer's abundant and readily available waters. In 1993, Federal Judge Lucius Bunton ordered the State of Texas to manage use of the Edwards Aquifer to maintain "critical habitat" for several endangered species that live in streams sustained by springflow from the aquifer (Votteler, 1998). For several years the city fought a losing court battle to restrict its use of Edwards Aquifer water. Only when the city realized the negative economic impacts of its insecure water supply did it fully embrace alternative water supplies and water conservation. In the following paper we describe and analyze the water supply alternatives, enhancements, and conservation measures considered and adopted by the San Antonio Water System (SAWS) since 1993. This discussion provides useful examples of contemporary measures that could be employed by water utilities across the U.S.to address their water needs. This analysis comes from the perspective of a water resources professor (Earl), Ph.D. student (Parr), and that of a water resources conservation planner (Wilcut). Our research is based upon information contained in SAWS and other regional water agency reports and the professional literature.

2. BACKGROUND

San Antonio sits astride the Balcones Escarpment that forms the boundary between the Great Plains and Atlantic and Gulf Coastal Plains physiographic provinces (Fenneman, 1931; 1938). Most importantly the escarpment also forms a line of springs known as the "Texas Spring Line" that runs from Waco to the northeast and west to Del Rio along the Rio Grande (Petersen, 1995) (Figure 1). The region was covered by the North American Seaway for most of the Craterous Period and experienced deposition of limestone, shale, and pockets of evaporates that form the Edwards Group and other rock units. Tectonic uplift associated with the Basin and Range orogeny to the west and sediment loading in the Gulf of Mexico caused a major break in the North American Craton thus forming the Balcones Escarpment in Miocene time (Baldridge, 2004). This break pushed rocks of the karst-weathered Edwards Group to the surface along the Balcones Escarpment, thus forming a line of major springs that has been the focus of settlement in the region. Rocks of the Edwards Group comprise the Edwards Aquifer that is noted for its rapid response to recharge, its high inter-annual variability, and its high conductivity (EAA, 2012). Due to stream dissection and impermeable units, the aquifer has three hydrologically distinct sections: the Northern Segment north of the Texas Colorado River,

the central Barton Springs Segment, and the Southern or San Antonio Segment south of Kyle and stretching west to Brackettville in Kinney County (TWDB, 2012). All except the western-most portions of the San Antonio segment, in Kinney County, are managed by the Edwards Aquifer Authority (EAA). This EAA region, and the watersheds downstream of the Texas Spring Line, coincide with Texas Water Development Board Water Planning Region L, South Central Texas, which is mandated to have drought management plans (TWDB, 2012).

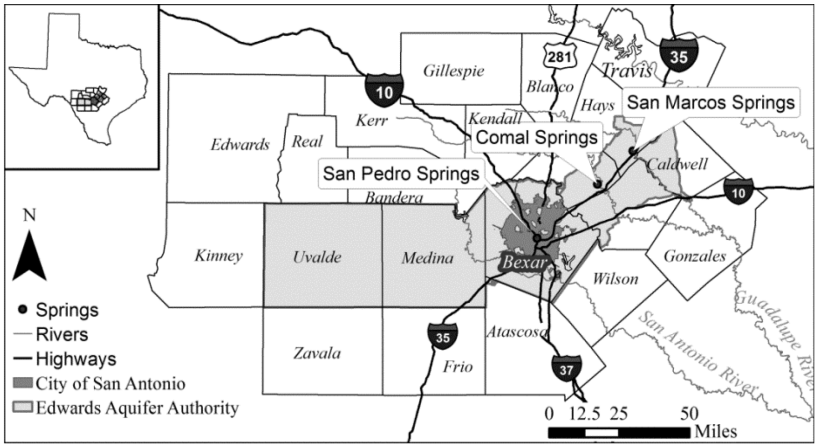


FIGURE 1
SAN ANTONIO AND THE EDWARDS AQUIFER

The San Antonio Segment of the Edwards Aquifer contains two of the largest springs in Texas, San Marcos Springs (mean 170 ft^3/sec) and Comal Springs in New Braunfels (mean 290 ft^3/sec), as well as San Pedro Springs in San Antonio (Brune, 1975; U.S. Geological Survey, 2013). Total capacity of the aquifer is measured in the tens-of-millions of acre-feet, its annual recharge is highly variable, and springflow discharge is a function of the aquifer water table level. Water pumping, in large part for irrigation, is inversely related to precipitation and recharge (Table 1).

An important, but troubling, aspect of the hydroclimatology of the region is the extreme year-to-year variability and the persistence of dry periods. In a 2006 study, Earl et al. found that wet periods had a median length of 1.5 years, and dry periods had a median length of 3.5 years. The period since that study has experienced comparable variability, with 2007 being wet, 2008 and 2011 being exceptionally dry and 2009, 2010, and 2012 being within 25% of mean annual precipitation (USNCDC, 2013).

San Antonio was founded in 1718, the same year as New Orleans, as an anchor for Spanish settlement in Texas and as a barrier to westward expansion of French settlement. Initially, settlement focused around four missions located along the San Antonio River. Each mission was surrounded by irrigation agriculture supplied by diversion of the river at small check dams. With the immigration of Spanish and Mexican families, it became the largest city and capital of the Spanish, later Mexican, province of Tejas (Tyler, 1996). Steady population growth continued, and was fueled by the post-Civil-War livestock boom and railroad connection in the nineteenth century, the expansion of military bases during World War II, and the post-World War II tourism and Sunbelt booms.

The first wells to tap the Edwards Aquifer were drilled in the late 1800s, and the city increasingly became dependent on this source of groundwater. Withdrawals from the aquifer increased faster than the population growth due to use of water for landscaping and other amenities. By1980, the city was withdrawing over 180,000 acre feet (a.f.) per year with a per capita water use over 200 gallons per person per day (GPD) (Table 2).

TABLE 1
MAJOR HYDROLOGIC CHARACTERISTICS OF THE SAN ANTONIO SEGEMENT, EDWARDS AQUIFER: 1934-2011 (EAA, 2012)

Total Capacity, acre feet	25,000,000 to 250,000,000
Mean Annual Recharge, acre feet	711,000
Median Annual Recharge, acre feet	559,000
Greatest Annual Recharge, acre feet (year)	2,485,000 (1992)
Lowest Annual Recharge acre feet (year)	44,000 (1956)
Greatest Annual Pumping, acre feet (year)	542,000 (1989)
Lowest Annual Pumping, acre feet (year)	102,000 (1934)
Mean Annual Pumping since 1997 acre feet	368,000
Median Annual Pumping Since 1997 acre feet	371,000

TABLE 2
SAN ANTONIO POPULATION AND WATER USE, 1850-2010 (EAA, 2001, 2011, 2012; Gibson, 1998; USCB 2002, 2012)

Year	Population (U.S. Rank)	Water Use acre feet*	Per Capita Gallons per Day
1850	3,000 (na)	Not Available	----
1870	12,000 (na)	Not Available	----
1890	38,000 (81)	Not Available	----
1910	97,000 (54)	Not Available	----
1930	232,000 (38)	Not Available	----
1950	408,000 (25)	75,000**	163
1970	654,000 (15)	121,000	165
1980	786,000 (11)	184,000	209
1990	936,000 (10)	184,000	175
2000	1,145,000 (9)	191,000(182,000*)***	164
2010	1,327,000 (7)	198,000 (179,000*)***	133

* Value is equal to 72 percent of all municipal withdrawals from the Edwards Aquifer.
** Estimated value based upon 1955 withdrawals.
***Does not include water reuse, after 1990.

The 1950-1956 drought precipitated the first major efforts to monitor and manage the aquifer. In central Texas, the 1950s drought was more severe than the 1930s Dust Bowl drought and has the legal status as "the drought of record." Considerable controversy has surrounded the recurrence interval for that drought with environmentalists and some academics calling it a "50 to 100-year drought," whereas others advocate a much longer recurrence interval that should not be included in drought planning (Mauldin, 2003; Votteler, 2004; Cleaveland, 2006; Earl, Dixon, and Day 2006). During this drought, Comal Springs ceased to flow for 144 days, San Marcos Springs declined to 46 ft^3/sec, and monitor well J-17 in Fort Sam Houston declined to a record low of 612 ft., compared to a long term mean of 665 ft., above sea level (USGS, 1998; EAA, 2012).

In 1959, the Texas legislature created the Edwards Underground Water District (EUWD) comprising the counties that contained the San Antonio section of the Edwards Aquifer. The EUWD was an application of the Texas 1949 Groundwater Management Act that authorized the creation of such districts. The district had data gathering authority, but limited management authority. Management was limited to setting well spacing and well sizes and, most significantly, did not include pumping limits (Kaiser, 1986). Periodic droughts prompted the Texas legislature to pass several incremental laws that gave the groundwater districts taxing authority to charge for industrial, but not municipal and agricultural, water uses.

By the 1980s, total pumping from the aquifer exceeded 500,000 acre feet in several years and caught the attention of environmentalists including the Sierra Club. In 1991, armed with the Endangered Species Act, the Sierra Club filed charges against the Secretary of the Interior for not protecting the critical habitat of several species.Shortly thereafter, the Guadalupe-Blanco River Authority, the City of New Braunfels, and the City of San Marcos, joined the Sierra Club. All of those organizations had major financial interests in the water emanating from the springs. Early in 1993, Federal Judge Lucius Bunton ordered the State of Texas to come up with a management program to protect springflow from the Comal and San Marcos Springs. Passed on the last day of the 1993 legislative session, Senate Bill 1477 created the Edwards Aquifer Authority with a prior appropriation permit system that limited pumping from the aquifer to 400,000 a.f. (after 2007) with further mandated reductions when springflow and monitor well levels fell below prescribed limits.

San Antonio and other large groundwater interests, mostly agricultural, sought relief in both federal and state courts. Ultimately the mandated management plan withstood these legal challenges and achieved full authority by 1996 (Votteler, 2004). San Antonio as an opposing party still did not embrace the realities of these restrictions until late 1996, when the Vice President of Sony told the mayor of San Antonio that Sony would not invest further in San Antonio until it "dealt with its water problem" (Dilanian, 1996). Almost overnight, San Antonio embraced an aggressive program for alternative water supplies and water conservation.

3. METHODS

The purpose of this study is to analyze the response of San Antonio to reduce its reliance on the Edwards Aquifer and to determine the relative merits of the methods employed. We primarily used data from the Edwards Aquifer Authority (EAA), San Antonio Water System (SAWS), and the state water plan (TWDB, 2012) to evaluate the effectiveness of these measures in terms of quantity, cost, and reliability under different conditions. The results of this analysis can provide useful benchmark values in water conservation and supply alternatives that may prove useful for other rapidly growing Sunbelt cities.

A major problem faced by students of water supply and water use is the significant disparity of water amounts among different sources of data. Data for San Antonio water supply and water use are no exception. We found variances of up to 20 percent among references from the Edwards Aquifer Authority, Texas Water Development Board, and the San Antonio Water System. "Detective" work revealed that some of this variance was due to one agency including water reuse in their values, and another not counting waste water reuse. This variance has increased in recent years as San Antonio is now reusing up to 40,000 a.f. per year of treated waste water (SAWS, 2013).

In stating San Antonio's withdrawals of water from the Edwards Aquifer, we had to make some assumptions as well. Prior to 2012, much of Bexar County was served by the Bexar Metropolitan Water District (BMWD), but with the purchase of BMWD, SAWS provided almost all the water in Bexar County. Prior to 2012, SAWS use amounted to 80 percent of the ground-water use in Bexar County, but now is greater than 95 percent (SAWS, 2012). For the years from 2000 to 2011, we found that Edwards Aquifer municipal withdrawals in Bexar County constituted between 89 and 91 percent of all municipal water withdrawals from the aquifer. Therefore, our values prior to 2011 for "San Antonio" water use of the Edwards constitutes 72 (0.80 X 0.90 = 0.72) percent of all municipal withdrawals from the Edwards Aquifer. The uncertainties caused by these differing values explain the difference in our calculated value of per capita water use in 2010. We calculated 133 GPD whereas SAWS in their 2012 water plan states that current water use is 143 GPD (SAWS, 2012).

4. WATER SUPPLY ACTIONS

Since the 1950s drought there have been various schemes and more concrete proposals to enhance the San Antonio water supply. These have ranged from the extravagant

North American Water and Power Alliance (NAWAPA) program that would have brought water from western Canada to the American Southwest to more realistic water transfers and conservation. In 1967, the Texas legislature proposed the Trans-Texas Project that would have transferred water from east Texas to south Texas via an aqueduct across the coastal plain. This plan was narrowly defeated in a 1968 referendum (Moore, 2005). In 1987, the city refused to exercise its option to purchase "developed water" from the Canyon Lake project on the Guadalupe River (Votteler, 2004).

Faced with the reality of looming water shortages, the city adopted a compromise water plan in 1987 that included conservation, water reuse, and a "clever" plan to trade two parts of treated San Antonio wastewater for one part Medina River water from the Bexar-Medina-Atascosa Water Control and Improvement District. A central component of this scheme was the Applewhite Reservoir that would store the treated effluent until needed by the irrigators. This plan was put before the voters on two occasions and was twice rejected. The major argument was the "high cost," almost $400 per acre foot of additional supply from the Medina River, whereas "unlimited" Edwards Aquifer water cost less than half as much (Putnam and Peterson, 2003; Blanchard *et al*., 2008)

Following the "Sony Incident," early in 1997 the city initiated an aggressive effort to obtain extra basin water inputs. In 1998, the city signed a contract for 40,000 a.f. per year from the ALCOA lignite mine and refinery, east of Austin. Next, they signed a contract with the Guadalupe-Blanco River Authority (GBRA) for 70,000 a.f. per year. In 2002, they signed a contract for 150,000 a.f. per year from the Lower Colorado River Authority (LCRA). Both the GBRA and the LCRA projects entailed diverting water from those rivers immediately upstream of where they entered the coast. This was a political concession to allay fears of upstream users of those streams. However, doing so significantly increased the distance and lift required to deliver the water to San Antonio and, consequently, dramatically increased the cost. Due to the cost of greater than $800 per a.f. and political pressure from the host water source regions, these water transfers have been postponed or canceled. (Votteler, 2004; SAWS, 2012).

Since the 1987 Water Plan, both water conservation and water reuse were central to the city's water supply. After 1997, those programs received additional impetus. Both residential and commercial programs reduced per capita and total water use. Residential programs including toilet retrofit, low flow fixtures, and landscape conservation have reduced per capita daily use from over 180 gallons per day (GPD) to around 140 GPD. The toilet retrofit program alone was shown to save 19.5 GPD in homes that participated in that program (Ramos, 2002).

One of the more innovative technologies developed in the conservation effort has been refrigeration condensate recovery from various cooling mechanisms such as air conditioners and refrigerators. Condensate recovery ranges from approximately 1 gallon per day for a residence to thousands of gallons per day from large facilities. When installed, these systems annually can produce approximately 1 a.f. of water per 20,000 ft^2 of air conditioned space. Unlike rainwater collection systems whose cost efficiency is lost due to the need to store the irregular supply of rainwater, these systems provide a much more reliable water supply. Additional savings can be achieved by better management of cooling tower water use and reuse. If applied throughout the SAWS service area, this could save almost 2,000 a.f. per year (Wilcut, 2006).

Local efforts to increase local water supplies provided significant returns. Starting in 1974, the EUWD built five "recharge structures" on streams that cross the Edwards recharge zone. Recharge contributions have mirrored the highly variable hydrologic regime. Wet years such as 1992, 1998, 2002, 2004, and 2007 have provided between 20,000 and 25,000 a.f. of additional recharge whereas dry years provide virtually none (EAA, 2012). Contributions of flood control, "detention" dams on the recharge zone, such as those on Salado Creek, the Dry Comal River, and the Upper San Marcos River provide similarly highly variable recharge amounts, with an average increase of 0.1 a.f. of water recharged by 1 acre of watershed above the flood control dam. (USSCS, 1978).

In 1997, the EAA Board of Directors decided to implement a "Precipitation Enhancement Program" (PEP) that began operations in 1999. Between 2003 and 2011, an average of 13,000 grams of silver iodide and 10,000 grams of calcium chloride per year produced an increase of between 55,000 (2008) and 351,000 (2004) acre feet of precipitation over 3.1 million acres. This translates to between 0.2 and 1.4 inches of increased precipitation (EAA, 2012). Converting this precipitation increase to actual increases in recharge is challenging. Assuming that five percent of this precipitation increase becomes recharge, annual recharge has been increased from a low of 2800 a.f. up to 18,000 a.f. in wet years.

Texas Senate Bill 1477 that created the Edwards Aquifer Authority allowed for the purchase and transfer of a fixed amount of water rights (permits) and for lease from agricultural uses. By 2012, San Antonio had purchased nearly 100,000 a.f. of water permits from other EAA permit holders and had lease arrangements for another 45,000 a.f./year (EAA, 2012).

One of the most recent supplements to the San Antonio water supply has been an Aquifer Storage and Recovery (ASR) Program that was initated in 2004. That program has 29 dual action wells (inject and withdraw) and a total storage capacity of 100,000 acre feet. During periods of high Edwards Aquifer levels, water is withdrawn and injected into the Carrizo-Wilcox Aquifer. Between March and September 2011 up to 40 million gallons per day (MGD) was withdrawn and provided up to 25 percent of SAWS water supply and reduced withdrawals from the Edwards Aquifer by 20,000 a.f. (SAWS, 2012).

In 2016, San Antonio will have its first brackish groundwater desalinization plant in operation. This method has been widely publicized throughout the Edwards Aquifer region and is considered cost effective at approximately $400 to $800 per a.f. (Arroyo and Shirazi, 2012). The initial phase of the San Antonio facility will have a capacity of 12,000 a.f. per year, but will be expanded to an annual rate of 30,000 by 2026 (SAWS, 2012).

5. DISCUSSION, ANALYSIS, AND CONCLUSIONS

San Antonio's multifaceted program to enhance and stretch its water supplies provides a useful way to evaluate water supply options faced by many other Sunbelt cities. Probably the greatest accomplishment, and surprise to some, has been the success of the water conservation programs. Per capita water use has dropped from 200 gallons per day in the 1980s to about 140 gallons per day today. This places San Antonio, along with El Paso, as the Texas City with the lowest per capita water use (TWDB, 2013). These low per capita water values can be attributed to both cities having faced water supply crises in which seemingly cheap and abundant local water supplies were blocked by legal means (Earl and Czerniak, 1995; Schmidt, 2005).

One water supply enhancement that has been studied but has not been widely applied in the EAA/SAWS region, is brush management that involves replacing invasive shrubs, especially Ashe juniper, with grasses. Studies conducted elsewhere in the central Texas region have shown that such programs increase surface water supply when annual precipitation exceeds 18 inches and that in a year with 30 inches surface water will be increased by approximately 1/3 a.f. per acre of treated land (TAES, 2000). Another more recent study (Bazan et al, 2012) claimed that the benefits of brush management were excessive, which has been used by the EAA as a justification to refrain from financing brush management programs. Elsewhere, brush management programs are often partially funded by the U.S. Natural Resource Conservation Service and cooperating river authorities, such as the Lower Colorado River Authority (LCRA 2013). Such programs would increase both in situ recharge and channel recharge. Employing a conservative value of 1/10 acre foot per acre recharge increase applied to ten percent of the approximately 3000 mi^2 of the contributing and recharge zones, would add approximately 10,000 to 20,000 a.f. per year.

Of the water supply enhancements available, there are broad differences in the effectiveness and applicability of the water supply sources adopted by San Antonio. Some measures provide or enhance water supply independent of precipitation inputs. Others are directly dependent on precipitation. Some methods are effective in lengthening the water

supply into drought periods. Others that are independent on precipitation are presently prohibitively expensive but may have to be considered in the future when lower priced supplies can no longer meet the demand.

Among the options that are independent of precipitation, the two most significant are conservation and reuse of treated wastewater. Obviously, conservation only reduces demand, but the examples set by El Paso and San Antonio demonstrate that a significant decreases in demand can be met by multifaceted conservation programs. San Antonio currently directly reuses about 40 percent, or 40,000 acre feet per year. This means that annual per-capita wastewater production is about 1/12 acre foot per person. Future inside-the-house water conservation measures will decrease this slightly, from the present 80 GPD to 70 GPD. Significant increases in this use are still possible because only about 40 percent of San Antonio's wastewater is being reused. A possible legal challenge to dramatic increases in waste water reuse for consumptive uses such as landscape irrigation could be initiated by the reduced wastewater discharges into streams that would decrease flows upon which downstream users currently depend. Texas water law gives the water utility ownership of the water *until* that water is discharged into streams, after which the city would have to apply for a "bed and banks" permit from the Texas Commission on Environmental Quality (Kaiser, 1986).

TABLE 3
SAN ANTONIO WATER SUPPLY 1990, 2012, 2020 (ACRE FEET) (SAWS 2012+ other)

Groundwater	1990	2012	2020
Edwards Aquifer	184,000	----	----
Edwards Permits	----	249,000*	304,000***
Edwards Lease	----	45,000*	----
Carrizo Wilcox Aquifer	----	6,000	17,000
Trinity Aquifer	----	----	2,000
ASR		20,000	>20,000
Recharge Enhancement	0 to >25,000	0 to >25,000	0 to >25,000
Precipitation Enhancement	----	2800 to 20,000	2800 to 20,000
Desalinized GW	----	----	14,000
Surface Water			
Canyon Lake (GBRA)	----	8,000	8,000
Medina River	----	9,000	0 to 13,000
Reuse	----	40,000	>45,000
Conservation over previous value (per capita water use: GPD)	26,000 (175)	63,000 (ca. 140)	14,000 (135)

* Subject to up to 44 percent decrease during drought.
** Includes both permits and leases.

Other water supply additions that are largely independent of precipitation include air conditioning (AC) condensate and desalinized local groundwater. Based upon the rate of 1 a.f. condensate produced per 20,000 ft^2 of refrigerated floor space, this method could generate over 20,000 a.f. annually. Desalinization of brackish groundwater already supplies El Paso with 24 percent of its water supply and a comparable sized facility is being constructed by SAWS (SAWS, 2012; EPWU, 2013).

The two major water supply enhancement methods that are dependent on precipitation are cloud seeding and recharge enhancement. A review of the literature on cloud seeding demonstrates that there are widely divergent estimates on the effectiveness of that method (Benjamini, 1986). As mentioned in the preceding section, both methods produce almost no increase in dry years but in wet years can increase recharge in the tens of thousands of acre feet (EAA, 2012). A brush management program, if applied to ten percent of the area that drains to the Edwards recharge area would contribute a comparable amount. These recharge increases would provide a "cushion" for the first year or two of protracted drought.

On a cost per a.f. of water produced, SAWS has found that purchasing water rights is the most cost effective means to increase its water supply. By SAWS' calculation, purchasing permits or leasing Edwards water costs approximately $300 per a.f. Even when considering that permitted water can be reduced 44 percent during designated droughts, that water still costs less than any of the other means, with the possible exception of certain conservation programs and recharge enhancement. However, there is an upper limit on how many more permits will be available and by SAWS' analysis they can expect to be able to purchase no more than an additional 10,900 a.f. by 2020 and no additional future purchases without changes in legislation (SAWS, 2012).

The success of the San Antonio Water System in expanding its water supply and reducing per capita water use provides a strong case for the cost efficiencies of local solutions before considering importation of water. Conservation, reuse, programs to enhance local supplies, and outright purchase of local water has provided San Antonio with a net increase in water supply while reducing per capita water use by over 30 percent. However, these measures have limits and if population continues to grow, the city will eventually have to rely on more expensive water importation, and ultimately, desalinized seawater. This day of reckoning may be sooner than later if predictions of the reduction in water supply that will be produced by anticipated regional climate change prove correct (Seager, Tzanova, and Nakamura, 2009; Lui *et al*., 2012).

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