Groundwater Recharge for Drought and Endangered Species Protection: The H_2Oaks Aquifer to Aquifer Transfer for Storage and Recovery, San Antonio, Texas

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ABSTRACT San Antonio Water Systems (SAWS) developed its H2Oaks aquifer storage and recovery project in response to pumping restrictions set on its primary source of water supply, the Edwards Aquifer. The H2Oaks project pumps water from the Edwards Aquifer during wet years and transports it to the H2Oaks project site, where it is injected into the Carrizo-Wilcox aquifer for storage. Stored water is withdrawn to meet municipal demand when restrictions on Edwards Aquifer pumping are in place. Although created for the purpose of securing supplies for SAWS, the H2Oaks project became a centerpiece for regional water management. Storage is used during drought to mitigate impacts on pumping while ensuring minimum springflows needed to protect endangered species in the Edwards aquifer. Currently, the project stores over 176,000 acre-feet of water. This case study traces the development of the H2Oaks project from the passage of the Edwards Aquifer Act to the project's current implementation. The H2Oaks project demonstrates the potential for groundwater recharge projects to store water as protection against drought conditions. It also demonstrates how storage by one entity can support water management needs across the broader community of water users. **KEYWORDS** groundwater, managed aquifer recharge, aquifer storage and recovery, institutions, governance

OVERVIEW

Location	San Antonio, Bexar County, Texas
Groundwater challenges	Perceived vulnerability of groundwater supplies during drought
MAR motivating factors	Pumping restrictions on the Edwards aquifer with no carryover provision; cost of imported supplemental water, endangered species protection
MAR project goal	Create a drought reserve
Recharge method	Injection wells
Water source	Edwards Aquifer water
Key actor	San Antonio Water System
Challenges	Technical—Finding additional storage capacity if current storage capacity of the H_2Oaks project is reached and managing distribution system logistics
	Institutional—Resolving conflicts over water storage and water quality with neighboring groundwater users and tracking recharged water

(continued)

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Milestones	1991—The Sierra Club sues the U.S. Fish and Wildlife Service for failing to protect springflows fed by the Edwards Aquifer
	1993—The Edwards Aquifer Authority is created by the Texas Legislature
	1996—Texas Water Development Board awards SAWS a $200,000 grant to conduct a feasibility study
	1999—SAWS purchases its first tract of land over the Carrizo-Wilcox Aquifer
	2001—SAWS obtains required permit approvals from the Texas Commission on Environmental Quality
	2002—Construction of the H_2Oaks project begins
	2004—The H_2Oaks project begins operations
Current status	Operational; project currently has a 67,000 AFY recovery production capacity and 176,000 AF in storage.
Cost	$250 million for entire project

INTRODUCTION

The H_2Oaks Aquifer Storage and Recovery project is located in the southern tip of Bexar County and is the largest of three aquifer storage and recovery (ASR) facilities in Texas [1]. Unlike most managed aquifer recharge (MAR) projects, H_2Oaks does not use surface water. Instead, it is an aquifer-to-aquifer storage project that delivers water by pipeline from the Edwards aquifer to the Carrizo-Wilcox aquifer, just over 40 miles away. The project was developed by the San Antonio Water System (SAWS), a public water utility that serves Bexar County and neighboring areas [2]. Initially, H_2Oaks was intended as a mechanism for storage of seasonally available supplies—specifically water pumped from the Edwards aquifer during high water level conditions—for use when pumping from the Edwards aquifer was restricted. As the project moved forward and SAWS developed additional supplies, the project shifted from serving as a potential seasonal supply to an additional source of water that could be utilized during drought periods or emergencies. In 2012, the project became a tool for broader cooperative water management in the region by serving as a mechanism for maintaining springflows in order to protect endangered species dependent upon the Edwards aquifer.

The H_2Oaks project provides an example of how MAR can be used as a storage system to ensure the availability of supplies during low flow conditions while supporting groundwater dependent ecosystems. The H_2Oaks project provides a rare example of MAR that stores source water from a more transmissive aquifer (the Edwards) in an aquifer more supportive of storage (the Carrizo-Wilcox). Finally, the expanding mission of the H_2Oaks also serves as a lesson as to how, once operational, recharge projects can be used to provide not only physical but also environmental and regional water management benefits beyond those initially conceptualized when designing the project.

CASE EXAMINATION

Methods

This case study forms part of the journal's special collection entitled "Institutional Dimensions of Groundwater Recharge." The collection examines empirical examples of MAR from across the United States to provide insights on the institutional structures and motivations of MAR implementation. An in-depth description of the special collection and its objectives, along with a discussion of the wider context of groundwater management concerns that MAR aims to address, is included in Miller et al [3]. Each of the case studies in the collection examines a different physical and institutional design for MAR. Case studies were developed through an analysis of documents and expert interviews. Documents reviewed include reports from governmental agencies implementing the MAR projects, permits and reports from regulatory agencies, state laws and regulations, academic literature and technical reports, and news articles. Interviews were conducted with key individuals involved in the development of each project, including government officials, regulators, and project implementers.

Local Background

SAWS was formed in 1992 by consolidating three existing city utilities, making it the sole agency responsible for wastewater, drinking water, stormwater, and water reuse [4]. SAWS supplies water to a primarily urban and suburban area, including residential and commercial customers [5]. SAWS sources its water from three major regional aquifers: Edwards, Trinity, and Carrizo-Wilcox [6]. The Edwards aquifer is considered the "cornerstone" of the San Antonio Supply [6] accounting for 66% of its total water supply in 2018 [7]. SAWS purchases additional supplemental water from other water suppliers withdrawing from the Trinity aquifer, Carrizo-Wilcox aquifer, Canyon Lake, Medina System, and Lake Dunlap [8].

Texas Groundwater Laws and Regulations

The common law "rule of capture" provides the foundation for groundwater law in Texas. This rule holds that landowners have the right to pump as much water as they want from beneath their property. Adopted by the Texas Supreme Court in 1904, the rule of capture provides no compensation to individuals whose wells go dry due to their neighbor's pumping. Unlike most other states, Texas does not apply a "reasonable use" limitation to groundwater pumping [9]. Where groundwater conservation districts (GCDs) have been established, additional rules and regulations may apply. Further, the Edwards Aquifer Authority Act and regulations related to ASR projects also govern groundwater use in Texas.

THE EDWARDS AQUIFER AUTHORITY ACT. In 1991, the Sierra Club and Professor Clark Hubbs filed a lawsuit against the U.S. Fish and Wildlife Service (USFWS) asserting that by failing to maintain springflows at the San Marcos and Comal Springs, USFWS had allowed 'takings' of listed species under the Endangered Species Act (ESA) [10]. These springs are fed by outflows from the Edwards aquifer and pumping that lowers groundwater levels impacts flows at these springs [11]. The court ruled in favor of the Sierra Club, requiring springflows to be maintained and suggesting that Texas create a regulatory system to restrict withdrawals from the Edwards aquifer or face potential federal intervention [11]. To avoid this outcome, Texas State Legislature passed the Edwards Aquifer Authority Act in 1993, creating the Edwards Aquifer Authority (EAA) to manage and protect the Edwards aquifer [11]. After several court challenges and amendments to the Act, the EAA became operational in 1996 [12].

The EAA manages the aquifer by issuing permits for withdrawals, with approximately 572,000 AF permitted for withdrawal each year. Allocations were initially determined based on historical use and conservation goals. The EAA can impose restrictions during times of drought, reducing withdrawals by up to 44% of the permitted amount based on aquifer levels and springflow [13]. All permitted users are assessed an aquifer management fee by EAA. For nonagricultural users, this annual fee is based on the amount of groundwater allocated to the water user each year, whereas for agricultural users, the fee is calculated from the previous year's groundwater use. In 2019, nonagricultural fees were $84/AF and agricultural fees were $2/AF, a value determined in the Edwards Aquifer Act [14]. Allocations are yearly amounts; no carry over between years is allowed due to the flow rates of the karst aquifer [15]. This restriction has led to the creation of a water market for Edwards aquifer water in which water rights, or portions of them, can be sold or leased.

As a result of the pumping limitations imposed on the Edwards aquifer, SAWS had to adjust its water management and operations. SAWS, as with other Edwards aquifer pumpers, was no longer able to access an unlimited amount of water. Instead, the utility was assigned a specific allocation of water each year. If SAWS failed to pump its entire allocation, SAWS' unused share of water would not be credited to the utility but instead lost. This lead SAWS to investigate ASR as a mechanism for "carrying over" unused water from one year to the next.

ASR IN TEXAS AND REQUIRED PERMITS. Texas law recognizes ASR as a beneficial use of surface water and defines ASR as storing water underground for later beneficial use using injection wells [16]. The TCEQ administers the Underground Injection Control Program within the state, which it operates under the primacy enforcement authorities delegated to it by the EPA for permitting in relation to the 1974 Safe Drinking Water Act. The program requires all injection wells to be permitted as Class V injection wells [17]. SAWS received a Class V Injection Well Permit from the TCEQ for operation of their ASR project.

GCDS. Across Texas, a number of regions are governed by GCDs. GCDs can be created by an act of the legislature, landowner petition, or by the TCEQ when local action is not taken within a priority groundwater management area. These districts have the authority to regulate local groundwater use by requiring all wells to be permitted and developing a management plan for their region—in essence, GCDs override the rule of capture for groundwater in Texas. GCDs are required to develop groundwater management plans and are granted the jurisdictional authority to permit wells and regulate well spacing and the production of groundwater, including allocating a given share of water in an aquifer to a landowner on a proportionate basis [18]. As of February 2019, about 70% of Texas counties are covered or partially covered by a GCD [19].

The H_2Oaks project stores water in the portion of the Carrizo-Wilcox aquifer located in Bexar County. This region is not regulated by a GCD. However, just south of Bexar County, the Evergreen Underground Water Conservation District (Evergreen District) has jurisdiction.

THE ASR PROJECT AT THE H_2OAKS CENTER

As the urban population in SAWS' service area grew, it became increasingly clear that the utility needed a more stable source of water [20]. As described above, during wet years, SAWS was not pumping its full Edwards aquifer allocation [21] and was losing its entitlement to the unpumped water while still paying its yearly Edwards aquifer fee [22]. Additionally, dry year pumping restrictions on the Edwards aquifer could potentially curtail pumping by up to 44% of SAWS' permitted amount. Consequently, during dry years, SAWS was spending millions of dollars purchasing supplemental water, while in wet years a portion of its Edwards aquifer water allocation was going unused. These factors led SAWS to search for an efficient method to store unused water during wet years for use during dry years. SAWS concluded that ASR would be the most feasible way to accomplish this goal.

In September 1996, SAWS was awarded $200,000 by the Texas Water Development Board to conduct a recharge feasibility study to evaluate the suitability of potential recharge sites [23]. The Carrizo-Wilcox aquifer was ultimately selected as the most cost effective site for the proposed project [24]. In September 1999, SAWS took the first step toward developing an ASR project by purchasing a tract of farmland over the Carrizo-Wilcox aquifer [25]. Construction of the H_2Oaks project began in August 2002, and the facility was opened in June 2004 [26].

During the development of the H_2Oaks project, residents near the project site were concerned about the impact the project would have on their groundwater. These residents asked to be annexed into the Evergreen District, which would have subjected SAWS to pumping restrictions. The annexation vote failed. To address concerns about potential project impacts within Bexar County and adjacent areas, SAWS entered into a "Water Resource Protection and Management Agreement" with the Evergreen District. Under this agreement, SAWS agreed to limit their pumping of native Carrizo-Wilcox aquifer water at the recharge site to 2 AF per acre of land, amounting to a total of 6,400 AF per year that can be pumped in addition to recovered Edwards aquifer water. The agreement only allows Edwards aquifer water to be recharged at the site (i.e., no reclaimed wastewater) to mitigate fears of contaminating the groundwater within the region [27]. SAWS was also required to develop a monitoring and mitigation program that would extend outside of Bexar County to limit any negative impacts of recharge and recovery operations on other groundwater users [28].

In the years following the development of H_2Oaks, policy regarding use of the Edwards aquifer progressed. In 2006, the USFWS convened a multi-stakeholder process to develop the requisite recovery implementation plan for the species dependent on the Edwards Aquifer that were listed under the ESA [29]. A central component of protecting and recovering those species is ensuring minimum flows at the San Marcos and Comal Springs. After much deliberation, the stakeholders agreed to and the USFWS approved a Habitat Conservation Plan for the Edwards aquifer. HCPs detail the management strategies that will be undertaken to mitigate and compensate for actions that may lead to unintentional impacts to species listed under the ESA. Without an approved HCP, users of the EAA would be unable to continue pumping of the aquifer [30].

Among the many elements in the Habitat Conservation Plan was the agreement to use the H_2Oaks facility for storing and distributing water in a manner that would support minimum springflows. The H_2Oaks stores water on behalf of the EAA, and, when water-level triggers are reached, signifying a threat to minimum springflows, stored water is used in lieu of pumping from the Edwards aquifer [31]. In addition, the Habitat Conservation Plan included a commitment to build a transmission pipeline and pump station to convey water from SAWs desalination programs located at the H_2Oaks facility in order to transport water to the southwestern and western portions of San Antonio [32].

Recharge

The H_2Oaks ASR project recharges water pumped from the Edwards aquifer into the Carrizo-Wilcox aquifer during wet years or years with low demand [33]. A pipeline carries Edwards aquifer water 30 plus miles from the SAWS Edwards aquifer production wells to the H_2Oaks facility's 29 injection and recovery wells [34]. Before injection, the water is disinfected to drinking quality

standards. The water is then injected into the 400- to 600-ft level of the Carrizo-Wilcox aquifer, where it forms a stable water bubble in the confined sand aquifer.

Accounting

SAWS tracks the amount of water in storage and is entitled to recover at a 1:1 ratio, of injection to withdrawal. The Carrizo-Wilcox aquifer is a confined aquifer that was near-equilibrium conditions prior to the start of the project. SAWS expects these factors will prevent loss of stored water to adjacent stratigraphic layers and does not apply a loss factor [35]. The utility has measured that the aquifer has the capacity to store a total of approximately 200,000 AF. As of July 2019, 176,000 AF were stored, the equivalent of more than half the year's potable demand [36, 37]. Much of that water is in support of the Edwards aquifer Habitat Conservation Plan, with 110,448 AF stored on behalf of the EAA [38]. This successful buildup of supply is in part due to fortuitous timing of the project. Several wet years occurred after the project came on line in 2004, allowing SAWS to build up a drought reserve and allowing the EAA to negotiate leases and purchases of water for storage. If storage in H_2Oaks reaches full capacity, SAWS may need to change operations across its multiple sources of supply in order to maximize the benefits of the storage capacity.

SAWS operates an extensive monitoring and mitigation program to address any offsite impacts of the recharge and recovery program at H_2Oaks. Thirteen monitoring wells are used to track water quality and water levels in Bexar, Wilson, and Atascosa counties. Mitigation activities have included replacing wells and lowering pumps [39].

Recovery

Water is recovered when needed during dry periods through the same 29 wells used for injection. Two pipelines are used to recharge and receive stored water [40]. The existence of two pipelines gives SAWS the ability to inject water at the site while simultaneously distributing water to customers. The recovery capacity is approximately 67,000 AF per year [41]. During the drought that occurred between 2011 and 2014, SAWS recovered over 50,000 AF of stored water to meet ratepayer demand [42].

Recovered water must be treated before use. The Carrizo-Wilcox aquifer has a pH of 5.5 and contains elevated iron, manganese, and hydrogen sulfide. Although there is limited mixing of recharged water with native Carrizo-Wilcox aquifer water, and 80% of recharged water can be recovered without inducing mixing, native Carrizo-Wilcox aquifer water is of moderate quality [43, 44]. Since some native Carrizo-Wilcox aquifer water is also pumped by SAWs at other wells, a full-scale water treatment plant was constructed at the site [45].

SAWS continues to make infrastructure updates to its facilities to improve capacity and distribution. One such improvement includes the recent completion of the first phase of a western integration pipeline to add a second avenue for distributing water in and out of the H_2Oaks site. This second integration pipeline creates flexibility in the operation of the site by providing SAWS with the ability to integrate greater quantities of stored water back into its distribution system.

Institutional Arrangements

SAWS is the primary decision maker regarding the operation of the H_2Oaks project, both for day-to-day management and for long-term project improvements. However, since SAWS is a public utility owned by the City of San Antonio, the San Antonio City Council has a key oversight role. The utility is governed by a Board of Trustees, which is comprised of the Mayor of San Antonio and six members appointed by the San Antonio City Council [46]. The Board is responsible for directing the utility by setting policy goals, which are then implemented by the SAWS President/CEO [47]. The day-to-day operation and maintenance of the ASR facility is conducted by the Production and Treatment Group, a group of 388 employees who manage the entire SAWS wastewater and water system [48, 49].

Although the EAA is not involved in the management of the ASR project, it has a large influence on how and when the project operates, due to its authority to regulate Edwards aquifer withdrawals. Currently, the H_2Oaks facility only injects Edwards aquifer water, making EAA permitting a vital part of the project. The EAA determines how much SAWS and other entities are allocated yearly based on the hydrologic condition of the Edwards aquifer and projected flows at the springs on the eastern edge of the Edwards aquifer. However, SAWS can always obtain more Edwards aquifer water by purchasing or leasing additional Edwards aquifer water rights.

SAWS customers play an important role in supporting SAWS and the H_2Oaks project, both through funding and

participation in advisory committees and panels. The Capital Improvements and Advisory Committee, for example, advises and assists with implementation of fees for SAWS to recuperate the costs of off-site capital improvements. In a similar vein, the Rate Advisory Committee helps SAWS develop a rate structure that fairly balances operational needs with available financial resources. Additionally, the Citizens Advisory Panel helps SAWS management assess customer interest and support for new water supply projects, plans, and policies that look to develop more sustainable and affordable water programs. SAWS also has two sustainability focused committees that generate ideas and bring local citizens and groups together to speak about conservation, water, and future planning. Such citizen committees demonstrate emphasis placed on nonmonetary ratepayer support of SAWS. Not only are the customers paying for the maintenance of the project, they are also involved in determining need for new development, current projects, and in construction of rates.

Costs and Financing

The total cost of constructing the H_2Oaks ASR facility, including transmission pipelines, water treatment facilities, ASR wells, the mitigation program, land acquisition, engineering, and permitting, was approximately $250 million [50]. From 2019 to 2023, SAWS estimates that it will spend approximately $39.5 million in capital improvements for H_2Oaks [51].

The H_2Oaks ASR project was the first project at SAWS to be funded almost entirely by its ratepayers who pay a Water Supply Fee to fund the development of new water sources [52]. The rate is assessed monthly on potable water usage and follows a tiered structure within each use category to encourage conservation [53]. SAWS also passes EAA permit fees on to customers at a cost of $.03561 per 100 gallons of usage [54]. SAWS customers pay for the water they use through monthly service and volume charges, which vary based on meter size and water use [55].

Benefits

The SAWS ASR project benefits SAWS and its ratepayers by providing an additional water source in times of drought. EAA pumping restrictions directly incentivized creation of the H_2Oaks program. SAWS initially envisioned using the project regularly by storing excess water in wet years to meet peak demand year-round. However, due to the development of alternate supplies through conservation and other projects, including a desalination plant located at the H_2Oaks facility [56], the pumping restrictions put in place by EAA had less of an impact than initially expected. Consequently, SAWS transitioned the project to storing water for drought. As environmental regulation of the Edwards aquifer progressed, SAWs transitioned its management of H_2Oaks to provide regional water management benefits. Much of the water currently stored in the H_2Oaks project is held by the EAA and will be used to minimize supply disruptions in the region while ensuring the minimum springflows needed to protect endangered species in the Edwards Aquifer system.

CONCLUSION

The SAWS H_2Oaks project is an example of MAR that uses injection wells to recharge groundwater with another groundwater source, making it distinct from most other recharge projects, which typically utilize excess surface water. While this aquifer-to-aquifer transfer appears unusual at first glance, the rationale for the project becomes clear once the restrictions on Edwards aquifer groundwater pumping are considered in conjunction with its annual groundwater allocations, which do not include a carryover provision. Restrictions on pumping in the Edwards aquifer led SAWS to develop an underground storage program as a way to save unused portions of their Edwards aquifer allocation for future dry periods. The program has been successful and has led to increased water security within the region.

As a large regional utility, SAWS possesses the financial and institutional capacity to take on a project of this scale. Critical to the project's success was the ability to purchase land over the Carrizo-Wilcox aquifer, which was naturally suited for water storage. SAWS avoided potential backlash against the project by leasing land to agricultural users, preventing the land from being taken out of production. Since the H_2Oaks site is located in an area without a GCD, SAWS can withdraw as much stored water as needed without facing local groundwater pumping restrictions. The relative stability of the Carrizo-Wilcox aquifer provides an additional assurance that water stored will be available for later withdrawal.

The SAWS H_2Oaks project has helped to spur discussion of water sustainability and security throughout Texas. State officials have encouraged the construction of new ASR in other districts in the state, analyzing H_2Oaks as

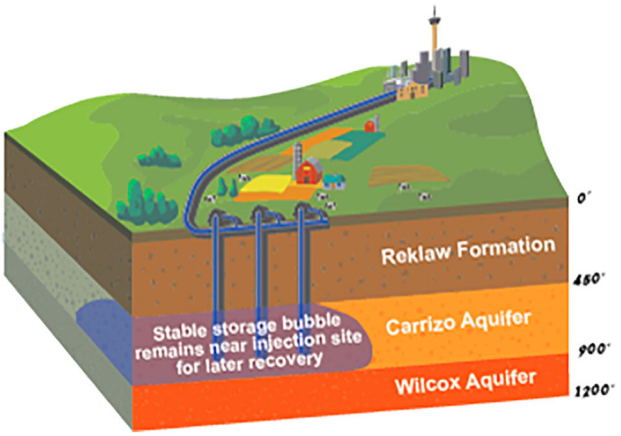

FIGURE 1. Depiction of the geologic formations at the H_2Oaks Center, including the Carrizo Aquifer. Source: San Antonio Water System website [33].

an effective method of drought management due to minimal water loss from evaporation and sustainability [57].

KEY TERMS AND ACRONYMS

(AF) *Acre-feet*—A volume of water that would cover one acre at a height of 1 ft. Equivalent to 325,851 gallons or 1,233 m^3.

(ASR) *Aquifer storage and recovery*—A form of managed aquifer recharge that specifically intends to store water for future recovery.

(EAA) *Edwards Aquifer Authority*—The regional water management agency that was created to manage, enhance, and protect the Edwards aquifer.

(ESA) *Endangered Species Act*—A legislative act passed by the U.S. Congress in 1973 with the goal of protecting threatened and endangered plant and animal species.

(Evergreen District) *Evergreen Underground Water Conservation District*—The groundwater conservation district in Texas that governs a portion of the Carrizo-Wilcox aquifer located near the H_2Oaks ASR project.

(GCD) *Groundwater Conservation District*—A local governmental agency with authority over groundwater in Texas.

(H_2Oaks) *Twin Oaks*—The name of the SAWS's aquifer storage and recover project that is the subject of this case study.

(HCP) *Habitat Conservation Plan*—A plan of action that delineates steps that will be taken to mitigate the effects of human activities that threaten or negatively impact species listed under the ESA. HCPs are required under the ESA in order to obtain an incidental take permit, which grants permission to undertake limited actions that have impacts on listed species.

(MAR) *Managed Aquifer Recharge*—A project that intentionally induces water to flow into an aquifer.

(SAWS) *San Antonio Water System*—The water utility serving the greater San Antonio region.

(TCEQ) *Texas Commission Environmental Quality*—The state-level agency in Texas responsible for regulating air and water quality, among other responsibilities.

(TWDB) *Texas Water Development Board*—The state-level agency in Texas responsible for planning, financial assistance, and education related to conservation and responsible development of water in Texas.

(USFWS) *United States Fish and Wildlife Service*—The federal-level agency in the United States that enforces federal wildlife laws, manages national wildlife refuges, protects endangered species, manages migratory birds, and restores nationally significant fisheries, among other responsibilities.

AUTHOR CONTRIBUTIONS

KM researched and wrote the original draft. AM, MB, MK, and JT contributed to research and writing. MK conceptualized and secured funding for the project.

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COMPETING INTERESTS

The authors have declared that no competing interests exist.

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REFERENCES

1. Blumberg F. Presentation. The State of Aquifer Storage Recovery in Texas. Texas Innovative Water; 2010. Copy of the file with authors.
2. This includes small areas of Comal, Medina, Atascosa, and Kendall Counties in southern Texas. San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019.

3. Miller K, Milman A, Kiparsky M. Introduction to the Special Collection: Institutional Dimensions of Groundwater Recharge. Case Studies in the Environment. 2021; doi: 10.1525/cse.2021.1245648
4. San Antonio Water System. History & Chronology. Available: https://www.saws.org/about-saws/history-chronology/. Accessed 15 December 2019.
5. Texas Association of Counties, The County Information Program. Bexar County Profile. Available: http://www.txcip.org/tac/census/profile.php?FIPS=48029. Accessed 15 December 2019.
6. San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019.
7. Personal Communication, San Antonio Water System. The exact percentage of the portfolio provided by the Edwards Aquifer varies from year to year. SAWS holds permits to produce 292,000 AF per year from the Edwards Aquifer, subject to regulatory, negotiated, and voluntary cutbacks. SAWs also holds contracts, permits, and leases for up to approximately 73,000 AF per year from other ground and surface water sources and can produce approximately 94,000AF in desalinated and recycled water. See San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019.
8. San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019. SAWS also acquired additional water rights after absorbing the Bexar Metropolitan Water District (Bexar Met) in 2011. Through the merger, Bexar Met ratepayers decreased their water rates, and SAWS gained Bexar Met's 23,238 AFY of Edwards Aquifer water rights, as well as their Canyon Regional Water Authority, Medina Lake, and Trinity Aquifer water allocations. Texas A&M Institute of Renewable Natural Resources, Texas Water Resources Institute. Final Report: Cities of San Antonio and Fair Oaks Ranch Water Policy Analysis (2015). Available: https://nri.tamu.edu/media/1123/cosa-for-final-water-report.pdf. Accessed 15 December 2019.
9. Texas A&M University. Texas Water Law. Available: https://texaswater.tamu.edu/water-law. Accessed 15 December 2019.
10. Votteler T. The little fish that roared: the Endangered Species Act, state groundwater law and private property rights collide over the Texas Edwards aquifer. Environ Law. 1998;28 (4): 845–880.
11. Gulley RL. Heads Above Water: The Inside Story of the Edwards Aquifer Recovery Implementation Program. Texas A&M University Press; 2015.
12. Edwards Aquifer Authority. EAA Timeline. Available: https://www.edwardsaquifer.org/eaa/history/eaa-timeline. Accessed 15 December 2019.
13. Texas A&M Institute of Renewable Natural Resources, Texas Water Resources Institute. Final Report: Cities of San Antonio and Fair Oaks Ranch Water Policy Analysis (2015). Available: https://nri.tamu.edu/media/1123/cosa-for-final-water-report.pdf. Accessed 15 December 2019.
14. Edwards Aquifer Authority. 2019 Operating Budget. Available: https://www.edwardsaquifer.org/wp-content/uploads/2019/04/2019-Adopted-Operating-Budget.pdf. Accessed 15 December 2019.
15. Texas A&M Institute of Renewable Natural Resources, Texas Water Resources Institute. Final Report: Cities of San Antonio and Fair Oaks Ranch Water Policy Analysis (2015). Available: https://nri.tamu.edu/media/1123/cosa-for-final-water-report.pdf. Accessed 15 December 2019.
16. See Texas Water Code § 11.153 and § 27.151.
17. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
18. See Texas Water Code §2.36. Available: https://texas.public.law/statutes/tex._water_code_title_2_subtitle_e_chapter_36. Accessed 15 December 2019.
19. Available: https://www.tceq.texas.gov/assets/public/permitting/watersupply/groundwater/maps/gcd_text.pdf. Accessed 15 December 2019.
20. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery in Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
21. Currently, SAWS has an entitlement for 272,372 AF per year of Edwards Aquifer water. This water is a combination of leased and owned water rights. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
22. Fees for entitlements to groundwater from the Edwards Aquifer are based on the total amount of the entitlement, regardless of whether or not that water is pumped. At the current rate of $84/AF, SAWS' annual Edwards Aquifer fee is approximately $23 million.
23. Texas Water Development Board. Aquifer Storage and Recovery (September 2015). Available: http://www.bcragd.org/wp-content/uploads/2016/12/AquiferStorageRecovery.pdf. Accessed 15 December 2019.
24. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report

0904830940: An Assessment of Aquifer Storage and Recovery in Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.

25. SAWS purchased a total of 3,200 acres of land—more than needed for the project. By purchasing a larger amount of land than strictly needed for recharge operations, SAWS sought to protect its recharged water by preventing nearby withdrawals by other groundwater users. The land is leased back to its original owners and continues to be used for agriculture and grazing. Personal Communication, SAWS. See also Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019; San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019.
26. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
27. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
28. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
29. An HCP must be approved for the U.S. Fish and Wildlife Service to issue an incidental take permit. For more on the Edwards Aquifer Recovery Implementation Plan and the ESA, see Votteler T, Gulley R. The Edwards aquifer habitat conservation plan. The Water Report 2014;24: 1–10; and Gulley, Robert L. Heads Above Water: The Inside Story of the Edwards Aquifer Recovery Implementation Program. Texas A&M University Press; 2015.
30. An HCP must be approved for the US Fish and Wildlife Service to issue an incidental take permit. For more on the Edwards Aquifer Recovery Implementation Plan and the ESA, see Votteler T, Gulley R. The Edwards aquifer habitat conservation plan. The Water Report 2014;24: 1–10; and Gulley, Robert L. Heads Above Water: The Inside Story of the Edwards Aquifer Recovery Implementation Program. Texas A&M University Press; 2015.
31. EAA pays SAWS for the cost of operation and maintenance for the storage of this water, which amounts to $41/AF to store, and $110–130/AF for recovery. Personal Communication, SAWS; San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
32. ReCon Environmenta, Edwards Aquifer Recovery Implementation Program. Habitat Conservation Plan (2012). Available: https://www.edwardsaquifer.net/pdf/Final_HCP.pdf. Accessed 15 December 2019.
33. San Antonio Water System. Aquifer Storage and Recovery. Available: https://www.saws.org/your-water/new-water-sources/current-water-supply-projects/aquifer-storage-recovery/. Accessed 15 December 2019.
34. Texas A&M Institute of Renewable Natural Resources, Texas Water Resources Institute. Final Report: Cities of San Antonio and Fair Oaks Ranch Water Policy Analysis (2015). Available: https://nri.tamu.edu/media/1123/cosa-for-final-water-report.pdf. Accessed 15 December 2019.
35. This 1:1 storage to recovery factor is the result of an agreement between SAWS and neighboring groundwater districts. (Personal Communication, SAWS). The amount is reported to the Texas Council on Environmental Quality. See Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas. (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
36. San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/; Personal Communication, SAWS. Accessed 15 December 2019.
37. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
38. See the Edwards Aquifer Habitat Conservation Plan 2019 Annual Report (2020). Available: https://www.edwardsaquifer.org/wp-content/uploads/2020/03/2019-EAHCP-Annual-Report.pdf. Accessed 15 May 2020.
39. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board.

Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.

40. SAWS has begun construction on a second pipeline to distribute project water to the western portion of its distribution system. The first phase was completed in 2016 and covers 28 miles (Personal Communication, SAWS).
41. Texas Water Development Board. Aquifer Storage and Recovery (September 2015). Available: http://www.bcragd.org/wp-content/uploads/2016/12/AquiferStorageRecovery.pdf. Accessed 15 December 2019.
42. San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019.
43. Morris T, Macias R, Pyne RD. Design, Installation, and Operation Challenges of Large-Scale Aquifer Storage and Recovery Wells in San Antonio, South Texas. In: Ni-Bin Change, editor. Effects of Urbanization Groundwater: An Engineering Case-Based Approach for Sustainable Development. Proquest; 2020. pp. 6–25.
44. Texas A&M Institute of Renewable Natural Resources, Texas Water Resources Institute. Final Report: Cities of San Antonio and Fair Oaks Ranch Water Policy Analysis (2015). Available: https://nri.tamu.edu/media/1123/cosa-for-final-water-report.pdf. Accessed 15 December 2019.
45. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
46. San Antonio Water System. Board of Trustees—Our Board. Available: https://saws.org/who_we_are/board/. Accessed 1 September 2019.
47. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
48. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
49. Available: http://www.saws.org/your_water/waterresources/projects/asr.cfm. Accessed 15 December 2019.
50. Malcolm Pirnie, Inc., ASR Systems, LLC, Jackson, Sjoberg, McCarthy & Wilson, LLP, El Paso Water Utilities Board. Texas Water Development Board Contract Report 0904830940: An Assessment of Aquifer Storage and Recovery In Texas (2011). Available: http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830940_AquiferStorage.pdf. Accessed 15 December 2019.
51. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available at http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
52. San Antonio Water System. Water Supply Fee. Available: https://www.saws.org/service/water-sewer-rates/water-supply-fee/. Accessed 1 September 2019; San Antonio Water System. Aquifer Storage and Recovery. Available: https://www.saws.org/your-water/new-water-sources/current-water-supply-projects/aquifer-storage-recovery/. Accessed 1 September 2019.
53. In the residential use category, fees start at $0.074 per 100 gallons when at least 2,992 gallons per month are used and rise to $.4809 per 100 gallons when over 20,199 gallons are used each month. There are also three other classes: general, wholesale, and irrigation, each with its own fee structure. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
54. San Antonio Water System. Water Supply Fee. Available: https://www.saws.org/service/water-sewer-rates/water-supply-fee/. Accessed 1 September 2019.
55. San Antonio Water System. Annual Operating Budget and Capital Improvement Program, Fiscal Year Ending December 31, 2019. Available: http://www.saws.org/wp-content/uploads/2019/04/2019_SAWS_Budget.pdf. Accessed 15 December 2019.
56. SAWS recently completed the first phase of a desalination plant at the H_2Oaks site, which can desalinate 11,200 AFY of brackish Lower Wilcox Aquifer water. SAWS also produces to 25,000 acre-feet per year (AFY) in treated recycled water, which primarily is used by commercial and industrial customers, as well as golf courses and parks. San Antonio Water System. 2017 Water Management Plan. Available: https://www.saws.org/your-water/new-water-sources/2017-water-management-plan/. Accessed 15 December 2019.
57. Texas Water Development Board. Technical Note 15–04: Aquifer Storage and Recovery in Texas, 2015. Available: http://www.twdb.texas.gov/publications/reports/technical_notes/doc/TechnicalNote15-04.pdf. Accessed 15 December 2019.