CONJUNCTIVE WATER MANAGEMENT PRACTICES FOR THE EDWARDS AQUIFER, TEXAS

A Thesis

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Abstract

Conjunctive water management, defined as management that acknowledges surface water and groundwater to be interconnected, is a formal system in many states to account for and assure water supply. Most western states are experiencing rising temperatures, longer droughts, and population growth, which makes a challenging combination of decreased water supply yet increased demand. Many states have adopted conjunctive management strategies to address these challenges, but Texas faces unique legal and cultural obstacles. The Edwards, a karst aquifer in south-central Texas, is a prime example of how bifurcated law, limiting judicial processes, decentralization, and the underfunding of Texas water regulation hinders conjunctive management. Despite this, many water-using entities in the Edwards have successfully implemented projects such as aquifer storage and recovery, recharge enhancing infrastructure, bed and banks permitting, voluntary irrigation suspension programs, and drought contingency plans. These initiatives increase water supply for the aquifer's in-stream flows for endangered species and growing municipal demand. This paper analyzes the past, present, and future of conjunctive management in Texas to secure water for increasing municipal demand and to ensure adequate water levels for environmental support.

Water Terminology and Acronyms

ASR	Aquifer Storage and Recovery	A system of storing excess water in an aquifer and then pumping it out later when water is needed.
Acre/ft	-----	The amount of water to cover one acre in a foot of water
CM	Conjunctive Management	Managing groundwater and surface water together
CPM	Critical Period Management	Type of conservation initiative implemented by the EAA
DFC	Desired Future Conditions	Conditions a GCD determines that influences their management plan
EAA	Edwards Aquifer Authority	Created to protect endangered species. State run authority for all things related to the Edwards
GCD	Groundwater Conservation Districts	Districts with appointed or elected boards which oversee an area's well spacing and production. GCDs are often created voluntarily
GMA	Groundwater Management Area	Districts that cover the entire state to help GCDs stay coordinated.
HCP	Habitat Conservation Plan	A plan implemented by the EAA to protect habitats, particularly for endangered species
MAG	Modeled Available Groundwater	A model of groundwater created by the TWDB based on DFC's to help GCDs create management plans
RWPG	Regional Water Planning Groups	Large areas that contribute to regional and state water plans
SAWS	San Antonio Water Services	Municipality that supplies San Antonio with their water. Owns ASR operation.
TCEQ	Texas Commission for Environmental Quality	Manages all surface water in the state.
TWDB	Texas Water Development Board	Provides resources and modeling for GCDs, GMAs, and RWPGs
VISPO	Voluntary Irrigation Suspension Program Option	Conservation effort to reduce irrigation demand

Introduction

They say everything is bigger in Texas, and that is not far off when describing the state's water management challenges. Unfortunately, increasing temperatures, climate variability, and more intense droughts coupled with a booming population means the future of Texas's water is at stake. Postcolonial Texas has managed its water with a *laissez-faire* attitude. However, given climate change and increasing population demands, it is clear there needs to be some alterations to the state's laws, governing structures, and management techniques. Conjunctive management (CM), the technique of integrating the use and management of both groundwater and surface water, holds a promising role in adapting these necessary changes. This article analyzes the past, present, and future of conjunctive management in Texas to secure water for increasing municipal demand and to ensure adequate water levels for environmental support. Specifically, this study focuses on the Edwards Aquifer, a unique karst aquifer in South Central Texas that is home to several endangered species and two million residents, both of which have extensive water demands that are in jeopardy. Can conjunctive management be used to sustainably manage the Edwards Aquifer?

Methods

I approached this research question by looking at the use of conjunctive management at many scales. I started by looking at the Southwestern United States and then used the Texas water code as an applicable framework since the state lacks the same progress its western neighbors have made. I examined the Edwards Aquifer to provide a case study of how CM can be implemented in an area providing water for many types of use. This research allows for a thorough understanding of on-the-ground management regimes, while also presenting highly adaptable techniques for use in other aquifers and states.

In this thesis, I use both primary and secondary sources to answer my research question. Most of the data collected was qualitative based on others' experiences in the field of water management. My primary research consisted of a dozen video interviews with professionals, authors, and residents. I attended water planning meetings and explored the water basin through its rivers, springs, lakes, recreation, and water users. Secondary sources in this paper provide a second set of analyses for the basis of conjunctive management throughout the watershed and state. The literature and research on CM is not as abundant as it is for other water management sources and strategies since it, by definition, is multifaceted. Together, the primary and secondary sources in this paper are used to tell a story of the past, present, and future of CM in the Edwards.

Conjunctive Management in the West

The Southwest United States is currently facing the brutal effects of climate change including unprecedented drought and increasingly high temperatures, both of which threaten the region's fragile arid ecosystems and question its water reliability for its growing demand (deBuys, 2011). The timing of demand for water in the Southwest is often disconnected from the supply since the demand is highest in the summer months while the supply is highest in the winter months. It is also becoming apparent that the twentieth-century tools to meet water demands are becoming outdated and less viable. Daming, diverting, and channeling surface water is no longer an ideal way to ensure water demands are met (Blomquist et al., 2018). Historically, surface water has been the primary source for municipal, agricultural, and industrial uses, but with increasing temperatures, surface water is especially prone to evaporation which causes precious and expensive water to disappear in thin air (Reisner, 1986).

The United States' current and historical approaches to water management often complicate the already challenging task of finite resource management. Unless the water pertains to Native American ownership or is critical for the life of an endangered species, all water management is managed at the state level, not by federal agencies or authorities (United States Department of Justice, 2015). State water codes vary tremendously and range in effectiveness and efficiency (Bryan, 2015). While experts cannot always agree on the same management practices, there is a consensus that without an improvement in planning, the water supply of future generations is at stake (Pisani, 1996).

Western states are facing depleted surface and groundwater, high temperatures, decreased snowpack, and inappropriate policy. Current policy attempts to combat surface water depletions without recognizing or addressing its interconnectivity to groundwater, ultimately limiting management options. Groundwater is a finite resource and even with the best policies, it can be challenging, if not impossible, to fix depletion issues if the supply is less than the demand. Since the advent of pumping technologies, it is common for groundwater to be the primary or only source for many towns and cities across the West. This increase in groundwater usage can deplete aquifers at a rate that can not be recharged naturally, ultimately lowering the water table or decreasing artesian pressure, as has been the case in several southwestern states (Glennon, 1995). Many streams rely at least partially on groundwater for their flow, so when the water table drops lower than a stream's groundwater input, or there is not enough artesian pressure to allow discharge at artesian wells, it can decrease or completely halt in-stream flows (Alley et al., 1999). This shift from perennial to ephemeral regime flow produces negative effects for local water supply, local recreation, indigenous cultural practices, and meeting the federal demands for endangered species management.

Conjunctive management is a way of managing water with the understanding of the interconnectivity between the many phases of water, usually ground and surface water. It also recognizes how actions that affect one phase of the water cycle will affect other phases (Templer, 1980). CM is particularly important in hydrological systems that have many connections since these conduits facilitate extensive movement. Many see CM as an ideal management technique since its direct purpose is to coordinate water to reduce drought exposure, maximize supply, protect water quality, protect environmental and ecological needs, and sustain aesthetic and recreational uses. Additionally, it can improve the security of water supply, reduce costly technological interventions, and protect aquatic life and habitat (Blomquist et al., 2018, p. 654). It also "means optimizing the use of multiple water sources over time in response to changing conditions" (Welles, 2013, p. 502). Often cited as the primary advantage of CM is that *both* environmental and human needs are being attended to while not sacrificing the other. CM has even been shown to be more cost-effective at securing water for peak or emergency demands than dams and reservoirs (Fisher et al., 1995).

Texas has fallen behind on implementing CM compared to other states in the West (Sugg et al., 2016). To understand the specifics of Texas water law in relation with CM, this thesis will scale down even more to look at the Edwards Aquifer, a limestone karst aquifer in South Central Texas which exemplifies the effects of the state's bifurcated water laws, fragmented jurisdiction, federal versus state law, the role of the Endangered Species Act, as well as new technological approaches to CM. Additionally, the findings about Texas and the Edwards can often be inseparable with the unique laws the state has in place or the particular geology present in the aquifer, but the concepts and adaptive measures can be seen as universal techniques that can apply to most arid regions.

Texas Water Management

Texas operates in a bifurcated system where it governs surface water and groundwater separately by different legal doctrines. The reason for this bifurcation lies in the fact surface water was the initial primary supply and was influenced by Spanish law, leading to the practice of prior appropriation (Mace, 2022). Eventually the cultural preference trended towards groundwater use because surface water was perceived as polluted and dirty (Eckhardt, 2021). Since Texas lacked legislation for ground water, the Supreme Court deferred to English Common Law and therefore started governing what was interconnected with two separate codes (Mace, 2022).

In Texas, surface water is state property and is highly regulated with all management and permitting done by the Texas Commission on Environmental Quality (TCEQ). Surface water is ruled by both the riparian doctrine and the prior appropriation doctrine. The riparian doctrine, based on English common law, designates private water rights to the owners of property bordering a natural river or stream. The Water Adjudication Act of 1967 merged the riparian system into the prior appropriation system. This act created a unified water permitting scheme which requires all surface water users to be granted a water right from the TCEQ based on a first-in-line first-in-right system (Kaiser, 2002.).

Texas' Groundwater on the other hand has traditionally been governed by the rule of capture. Historically, groundwater was completely unregulated unless it was being used wastefully, an owner used a slant well onto another property, the drawing of water caused land subsidence, or there was malicious harm to a neighbor. Under this law, a landowner may pump an immense amount of water, even at the cost of drying up their neighbors' wells and still have claim to said water, which is why this doctrine is dubbed "the law of the biggest pump" (Kaiser, 2002).

In 1949, with a better understanding of hydrology and then apparent effects of the depletion of groundwater across the state, Texas passed a law to create Groundwater Conservation Districts (GCDs) as a voluntary way to localize groundwater management. Since then, 98 GCDs have been created to cover nearly 70% of the state (TWBD, n.d.-a). GCDs "work to prevent waste, educate the public about groundwater and conservation, and prevent irreparable harm to the aquifer" (Kaiser, 2006, p. 7). See Table 1 (below) for the mandated and optional tasks of GCDs. While the rule of capture remains in place and is uncontested by the courts, Texas Legislation such as the introduction of GCDs can override this outdated system (Potter, n.d).

Table 1. GCD Mandated and Optional Tasks. *Source*: Kaiser, 2006, pp.7-8

GCD Mandated Tasks	*GCD Optional Tasks*
○ Work with regional planning grants, state agencies, and other GCDs to make a management plan ○ Create rules to implement the plan ○ Adopt goals to conserve, preserve, and protect the groundwater. Specifically, prevent waste, avoiding subsidence, and protect water quality ○ Register wells and require well permits. ○ Keep record on wells and the production and use of water ○ Create rules and financial procedures. ○ Hold regular meetings that are open to the public	○ Regulate the spacing and production of wells ○ Set rules to achieve their goals of conservation, preservation, and protection of groundwater ○ Buy, sell, transport, and distribute surface and groundwater ○ Provide community education about groundwater ○ Require wells to be capped or plugged ○ Require permits for water being exported out of the district ○ Implement export fees ○ Inforce rules by injunction and penalties

Groundwater Management Areas (GMAs) were created in 1995 as geographic regions that unified GCDs to promote joint planning. There are 16 GMAs and every GCD is a part of at least one GMA, while there is only one GMA with no GCDs (TWDB, n.d.-d). The Texas Water Development Board (TWDB) is a state level agency that provides the necessary resources and modeling for GCDs and GMAs (TWDB, n.d.-a). GCDs must create a set of Desired Future Conditions (DFCs) which the TWDB then uses to estimate Modeled Available Groundwater (MAG) (TWDB, n.d.-b,e). The DFCs and MAGs are then used to create a groundwater management plan (TWDB, n.d.-c). All groundwater management plans are then submitted to the TWDB, which approves them to be administratively complete. The TWDB is not in charge of commenting on or altering the management strategies proposed in these groundwater management plans as the GCDs can propose anything so long as their stakeholders agree and it correlates to their DFCs. This spatially uneven web of districts and areas are intended to execute all resource management while the state provides technical support and long-term planning.

The other job of the TWDB is to create a State Water Plan every five years. Since the principal purpose of the TWDB is to be an unbiased and trusted source, it rarely pushes for particular management ideas or outcomes (Dupnik, 2021). To create the State Water Plan, the TWDB created 16 Regional Water Planning Areas. Each area has around 20 members in their Regional Water Planning Group with diverse backgrounds and a multitude of responsibilities. The Regional Water Planning Groups are essentially separate from the GCDs and GMAs despite also working with the TWDB (TWDB, n.d.-f). Figure 1 (below) illustrates these processes as state water planning, joint regional planning, and GCD processes while Figure 2 (below) maps the different districts and areas .

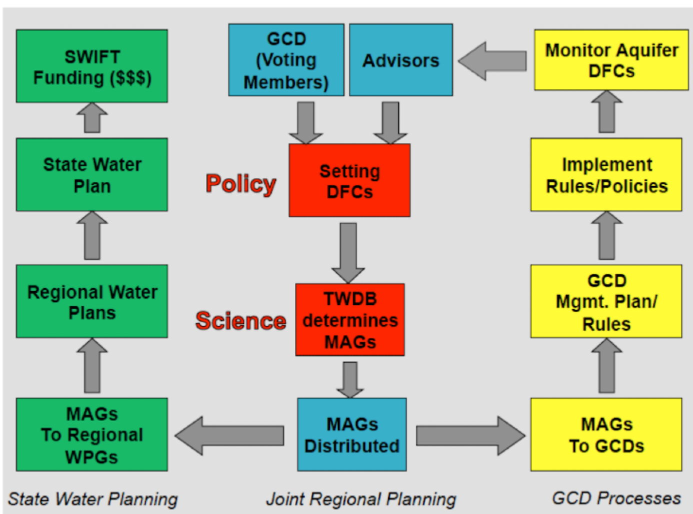

Figure 1. Water Management Flowchart from State, Regional, and District levels.
Source: Norman, 2018

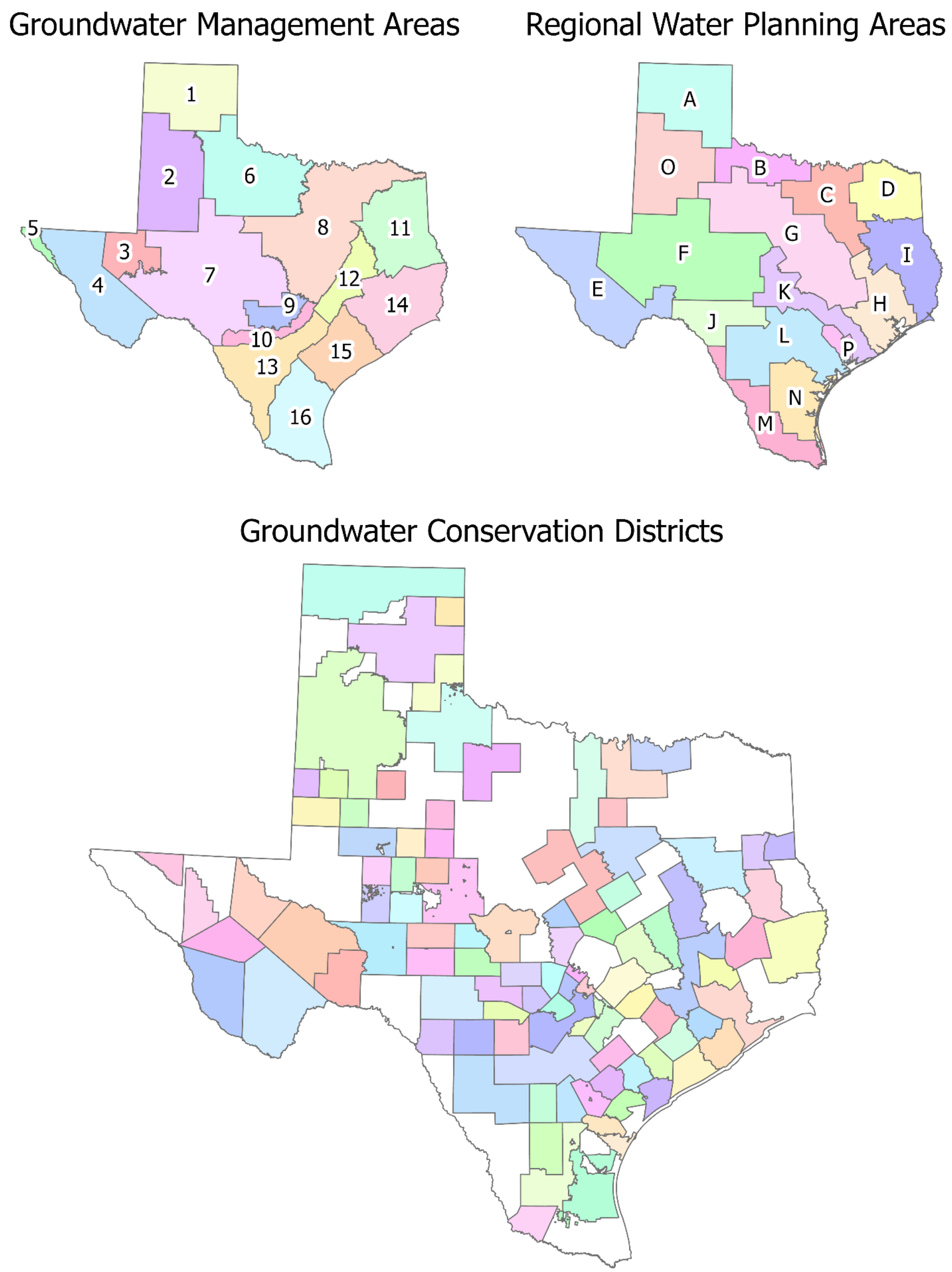

Figure 2. Groundwater Management Areas, Regional Water Planning Groups, Groundwater Conservation Districts. Note the many areas without GCDs. Maps made by the author.

The Edwards Aquifer

The Edwards Aquifer is a highly faulted karst aquifer made of a honeycomb-like limestone which makes it very permeable and allows for water to be transported quickly (Eckhardt, n.d.). The Edwards is a confined aquifer which allows for hydrologic pressure to feed its artesian springs which have been an important part of the area's culture throughout history (Glennon, 2002). Picture 1. (below) shows Barton Springs, an outdoor swimming area in Austin, Texas that is fed exclusively from Edward's spring water. The aquifer is also a single water bearing system, so any act taken, be that pumping, spring discharge, or recharge, affects the water levels and hydrologic pressure across the entire system (Kaiser, 2006). Stretching across central Texas, the aquifer holds around 45 million acre/ft of water and supplies almost 2 million people, including the entire City of San Antonio. The only treatment necessary for Edwards Aquifer water is some chlorine and added fluoride before distribution (Eckhardt, n.d.).

Picture 1 a) Barton Springs swimming area. b) Educational plaques about hydrology and endangered species at the entrance to the swimming area. Photos by the author.

Throughout the aquifers' caverns, springs, streambeds, pools, and rivers live seven endangered species including blind salamanders, fish, beetles and wild rice. These species rely on the steady flow of the aquifers' spring and streams as well as its well-regulated temperatures to survive (Eckhardt, n.d.). The federal government can intervene in any state's water management system if there is a threat to an endangered species, but to the average Texan, federal intervention is not considered an ideal outcome. In the 1990s, the Sierra Club sued regarding the presence of endangered species in these springs. They won several court cases which prompted the state legislature to pass the Edwards Aquifer Authority Act in 1993 to limit groundwater withdrawal (Thompson, 2011, p. 19).

The creation of the Edwards Aquifer Authority (EAA) allowed the state autonomy from federal intervention. The EAA regulates pumping based on permits and drought management to ensure a suitable environment for the endangered species. This permitting setup allows for a water marketing program within the aquifer as well as establishing a pumping fee system which provides the authority's revenue (Kaiser, 2006, p. 12). Since its creation, the pumping cap has fluctuated between 450,000 and 572,000 acre/ft per year, and is now fixed at the later. The authority enforces this cap by purchasing excess rights, reducing water proportionally, assigning junior rights to the permits over the cap, and implementing conjunctive strategies which are discussed later in this article (Kaiser, 2006, p.13). The EAA is the only agency of its kind in Texas and is unique in its explicit powers to ensure particular aquifer levels. The EAA is considered an active adaptive management model and many wish its framework could expand to other aquifers in the state and region. Figure 3 (below) shows the many jurisdictions, areas, and districts that make up the Edwards Aquifer.

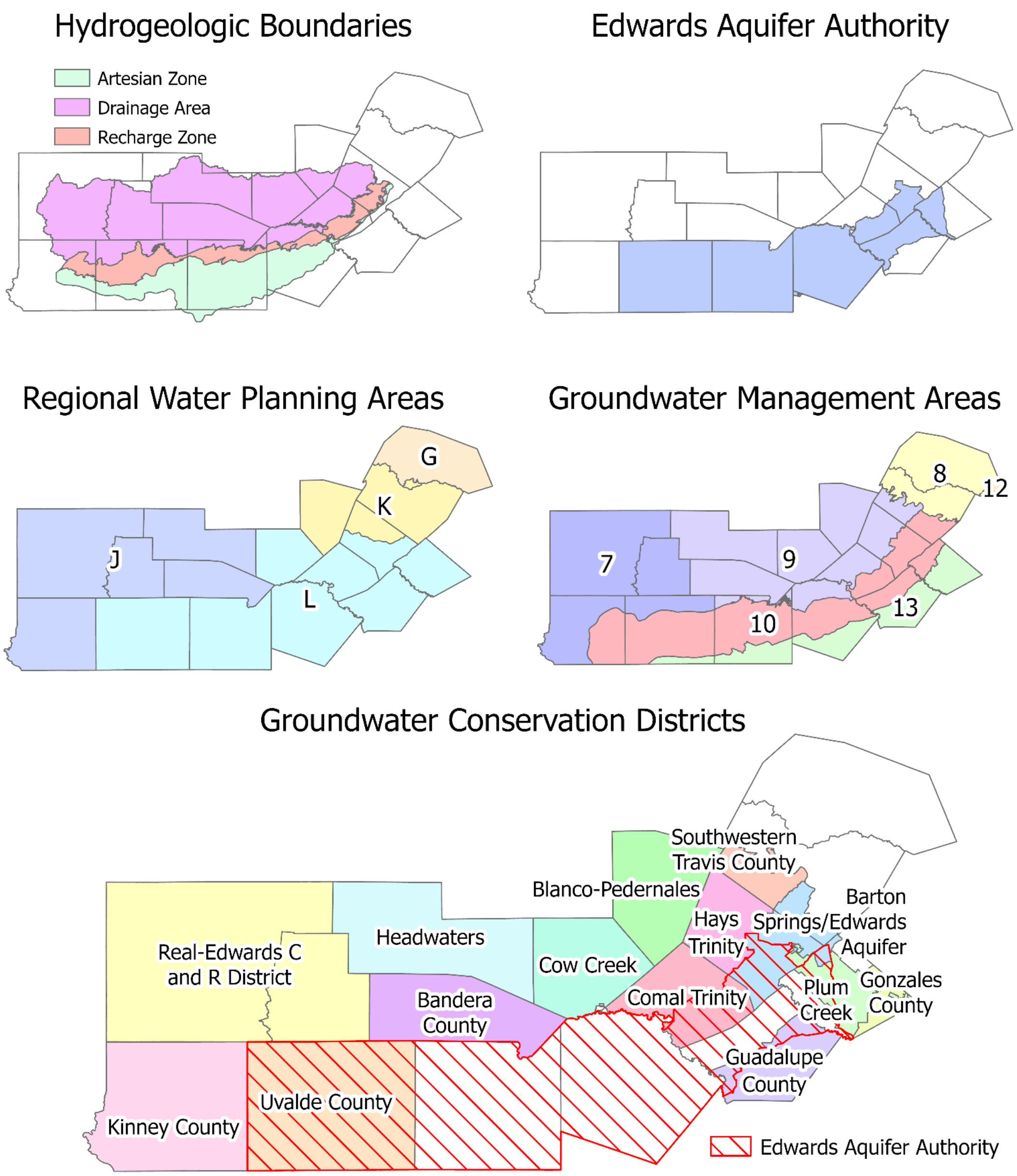

Figure 3. Boundaries, jurisdictions, areas, and districts of the Edwards Aquifer. The Edwards Aquifer is part of Regional Water Planning Areas J, L, and K, Groundwater Management Areas 7, 9, and 10. It is also a part of multiple Groundwater Conservation Districts and sees jurisdiction from both the Edwards Aquifer Authority and the TCEQ. *Source*: Maps made by the author with inspiration from maps from Eckhardt, n.d.

Current Conjunctive Management in the Edwards

Conjunctive Management in the Edwards provides for growing municipal demands and directly helps in-stream flows which benefit groundwater dependent ecosystems (GDEs) by keeping the water levels from falling below a damaging threshold (Thompson, 2011).The Edwards participates in CM through its large Aquifer Storage and Recovery (ASR) facility, a complex system of recharge dams, using transportation rules such as bed and banks permits, and engaging in conservation efforts throughout the aquifer.

The TWBD outlines water supply strategies in their 2022 State Water Plan and 0.3% (5,061 acre/ft per year) is from conjunctive use, and 1.1% (18,868 acre/ft per year) is from ASR. While these direct CM strategies do not rack up like the 50.9% from water conservation and demand reduction, they will play an important role in supplying water for the areas that cannot lower their use or reuse their water (TWBD, 2021). Implementing CM requires a multitude of factors, including adequate infrastructure, geological conditions, hydrological conditions, institutions, laws, funding, and more (Sugg et al., 2016). Additionally, CM helps to address the expense of a high peak water demand as it can provide backup sources and emergency reserves.

Aquifer Storage and Recovery

ASR was originally defined as “the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed” (Sheng, 2005, p. 369). That definition remains accurate, but modern ASR can also include recharge through spreading basins, infiltration galleries, and recharge wells, as well as withdrawal from neighboring production wells or increasing the base flow in streams as needed (Sheng, 2005, p. 369). There are four main subsystems within ASR which include: a source water to be stored, a storage space-aquifer, recharge facilities accompanied by necessary delivery pipelines and/or channels, and recovery facilities with an adequate distribution network (Sheng, 2005, p. 375). It is required that the water pumped into an aquifer is chemically compatible with the water already in the aquifer, and to abide by Texas law, this water must be up to drinking water standards (Texas Living Waters Project, 2017). Additionally, to ensure the people who are using and paying for the process are the ones benefiting from it, it is ideal if the hydrology of the aquifer prevents injected water from traveling or connecting to other aquifers (Eckhardt, 2022). ASR is an extremely flexible technological approach to CM as it can turn the variability of precipitation and surface water into a reliable source by using groundwater aquifers (Thompson, 2011, p. 28).

Compared to surface water reservoirs, ASR is an ideal way to store large amounts of water since it has a drastically smaller footprint than reservoirs, it does not face the long-term issues of sediment accumulation that limits storage capacity, it does not lose water to evaporation, it is much harder to contaminate, and it rarely poses any environmental concerns. ASR is often less costly than building dams and reservoirs, especially since reservoirs require an extensive amount of land that becomes unusable after construction (Thompson, 2011). For example, the ASR facility in San Antonio operates on land that can still be leased out to cattle farmers (Eckhardt, 2021).

One of three ASR projects in Texas is on the Edwards in San Antonio and is called H2Oaks (formerly Twin Oaks). It is managed by San Antonio Water Services (SAWS) and is currently storing around 175,000 acre/ft out of its approximate storage capacity of 200,000 acre/ft (Eckhardt, n.d.). The H2Oaks facility takes excess water from the Edwards and stores it in the Carrizo-Wilcox aquifer. The use of a second aquifer for storage is because the conduit system in the Edwards promotes fast moving water so injected water would migrate and no longer be retrievable. The EAA granted SAWS a permit for about 284,000 acre/ft per year which is around half of all water the EAA permits (SAWS, n.d). In the years SAWS does not use and distribute all of its permitted water for their municipality customers, they can store the excess in the Carrizo-Wilcox for later use. During times of drought they can use the same wells they used for injection to recover their stored water and supply it to their customers or use it to maintain springflow. The EAA also pays SAWS to store its own excess water through the H2Oaks facility for its Habitat Conservation Plan (HCP) (SAWS, n.d.). This water can then be used during droughts to maintain spring flows in areas such as New Braunfels and San Marcos for endangered species. At the end of 2020, around 122,904 acre-ft or 69% of all the water in storage at the H2Oaks facility was dedicated solely to the Habitat Conservation Plan for spring flows, thus freeing up Edwards water for other uses (Mace, 2021).

Recharge

Another CM strategy is to mimic or support natural aquifer recharge by either constructing artificial recharge zones and dams or by enhancing and/or protecting naturally occurring recharge. Dams usually slow down water by holding it back above a naturally occurring recharge zone so the water has more time to percolate into the ground (Eckhardt, n.d). There are also initiatives that divert water into large sinkholes and pit caves which quickly transport water into the aquifer (Doty, 2021). Texas is prone to inconsistent precipitation patterns and when there is an excess of precipitation or a flood event, not all of that water can be recharged naturally back into the underlying aquifer. The EAA is tasked with recharge efforts in the aquifer (see figure 4) and current EAA dams recharge around 3,300 acre/ft per year during average weather conditions and an estimated 200 acre/ft per year during drought conditions (Hamilton & Boenig, 2017, p.6). This is the only time the EAA is involved in the management of surface water and the agency is facing legal issues since these recharge enhancement structures are technically surface water withdrawals that do not have official permits from the TCEQ (Doty, 2021).

The major concern of artificial recharge is that it keeps water from flowing downstream and prevents runoff from collecting elsewhere. This threatens the supply of downstream surface water users, could limit environmental and in-stream flows, and even decrease the recharge of other aquifers such as the Carrizo-Wilcox (Eckhardt, n.d.).

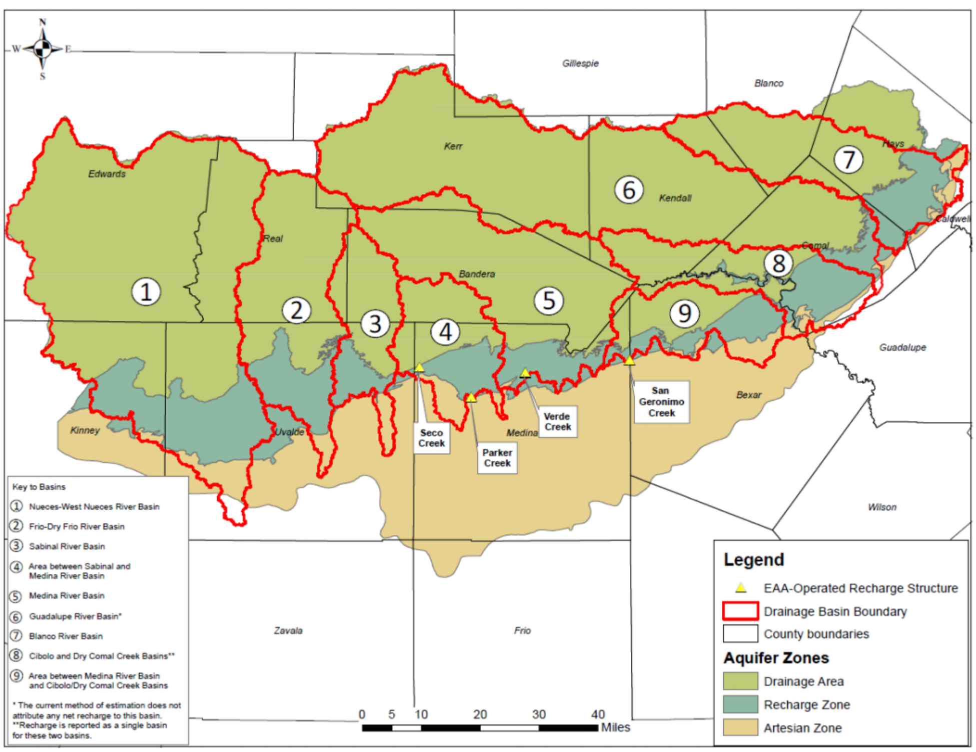

Figure 4. Major Drainage Basins and EAA-Operated Recharge Structures in the Edwards

Source: Edwards Aquifer Authority 2019.

Bed and Banks Permitting

A new management strategy uses “bed and banks” permits issued by the TCEQ as a way to supplement in-stream flows. These permits allow users to transport groundwater through a river or stream and remain privately owned despite the bed and banks of the river being state-owned (Eckhardt, 2021). To be issued a bed and banks permit the state requires the owner to have control over the water, know how much water is being released into the watercourse, withdraw approximately the same amount of water, or know how much water was lost in transit so they only withdraw the remaining amount (Shelley, 2010, p.5). Throughout history there have been several court cases debating the specifics of water transportation rules since some believe it is wasteful and unfair as evaporation and infiltration depletes the quantity initially entered, yet permit holders can still withdraw their original inputs (Welles, 2021). These permits are most often used when users want to move their water downstream to another area, but until recently no one has used them for in-stream flow purposes.

In 2013, SAWS applied for a bed and banks permit to transport a dedicated 50,000 acre/ft per year to flow down the San Antonio river for environmental purposes. And while it is still awaiting approval, the idea is for the water to be transported almost all the way down the river which would not only benefit the environment but also the downstream users by providing water to support their economy through recreation and tourism (Eckhardt, 2021). One complication is that groundwater, or water that is still legally considered groundwater, cannot be put into a watercourse without a purpose. Therefore, letting it flow directly into the ocean is illegal since that is considered wasteful use (Mace, 2021). Since the permit can not officially transfer the water straight to the San Antonio Bay, the water would be diverted into a ranch’s airboat canals and will eventually drain into the bay. Even though the real motivation behind this project is to promote environmental flows, the TCEQ is bound to a regulatory box in which it requires a beneficial use for transportation, which in this case would be considered navigational purposes. This is yet another example where the law is lagging behind the desires and needs of the state’s water infrastructure and projects (Eckhardt, 2021). Bed and bank permits are seen as a loophole to use existing Texas water law for CM since allowing water to be under the same ownership in the ground and while on the surface is a phenomenon that rarely happens within the state’s bifurcated system.

Conservation

Water conservation has a complicated history in the West as the practice of prior appropriation creates absolute rights which provides little incentive to minimize water use (Pisani, 1996). Furthermore, conservation used to mean not letting any water go unappropriated, as letting water flow to the ocean unused was seen as wasteful (Reisner, 1986). Despite this, contemporary conservation (using water efficiency to prevent unnecessary use and to ensure future supply) has become one of the largest focuses in water management. Today conservation reprepresents over a quarter of the strategies in the state water plan to meet Texas' water demand for 2070 (TWBD, 2021). In addition to overriding the historic practice of "use it or lose it", Texas and the Edwards have implemented a strong focus on water conservation as a main way to decrease demand, especially in the summer months. Two practices in the Edwards include Critical Period Management (CPM) and the Voluntary Irrigation Suspension Program Option (VISPO). While conservation is often seen as separate from CM, a major component of managing water conjunctively is lowering demand to take the pressure off of groundwater and surface water supplies.

The EAA implements water pumping caps by using the CPM system which has 5 stages of drought, each correlating to a percentage of water withdrawal reduction (see Figure 5, below). These withdrawal limitations apply to all users who pump over 3 acre/ft per year, including municipalities which then distribute water to their customers. Since the EAA only enforces the direct withdrawal limitations, the agency is not in charge of activity regulation, such as lawn watering, which becomes the duty of the municipalities or users (EAA, 2021-a).

CRITICAL PERIOD TRIGGERS, STAGES, AND WITHDRAWAL REDUCTIONS

EDWARDS AQUIFER AUTHORITY

The following Critical Period triggers and percent reductions apply to all Municipal, Industrial and Irrigation users authorized to withdraw more than 3 acre-feet.

San Antonio Pool

Critical Period is declared in the San Antonio Pool when the 10-day average of the rate of springflow at either the Comal or San Marcos springs, or aquifer reading at the J-17 Index Well in Bexar County drops below the Stage I trigger level. Likewise, a more restrictive stage of Critical Period is activated by any one of these triggers. However, the declaration of a less restrictive stage of Critical Period requires the 10-day averages of all three trigger levels to be above the activation thresholds of the particular stage in effect at the time.

TRIGGER (based on 10-day average)	CRITICAL PERIOD STAGE I	CRITICAL PERIOD STAGE II	CRITICAL PERIOD STAGE III	CRITICAL PERIOD STAGE IV	CRITICAL PERIOD STAGE V
Index Well J-17 Level (MSL)	<660	<650	<640	<630	<625
San Marcos Springs Flow (CFS)	<96	<80	N/A	N/A	N/A
Comal Springs Flow (CFS)	<225	<200	<150	<100	<45/40*
Withdrawal Reduction	20%	30%	35%	40%	44%

Uvalde Pool

The Uvalde Pool enters Critical Period at Stage II based on the 10-day average of aquifer level readings at the J-27 Index Well in Uvalde County.

TRIGGER (based on 10-day average)	CRITICAL PERIOD STAGE I	CRITICAL PERIOD STAGE II	CRITICAL PERIOD STAGE III	CRITICAL PERIOD STAGE IV	CRITICAL PERIOD STAGE V
Index Well J-27 Level (MSL)	N/A	<850	<845	<842	<840
San Marcos Springs Flow (CFS)	N/A	N/A	N/A	N/A	N/A
Comal Springs Flow (CFS)	N/A	N/A	N/A	N/A	N/A
Withdrawal Reduction	N/A	5%	20%	35%	44%

***San Antonio Pool only:** *In order to enter into Critical Period Stage V, the applicable springflow trigger is either less than 45 cfs based on a ten-day rolling average or less than 40 cfs based on a three-day rolling average. Expiration of Critical Period Stage V is based on a ten-day rolling average of 45 cfs or greater.*

Figure 5. Critical Period Triggers, Stages, and Withdrawal Reductions. *Source*: Edwards Aquifer Authority, 2021-a.

The VISPO program, an initiative of the HCP, "is an irrigation suspension program and compensates irrigation permit holders for being enrolled in the program but it also pays an additional suspension rate in years where irrigation suspension is required" (EAA, 2021-b). The suspension is determined based on the levels of the J-17 index well in Bexar County and is administered yearly. If the levels do not trigger a suspension program, the permit holder is in control of all their water, allowing those who lease their permits out to continue doing so. The enrollment goal is 41,795 acre/ft of irrigation water and users are compensated between $54-$214 per acre/ft per year depending on if the suspension is triggered (EAA, 2021-b).

Outcomes of Conjunctive management in the Edwards

While it is hard to track which water successes have been because of CM, simple modeling can predict what water levels will be like with and without CM projects. Modeling examples such as Figure 6 (below) show how each of the CM and conservation initiatives currently implemented on the Edwards would have affected the water supply of the past. The dotted line is 45 cfs, which is the minimum spring flow needed for Comal Springs. The graph suggests that with the use of VISPO, conservation, SAWS ASR, and Stage V drought response from CPM, the spring flow at Comal Springs would have been maintained even during the drought of record in the 1950's (Votteler, 2021). While there are many altered factors today, such as population and per capita use, this chart indicates how these tools are wildly helpful during times of drought.

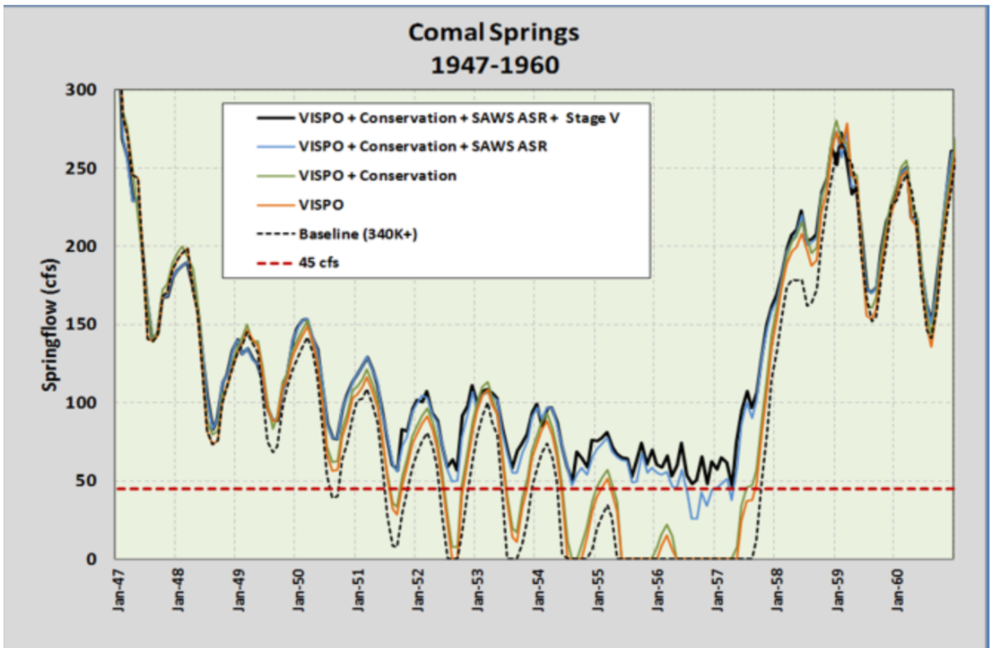

Figure 6. Effects of Conjunctive Use Modeled on Past Conditions. *Source*: Votteler, 2021

The actions and perceptions of stakeholders such as water municipalities, protection agencies, permit holders, crop irrigators, and more can reflect how people perceive the efficacy and viability of CM. Every single interviewee I spoke to for this project agreed that CM was in fact a positive strategy that would help maintain the state's water supply. Having a management strategy that is widely agreed upon is rare, especially for such a large state with a variety of interests. Many resource managers agree that a large portion of adapting any sort of management regime relies on the support of the public, something CM luckily has. See figure 7 (below) for a summary of how CM and conservation initiatives interconnect within the aquifer and its management regimes.

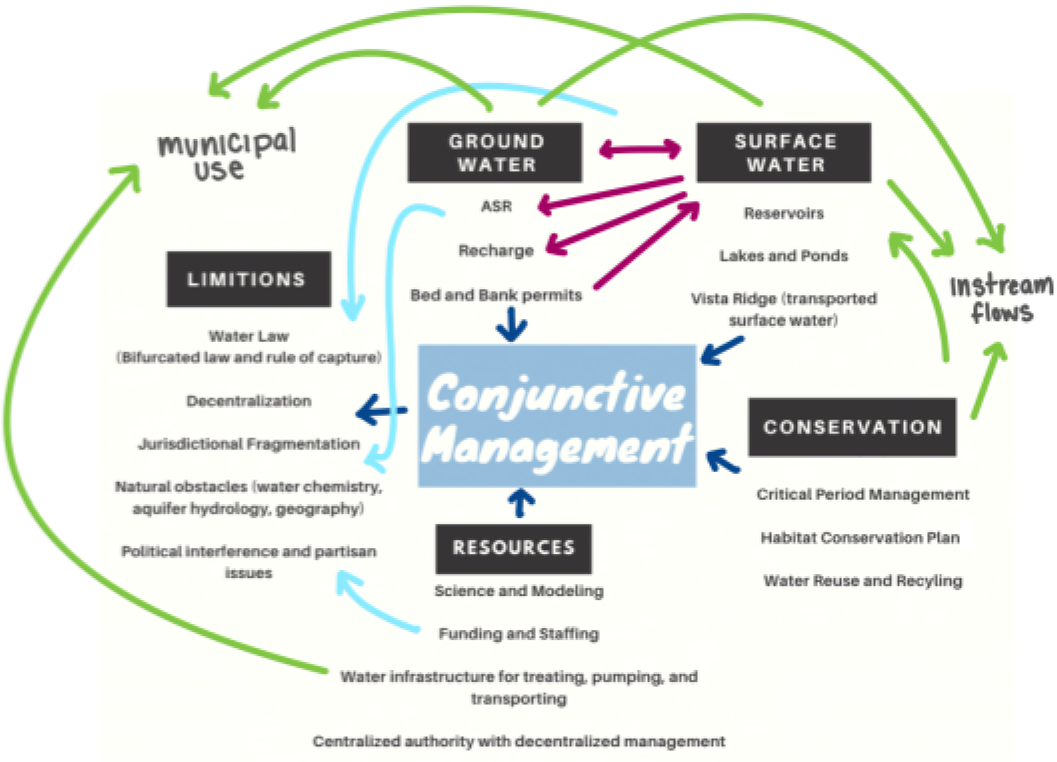

Figure 7: Conjunctive management in the Edwards aquifer flow chart. *Source*: Illustration by the Author.

Limiting Factors to Conjunctive Management

Texas could achieve much more by more actively pursuing strategies such as conjunctive use, ASR, bed and banks initiatives, and conservation - But why aren't they? Limiting factors to CM range from financial to social, and while it is improbable Texas will take part in a widespread water management reform, finding these limitations can get the state farther on its way to implementing more progressive management strategies.

Water Law

Most Texas water experts would agree that the bifurcated system of managing surface water and groundwater is the greatest limitation to implementing CM. An ideal way of managing water would allow water to move above and below the ground without changing the law it is subject to, its legal jurisdictions, and its permitting regimes. That said, unifying the two systems to be under the jurisdiction of a single authority is not currently feasible since taking away a landowner's constitutionally protected ownership of groundwater would require compensation, and therefore a lot of money. It has been estimated that at a price around $2,500 per acre-foot (the amount that was established in *EAA vs Day*), it would cost around $25 billion to settle the state's allocated and permitted groundwater, a cost Texas would not remotely consider (Shelley, 2010, p. 12).

Besides the system being bifurcated, CM faces issues with common law and the side effects of rule of capture and prior appropriation. These practices are not well suited for CM as "common law also fails to provide adequate guidance for merging the divergent legal regimes governing groundwater and surface water, leading to uncertainty that undermines conjunctive management efforts" (Welles, 2013, p. 505). Additionally, the system of rule of capture where users can legally pump any amount of water so long as it is for 'beneficial use' will not promote the most conservation focused culture. Even though the EAA and GCDs are able to override the rule of capture, the written law makes it harder to take pumping issues to court. Prior appropriation also means surface water rights often come out ahead of groundwater rights and the users who are claiming the most water are not necessarily the ones who are using it for the highest value, economic or otherwise (Thompson, 2011, p. 26)

Decentralization

The second most noted limiting factor is the state's decentralized management system. The TWDB does not adopt or promote particular management regimes but rather fulfills administrative duties and provides scientific modeling and financial resources. This leaves most of the planning and management to the state's decentralized GCDs, GMAs, and RWPGs. Most experts note there are pros and cons to decentralization and the efficacy of the model is mostly based on funding, staffing, scientific knowledge, and a good balance between stakeholder input and expert knowledge (Sugg, 2021).

Benefits of a decentralized management model include the ability for the rules and regulations to reflect that area's hydrology, geology, institutions, and stakeholder's interest. Decentralized governance also allows for a variety of perspectives to combine, which creates a more holistic look at an issue and satisfies the needs of more users and industries. Additionally decentralization aligns well with the cultural and political values common in Texas as it allows users to go downtown, walk into an office, and talk to someone about their issue or suggestion instead of having to deal with the state or an outside agency (Sugg, 2021).

There are downsides to a decentralized model, especially one like the GCDs which are not always equipped with ample resources or water specialists. Decentralized management also lacks consistency and efficiency since individual districts can have contradicting goals and management plans. GMAs were intended to coordinate GCDs' DFCs and groundwater plans, but that is not always the reality, especially since it is a newer objective and GCDs have very little restrictions for what their DFCs must entail. Last, decentralization can cause many gaps in who handles what. Centralization can provide what decentralization cannot, such as creating unified systems, developing an all-inclusive view, promoting efficiency, and being able to address externalities, but does not have the same customization, ability to include stakeholder input, and creative freedom that decentralization provides.

From Settler to Resource Colonialism

One of the main reasons water in Texas is not currently managed conjunctively is because of the ways colonization has affected and continues to affect how the state views private property and natural resources. Throughout history, indigenous cultures of the region did not have a worldview or concept of "private" property (for either land or water) and certainly did not view water as a commodifiable resource. These practices of private land tenure and water rights ownership began when the Spanish settled what is now Texas in the early 1700s. Since then, water has been contorted to fit into the cultural institutions settlers thought to be most effective. Unfortunately, when it comes to groundwater and many other resources, what was done in the name of efficiency was really done to gain power, increase inequality, and satisfy the few instead of the many. These practices paved the way for the very issues CM has been designed to fix (Reisner, 1986)

First, settler colonialism and its "first occupancy" trope led to the formation of the private property regime (Emel et al. 1992, 45). Colonization and the influx of settlers on stolen land led to the idea that what is unowned should become owned, privately and not commonly. The first occupancy argument paved the way to first in line, first in right (prior appropriation) which causes a host of barriers to CM. Additionally, privatizing groundwater, especially in a different way than surface water is privatized, has created a barrier between surface and groundwater that is unrepresentative to how the water cycle works. Additionally, the privatization of water is heavily entangled with the colonial desire for self defined freedom. Emel et al. suggests, "political liberty has been more important in shaping private property in groundwater in Texas than has efficiency" (Emel et al., 1992 p. 43). Ultimately this value has led to issues of decentralization throughout Texas's resource management (GCDs being the best example of this).

Second, resource colonization has instilled the western view that groundwater is a natural resource to exploit and mine. Many indigenous cultures view water as a part of their community, not something the community has rights over. Additionally, indigenous communities see water as a live relation, not a dead object (opposed to the western views that see water as just a resource). Curley suggests "resources is just another word for colonialism" as viewing our natural world as a source of capital is not only anthropocentric but a common way people violently obtain power over others and their environment (Curley, 2021). The belief that groundwater and surface water were ever separate, scientifically or from a management sense, was a reflection of ignorance by early Anglo-Texan settlers. A sacred holistic relation around the Edward's spring water was already practiced by the many bands that made up the Coahuiltecan Nation prior to Spanish settlement (Panich & Schneider, 2014).

Fragmentation

Jurisdictional fragmentation is an inevitable part of creating a multi-level resource management governance, especially when there are a variety of districts, authorities, and boundaries at play. Jurisdictional fragmentation can be defined as when "responsibility is divided or allocated among multiple actors and/or agencies; fragmentation may manifest as duplication, overlap, or gaps in authority" (Bakker et al., 2011, p. 193). This concept is best highlighted in Texas's bifurcated system, but it can also relate to the way GCDs and GMAs overlap authority and are not connected to the regional planning groups.

In addition, the management of natural resources usually faces spatial fragmentation in which hydrological and geological boundaries seldom correlate to jurisdictional boundaries. For example, with the Edwards, it would be more effective to make a regional planning group or even a GMA that encompasses the entire aquifer along its hydrological boundaries to ensure consistent, comprehensive management. Luckily, there is the EAA to do this job, but that is not the case for the other aquifers in the state. Centralization is a way of minimizing jurisdictional fragmentation since it includes all areas of the state as well as preventing spatial fragmentation since it often creates boundaries that correlate to natural features.

Legal and Judicial Obstacles

As an additional limitation, the way in which water cases are brought through the Texas judicial system has hindered many progressive strategies, including CM. In the current framework, one of the few pathways to change any part of the water code is to take a case to the Texas Supreme Court. The famous *EAA v. Da*y case was one such example as its decision further defined specifics of groundwater rights, reinforced the state's code stating that groundwater and surface water are interconnected, and started the trend of ruling on groundwater similarly to oil and gas.

In 1994, two farmers, R. Burrell Day and Joel McDaniel, bought a farm with an Edwards Aquifer artesian well that free-flowed into a small lake on their property. They used this lake for recreation and to irrigate their crops. After it was created, the EAA required all non-exempt water users in the region to request a groundwater pumping permit before the end of 1996. Day and McDaniel sought a 700 acre-ft per year permit to irrigate their 300 acres as well as 100 acre-ft of water per year for the recreational use of their pond. The EAA initially granted a 600 acre-ft permit for irrigation (their Act required the EAA to grant permits of 2 acre-feet per year per acre for historically irrigated land) and then, at the invitation of Day and McDaniel, the EAA visited the farm regarding the other 100 acre-ft per year the farmers were looking for.

Once on-site, EAA staff realized that the water from the well was actually being discharged into a small channel and then into the farmers' pond, which was part of a state watercourse (Mace, 2016). This slight difference meant that the produced groundwater had become state property, ultimately leading the EAA to leave Day and McDaniel with a permit for only 14 acre-ft per year to attend to the 7 acres of crops that were being directly irrigated from the well. In response, Day and McDaniel sued the agency claiming they had taken their property (via state curtailment) without compensation, which violated the Texas Constitution (EAA v. Day, 2008). After a number of appeals, the case made it to the Texas Supreme Court in 2012. The court agreed with the 14 acre-ft per year allowance, suggested by the EAA, as the agency was within their statute to decide on this permit and had appropriately distinguished when water is considered state property (EAA v. Day, 2012).

However, for the first time, the Courts found that landowners have a property right in groundwater, and therefore could also experience a taking of their groundwater. That said, the courts made it clear that this situation was local in scope and that future cases would need their own litigation for individual outcomes (EAA v. Day, 2012). Additionally, the court confirmed that the water in the lake was surface water and was owned by the state. Because the court strictly followed the state's water code, their decision ironically did not legally recognize groundwater and surface water as interconnected. Some believe this was a missed opportunity to change how the code is interpreted for future cases and to apply the most current scientific hydrologic understanding in policy (Welles, 2013).

Lastly, the case started the trend of ruling on groundwater pumping in the same manner as ruling on oil and gas with the law of ownership in place and fair share (Mace, 2022). Some groundwater experts would suggest that is an inappropriate way of regulating a completely different natural resource, (Votteler, 2021) while others suggest its potential viability as ownership in place is similar to the Rule of Capture while fair share could be an improvement to groundwater regulation (Mace, 2022).

While experts arguably disagree as to what this case means for the future of Texas water law, it is important to note that *EAA v. Day* did not set significant precedent for CM as it determined these types of disputes are inherently single-case instances, highly contextual, and must be litigated on a case by case basis. Additionally, because it is the role of the courts to abide by the state's water code, which explicitly disconnects groundwater and surface water, it will be up to water authorities and state legislature to work with the courts in the future to establish policy that formally recognizes a new role for CM. Thus, the current legal limitations restrict CM and the judicial system simply moves too slowly in altering outdated water codes that the legislatures control. Getting more cases to the Texas Supreme Court could allow for clarification and alteration of ineffective parts of Texas's current water code (Doty, 2013), yet it may not alter what is fundamentally needed in the state's water code by legislation for CM.

Natural limitations

Natural limitations to CM exist and it is important to understand these obstacles to avoid wasted water, expensive fixes, or even full blown safety crises. Geographic, geologic, and hydrologic limitations can sometimes be solved with technology but it can be a matter of balancing the benefits with the cost of new infrastructure and systems. For example, the Edwards aquifer is considered a very poor aquifer to use for ASR since it cannot keep water in the same place for long. A few of the proposed ASR projects on the Edwards look at injecting into the more stationary saline zone of the aquifer which would create a freshwater bubble, but there is risk for contamination and it is possible the freshwater would be transported elsewhere (Mace, 2021). Additionally, it is critical that water chemistry is carefully considered when using ASR, especially if there are inter-basin or inter-aquifer transfers involved.

Cultural hurdles

The other limitations to CM in Texas include cultural ideals and partisan views as well as poor funding and understaffing. While the role of partisan issues is a subjective topic, many experts note that water issues are not inherently partisan, but the structure of resource management politics can often be polarizing since ideals in regulation and government involvement vary. Some say partisan views are less of an issue amongst water experts since all management issues are seen as scientific and procedural, not political. That said, policy heavily depends on elected officials, many of whom were elected for their political agendas which have nothing to do with resource management (Norman, 2021). This allows people who are not well versed in the complexity of water management, resource planning, or hydrology to be in charge of the funding and management schemes for the entire state.

These political and legislative moves are often what determine the funding for state water management which correlates to employment and resources. For example, more money would allow the TWDB to increase their grants, loans, and funding initiatives to allow GCDs to develop into the stronger decentralized systems that were originally envisioned. Additional funding would allow the most accurate modeling by improving data collection, data quality, improved analysis, and staffing.

Future Prospects for Conjunctive Management

Looking forward, many agree that the first step to implementing more CM in Texas is to incentivize it. This could look like changing restrictive laws that limit ASR or conjunctive use, or could include tax subsidies, payback systems, or other encouragement for municipalities and users to adopt CM techniques. Other smaller tweaks to the system include requiring state water plans and regional water plans to include conjunctive strategies. Changing the word of the law to require CM instead of just suggesting it could lead to more innovation and would also eliminate the issues that arise in cases such as EAA v. Day (Shelley, 2010).

The TWDB also lists 77 proposed ASR initiatives totaling over 3.7 billion dollars in their 2022 state water plan. Another 115 projects costing over 8.7 billion are proposed for implementing conjunctive use (TWDB, 2021). If the funding, science, and policy allows, these ASR and conjunctive use projects will continue to progress, making CM more of a norm across the state.

Since Texas faces strict groundwater laws and the vast majority of groundwater is already held in permits, many think the most successful way to integrate water would be to start with surface water. To make restructuring more productive, it would be beneficial if groundwater permits were subject to a single authority, like the TCEQ, since it would ensure surface water rights do not compete with any groundwater permits and vice versa (Shelley, 2010). If the state unified their water law systems like other Western states such as Arizona, Texas could move away from the bifurcated system and decrease jurisdictional and spatial fragmentation (Shelley, 2010). Additionally, the rule of capture would ideally be eliminated since it is an out-of-date system given the knowledge that aquifers are finite and water is a limited resource. By altering the bifurcated system and the rule of capture, Texas would be able to effectively implement CM without fighting so many legal, technical, and financial battles.

Thompson suggests a few ways of restructuring the management system to promote CM including a flexible water 'market' approach and integrated regional water management. Market systems would allow economic efficiency even when demands, sources, and conditions change over time (Thompson, 2011). Thompson argues that in theory, markets could be successful even if surface and groundwater rights were not integrated so long as water rights are well defined, rights can be retired, and groundwater overdrafting is prohibited (Thompson, 2011p.32). An integrated regional water management system would look similar to the intended set up of GMAs and RWPGs overseen by TWDB resources. In reality, the approach Texas has taken is not there yet and would need to improve its coordination and adaptability (Thompson, 2011).

All of this considered, the largest issue Texas water will ever face is the impending doom of climate change. Droughts will become longer, precipitation events will become more drastic, temperatures will rise, and the need for water will increase. While the outlook does not seem ideal, these stressors will in fact spark innovation and alternate solutions to the water quantity and quality crisis.

Conclusion

Conjunctive practices connect the latest hydrological science with environmental management, a phenomenon we often take for granted or has been rare. When water is managed conjunctively, it can be used based on demand, spatial extent of the system, value of users, and economics (Doty, 2021). Striving towards CM as an integrative approach seems logically prudent to fulfill the needs of people across the Southwest.

The implementation of CM in Texas can be seen in two ways. As a cautionary tale, the lack of CM can show the effects of a limiting and outdated legal and political approach to water management. It can also be seen as the success story of a state who jumped through its own hoops to implement what they knew was best for their people and environments. Either way, you look at it, there is plenty to learn from the Lonestar State. It is hopefully just a matter of time before the impressive proposed projects can take root and major restructuring in the foundation of the state's water law is done. As states across the Southwest use CM, it is important for them to understand the approaches and practices of other states to streamline their own adaptive and integrative management processes. Additionally, it is not only the Southwestern states that will face the harrowing effects of climate change, they are just the states to feel it first.

While it may be convenient to blame climate change, or droughts, for water shortages, Pisani suggests that "culture counts for more than climate" (Pisani, 1996, p. 2). In other words, the water problems we are facing in the Southwest are a result of our colonial approach to resource management and the unintended consequences of historical policy, such as the Homestead Act (Reisner, 1986). Pisani cites that the aridity of the West did not produce the problematic practice of prior appropriation, lawmakers did (Pisani, 1996). Climate change may nevertheless be what motivates water resource reforms in Texas. Thus, without a change in contradictory laws, politics, public beliefs, management structures, and technological limitations, we will not see improvement in water availability and ecosystem protection (deBuys, 2011). Additionally, understanding that a West without water is not only possible, but part of the actual paleo-historical record, may also spur policy movement towards CM (Ingram & Malamud-Roam, 2013)

The Edwards aquifer is living proof that CM strategies can provide water for water-scarce regions in Texas and the Southwest where it is truly needed. The future climate system and hydrological conditions will not behave like they have in the past. And while overall net use of water per capita has declined, a growing population with a higher net water footprint is an additional challenge. Even in a state where water management was historically difficult or simply not practiced, conjunctive management can instill an adaptive plan for the future, ease the transition from old to new water infrastructure, and ensure robust water sources and supplies for both humans and ecological concerns.

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