FIVE GALLONS IN A TEN GALLON HAT: GROUNDWATER SUSTAINABILITY IN TEXAS

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MEMBER **THE TEXAS STATE UNIVERSITY SYSTEM**

Front/Back Cover Photo: Underwater view of the San Marcos Springs in San Marcos, Texas by Jennifer Idol (www.theunderwaterdesigner.com/).

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SAN MARCOS SPRINGS ©JENNIFER IDOL

EXECUTIVE SUMMARY

Despite the hopes and desires of scientists, engineers, and planners, the projected future of groundwater production in Texas is unsustainable. About 95 percent of locally-expressed desired future conditions are based on water-level declines, groundwater is currently being produced at 1.8 times the maximum sustainable amount, and groundwater is expected to be produced 2.4 times the maximum sustainable amount. However, Texas has an opportunity to consider groundwater sustainability since current production for all aquifers excluding the Ogallala Aquifer is only 80 percent of the maximum sustainable amount of production.

Of the 21 aquifer systems analyzed, 13 are currently being produced at or below the maximum sustainable production amount (5 of the 8 major aquifer groups and 8 of the 13 minor aquifers). However, again excluding the Ogallala Aquifer, groundwater conservation districts have made almost twice as much groundwater available for use in 2070 than can be produced sustainably in these aquifers. In other words, Texas plans to unsustainably produce groundwater from more aquifers in the future, reducing the number of aquifer systems being produced sustainably from 13 to 5 (resulting in sustainable production from only 2 of the 8 major aquifer systems and only 3 of the 13 minor aquifers).

To better understand how groundwater is produced sustainably, I identified five types of sustainable groundwater management in Texas: (1) hydrologically-forced, (2) court-forced, (3) legislatively-forced, (4) desire-driven, and (5) de facto. There is also the situation where it is politically difficult to achieve sustainability, generally when production far exceeds sustainable production, thus requiring controversial production reductions. Hydrologically-forced sustainable production seems to only occur when aquifers are small and highly productive. In Texas, part of the Edwards and Gulf Coast aquifers are sustainably managed due to court and legislative forcing, the latter in response to the former. Through the establishment of desired future conditions, a dozen or so groundwater conservation districts have explicitly expressed a desire to manage groundwater resources sustainably. And there are cases of aquifers being produced sustainably without any management action—at least for now. But there are also many aquifers not produced sustainably because production or permits have exceeded maximum sustainable production.

Based on the results of this study, I recommend that (1) groundwater conservation districts include decadal water budgets in explanatory reports for desired future conditions or the Texas Water Development Board include these budgets as part of the delivery of modeled available groundwater numbers, (2) the Texas Water Development Board carefully consider the process of estimating maximum sustainable production if and when they are required to provide those estimates, and (3) the Legislature consider requiring maximum sustainable production as another factor for groundwater conservation districts to consider when establishing desired future conditions.

PROLOGUE

Although George Washington Brackenridge was not born in Texas, he got here as soon as he could, moving with his parents and siblings to Texana in 1851 after he received degrees in engineering and law from Harvard (Morgan 1961)[1]. He worked in his father's general store before investing in land in West Texas only to have drought steal his fortune down through his horse and saddle. Lacking even stagecoach fare, he walked back to Texana, becoming the land surveyor for Jackson County (Morgan 1961, Sibley 1973).

As the drums of civil war beat louder in the late 1850s, tensions built between those in favor of the union and those in favor of secession. When Texana locals, generally favoring secession, learned that Brackenridge sympathized with the Unionists, they angrily descended on his home. He barely escaped by horse and skiff and was saved by a federal gunboat. He then found himself on the Rio Grande, buying and shipping cotton. When the Civil War finally started, he fled Texas and—through his father's friendship with Abraham Lincoln—started working for the U.S. Treasury in 1863 in New Orleans after Union forces captured the city. After the war, and no longer welcome in Texana, he moved to San Antonio in 1866—a city that voted against secession—and became a successful businessman, leveraging his treasury skills to open the San Antonio First National Bank (Ledbetter 1974).

Shortly after he arrived in San Antonio, Brackenridge began looking for a place to build a home. At one point, the city owned the headwaters of the San Antonio River but, by 1852, sold it by auction to a city alderman, James R. Sweet, to finance the construction of a new courthouse. After exchanging hands several times, including to his mother, Brackenridge bought the headwaters, naming his estate Fernridge. He built his home just up the hill from the headwaters spring—now known as Blue Hole—

1 Unless otherwise noted, all information in the discussion of Brackenridge is from Morgan (1961).

next to the homestead built by Sweet. After some time, he and his mother accrued some 240 acres of the headwaters.

After a discussion with the editor of the San Antonio Daily Express and being motivated to do the right thing, Brackenridge decided that the city should own the headwaters of the river which served as the city's water supply. He offered to sell his and his mother's properties to the city for a sweetheart deal of $50,000, due in 50 years, at 8 percent interest, payable twice a year, where he would rent the property back from the city at the cost of the interest (an early land conservation deal!). Due to paranoia, miscommunication, misread circumstances, bitter politics, and bizarre uncertainty as to whether the sale had gone through, city leaders ultimately rescinded the purchase.

As San Antonio grew without a sanitary sewer system, the river, acequias, and shallow wells became sources of cholera, typhoid fever, and malaria. In 1877, the city awarded Jean Bastiste LaCoste and associates a contract to provide pure water sourced just downstream from the headwater springs. Although skeptical of the endeavor's viability, Brackenridge invested in LaCoste's San Antonio Water Works Company. Due to the slow uptake of the new water supply by San Antonians and continuing contractual issues with the city, LaCoste sold his interests to Brackenridge and associates in 1883. Now leading the company and understanding the value of water rights, Brackenridge purchased properties down the river to secure historical surface-water rights to the springflow.

A successful artesian well drilled outside of Fort Worth in 1876 started a frenzy of drilling across Texas in search of flowing artesian waters, including in the San Antonio area (Mace 2016). Artesian wells, drought, and the increasing population of San Antonio caused Brackenridge to worry about the ability of the springs to meet the city's water needs. After the Crystal Ice and Manufacturing Company sunk a successful flowing artesian well in 1887 in San Antonio, Brackenridge drilled an unsuccessful 3,000-foot-deep well near the headwaters in 1890. The following year, the water company bought property on Market Street near the river and sank a well 890-feet deep into the aquifer, a well that flowed an astounding three million gallons a day. With that resounding success, he—and others—drilled more and more wells to meet San Antonio's growing need for a reliable water supply.

With more and more groundwater production and greater reliance on wells, including those drilled by the water company, San Antonio Springs began to fail, especially during droughts. Brackenridge adored the spring down the hill from his house, and his spirits rose and fell with the springflow. During an ebb in the flow, he wrote to Mason Williams:

> *"I bought this land and built my house on the head of the River when the River's head was a bold, dashing spring, and the River, which it fed, played and sang over the rocks and eddied quietly through mossy nooks—where ferns fringed its path, and the little, fat squirrels and red birds and mockingbirds—and in winter the red robbins—quenched their thirst. And I have seen this bold, bubbling, laughing river dwindle and fade away. It now is only a little rivulet, whose flow a fern leaf could stop and its waters are hardly enough to quench the thirst of a red bird. This river is my child, and it is dying, and I cannot stay here to see its last gasps. It is probably caused by the sinking of many artesian wells. I have paid thousands of dollars for legal opinions on the question of stopping the boring of wells, but they all say I have no remedy,—and I must go."*

Heartbroken, he sold Fernridge—which included his house, the surrounding land, and the failing springs, including Blue Hole—for a nominal amount to the Sisters of Charity of the Incarnate Word in 1897, encouraging them to open a college for women. As the water company was now relying on wells for its supply instead of the dwindling water rights from the river, the water company, through Brackenridge, conveyed its river-front land holdings to the city to establish a park. In 1905, after yet another failed attempt to sell the water company to the city, Brackenridge sold his interests to George Kobusch of St. Louis, who then later sold the company to investors in Belgium (SAWS 2021). In 1925, after yet another contract disagreement, the city finally bought the company for $7 million (SAWS 2021).

INTRODUCTION

I start this report with Brackenridge because his experience contains many elements of the story of groundwater sustainability in Texas, including the initial sustainable use of an aquifer through springflow, growing demand, growing production from wells, decreasing springflows, impacts to surface water and the environment, the tug-and-pull of unintended consequences, the impact of law, and the heavily weighted balancing act of economic needs versus undesirable outcomes. Brackenridge's story also demonstrates that sustainable production (groundwater production that can occur indefinitely), which it was at that time on an aquifer-wide basis, can also have local, undesirable effects, at least for some.

Sustainable water resources are critical to a sustainable Texas. Sustainable water is needed for our environment, our people, our agriculture, our energy, our industry, and our recreation. While sustainable management of surface-water resources, at least as a municipal supply, is a fundamental goal for the state[2], it is not for groundwater, even though groundwater has been the primary water supply for Texas. That is not to say that there are not aquifers or parts of aquifers managed sustainably—there are—but Texas does not require the sustainable management of the state's aquifers nor the consideration of sustainable management. Consequently, many aquifers, most infamously the Ogallala Aquifer, are slowly being drained over time. Furthermore, the use of one set of private-property rights—namely groundwater—can adversely affect another set of private-property rights—surface-water permits[3]. Furthermore, unsustainable production depletes the private property rights of landowners who have not employed their rights. Indeed, in many cases, we are robbing Peter to pump Paul.

Groundwater currently provides about 54 percent of the state's water (TWDB 2018). Although down

2 I write while acknowledging that the state's management is prefaced on past climate and that sedimentation of reservoirs is a challenge for long-term sustainability.

3 While surface water is owned by the state, the state grants permits for use which can be (and are) bought and sold.


SAN MARCOS RIVER © ANDREW SHIREY

from providing 70 percent of the state's water in 1959 (TBWE 1961), the volume produced has been about the same at about 8 to 10 million acre-feet per year (reservoir construction and surface-water use has increased over time, especially for municipal uses). A warming climate is expected to adversely affect surface-water resources through more frequent and more intense drought (IPCC 2021) thus increasing the reliability on aquifers, many of which are less affected by changes in rainfall (Mace and Wade 2008).

The purpose of this report is to (1) present a background on sustainable management of groundwater, both from a theoretical standpoint and, in Texas, an historical and practicable standpoint, (2) discuss the current state of the state's aquifers with respect to sustainability, and (3) show where there are gaps in our planning and regulatory framework. This report is not intended to advocate for groundwater sustainability; rather, it is to provide an historical policy analysis and a scientific summary to inform ongoing discussions on how to manage groundwater in Texas.

This report includes three broad areas of review and analysis. The first area is focused on background, including sections to provide (1) a brief introduction to the state's aquifers and basic hydrogeology; (2) a history of safe yield and sustainability with definitions; and (3) the history of groundwater sustainability in Texas from water planning to groundwater governance. There has been quite a bit of debate in the Texas policy and science circles and, quite frankly, hydrogeologic science in general, on proper terminology for groundwater sustainability discussions. Based on my historical analysis of the development of the terms, I provide my recommendations on proper terminology. The second area focuses on analyses of sustainability information in Texas, including (1) an investigation of desired future conditions; (2) a summary of sustainability analyses performed by various parties, but mostly conducted by Texas Water Development Board staff for the first round of desired future conditions delivered in 2010; and (3) a categorization of aquifers managed sustainably into types that explain or influence current or future sustainable or unsustainable management. Finally, I offer up some recommendations on how information on groundwater sustainability can be improved by groundwater conservation districts in groundwater management areas, the Texas Water Development Board, or the Legislature.

THE AQUIFERS OF TEXAS

Texas is blessed with numerous aquifers that cover almost the entirety of the state. The Texas Water Development Board recognizes 9 major aquifers (Figure 1) and 22 minor aquifers (Figure 2) where a major aquifer is a large aquifer with high well yields and minor aquifers are either small aquifers with high well yields or large aquifers with moderate well yields (George and others 2011; note that the Texas Water Development Board added the Cross Timbers Aquifer after publication of this report).

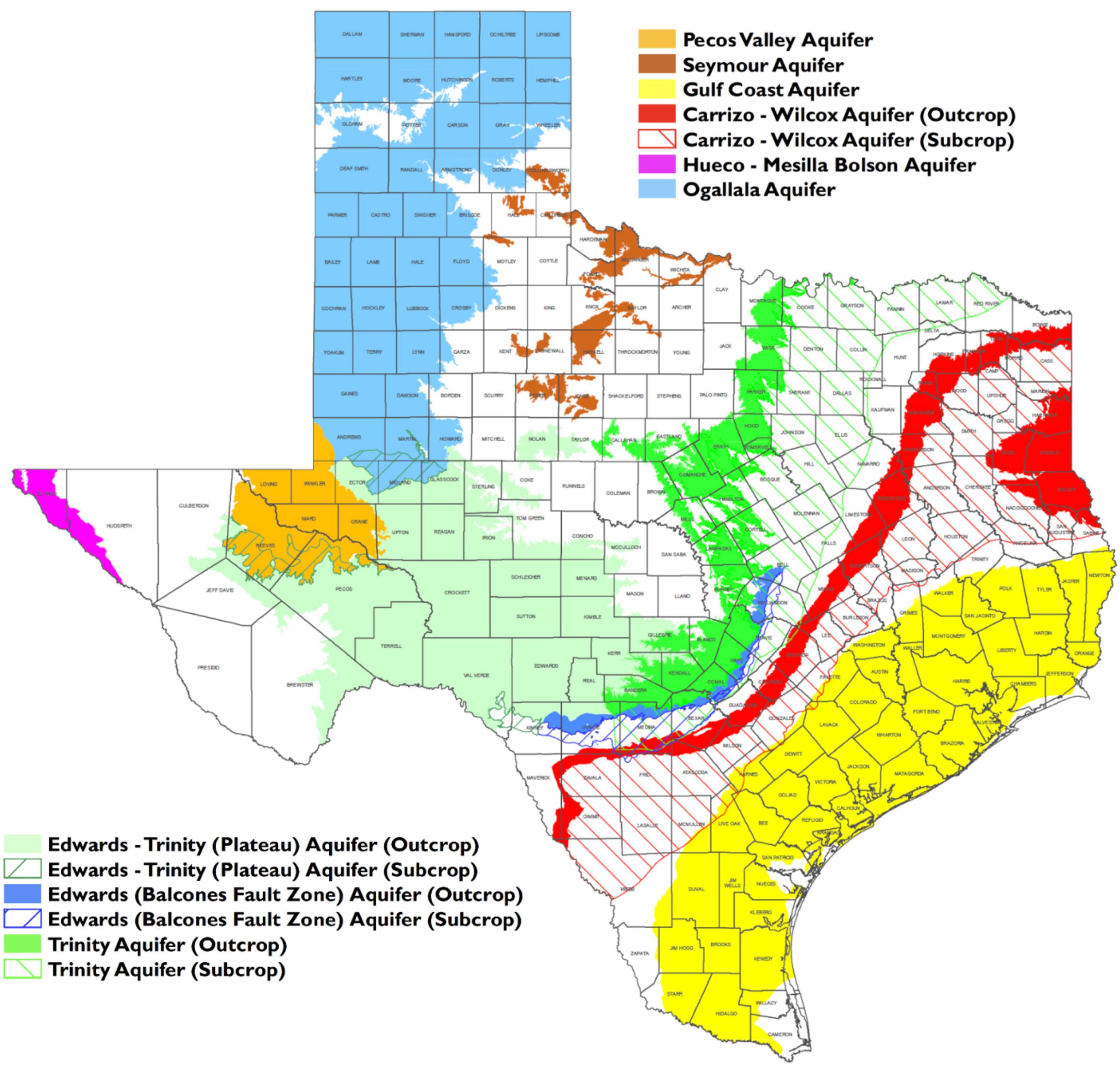

FIGURE 1: MAJOR AQUIFERS OF TEXAS (AFTER TWDB 2019A).

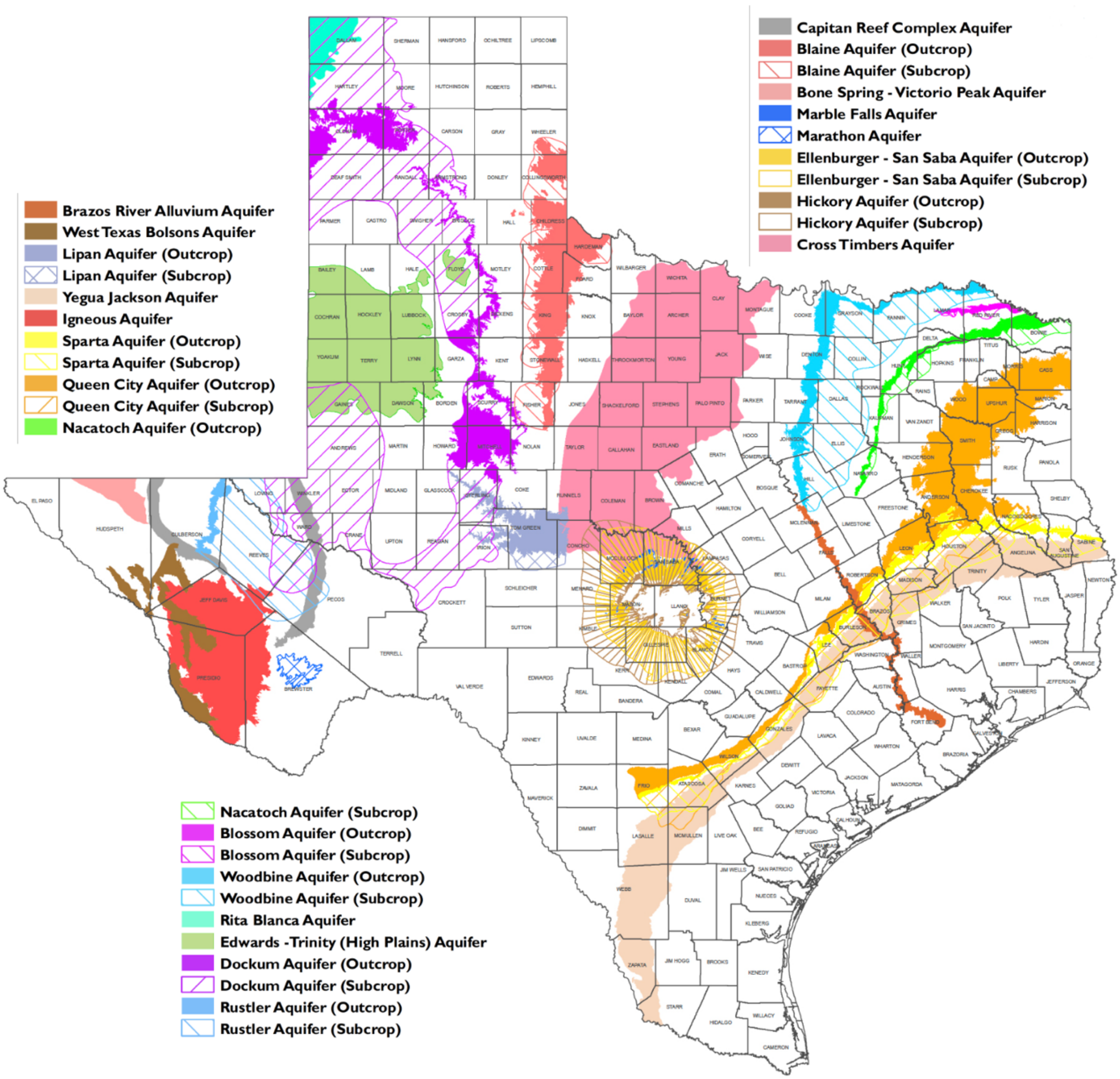

FIGURE 2: MINOR AQUIFERS OF TEXAS (AFTER TWDB 2019B).

Of the major aquifers, the Gulf Coast, Hueco-Mesilla Bolsons, Ogallala, Pecos, and Seymour aquifers are comprised of unconsolidated sands and gravels. The Edwards (Balcones Fault Zone), the Edwards part of the Edwards-Trinity (Plateau), and parts of the Trinity in the Hill Country and the Plateau are karstified limestones with high productivity (which is less prevalent in the Edwards-Trinity [Plateau] and Trinity aquifers). The Edwards (Balcones Fault Zone) Aquifer is hydrologically divided into the San Antonio Segment, the Barton Springs Segment, and the Northern Segment based on groundwater divides located near the City of Kyle and the Colorado River. The Trinity, Trinity part of the Edwards-Trinity (Plateau), Carrizo-Wilcox, and Gulf Coast aquifers mostly consist of sandstones.

Of the minor aquifers, the Brazos River Alluvium, Lipan, parts of the Rita Blanca, Sparta, West Texas Bolsons, and Yegua-Jackson aquifers are comprised of unconsolidated sands and gravels. The Blaine, Bone Spring-Victorio Peak, Capitan Reef Complex, parts of the Cross Timbers, Edwards part of the Edwards-Trinity (High Plains), Ellenburger-San Saba, Marathon, Marble Falls, and Rustler aquifers are karstified limestones, dolomites, and/or evaporites with high productivity. The Blossom, parts of the Cross Timbers, Dockum, Hickory, Nacatoch, Queen City, parts of the Rita Blanca, and Woodbine aquifers mostly consist of sandstones. The Igneous Aquifer consists of volcanic rocks.

Withdrawal from the aquifers was less than 1 million acre-feet per year before 1940 but increased during the late 1940s and early 1950s to about 11 million acre-feet per year (Figure 3). This increase in groundwater withdrawal was due to the Drought of the 1950s (which remains the drought of record for the state as a whole), the availability of affordable deep-hole centrifugal pumps, and an affordable energy supply to operate those pumps (Green 1973). By 2003, about half a billion acre-feet of water had been pumped from the state's aquifers (Figure 3). Groundwater withdrawals have remained about the same since 2003, which means an additional 200 million acre-feet has been produced for a total of 730 million acre-feet since 1937.

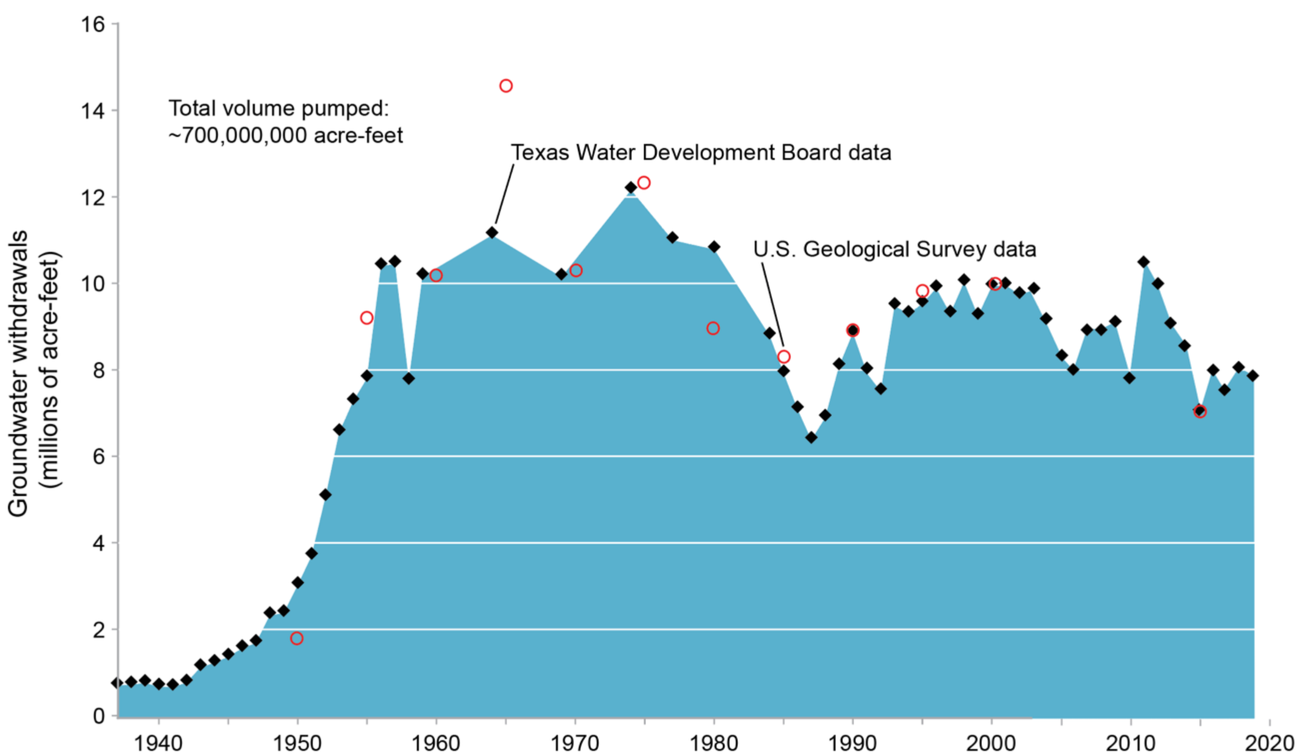

FIGURE 3: HISTORICAL ESTIMATES OF GROUNDWATER WITHDRAWALS FROM 1937 TO 2019.

Anytime water is produced from an aquifer, there is a change in storage as reflected by a decline in water level. Historical water-level declines in the state are more than 800 feet in the Dallas-Fort Worth and Waco areas; more than 400 feet in the Lufkin, Houston, and Tyler areas; more than 300 feet in the Wintergarden area southwest of San Antonio; more than 200 feet in the Bryan-College Station and parts of the High Plains; and upwards of 200 feet in the upper Pecos River in Texas, the El Paso area, large parts of the High Plains, and the irrigation area in Glasscock and Reagan counties (Figure 4). The larger water-level declines (greater than 200 feet), except for the Ogallala Aquifer, are in confined aquifers. Confined—also referred to as artesian—aquifers are under pressure such that water levels rise above the top of the aquifer (Figure 5). Water released from these aquifers is released from the compressive storage of the aquifer, which is much less than the drainable storage of an unconfined, water table, aquifer for the same decrease in water level (Figure 5). For example, almost 30 times more water is produced from the Ogallala Aquifer than the Trinity Aquifer, yet maximum water-level declines in the Trinity Aquifer are three to four times greater.

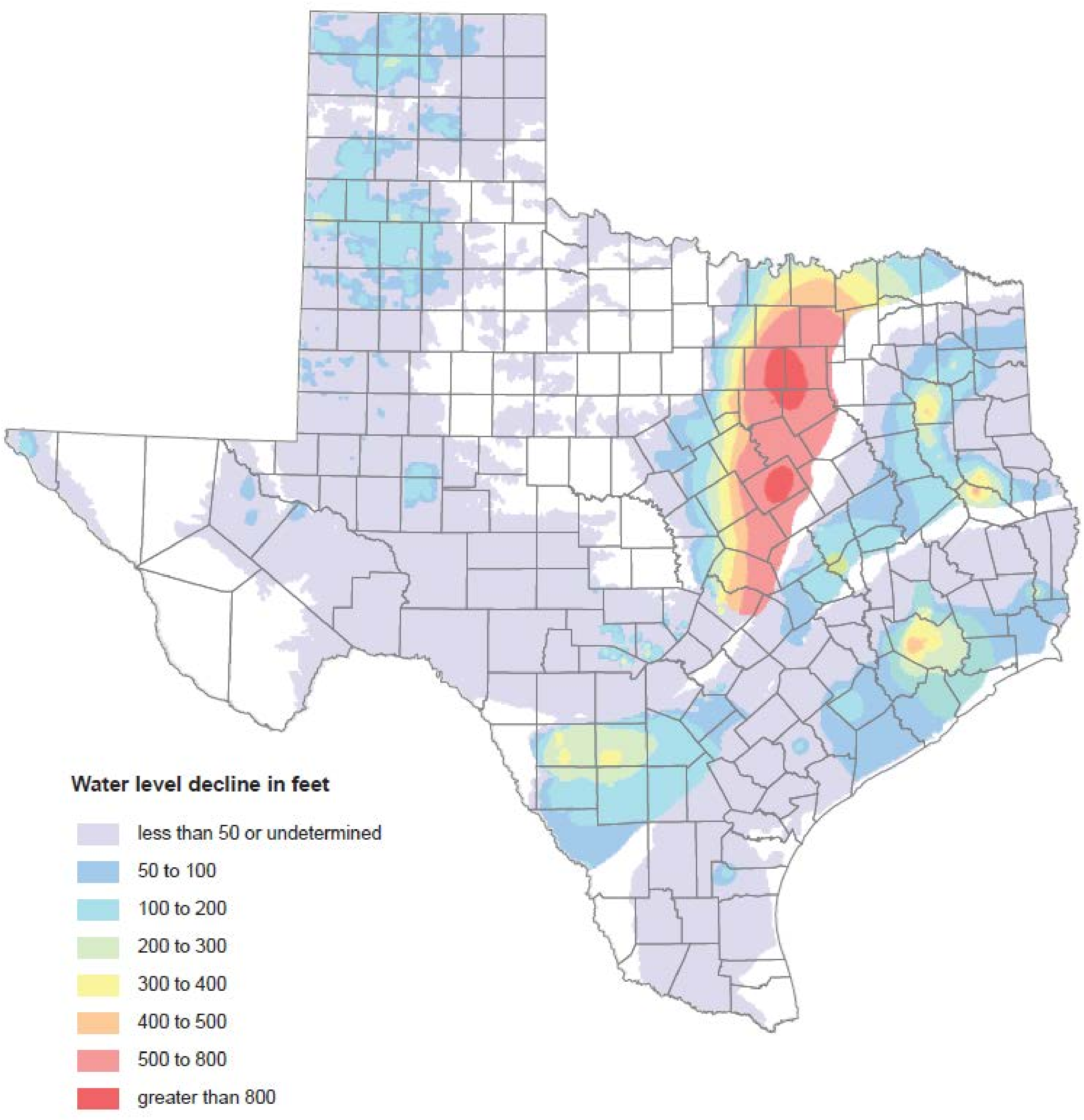

FIGURE 4: ESTIMATED TOTAL WATER-LEVEL DECLINES IN THE MAJOR AQUIFERS OF TEXAS (FROM GEORGE AND OTHERS 2011).

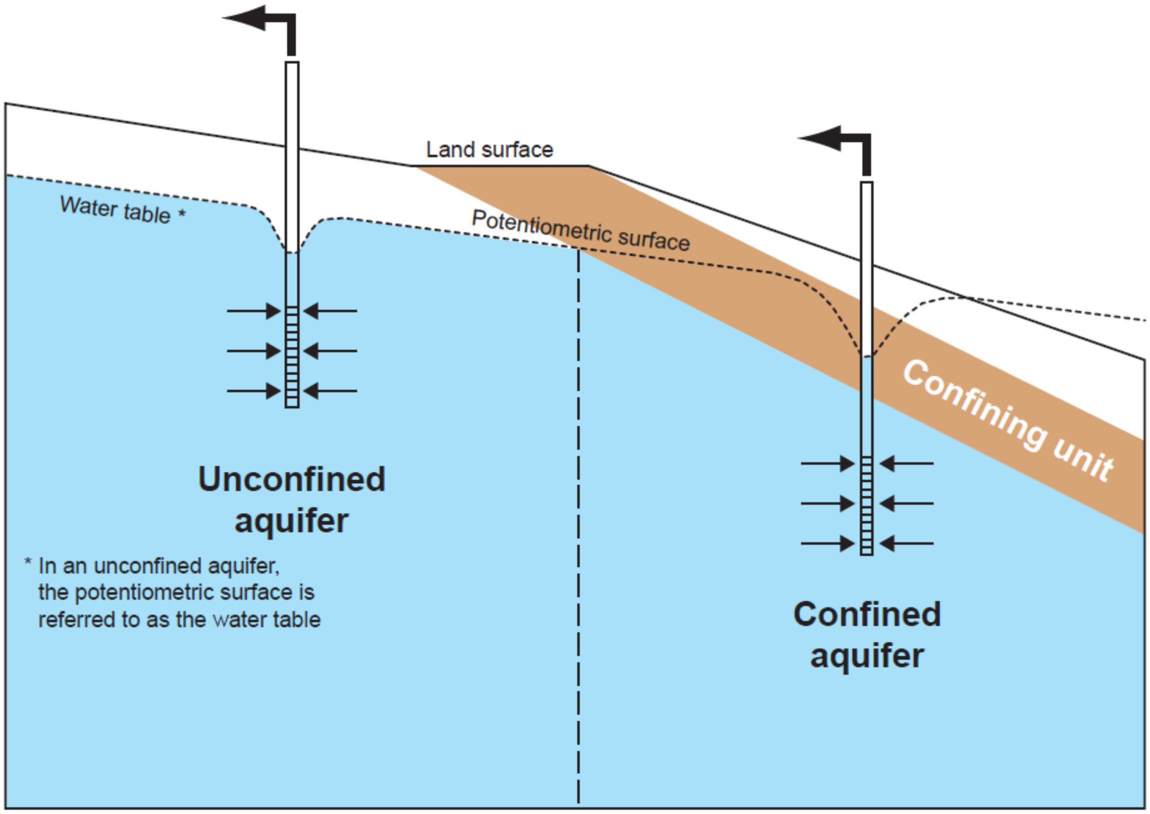

FIGURE 5: UNCONFINED AND CONFINED CONDITIONS IN AN AQUIFER (FROM GEORGE AND OTHERS 2011).

FROM SAFE YIELD TO SUSTAINABILITY[4]

Interestingly, the earliest discussions on how to manage groundwater were focused on managing groundwater sustainably (albeit initially from the standpoint of maximizing production in perpetuity solely for the benefit of human needs). Engineers were the first to weigh in on this, bringing their surface-water experience to the topic.

Safe yield for a surface-water reservoir is the maximum amount of water that can be annually produced from a reservoir during a repeat of the drought of record[5]. Generally, this involves draining out the conservation pool (the volume of water intended for use) by the end of the drought of record. Lee (1915) was the first to import the term safe yield to the groundwater management discussion. Lee (1915) restricted his discussion to closed-basins and provided two definitions of safe yield: (1) "…the net annual water supply which may be developed by pumping and Artesian flow without persistent lowering of the ground-water plane" and (2) "…the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." Lee (1915) recognized that production could increase recharge, recharge could be increased artificially, and natural discharge to springs and wetlands would be decreased but focused his analysis on maximizing groundwater production. Although he restricted his analysis to closed basins (in his paper, he analyzed the safe yield of Owens Valley, California), commentors on his paper noted that the safe yield concept could be applied to aquifers across the country.

O.E. Meinzer, an influential engineer with the U.S. Geological Survey, adopted the term thus ensuring its use in hydrogeology thereafter (Meinzer 1920, 1923a, 1932). Like Lee, Meinzer focused on maximizing the sustainable production from an aquifer for the benefits of humans, settling on a definition for safe yield as "the practicable rate of withdrawing water from an underground reservoir perennially for human use."

Although engineers were developing and refining the concept of safe yield to manage aquifers, how people were using and managing aquifers was not sustainable. Aquifers with flowing artesian wells, including in California and Texas, were not being managed such that production could be maintained indefinitely, and there were growing concerns about groundwater development of the Ogallala Aquifer in Texas. Meinzer (1932) noted that "the most urgent problems in ground-water hydrology at the present time are those relating to the rate at which rock formations will supply water to wells in specified areas—not during a day, a month, or a year, but perennially."

By the 1950s, scientists and engineers began to recognize that landowners were producing groundwater from some aquifers beyond their safe yield. McGuiness (1951) observed that an alternative approach to safe yield may be needed in aquifers such as the Ogallala. Thomas (1955) noted that public opinion supported non-sustainable groundwater production. By the 1960s, economics began to creep into groundwater management discussions (Renshaw 1963; Burt 1964, 1967; Young 1970). For example, Bear and Levin (1967) suggested that mining—producing groundwater more than the safe yield—may be a reasonable economic outcome depending on societal objectives.

The effect of groundwater production on the environment began to be identified in the 1970s. Fetter (1972) observed that the traditional factors used to define safe yield at that time did not include environmental impacts and concluded that environmental factors should be considered when establishing

4 I am currently writing a book on the general topic of groundwater sustainability; much of the content in this section sources from that book in progress.

5 In Texas, this is the definition for firm yield; safe yield involves adding a safety factor, namely time, to the firm yield analysis. Different states define firm and safe yield differently.

the safe yield of aquifers that discharge to estuaries. Freeze and Cherry (1979) noted that groundwater was more than a resource—it was an important part of the natural environment.

The International Union for Conservation of Nature and Natural Resources (1980) introduced the concept of sustainable development in the 1980s, later appearing in the books *Building a Sustainable Society* (Brown 1981) and *Gaia: An Atlas of Planet Management* (Myers 1984). The Brudtland Commission popularized the concept in their report, *Our Common Future* (WCED 1987). The Brudtland Commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The word "sustain" was first matched with the word "yield" for groundwater by McGuiness (1951) when he used sustained yield as an alternative name for safe yield (and restricted it to a function of the properties of the aquifer as constrained by how groundwater is developed). It next appeared in 1961 when the American Society of Civil Engineers attempted to clarify definitions of aquifer yields by introducing the terms maximum sustained yield and permissive sustained yield (CG-ASCE 1961). They defined maximum sustained yield as the maximum rate groundwater can be produced perennially and permissive sustained yield as the maximum rate groundwater can be economically and legally produced without causing an undesired result. Mann (1963) proposed using sustained yield or perennial yield instead of safe yield, and Walton (1964) proposed the term practical sustained yield.

Todd and Meyer (1970, 1971) appear to be the first to use the term sustainable yield for groundwater as an alternative to safe yield, later used by Toth (1973), Hopkins (1987), Hamlin and Anthony (1987), and others. ASCE (1998) defined sustainable water resource systems as those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity. Alley and others (1999) defined **groundwater sustainability** as the "development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences."

One element of safe yield, sustainable yield, and sustainability that engineers and scientists struggled with was the policy component. Thomas (1951) called safe yield an "Alice-in-Wonderland term which means whatever its user chooses." Lee (1915), in his definition of safe yield, mentioned avoiding "dangerous depletion." But what exactly is "dangerous?" And who determines that? Meinzer, perhaps attempting to work around the word "dangerous," incorporated the "practicable rate" of production into his definition. But what is "practicable?" And who decides that? Over time, as understanding and societal mores progressed, safe yield incorporated water quality, economics, consumptive use, effects on rights in adjacent groundwater basins, socioeconomics and social welfare, the environment, and future generations.

Fetter (1977) correctly concluded—and without judgment—that "[t]he safe yield of an aquifer system is not a physical phenomenon but is, rather, a subjective phenomena based upon human values." However, physical phenomena—how the aquifer responds to production—provides an upper limit to the safe yield: the maximum amount that can be pumped sustainably. Similar to safe yield, some groundwater scientists have disparaged groundwater sustainability as "value laden" (for example, Wood 2001). However, it is not possible to divorce policy from sustainability decisions. Even a decision to use a maximum sustainable yield for groundwater management—the closest thing to a number divorced from policy—is a policy decision.

Definitionally, safe yield is the same as sustainable yield, but hydrogeologists tend to use **sustainable yield** because, in part, of the misdirected confusion that safe yield is equal to recharge (Bredehoeft and others 1982, Bredehoeft 1997, Bredehoeft 2002). While safe yield can be equal to recharge in special cases, in many cases it is less, and usually far less. So sustainable yield is the quantified amount of groundwater that can be produced to achieve groundwater sustainability. In Texas groundwater parlance, groundwater sustainability is analogous to the desired futured condition while sustainable yield is analogous to the modeled available groundwater amount.

Groundwater sustainability, and thus sustainable yield, cannot be determined without a policy process. Someone must determine what the acceptable environmental, economic, or social consequences are. At a minimum, the policy process needs to include the decisionmakers—those that will be codifying decisions and managing the aquifer. Ideally, the decisionmakers—as part of their process—include stakeholders in the discussions and decisions. The outcome of the decisions can then be used to define the sustainable yield (although, ideally, the science has accompanied the policy discussions all along to share information about sustainability, the aquifer, and potential outcomes [such as strawman sustainable yields]) for different goals. Finally, the policy process should be adaptive—that is, allowed to change with time as science, conditions, and societal values change.

Note that sustainable production is not the same as sustainable yield. The sustainable yield is a special case of sustainable production where the production can be accomplished without causing unacceptable environmental, economic, or social consequences. There is a spectrum of sustainable groundwater production from nearly zero to the maximum rate which does not consider unacceptable environmental, economic, or social consequences (Figure 6). The sustainable yield—as defined through a policy process—rests somewhere along that spectrum.

To conclude with recommended definitions:

Groundwater sustainability is the development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley and others). Groundwater sustainability has to be defined by a decisionmaker, ideally through a stakeholder process.

Sustainable yield is the amount of groundwater that can be produced to achieve groundwater sustainability.

Maximum sustainable production is the maximum amount of groundwater that can be produced sustainably.

Sustainable production or the words **sustainable** or **sustainably** outside of the above contexts refers to any action that can be performed indefinitely. Sustainable yield and maximum sustainable production are special cases of sustainable production.

SUSTAINABILITY & WATER PLANNING

After the Drought of the 1950s and concerns over the federal government planning the future of Texas' water resources, the Texas Legislature began requiring the development of a state water plan. Part of water planning is assessing how much water is available for use. For aquifers, Texas has referred to the amount of groundwater available for use as groundwater availability. Groundwater availability is a general term state water planners in Texas have used (and continue to use) that includes sustainable and non-sustainable groundwater use depending on policy decisions.

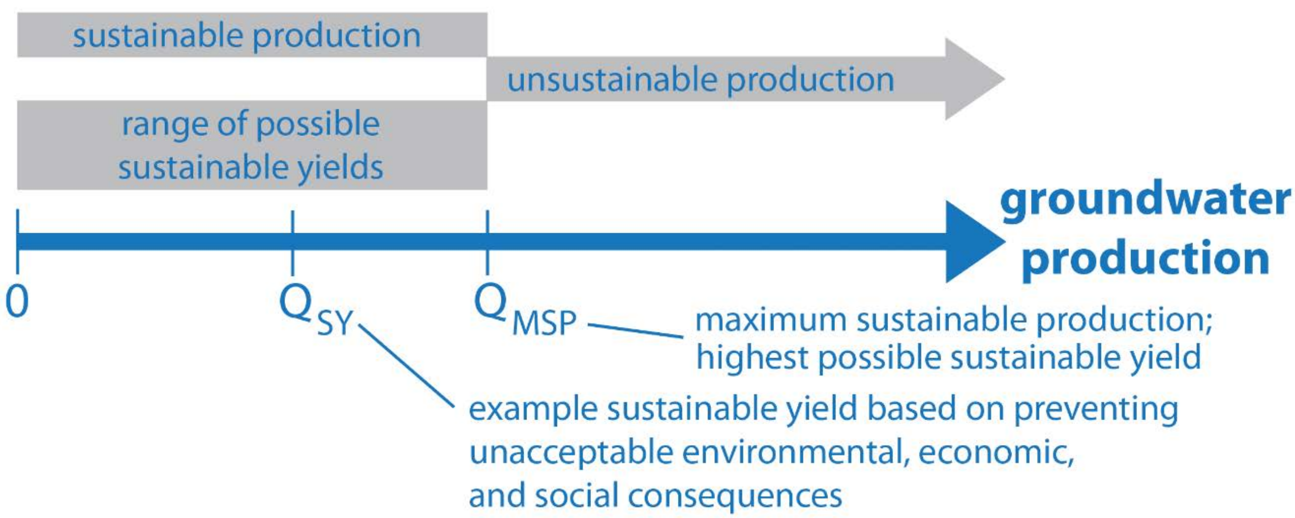

FIGURE 6: A SIMPLE CONCEPTUAL MODEL OF SUSTAINABLE AND UNSUSTAINABLE GROUNDWATER PRODUCTION.

Except for the Ogallala Aquifer and several others, state water planners in the earliest water plans presumed that sustainable development would be preferred once locals formed groundwater conservation districts, something that had been allowed since 1949. In the 1961 State Water Plan, TBWE (1961) identified aquifers subject to depletion (the Blaine, Ogallala, and Seymour aquifers as well as some local alluvial aquifers) and those not subject to depletion (Bone Spring, Capitan Reef, Carrizo-Wilcox, Edwards, Edwards-Trinity, Gulf Coast, Santa Rosa, Sparta, Triassic Sands, and Woodbine aquifers) with a qualitative estimate of how much could be pumped relative to the amount being pumped at the time (no additional water, few times greater, several times greater, many times greater).

The 1968 State Water Plan (TWDB 1968) is infamous for proposing to import water from the Mississippi River to the High Plains and along the Gulf Coast. What is perhaps less appreciated is that the primary driver for this import—at least what is stated in the plan—was to manage the state's aquifers sustainably. Accordingly, one of the plan's guiding principles was for groundwater resources to "…be developed and used on a safe-yield basis" and "[i]n ground water aquifers subject to overdraft, ground water pumpage will be reduced to safe yield as rapidly as possible by substitution of surface water supplies." Included in the list of undesired results from uncontrolled groundwater production was the loss of springs, at least for the Edwards Aquifer, and land subsidence.

With the failure of a bond election to start the construction of the massive import project (Green 1973), the 1984 State Water Plan dropped the import of water from the Mississippi River and sought to meet water needs through resources internal to the state (TWDB 1984). For groundwater, the plan stated that "[t]he estimate of the ground-water supply capability of each area of the State is based on the assumption that some form of ground-water management program will be instituted in each area of the State where it is prudent to do so." With the removal of a large source of surface-water, the plan envisioned continued groundwater mining in many of the aquifers in West Texas with decreasing use over time due to the decreased abilities of the aquifers to provide supply. For the rest of the state's aquifers, planners estimated groundwater availability based on the assumption of safe yield.

The 1984 State Water Plan noted that "extensive development" had resulted in production exceeding recharge in the Ogallala Aquifer and caused land subsidence, saline water encroachment, and fault activation in parts of the Gulf Coast. The plan recommended amendments to the Texas Water Code to allow the Texas Water Commission to hold hearings to designate groundwater conservation districts where needed and to give the Texas Water Development Board "...the authority to set minimum standards for operation and management of local ground-water districts."

The 1990 State Water Plan followed a similar approach to the 1984 plan with respect to groundwater mining and safe yield assumptions (TWDB 1990). The 1990 plan also had projects specifically proposed to avoid continued mining of groundwater supplies (in other words, there were water management strategies to bring certain aquifers back into sustainable management). While caveating their policy recommendations under the umbrella of landowners' rights to groundwater, the Texas Water Development Board noted that "over-development of ground water has caused many problems, including water supply shortages, reduction or loss of springflow, land-surface subsidence, intrusion of poorer quality water, and increased potential for contamination by pollution sources." The Texas Water Development Board also noted that the state had created groundwater conservation districts to approach "the over-use of groundwater."

The 1997 State Water Plan, the last water plan before the regional water planning process started, stated that "A pivotal element of the debate over the State's ground-water future is which allocation method(s) best protects private property rights... methods that emphasize unlimited freedom of action or those that provide some recourse to prevent or mitigate unreasonable use?" [ellipses are in the original text; TWDB 1997]. The plan goes on to state that "The marketing of ground water to help future needs could be enhanced if it were a measurable right and could be afforded greater legal protection vis-a-vis other existing or future users of the same ground-water resource." The 1997 plan noted that existing state law did not recognize the connection between surface water and groundwater and that resulted in "conflicting management schemes." Ultimately, the Texas Water Development Board recommended that the legislature should consider "Reassessing ground-water law doctrines to ascertain if improvements can be made to State law to provide for better management of ground-water resources." The 1997 State Water Plan referred to perennial yield and used it in "problem areas" and used managed depletion in areas where groundwater mining was not expected to cause "deleterious side-effects."

In 1997, after a severe drought in 1996 that left several small towns struggling with their water supplies, the legislature passed Senate Bill 1, which moved many of the planning decisions from the Texas Water Development Board to newly created regional water planning groups, 16 in total. Along with planning decisions (which strategies each region would pursue for additional water supplies in the future), the regional water planning groups also gained control of groundwater availability decisions, something state planners had previously handled. Furthermore, state law said that whatever groundwater availability decisions groundwater conservation districts made in their groundwater management plans, those groundwater availability numbers had to, at a minimum, accommodate the groundwater strategies in the regional water plans. This created an interesting situation where a non-regulatory planning group set the minimum value for groundwater availability for local groundwater regulators.

The 2002 State Water Plan (TWDB 2002) was the first state water plan developed through the regional water planning process introduced by Senate Bill 1 in 1997 where regional water planning groups developed regional water plans which then rolled into the state water plan. Regional water planning groups were allowed to make legislative recommendations and, under the new planning process, the

Texas Water Development Board retained its ability to make legislative recommendations. The agency noted issues with continued groundwater use, particularly for rural Texas, and asked the question "Should aquifers be managed on a sustainable basis or on the basis of eventual depletion?" The agency recommended that the legislature "...should consider requiring groundwater conservation districts to include in their groundwater management plans a management goal quantifying the desired future condition of the aquifer." The agency also recommended that "Groundwater conservation districts and regional water planning groups should determine whether sustainable management is appropriate for their area or whether another management scenario better fits the needs of their locality."

The regional water planning groups also made policy recommendations in the 2002 State Water Plan. Region K (essentially the footprint of the Lower Colorado River Authority) recommended supporting efforts by the region's groundwater conservation districts to control or limit groundwater mining regions J (Edwards Plateau) and M (Lower Rio Grande Valley) recommended studies on the effects of groundwater production on surface-water flows, including springs.

The Texas Water Development Board made 42 major policy recommendations to the legislature in the 2002 State Water Plan. The Board has been much more reserved in recommending policy changes since the 2002 State Water Plan, with seven in the 2007 plan (TWDB 2007), two in the 2012 plan (TWDB 2012), three in the 2017 plan (TWDB 2017), and two in the 2022 plan (TWDB 2021) with two of the recommendations in all of these recent plans part of the "standard" recommendations informed by the regional water planning groups concerning unique stream segments and unique reservoirs sites[6].

Similar to the national discussion on how to best manage groundwater, state water planners sought to manage Texas' groundwater resources in a sustainable manner using safe yield concepts. Up through the 2002 State Water Plan, the Texas Water Development Board encouraged the legislature and, in the 2002 plan, regional water planning groups and groundwater conservation districts, to consider sustainable management of the state's groundwater resources. With the advent of regional water planning and growth in the number of groundwater conservation districts (see next section), the Texas Water Development Board has retreated from policy discussions on groundwater management and sustainability (among other topics).

6 The change in the number of recommendations between 2002 and 2007 was primarily due to having too many recommendations for the legislature consider; the subsequent decline between 2007 and 2012 was a change in management philosophy on making legislative recommendations (William F. Mullican, III, former Deputy Executive Administrator, October 27, 2021). The lower number of recommendations in recent plans may be due to administrative inertia.

SUSTAINABILITY & GROUNDWATER GOVERNANCE

Groundwater governance "…is the decision of which management actions should be taken, when, by whom, and for what purpose" while groundwater management is the implementation of that decision (Villholth and Conti 2017). Before the Texas Supreme Court ruling in the East case in 1904, groundwater users did whatever they wanted regardless of the impacts to neighbors or surface-water resources. After the ruling in the East case, when the Texas Supreme Court formally established the Rule of Capture in Texas, groundwater users could still do want they wanted, but they now had case law to formidably support them. From the governance perspective, and absent any action by the legislature, the Rule of Capture effectively says that each landowner has say over the groundwater beneath their land, for whatever purpose they so desire, so long as they don't waste the water or pump it to maliciously damage a neighbor.

The artesian well-drilling boom in the late 1800s resulted in thousands of wells flowing an estimated 50 million gallons per day across the footprints of the Trinity and Edwards aquifers by 1892 (Mace 2016). Well owners generally let their artesian wells flow 24 hours a day, in part due to bad scientific assumptions (Robert T. Hill with the U.S. Geological Survey thought 50 percent of rainfall fed the artesian portion of the Trinity Aquifer; our current best estimate is 0.04 percent) and crackpots (different "experts" connected the Trinity Aquifer to the Rocky Mountains, the Great Lakes, and, inexplicably, the Arctic Ocean; Mace 2016).

The outcome of leaving wells flowing uncontrolled for Fort Worth was that 237 of 240 wells stopped flowing by 1894; many wells across the Trinity Aquifer had stopped flowing by 1903 (Mace 2016). In response, the legislature passed the state's first groundwater management legislation in 1913 as part of the Burges-Glasscock Act. The Act created the Texas Board of Water Engineers, a predecessor agency for the Texas Commission on Environmental Quality (and, arguably, the Texas Water Development Board) which required the registration of artesian wells with the state and disallowed the waste of groundwater.

In 1917, the Legislature proposed, and the voters approved, what is now known as the Conservation Amendment (known then as the Conservation District Amendment) to the state constitution. This amendment allowed for the creation of locally-controlled districts to conserve water. Back in those days, conserving water meant reducing water to human use through capture (Jarvis 2005). Regardless, it wasn't until 1949 after several post-Dust Bowl legislative sessions of back-and-forth between Ogallala irrigators who wanted unrestricted groundwater production and municipalities concerned with declining water levels that the legislature employed the Conservation Amendment to allow for the creation of groundwater conservation districts.

The legislature's actions appeared to finally bring groundwater management to Texas, but the irrigators trumpeted it as a win for pumpers, crowing that "West Texans can consider the water their own—to use or waste as they please" (Green 1973). From the governance perspective, the creation of groundwater conservation districts allows a locally-elected board—therefore, the voters—to decide how to manage groundwater within their district[7]. Given that board members have terms and, over time, there are numerous elections, groundwater management in this manner is adaptive and can reflect the changing mores and desires of the electorate—if those mores and desires change.

Over time, the legislature has modified groundwater conservation district authority, providing a menu of management tools for the districts. "Menu" is the key word here because districts can pick and choose which tools to use, including none, thus allowing almost unfettered use of their groundwater

7 Some districts have appointed boards, usually by county commissioners or communities; one has a member appointed by the governor.

resources, choosing to manage sustainably, or, more commonly, something in between. Districts can also choose tools to control well spacing and production. The state does not specify how aquifers should be managed except for two special cases: (1) the subsidence districts in the Houston Area (to prevent groundwater-production caused land subsidence) and (2) the Edwards Aquifer Authority (to protect endangered species in San Marcos and Comal springs), neither of which are currently considered groundwater conservation districts[8].

Most districts formed following county lines rather than aquifer boundaries, creating different rules—and goals (if they had goals)—over the same aquifer (Figure 7). Because of this, the 2002 State Water Plan recommended that the legislature require groundwater conservation districts to establish desired future conditions for relevant aquifers in their groundwater management area. The Texas Water Development Board defines groundwater management areas, in their current realization, which approximate the major aquifers of the state with the Carrizo-Wilcox and Gulf Coast Aquifer divided into three large pieces and the Trinity, Ogallala, and Edwards (Balcones Fault Zone) aquifers divided into two large pieces (Figure 7).

The term "desired future conditions" wasn't passed into law by the legislature until 2005 with House Bill 1763 after a conflict arose between what a district wanted for groundwater availability and what was in the regional water plan. Groundwater conservation districts in each groundwater management area meet to establish their desired future conditions, the quantified conditions of an aquifer, such as through water levels, water-level declines, spring flows, or aquifer storage for the next 50 years. The districts provide their conditions to the Texas Water Development Board where technical staff estimate how much can be pumped to achieve the desired future condition—called the modeled available groundwater—and then delivers those estimates to the districts and the planning groups. Districts are then required to develop, pass, and enforce rules to achieve their desired future conditions. Districts meet every five years to revisit the science and policy associated with their desired future conditions.

The state, barring the aforementioned cases of subsidence and endangered species, does not specify what the desired future conditions should be, but it does specify the process and what information should be considered and requires the districts in groundwater management areas to provide an explanatory report about their decisions.

At present, groundwater governance in Texas is a combination of federal influence (endangered species issues leading to the creation of the Edwards Aquifer Authority, Federal court decisions), state influence (the Texas Water Code, state court decisions), regional influence (through groundwater management areas), local control (through groundwater conservation districts), and voters. The state charges local districts with making and enforcing rules to achieve the desired future condition. Federal and state governance has indirectly forced the sustainable management of most of the San Antonio Segment of the Edwards Aquifer leaving management decisions to the elected board of the Edwards Aquifer Authority (the policy driver was endangered species; those species happen to rely on springflow for their survival) and state governance has indirectly forced the sustainable management of the Gulf Coast Aquifer in Harris and Fort Bend counties (the policy driver is land subsidence caused by groundwater production).

For most of the groundwater resources in the state, groundwater conservation districts make the policy decisions on how to manage groundwater, including whether or not to manage their resources sustainably.

8 Both used to be considered groundwater conservation districts since their enacting legislation included reference to Chapter 36 of the Texas Water Code; however, subsequent modifications to their enacting legislation removed them from said chapter.

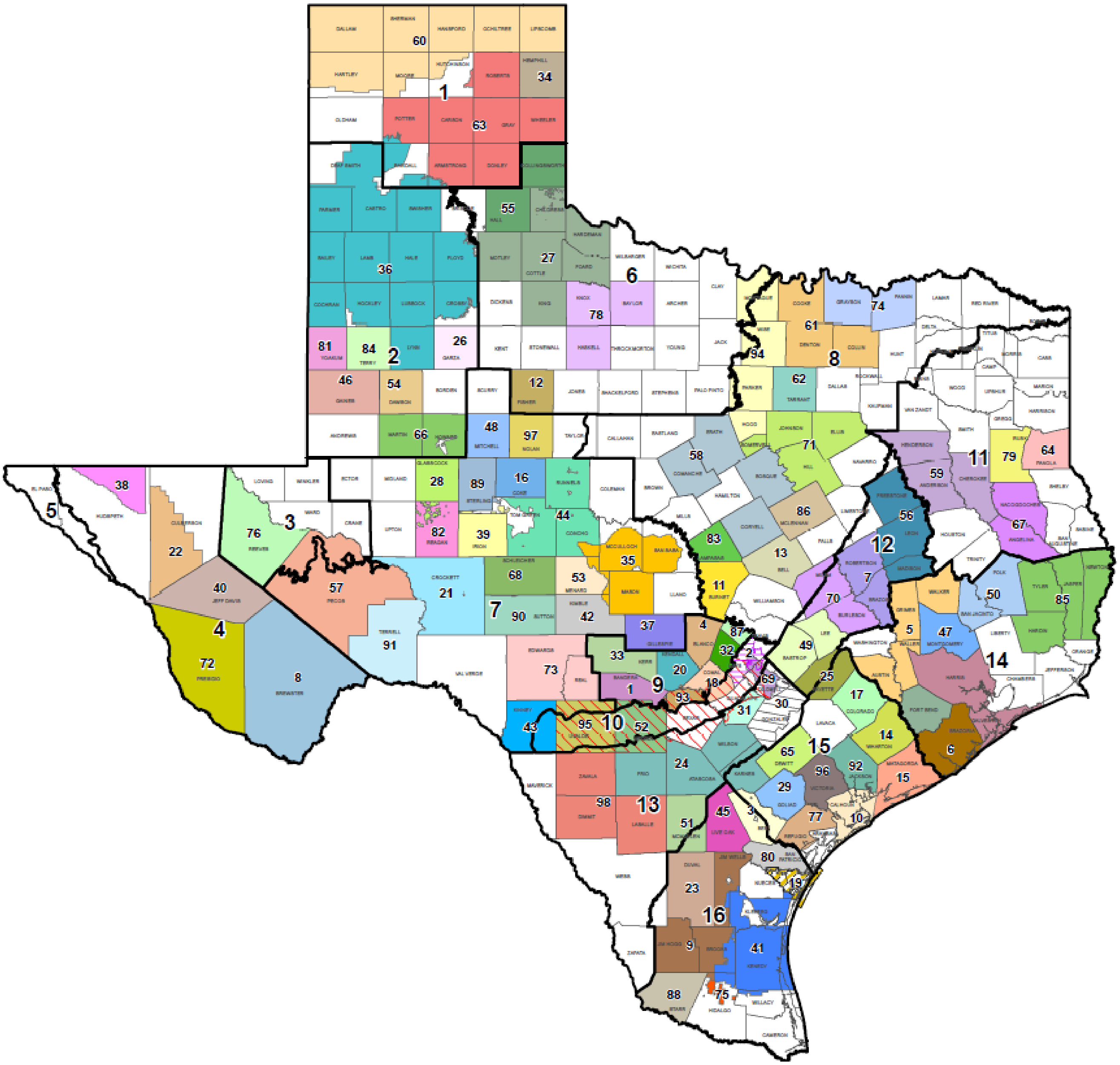

FIGURE 7: GROUNDWATER CONSERVATION DISTRICTS (COLORED AREAS) AND GROUNDWATER MANAGEMENT AREAS (OUTLINED IN BLACK) IN TEXAS—AREAS SHOWN IN WHITE DO NOT HAVE A GROUNDWATER CONSERVATION DISTRICT, AUTHORITY, OR SUBSIDENCE DISTRICT AND ARE FULLY SUBJECT TO THE RULE OF CAPTURE (MODIFIED FROM TWDB 2019C; PLEASE VISIT THE TEXAS WATER DEVELOPMENT BOARD'S WEBSITE FOR INFORMATION ON THE INDIVIDUAL GROUNDWATER CONSERVATION DISTRICTS.

SUSTAINABILITY & DESIRED FUTURE CONDITIONS

A potential source of information on groundwater sustainability in Texas is the desired future conditions chosen by groundwater conservation districts in their groundwater management areas. In some cases, it is easy to identify sustainable desired future conditions because the condition is defined by maintaining springflow and/or baseflow (if you are seeking to indefinitely maintain springflow, you have to manage the aquifer sustainably). In other cases, it is not clear because, as we will see, most desired future conditions are defined by projected water-level declines. Without decadal water budget information from the groundwater availability models, we can't tell if the projected water-level declines result in unsustainable or sustainable groundwater production.

You might think that any drawdown indicates unsustainable use, but that is not necessarily the case. Any production from an aquifer results in water-level declines, including sustainable groundwater production (see Theis 1940 for a thorough explanation of how aquifers respond to production). The key difference between sustainable and unsustainable groundwater production is that sustainable groundwater production will result in water-level declines stabilizing over time whereas unsustainable groundwater production will result in water-level declines through time until the aquifer is essentially drained or, more likely, production is no longer economical for existing uses. But even here, there are technical nuances. For example, it can take a long time for a confined aquifer to approach equilibrium, requiring decades to centuries or even thousands of years. To further complicate matters, water-levels in a confined aquifer theoretically never arrive at a true equilibrium. Year-to-year drawdowns may get exceedingly small, but they will never reach zero.

Despite the above complications, it is useful to analyze the desired future conditions since they do offer clues into which areas are explicitly considering sustainable management and which areas are not and what the consequences might be (as expressed by water-level declines, available water over time, and impacts to the water budget, including spring and baseflow). To do this, I used the desired future conditions and modeled available groundwater values for 2020 and 2060 or 2070, whichever was the latest decade that the groundwater conservation districts defined their desired future conditions for. Several of the groundwater management areas (1, 12, 15, and 16) only defined their desired future conditions to 2060. For water planning purposes, the Texas Water Development Board directed regional water planning groups to use 2060 values for the 2070 planning decade, so I did the same. However, note that an additional decade of groundwater production at 2060 levels would likely increase water-level declines in those aquifers greater than the official desired future condition.

Groundwater conservation districts in some groundwater management areas lumped their desired future conditions. In other words, the districts combined several aquifers into a single desired future condition and/or used a single desired future condition for the entire groundwater management area. Districts in other groundwater management areas split their desired future conditions. For example, districts defined conditions for each aquifer or each sub-aquifer with different conditions defined for each groundwater conservation district or county. Regardless, the Texas Water Development Board provided modeled available groundwater numbers for each aquifer-county-river basin-regional water planning area-groundwater management area split because regional water planning groups need groundwater availability at the aquifer-county-river basin-regional water planning area for planning purposes.

Because river basins and regional water planning groups were not a concern, I entered desired future condition and modeled available groundwater information for each aquifer-county-groundwater management area split. After removing entries where the modeled available groundwater was zero, there were 521 aquifer-county-groundwater management area splits, each with an applicable desired future condition and modeled available groundwater number.

Of the 521 aquifer-county-groundwater management area splits, 8 (1.5 percent) had desired future conditions based on springflows, 17 (3.3 percent) on zero or increasing water levels[9], 34 (6.6 percent) on remaining saturation (X percentage of the saturated thickness left after Y years), and 462 on water-level declines (88.7 percent). Since remaining saturation is, in essence, a water-level decline measured from a different perspective, 496 (95.2 percent) of the desired future conditions envision water-level declines in the state's aquifers.

The water-level declines envisioned in the desired future conditions range from 1 foot to 318 feet (Figure 8). About 90 percent of water-level declines are greater than 5 feet, half are 48 feet or higher, about 25 percent are greater than 116 feet, and about 10 percent are greater than 177 feet. Groundwater conservation districts envision these declines as occurring over 40 to 50 years.

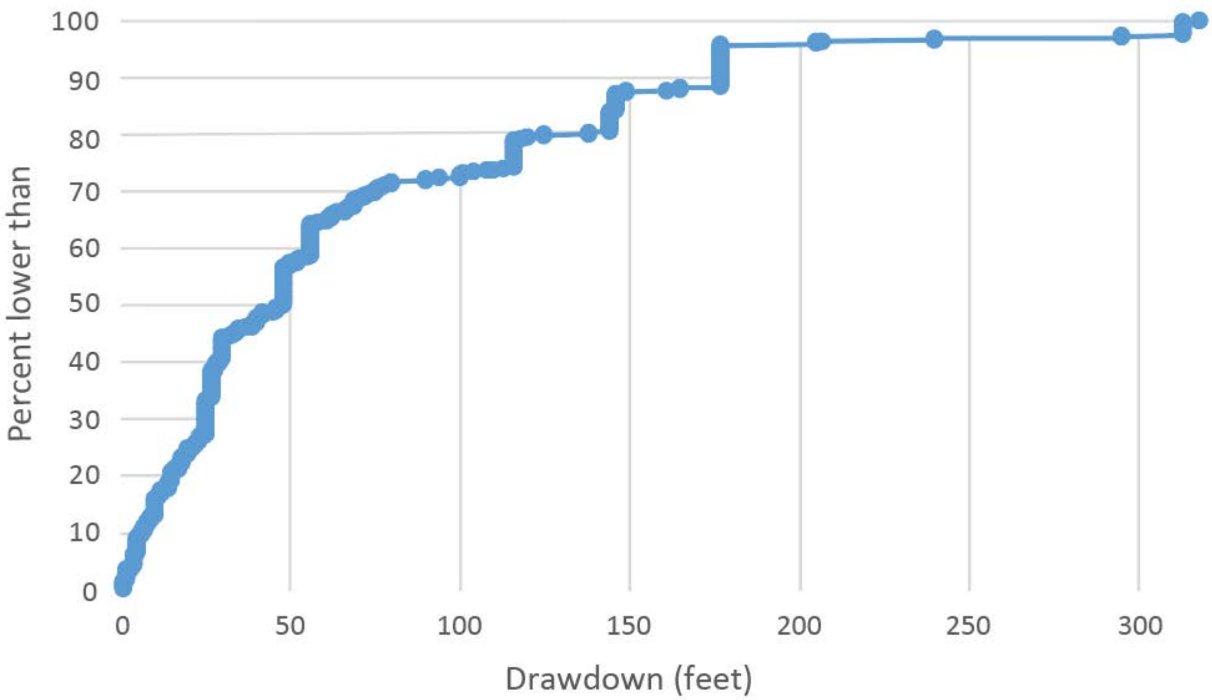

FIGURE 8: CUMULATIVE DISTRIBUTION FUNCTION FOR DRAWDOWNS ASSOCIATED WITH DESIRED FUTURE CONDITIONS AND COUNTY-AQUIFER-GROUNDWATER MANAGEMENT AREA SPLITS. DOES NOT INCLUDE VALUES EQUAL TO OR LESS THAN ZERO.

One of the factors that groundwater conservation districts in groundwater management areas must consider when establishing desired future conditions is "Other environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water." For the most part, the text describing the response to this factor in the explanatory reports is not illuminating, at least from understanding the goals of the desired future condition. In many cases, the reports point to a water budget from the relevant groundwater model that includes springflow and/or surface water-groundwater interaction. One exception is the explanatory report for Groundwater Management Area 1 where the districts describe historical impact to springflow and baseflow (decreased from 209,566 acre-feet per year in 1930 to 85,914 acre-feet in 2012 based on the groundwater model) and state that they expect more springflow decline (unspecified in the report) with their proposed desired future conditions.

9 One desired future condition called for a water-level decline of 0.04 feet. I rounded this to 0 for this analysis.

The explanatory report for the Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 7 states that "The primary consideration in the northeastern portion of GMA 7 was the maintenance of groundwater levels to maintain baseflow to the tributaries of the Colorado River." The "northeastern portion" is not defined, but probably represents about 10 counties, thus increasing the aquifer-county-groundwater management area splits maintaining springflow or baseflow from 8 (1.5 percent) to 18 (3.5 percent).

Another way to look at the data is how steady the groundwater supply is over the next 50 years—in other words, is the aquifer "forcing" a reduction in use over time? Of the 521 aquifer-county-groundwater management area splits, 74 (14.2 percent) are not providing steady supplies (greater than 95 percent of 2020 levels) over the next 50 years while the remainder (447, 86.8 percent) are. While a steady supply over the next 50 years does not mean an aquifer is being managed sustainably (which requires a steady supply in perpetuity), it does provide important feedback to users about the status of their supply. That feedback may be "You need to worry about the foreseeable future" or "You do not have to worry about the foreseeable future," at least for 50 years at the designated production level.

A total of 68 (13.1 percent) aquifer-county-groundwater management area splits have increasing modeled available groundwater values, 252 (48.4 percent) have the same value in 2020 as in 2070, 127 (24.4 percent) show a decrease greater than 0 percent but less than 5 percent, and 74 (14.2 percent) decrease more than 5 percent with the greatest decrease at 89.7 percent.

Of the 24 aquifers with aquifer-county-groundwater management area splits, 14 of them show a decline in modeled available groundwater over the 50-year planning period, 9 remain the same, and 1 shows an increase (Table 1). While the decline in 6 of the 15 is less than 1 percent, the declines of modeled available groundwater in the Ogallala (50.3 percent), Dockum (9.6 percent), Yegua-Jackson (6.7 percent), Seymour (4.7 percent), Blaine (4.5 percent), and Gulf Coast (3.7 percent) are much larger. The overall decline of 27.8 percent for all the aquifers is due in large part to the large modeled available groundwater in the Ogallala Aquifer and the magnitude of its decline over the next 50 years. Without the Ogallala, the decline in modeled available groundwater over the next 50 years is just 2.2 percent.

While desired future conditions—as currently presented and discussed in explanatory reports—provide limited information on groundwater sustainability, they do offer a glimpse into which area are explicitly protecting springflows and which areas are indicating declines in groundwater availability.

TABLE 1. CHANGES IN MODELED AVAILABLE GROUNDWATER BETWEEN 2020 AND 2070.

GMA	AQUIFER	MODELED AVAILABLE GROUNDWATER (ACRE-FEET PER YEAR)		% CHANGE
		2020	2070	
MAJOR AQUIFERS				
11,12,13	Carrizo-Wilcox	1,200,317	1,190,140	-0.8
8,10	Edwards (BFZ)	24,947	24,947	0.0
7,9	Edwards-Trinity (Plateau)	478,056	478,056	0.0
14,15,16	Gulf Coast Aquifer	1,866,216	1,797,776	-3.7
1,2,7	Ogallala	6,562,751	3,263,351	-50.3
3	Pecos Valley	420,541	420,541	0.0
6	Seymour	181,592	173,103	-4.7
8,9,10	Trinity	358,223	356,844	-0.4
MINOR AQUIFERS				
6	Blaine	74,182	70,874	-4.5
4	Bone Spring-Victorio Peak	101,400	101,400	0.0
12	Brazos River Alluvium	219,032	213,536	-2.5
3,4,7	Capitan Reef Complex	34,708	34,708	0.0
1,2,3,7	Dockum	311,349	281,537	-9.6
7,8,9	Ellenburger-San Saba	36,778	36,739	-0.1
7,8,9	Hickory	53,662	53,662	0.0
4	Igneous	11,333	11,328	0.0
4	Marathon	7,327	7,327	0.0
8	Marble Falls	5,639	5,631	-0.1
11,12,13	Queen City	226,054	220,999	-2.2
3,7	Rustler	9,630	9,630	0.0
11,12,13	Sparta	26,807	33,444	24.8
4	West Texas Bolsons	58,577	58,074	-0.9
8	Woodbine	30,634	30,553	-0.3
12,13	Yegua-Jackson	34,299	31,988	-6.7
	TOTAL:	**12,334,054**	**8,906,188**	**-27.8**
	TOTAL WITHOUT THE OGALLALA:	**5,771,303**	**5,642,837**	**-2.2**

__GMA__ = groundwater management area, __BFZ__ = Balcones Fault Zone

The numbers presented are only those for official modeled available groundwater.

MAXIMUM SUSTAINABLE PRODUCTION OF TEXAS AQUIFERS

Toward the end of the first round of groundwater conservation districts establishing desired future conditions, the board members of the Texas Water Development Board requested staff to brief them on the adopted desired future conditions and the resulting managed available groundwater numbers[10] before the executive administrator delivered the numbers to the districts and planning groups (Mace and Ridgeway 2009). Board approval was not required for desired future conditions or managed available groundwater numbers but, given the agency's critical role in the process, board members wanted to understand the outcomes and have an opportunity to comment on them. At the time, any petitions challenging the reasonableness of a desired future condition would come before the board members, so observers (and potential petitioners) might catch of glimpse of the board members' view of the outcomes.

The board members also asked staff to put the managed available groundwater numbers into context with other numbers, such as groundwater availability in the regional water plans and existing groundwater production. The Board also requested a comparison of managed available groundwater to the total amount of water stored in the aquifer, a predecessor to today's total estimated recoverable storage (which is now a factor the Texas Water Code requires groundwater conservation districts to consider when establishing desired future conditions). Board staff decided to yin the yang of the total amount of water stored by also providing an estimate of the maximum sustainable production[11].

Board staff estimated maximum sustainable production in several ways: through the groundwater availability models, through non-modeled estimates where models did not exist, and through existing analyses by the groundwater conservation districts. In some cases, such as in the Edwards Aquifer, groundwater conservation districts established desired future conditions to be sustainable, often to achieve stakeholder-driven sustainability. In these cases, such as with the Barton Springs Edwards Aquifer Conservation District, board staff used those values even though they were not technically an estimate of the maximum sustainable production[12].

The maximum sustainable production is the maximum amount of groundwater that can be produced indefinitely regardless of environmental, economic, or social consequences. This assessment doesn't necessarily mean that springs, baseflow, and shallow wells go dry, but they could, depending on the hydrogeology of the system. Board staff estimated maximum sustainable production because it is theoretically devoid of policy decisions and therefore wholly dependent on science. Since the purpose was to provide information to place desired future conditions and managed available groundwater numbers into context as to whether they were sustainable, maximum sustainable production provided the benchmark for this analysis. A true analysis of groundwater sustainability would require a stakeholder/decisionmaker process of identifying unacceptable environmental, economic, or social consequences. Groundwater conservation districts have already gone through a process of identifying unacceptable environmental, economic, or social consequences when establishing their desired future conditions, sustainable or not. Regardless, a stakeholder/decisionmaker process of identifying unacceptable environmental, economic, or social consequences for groundwater sustainability would likely result in a sustainable yield less than the maximum sustainable production (Figure 6).

10 Managed available groundwater was how groundwater could be permitted to achieve the desired future condition while modeled available groundwater, which superseded managed available groundwater in 2011, is how much groundwater can be produced to achieve the desired future condition. Subtle difference, but the latter includes exempt production while the former does not.

11 I was at the agency at the time these decisions were made. Board staff refer to this as "maximum sustainable pumping," but I am referring to it in this report as "maximum sustainable production" as a more general term since flowing artesian wells do not require pumping to produce water.

12 They were sustainable yields since there was a formal identification of undesirable outcomes to avoid.

The Board's analysis used the distribution of groundwater production in the groundwater availability model and scaled up and down from there, thus placing a preference on a scenario of the current plus the projected distribution of groundwater production. On one hand, groundwater production distribution could be optimized (in general, spread around) to maximize production and define "actual" maximum sustainable production. On the other hand, if policymakers pursued sustainable management and production exceeded an identified sustainable yield, groundwater production would most likely be proportionally reduced to achieve the new production level. In aquifers where production could be increased the location of new production could be optimized. A more advanced approach to distributing production could result in greater production if larger producers agreed to distribute their production more broadly in return for larger permits. In the end, it is important to note that the Board's estimates of maximum sustainable production are just that: estimates. And the purpose of those estimates was to place managed available groundwater amounts into context of sustainable management.

For aquifers that quickly come into equilibrium in response to production, board staff ran the models to assess maximum sustainable production as described above. For the confined aquifers, where the aquifers never come into equilibrium or take many years to do so, board staff ran the models out 500 years and increased or reduced production until the change in water-levels was less than a set amount of annual water-level decline change. For those aquifers without models, board staff used water budgets to estimate maximum sustainable production.

Board staff estimated maximum sustainable production for most of the major and minor aquifers. Because some aquifers are hydrologically connected or because the desired future conditions were based on a group of aquifers or an aquifer system, maximum sustainable production was sometimes defined for a combination of aquifers. In these cases, I summarized modeled available groundwater at the highest level presented across all relevant groundwater management areas (for example, if one groundwater management area combined three aquifers into one desired future condition thus resulting in a combined modeled available groundwater estimate, I combined the aquifers similarly in the other groundwater management areas). Except for Kinney and Uvalde counties, board staff did not apparently calculate the maximum sustainable production for the Edwards-Trinity (Plateau) Aquifer in Groundwater Management Area 7[13]. In this case, I used the modeled available groundwater number as the best available estimate since much, but not all of the area, appears to approximate sustainable production.

There is also not an estimate of maximum sustainable production for the San Antonio Segment of the Edwards Aquifer under the jurisdiction of the Edwards Aquifer Authority because the Authority is a special case where the legislature effectively set the desired future condition (protect the endangered species which resulted in setting minimum springflows) and the modeled available groundwater amount (a maximum production of permitted use of 572,000 acre-feet per year with reductions during droughts). I used the maximum production of permitted use (572,000 acre-feet per year) as the estimate of maximum sustainable production[14] and as the modeled available groundwater amount for this part of the aquifer.

Because there are no groundwater conservation districts over the Hueco-Mesilla Bolsons, there are no modeled available groundwater or maximum sustainable production estimates. Bredehoeft and others (2004) found that, based on the Heywood and Yager (2003) model, fresh groundwater being removed from storage at that time in the El Paso portion of the Hueco Bolson was between 18,000 and 33,000 acre-feet per year. In other words, production of fresh groundwater in the aquifer was not sustainable (predevelopment recharge is estimated to be about 7,000 acre-feet per year; the model suggested that the Rio Grande was losing about 50,000 acre-feet per year to the Hueco Bolson due to production with much of that flow into Mexico).

13 It is unclear why this was not determined for the Edwards-Trinity (Plateau) Aquifer.

14 In other words, if there is a sustainable yield for an aquifer or part of an aquifer, I used it as the maximum sustainable production amount.

Groundwater production from the US part of the Hueco Bolson in the late 1990s (the latest information presented in Heywood and Yager [2003]) ranged between 55,000 and 65,000 acre-feet per year. Taking the averages of fresh groundwater depletion (25,500 acre-feet per year) and groundwater production (60,000 are-feet per year) and the estimate of pre-development recharge, now intercepted by production (7,000 acre-feet per year) results in an estimate of maximum sustainable groundwater production of 41,500 acre-feet per year. Because there is no modeled available groundwater number for the Hueco Bolson, I used the production amount (60,000) for this value.

I was not able to find a Board-provided estimate of maximum sustainable production for the Brazos River Alluvium in Groundwater Management Area 12.

I compared maximum sustainable production to modeled available groundwater amounts for 2020 and production for 2019, both of which came from the Texas Water Development Board (Table 2 and Figure 9). Overall, the maximum sustainable production for the major and minor aquifers of the state amounts to about 4.0 million acre-feet per year while production (current use) is about 7.1 million acre-feet per year and modeled available groundwater in 2070 (allowable maximum use) is 8.9 million acre-feet. That means that Texas is currently producing its aquifers at 1.8 times the maximum sustainable rate and makes available 2.4 times the maximum sustainable production rate.

Because the Ogallala Aquifer is such a dominant water supply—it provided 64 percent of all the groundwater produced in the state in 2019—I also looked at sustainable production with the Ogallala excluded (Table 2). Overall, the maximum sustainable production for the major and minor aquifers of the state without the Ogallala amounts to about 3.3 million acre-feet per year while current production is about 2.6 million acre-feet per year and modeled available groundwater (allowable maximum use) is 6.3 million acre-feet. That means that Texas is currently producing these aquifers (without the Ogallala) 0.8 times the maximum sustainable rate but makes available 1.9 times the maximum sustainable rate. In other words, these aquifers are probably being produced sustainably, but groundwater conservation districts plan to produce them at an unsustainable rate in the future. This shows that there is still an opportunity for sustainable management (in other words, current production is not greater than the maximum sustainable production in many aquifers; therefore, production does not have to be reduced—an activity fraught with political peril) but that advocates would need to convince groundwater conservation districts that sustainable management is a better path than planned depletion.

On an aquifer-by-aquifer basis, of the 20 aquifer groups analyzed, 13 are currently being pumped sustainably (5 of the 8 major aquifer groups; 8 of the 13 minors) while 7 are not (Table 2 and Figure 9). Unsustainable production ranges from 1.1 times the maximum sustainable production in the Edwards-Trinity (Plateau)/Pecos Valley and West Texas Bolsons aquifers to 6.5 times the maximum sustainable production in the Ogallala. Sustainable production ranges from 0.02 times the maximum sustainable production in the Marathon and Marble Falls aquifers to 0.9 times the maximum sustainable production in the Gulf Coast Aquifer.

Modeled available groundwater values for 2070 are below maximum sustainable production amounts in 5 aquifers (2 majors; 3 minors) and above in the remaining 16 (Table 2). Unsustainable modeled available groundwater numbers range from 1.1 times the maximum sustainable production in the Bone Spring-Victorio Peak Aquifer to 7.2 times the maximum sustainable production in the Dockum. Sustainable modeled available groundwater numbers in 2070 range from 0.5 times the maximum sustainable production in the Marble Falls Aquifer to 1.0 times the maximum sustainable production in the Edwards and Seymour aquifers.

TABLE 2. MAXIMUM SUSTAINABLE PRODUCTION, ADJUSTED MODELED AVAILABLE GROUNDWATER IN 2070, AND GROUNDWATER PRODUCTION IN 2019.

AQUIFER	MAXIMUM SUSTAINABLE PRODUCTION (QM) (ACRE-FEET/YEAR)	MODELED AVAILABLE GROUNDWATER IN 2070 (MAG) (ACRE-FEET/YEAR)	MAG/QM	PRODUCTION (Q) (ACRE-FEET/YEAR)	Q/QM
Carrizo-Wilcox/Queen City/Sparta/Yegua Jackson	662,542	1,476,571	2.2	441,724	0.7
Edwards (Balcones Fault Zone)	625,986	596,947	1.0	391,644	0.6
Edwards-Trinity (Plateau)/Pecos Valley Alluvium	236,731	898,597	3.8	261,540	1.1
Hueco Bolson	41,500	60,000	1.4	60,000	1.4
Gulf Coast Aquifer	791,392	1,797,776	2.3	739,496	0.9
Ogallala	694,526	3,263,351	4.7	4,488,456	6.5
Seymour	127,466	173,103	1.4	125,936	1.0
Trinity	386,246	356,844	0.9	190,870	0.5
Blaine	25,856	70,874	2.7	47,799	1.8
Bone Spring-Victorio Peak	88,176	101,400	1.1	46,498	0.5
Brazos River Alluvium[a]	47,712	213,536	4.5	109,160	2.3
Capitan Reef Complex	14,155	34,708	2.5	9,796	0.7
Dockum	39,252	281,537	7.2	69,969	1.8
Ellenburger-San Saba	54,389	36,739	0.7	8,098	0.1
Hickory	19,870	53,662	2.7	16,942	0.9
Igneous	5,666	11,328	2.0	5,699	1.0
Marathon	12,542	7,327	0.6	258	0.0
Marble Falls	10,328	5,631	0.5	210	0.0
Rustler	8,213	9,630	1.2	5,600	0.7
West Texas Bolsons	29,461	58,074	2.0	31,488	1.1
Woodbine	8,006	30,553	3.8	23,619	3.0
TOTAL:	3,984,141	9,538,188	2.4	7,074,802	1.8
TOTAL (WITHOUT OGALLALA):	3,235,489	6,274,837	1.9	2,586,346	0.8

[a] *maximum sustainable production does not include Groundwater Management Area 12.*

Adjusted modeled available groundwater means that the permitted amount of pumping in the San Antonio Segment of the Edwards (Balcones Fault Zone) Aquifer is included and that estimated groundwater production for the Hueco Bolson Aquifer is used as a proxy for modeled available groundwater.

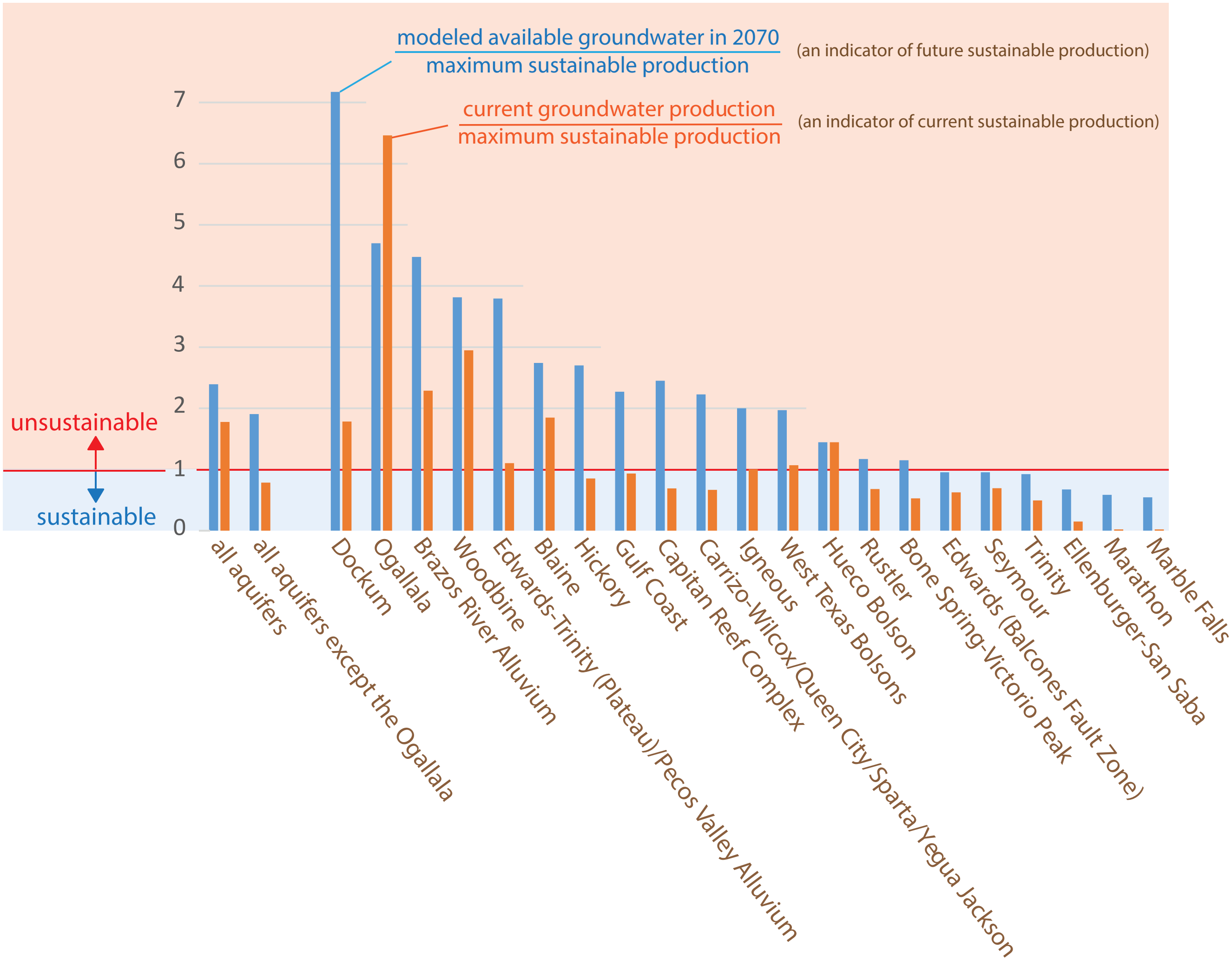

FIGURE 9. CURRENT AND FUTURE SUSTAINABILITY OF THE STATE'S AQUIFERS.

TYPOLOGIES OF GROUNDWATER SUSTAINABILITY IN TEXAS

In the previous section, I showed that, despite plans to unsustainably manage almost all of the state's aquifers, current production is lower than maximum sustainable production estimates in many aquifers, thus creating opportunities for sustainable management. How, then, is groundwater sustainability attained? The drivers and the potential for groundwater sustainability are generally controlled by hydrogeology, law, regulation, and desire. During my career, having worked with many of the aquifers of the state, been involved with the desired future conditions process, and followed developments outside of Texas, I have noticed that there are five different typologies of aquifers being produced sustainably: (1) hydrologically-forced, (2) legally-forced, (3) legislatively-forced, (4) desire-driven, and (5) de facto. There is also the situation where it is politically difficult to achieve sustainability.

HYDROLOGICALLY FORCED

In some cases, hydrogeology is the primary driver for sustainable production—an aquifer can only produce what it can produce. Ultimately, all aquifers will be hydrologically forced into sustainable production—but some arrive there more quickly (on the order of years to a few decades) while other take much longer (several decades to centuries). In the quick cases, at the risk of over-anthropomorphizing, an aquifer "manages" itself to sustainable production, but it is really the intersection of hydrogeology and economics experienced over a short time period that induces the sustainable production of the system, generally at or near the maximum level.

A good example of this type of sustainable production is the part of the Edwards-Trinity (Plateau) Aquifer that used to consistently feed Leon and Comanche springs in Pecos County (Mace and others 2020). Although part of a regional aquifer, local faulting and karstification have created an aquifer-inside-an-aquifer where water flows much more easily in the Leon-Belding area, where Leon Springs used to be, and over to Comanche Springs about eight miles to the east. This aquifer-inside-an-aquifer covers about 12,000 acres.

Groundwater production started in the late 1940s and increased rapidly until 1953 when a lawsuit by the irrigation district dependent on flows from Comanche Springs indirectly kept production at about 30,000 acre-feet per year for three years. After the groundwater producers won the lawsuit, production continued its upward trajectory, sealing the fates of numerous springs in the area. Scientists saw year-on-year water-level declines in the aquifer, a possible indicator of unsustainable production. Some users noticed that their well yields (how much a well can produce) decreased 10-fold as water-levels in the aquifer lowered during the irrigation season. This put farming operations located in less-desirable parts of the aquifer out of business, hence lowering production back to a sustainable level for decades without the intervention of a regulatory body.

A few attributes contributed to this sustainable outcome. One critical aspect was the responsiveness of the aquifer to production: some of the impacts due to unsustainable production were felt within a growing season with longer-term impacts being felt over a few years. This contrasts with other aquifers, such as the Ogallala, where decades are required to see broader impacts from unsustainable production. The responsiveness of the aquifer in the Leon-Belding Area is due to its high permeability from karstification, the relatively small size of the producing zone, and the relatively small volume of recharge compared to the production potential. The San Antonio Segment of the Edwards Aquifer is also highly permeable but is much larger with a much larger recharge rate than the highly productive zone in the Leon-Belding Area. Consequently, it took decades for groundwater production in the aquifer to threaten sustainable production although, as noted in the introduction, local effects of production could be severe.

Another example of a small and highly permeable aquifer self-managed to sustainability by its hydrogeology is the Lipan Aquifer near San Angelo. Consisting of unconsolidated eroded bits of the Edwards-Trinity Aquifer, the Lipan Aquifer has permeabilities that rival those of the Edwards Aquifer, therefore responding rapidly to groundwater production. This aquifer is generally pumped to economic exhaustion during the growing season and then refilled during the off-season.

Aquifers that achieve sustainable production through their properties generally maximize groundwater production to the detriment of other considerations such as springflows (see Comanche Springs). The baseline driver is the economics of unsustainably using the groundwater, the impacts of which are seen quickly.

COURT FORCED

In some cases, court decisions or threats and/or state and federal case law drive the sustainable development of groundwater. In Texas, sustainable management of groundwater through legal means has been a side effect of a larger issue such as land subsidence or endangered species.

One example of this in Texas was a lawsuit filed in 1973 alleging property damage due to groundwater-production induced land subsidence (Smith-Southwest Industries versus Friendswood Development Company, Ltd., 546 S.W.2d 890 [Tex. App.—Houston {1st District} 1977]; Mace 2016). The courts and the legislature worked in tandem to (1) make a groundwater producer liable for property damage caused by land subsidence due to their groundwater production and (2) create subsidence districts to regulate and manage groundwater production to prevent land subsidence. Consequently, water-levels—which had declined more than 300 feet before the creation of the subsidence districts—have since rebounded resulting in the sustainable management of their part of the Gulf Coast Aquifer.

Another example is the San Antonio Segment of the Edwards (Balcones Fault Zone) Aquifer between Kyle and the western edge of Uvalde County. In this example, a lawsuit brought by the Sierra Club in 1991 against the state concerning the protection of endangered species residing in Comal and San Marcos springs resulted in the sustainable production of the aquifer (Sierra Club versus Babbitt, No. MO-91-CA-069, slip op. at 69 [W.D. Tex. May 26, 1993]). After a threat of federal control of the aquifer, the legislature responded with the creation of the Edwards Aquifer Authority. Note that the Endangered Species Act is about protecting endangered species, not aquifers, but, because the species require springflow to maintain their native habitat, protecting springflow from drought and production is an important part of protecting the species.

It is also important to note that the Edwards (Balcones Fault Zone) Aquifer was not being produced unsustainably at the time of the lawsuit (even though San Antonio and San Pedro springs had been dried up by production, the aquifer did not show progressive declines in springflows at Comal and San Marcos springs or progressive non-seasonal declines in water levels), so what the lawsuit achieved was a certain level of sustainable production that protected flows in Comal and San Marcos springs. However, the drilling of the infamous catfish farm well—a well that could produce a quarter of San Antonio's water use—amplified the concern that the other springs were in jeopardy if not other groundwater producers as well, including San Antonio, due to unsustainable production.

LEGISLATIVELY FORCED

Legislatively-forced sustainability involves direct actions of a legislature. The examples above of Texas addressing land subsidence and endangered species issues included legislative action, but that action was inspired by court cases. What I mean here is that a legislature identifies unsustainable production of groundwater as an issue and passes laws to obligate sustainable groundwater management.

Outside of court-inspired legislation, there is no direct legislative forcing of groundwater sustainability in Texas. Through the Conservation Amendment, the Legislature first passed legislation in 1949 to allow for locally controlled groundwater conservation districts to manage their groundwater resources. That legislation and that for joint planning in groundwater management areas are broad enough to allow groundwater conservation districts to manage sustainably if they so choose (see Puig-Williams and others 2021).

Other states have legislatively forced sustainable groundwater management. For example, the California legislature passed the Sustainable Groundwater Management Act in 2014 to move toward sustainable management of their state's groundwater resources.

DESIRE DRIVEN

For this sustainability type, local managing authorities—outside of legal or legislative forcing—decide to manage groundwater sustainably. In Texas, that generally happens through the actions of groundwater conservation districts, either through the joint planning process when defining their desired future conditions or through their local management. That is not to say that the potential of hydrologic, legal, or legislative forcing does not influence management decisions (for example, concerns about endangered species reliant on springflows), but sustainable management is accomplished without those direct forcings.

In most (if not all) cases in Texas where desire-driven sustainable management has occurred, it has occurred where groundwater production was at or below the maximum sustainable amount of production, thus avoiding the formidable politics of having to reduce existing use. Where desired, sustainability is generally chosen to protect springs flows and baseflows (for example, many of the districts in the eastern half of Groundwater Management Area 7 and the Hays Trinity Groundwater Conservation District for Jacob's Well) or to protect the longevity of production from an aquifer (for example, the Middle Pecos Groundwater Conservation District with its management of the Leon-Belding area or El Paso Water Utilities in its use of the Hueco Bolson Aquifer). In almost all cases, examples of sustainable management and goals in Texas are in karstified limestones or unconsolidated sands and gravels with shorter response times to production and more dramatic impacts (that is, effects on springs and baseflows).

de facto

de facto means "being such in effect though not formally recognized" (Merriam-Webster 2021). In other words, *de facto* sustainable groundwater production means that groundwater is being produced sustainably through no purposeful or forced action. *de facto* sustainable production is where the production is not limited by hydrogeology, law, or management but by circumstance in the absence of management. It may be that the topography and/or soils above the aquifer are not conducive to irrigated agriculture or the aquifer is remote from municipal and industrial users to not be affordable to tap into (at least not yet). An example of *de facto* sustainability is the Edward-Trinity (Plateau) Aquifer in Val Verde County. The aquifer can be highly productive, but the area is not conducive to large-scale agriculture and easily meets the needs of the largest city in the area, Del Rio. Without a groundwater conservation district, the Rule of Capture applies, so there is no regulation of the resource. *de facto* sustainable groundwater production is not, of course, a guarantee that production will be sustainable in the future.

CHALLENGES TO AND OPPORTUNITIES FOR GROUNDWATER SUSTAINABILITY

In cases where current production has already exceeded the maximum sustainable production, it is often—if not always—politically difficult to claw groundwater production back to sustainable levels. For example, with production exceeding the maximum sustainable production more than ten times in the Ogallala Aquifer, it would be a monumental political task with massive economic consequences to reduce current production to a sustainable level.

While some attempt to use science to justify unsustainable groundwater management by saying that recharge is "too small," it is a fallacy that aquifers with "low" recharge rates ("too small" and "low" are in quotes because use of those words is normative) can't be managed sustainably (for example, Thomas 1955, Burt 1964 and 1967, numerous conversations I have had with policymakers and hydrogeologists over the years [most recently last week!]). The limitation on sustainable management is political, not scientific.

Reducing production has happened in Texas before such as with the creation of the subsidence districts, but that was a special case under special legal circumstance. It also helped that the existing production was mostly by municipal water providers (who have deeper pockets to pursue alternative sources; agriculture requires inexpensive water) and there were easily obtained alternative sources (namely surface water). In general, groundwater conservation districts do not want to reduce landowner's permits because that often leads to lawsuits. With most districts one or two counties in size, they do not have the budgets to fight lengthy lawsuits not to mention that recent case law suggests that they may struggle to win.

Another concern for districts is denying permits, another pathway to litigation or non-sympathetic legislative involvement. This has resulted in some districts, particularly those near growing urban centers, to grant permits that exceed their modeled available groundwater volume. For example, the Lost Pines Groundwater Conservation District has issued permits that exceed their modeled available groundwater amount by 2.5 times (Mace and Barr 2021), illustrating the challenges districts face to achieve management goals while avoiding lawsuits or violating landowners' private property rights.

Many districts, upon their creation, honor historic users of the aquifer, often a political prerequisite to district creation (if not a requirement baked into their enabling legislation). The Texas Supreme Court has stated that denying a landowner use of the aquifer beneath their land could be a regulatory taking and that "one purpose of groundwater regulation is to afford each owner of water in a common, subsurface reservoir a fair share" (Hecht 2012). However, historic use can far exceed a relative "fair share" if all users exercised their rights to access the groundwater beneath their property at the same level as historic users. And reducing historic users risks lawsuits. This makes it difficult for groundwater conservation districts to manage sustainably let alone achieve an unsustainable desired future condition.

One way (Example A) districts have attempted to tackle this issue is through granting permits with different conditions for new permittees. For example, the Barton Springs-Edwards Aquifer Conservation District has historic use permits but it also has interruptible permits for new users that are available for use when water levels are high but suspended during droughts to protect spring flows. The Middle Pecos Groundwater Conservation District has three tiers of permits: historic and existing use permits, production permits, and export permits. When production exceeds management goals, export permits are proportionally cut first followed by production permits and then, finally, historic and existing use permits.

Another way (Example B) at least one district is addressing the fair share issue is the Post Oak Savannah Groundwater Conservation District where they grant permits but with clawback clauses to reduce those permits when other landowners express their right to produce groundwater from their property. If every landowner in the district uses their groundwater rights, the end result is a correlative right where the modeled available groundwater number is proportionally divided out by acreage.

Yet another way (Example C) at least one district—the Guadalupe County Groundwater Conservation District—is assigning a correlative right as modified by sand thickness beneath the property and giving non-compliant users 30 years to come into compliance (that is, accruing more rights or reducing production; Blumberg and Collins 2016). The presumable thought here (although not expressed in the paper) is that investment backed expectations that would inform a takings case would be invalid after 30 years.

None of these approaches have been tested in court, but they are all options for groundwater conservation districts to achieve sustainable production although the last two options (examples B and C) are not used by the districts yet for sustainable management. Those last two options could be used to manage groundwater sustainably, but one challenge is that sustainable production divided by surface acreage over an aquifer is generally a small amount of water per acre.

Of the three examples, the last one (Example C) strikes me as the most likely to be legally defensible; however, I am not an attorney. Perhaps a combination of the last example with the second example is the best approach: everyone gets an explicit right but use of unused water is permitted with a temporary permit. However, this wouldn't allow a market to develop for third parties to buy down existing permits to bring back or enhance springflow (for example, see Mace and others 2020). On the other hand, permit reductions to maintain springflow during droughts could be used in weather-influenced aquifer systems.

RECOMMENDATIONS

Based on this study, I have a few recommendations concerning science and information. One is on including decadal water budgets in explanatory reports for desired future conditions (or including them with the delivery of modeled available groundwater numbers), one is on estimating maximum sustainable production, and one is on including maximum sustainable production as a factor when considering desired future conditions.

INCLUDE DECADAL WATER BUDGETS IN EXPLANATORY REPORTS

Groundwater conservation districts, the Texas Water Development Board, and/or the legislature should consider requesting or requiring explanatory reports to include, where possible (that is, for aquifers with models), water budgets at or near the beginning of the planning period, and for each planning decade through the planning period.

Water budgets are outputs from the groundwater availability models that show where water is coming from and where it is going, including to springs and surface water and out of aquifer storage. Including water budgets from the beginning through the end of the planning period would allow stakeholders to quantify the impact desired future conditions have on surface water-groundwater interaction as well as whether the aquifer is in equilibrium by the end of the planning period. Assessing equilibrium allows stakeholders (and other interested parties) to assess how sustainable the desired future conditions might be. Several groundwater management areas helpfully included water budgets from the beginning and end of the planning period, but decadal budgets would be more helpful in tracking trends over time.

An alternative would be for Texas Water Development Board staff to include decadal water budgets as part of their analysis when they deliver modeled available groundwater estimates to groundwater conservation districts and regional water planning groups.

ISSUES TO CONSIDER WHEN ESTIMATING MAXIMUM SUSTAINABLE GROUNDWATER PRODUCTION

In this study, I have used, for the most part, estimates of maximum sustainable production made by Texas Water Development Board staff for the benefit of Board member review for the first round of the joint planning process to establish desired future conditions for the state's aquifers. The intent of the numbers was to provide a ballpark estimate of sustainable production to place resulting managed (now modeled) available groundwater estimates into perspective. Since that time, the models have changed and (hopefully) improved such that the numbers presented here would probably be different (but hopefully not substantially different). Furthermore, the purpose of the original work was to provide aquifer-wide estimates for groundwater management areas, not to provide actionable information at the scale of groundwater conservation districts.

If directed to provide estimates of maximum sustainable production, the Texas Water Development Board should consider holding stakeholder meetings among groundwater policymakers and scientists to discuss how to best make these estimates and then make the estimates in a consistent manner across the state. Despite maximum sustainable production being the most science-based estimate of sustainable production, scientists still have to make a number of assumptions concerning time scales, production distribution, and other factors to develop estimates. Clarity and transparency here would be preferred for an estimate with greater expectations than briefing board members.

As part of this study, I, along with LRE Water LLC, investigated using an optimization routine to generate an estimate of maximum sustainable production independent of current or an assumed production distribution. However, the optimization routine appeared to place most of the production in the recharge zone rather than in the artesian zone where large hydraulic head differences between the top of the water-level (potentiometric) surface and the top of the aquifer greatly increase well yields and where, historically, large production is centered in the state's artesian, dipping aquifers. While it is probably physically possible to intercept much of the recharge in the recharge zone, it is also probably not economically possible—and therefore not practicable—to drill and connect potentially thousands of wells for larger users. Accordingly, caution should be employed with using optimization routines.

CONSIDER MAXIMUM SUSTAINABLE PRODUCTION WHEN ESTABLISHING DESIRED FUTURE CONDITIONS

In 2011, as part of Senate Bill 660, the Legislature required the Texas Water Development Board to provide estimates of total estimated recoverable storage and groundwater conservation districts to consider total estimated recoverable storage when establishing their desired future conditions as part of hydrologic conditions. The Legislature should consider doing the same for maximum sustainable production.

The Texas Water Development Board defines total estimated recoverable storage in its rules as "[t]he estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25% and 75% of the porosity-adjusted aquifer volume." While total estimated recoverable storage is relevant in an unconfined aquifer that is being systematically mined of groundwater through planned depletion—such as the Ogallala Aquifer—it makes less sense in confined aquifers and is irrelevant in sustainably-managed aquifers.

For an aquifer managed through planned depletion, the amount of water in total storage is key to quantifying modeled available groundwater. For example, many desired future conditions in the Ogallala Aquifer are defined as a certain amount of water in storage left after a certain amount of time (such as 50 percent of storage left in 50 years). In a confined (artesian) aquifer, groundwater is rarely removed from drainable storage, in part because the value of many of the state's confined aquifers is not the storage but rather the hydraulic head above the top of the aquifer which allows greater drawdowns in wells which allows larger well yields (it is not an accident that the Vista Ridge wellfield that provide water to San Antonio is in the confined part of the Carrizo-Wilcox rather than the unconfined (water table) part).

Without those larger well yields in the deep confined zone, groundwater users would have to drill additional wells to achieve the same production amount. Thompson and others (2020) investigated this issue for agricultural wells in the confined portion of the Carrizo-Wilcox Aquifer and found that economic constraints would affect users after only 1 percent of the water in storage was removed.

Bills filed in 2017 and 2021 in the legislature attempted to introduce "modeled sustainable groundwater pumping" or "modeled sustained groundwater pumping" as part of groundwater conservation districts' consideration when establishing desired future conditions (House Bill 3166 during the 2017 Regular Session and House Bill 2851 during the 2021 Regular Session but with a carve-out for the Ogallala Aquifer). The 2017 bill was based on a Texas Water Conservation Association consensus recommendation. Both bills passed the House but failed to receive a committee hearing in the Senate.

Similar to the Board staff response to the Board's request for drainable water from an aquifer, an estimate of modeled maximum sustainable production (which would be my preferred term) is another piece of information to place desired future conditions into context while also providing stakeholders and the general public with clearer information on how their groundwater resources are being managed. Therefore, I recommend that the legislature consider adding modeled maximum sustainable production to the mix of other hydrologic factors considered when establishing desired future conditions.

CONCLUSIONS

The earliest thoughts about how to manage groundwater were to manage it sustainably. Engineers imported the concept of safe yield from surface-water management to groundwater management and defined it as the amount of groundwater that could be produced in perpetuity without producing unacceptable consequences. Over time, safe yield included considerations of water quality, economics, consumptive use, effects on rights in adjacent groundwater basins, socioeconomics and social welfare, the environment, and future generations. After many years of concern over the ambiguity of safe yield and sustainable management, most scientists and engineers now recognize that safe (and sustainable) yield need to include policy considerations.

Sustainable development gained traction after several books and reports were published in the 1980s and safe yield was rebranded as sustainable yield. The U.S. Geological Survey defines groundwater sustainability as the "development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences." Sustainable yield is the amount of groundwater that can be produced to achieve groundwater sustainability.

The Texas Water Development Board, through its water planning efforts, sought to encourage the state to manage its aquifers sustainably where possible. A primary goal of the 1968 State Water Plan—infamous for proposing to import water from the Mississippi River to various parts of Texas, including the High Plains—was to bring the state's aquifers into sustainable management. As late as 2002, the Texas Water Development Board was encouraging regional discussions on groundwater sustainability, but—except for 2002—the agency has been quiet on the topic since the advent of regional water planning in 1997.

Of 521 aquifer-county-groundwater management area splits in the state, 8 (1.5 percent) of desired future conditions were based on springflows, 17 (3.3 percent) on zero or increasing water levels, 34 (6.6 percent) on remaining saturation, and 462 on water-level declines (88.7 percent). Since remaining saturation is a water-level based desired future conditions based on a saturated thickness rather than water-level declines, 95.3 percent of desired future conditions are based on water-level declines.

Of the aquifer-county-groundwater management area splits, 74 (14.2 percent) do not provide consistent supplies (greater than 95 percent of 2020 levels) over the next 50 years while the remainder (447, 86.8 percent) do. While consistent supplies over the next 50 years does not necessarily mean that the supplies are indefinitely sustainable, it does suggest that most groundwater users are not yet receiving hydrologic feedback of unsustainable management.

Overall, maximum sustainable production for the major and minor aquifers of the state amounts to about 4.0 million acre-feet per year while groundwater production (current use) is about 7.1 million acre-feet per year and modeled available groundwater in 2070 (allowable future maximum use) is 8.9 million acre-feet. That means that Texas is currently producing its aquifers 1.8 times the maximum sustainable rate and makes available 2.4 times the sustainable rate.

Because the Ogallala Aquifer is such a dominant water supply—it provided 64 percent of all the groundwater produced in the state in 2019—I also looked at sustainability of the state's aquifers with the Ogallala excluded. The maximum sustainable production for the major and minor aquifers of the state without the Ogallala amounts to about 3.3 million acre-feet per year while groundwater production is about 2.6 million acre-feet per year and modeled available groundwater is 6.3 million acre-feet. That means that Texas is currently producing these aquifers (without the Ogallala) 0.8 times the sustainable rate but makes available 1.9 times the sustainable rate.

On an aquifer-by-aquifer basis, of the 21 aquifer groups analyzed, 13 are currently being pumped sustainably (5 of the 8 major aquifer groups; 8 of the 13 minors) while 7 are not. Current unsustainable groundwater production ranges from 1.1 times the maximum sustainable production in the Igneous Aquifer to 6.5 times the maximum sustainable production in the Ogallala. Current sustainable groundwater production ranges from 0.02 times the maximum sustainable production in the Marathon and Marble Falls aquifers to 1.0 times the maximum sustainable production in the Seymour Igneous Aquifer. This analysis identifies opportunities for sustainable management where groundwater production has not yet exceeded sustainable production.

I identified five types of sustainable management in Texas: (1) hydrologically-forced, (2) court-forced, (3) legislatively-forced, (4) desire-driven, and (5) de facto. There is also the situation where it is politically difficult to achieve sustainability, generally when groundwater production exceeds the sustainable yield, thus requiring controversial groundwater production reductions. Hydrologically-forced sustainable production seems to only occur when aquifers are small and highly productive. In Texas, part of the Edwards and Gulf Coast aquifers are sustainably managed due to court and legislative forcing, although in both cases the legislative forcing was in response to court-forcing. Through the establishment of desired future conditions, a dozen or so groundwater conservation districts have explicitly expressed a desire to manage sustainably. And there are cases of parts of aquifers being produced sustainably without any management action—at least for now (for example, the Edwards-Trinity [Plateau] Aquifer in Val Verde County). There are also several aquifers not managed sustainably probably because groundwater production or permits have far exceeded maximum sustainable production, such as the Ogallala Aquifer.

I recommend including decadal water budgets in explanatory reports for desired future conditions (or including them with the delivery of modeled available groundwater numbers), careful consideration of estimating maximum sustainable production, and including maximum sustainable production as a factor when considering desired future conditions.

EPILOGUE

George Washington Brackenridge's homestead, artfully attached to that of James R. Sweet, still graces the hillside of Fernridge. According to his wishes, the University of the Incarnate Word sprang up around his house, now occupying most of his original estate, with San Antonio enveloping his formerly rural home. Just a short distance downstream, the land donated by the water company to the city has become San Antonio's central park, named Brackenridge Park, where denizens play baseball and stroll along the snaking riverbed. After the springs went dry, the city drilled and directed flows from wells into the riverbed to bring the river back to life, albeit artificially. The wells went silent with growing concerns about San Marcos and Comal springs, replaced by the quiet welling of treated wastewater on one of the river's bends. Every once in a while, when aquifer levels rise due to wetter-than-normal weather, Blue Hole—within sight of Fernridge—magically gurgles to life, a bittersweet reminder of what was and what could have been.

BLUE HOLE AT THE HEAD OF THE SAN ANTONIO RIVER ON OCTOBER 18, 2018. ©ROBERT MACE

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CHANGES TO THE REPORT SINCE PUBLICATION

- **December 9, 2021:** Changed “3,289,615” to “3,235,489”; “8,906,188” to “9,538,188”; and “Modeled Groundwater in 2070” to “Modeled Available Groundwater in 2070” in Table 2.

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