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# Exploring Groundwater Recoverability in Texas: Maximum Economically Recoverable Storage

Justin C. Thompson[1*], Charles W. Kreitler[2], and Michael H. Young[3]

**Abstract:** The 2017 Texas state water plan projects total supply deficits of 4.8 and 8.9 million acre-feet under drought-of-record conditions by the year 2020 and 2070, respectively, driven by a growing population concurrent with declining available water supplies. Reductions in groundwater supply account for 95% of anticipated declines in total water supply. Meanwhile, restrictive groundwater management plans may be creating a regulation-induced shortage of groundwater in Texas, given the significant groundwater storage volumes that are unutilized under many management plans. However, these estimates do not account for many of the physical and none of the economic constraints to groundwater recoverability. We report an analysis of groundwater extraction feasibility and simulate maximum economically recoverable storage for conditions representative of the central section of the Carrizo-Wilcox Aquifer under economic constraints associated with agricultural uses. Two key limitations are applied to simulate recoverability: (1) the value of water pumped relative to pumping costs and (2) the capacity of the aquifer and well to meet demand. Our results indicate that these constraints may limit certain uses to as little as 1% of current groundwater availability estimates. We suggest that Texas groundwater managers, stakeholders, and policymakers assessing groundwater availability need an alternate approach for estimating recoverability.

**Keywords:** groundwater availability, groundwater recoverability, pumping costs, total estimated recoverable storage, TERS, maximum economically recoverable storage, MERS

[1] Graduate Research Assistant - Bureau of Economic Geology, PhD Candidate - Jackson School of Geosciences, The University of Texas at Austin

[2] Retired - Energy and Earth Resources Graduate Program, Jackson School of Geosciences, The University of Texas at Austin

[3] Senior Research Scientist - Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

* Corresponding author: justin.thompson@utexas.edu

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**Terms used in paper**

| Acronym / Initialism | Descriptive Name |
|---|---|
| DFC | Desired Future Conditions |
| GCD | Groundwater Conservation District |
| GMA | Groundwater Management Area |
| MAG | Modeled Available Groundwater |
| MERS | Maximum Economically Recoverable Storage |
| TERS | Total Estimated Recoverable Storage |
| TWC | Texas Water Code |
| TWDB | Texas Water Development Board |

# INTRODUCTION

Is Texas running out of groundwater, blessed with abundance, or somewhere in the middle? This question, historically shrouded in scientific uncertainty and political controversy, represents a complex nexus of hydrogeology, economics, and policy with many relevant and potentially conflicting considerations. Hydrogeologic conditions and management objectives vary significantly across the state, and as a consequence there is no universal yield solution.

Nonetheless, one key element common to all human groundwater demand is *recoverability*, defined as the relative ease or difficulty of extraction. Recoverability is constrained by aquifer characteristics, well design, and economics. While recoverability data is crucial to groundwater planning and management, particularly with respect to availability assessments, Texas' best estimates of recoverable groundwater volumes reflect only the volume in storage and take no account of well design or economic constraints. This study therefore addresses the question: What are the economic and physical limits to recoverability? By establishing these limits, we can better estimate potentially available groundwater for given uses and infrastructure.

## Goals and objectives

We seek here to (a) develop improved methods for quantifying groundwater recoverability by integrating aquifer and well dynamics with economics and (b) contextualize our results within existing policy frameworks and discussions. The key purpose of this study is to facilitate the exploration of planned and potential changes in groundwater recoverability by developing methods for analytically calculating the physical and economic constraints and limitations to pumping associated with changes in depth-to-water over time.

This study does not seek to establish a yield prescription for groundwater management, but it does estimate a reference limit we term maximum economically recoverable storage (MERS). While not designed to be economically efficient, MERS is intended to establish clear and rational limits to groundwater recoverability for the purpose of evaluating groundwater availability under variable uses and infrastructure. Moreover, because MERS is, in part, a function of depth-to-water, its limits are directly comparable to existing or proposed depth-to-water based groundwater management goals.

For any pumping groundwater well, the maximum volume of recoverable water is a subset of total aquifer storage, which may be numerically simulated using simplified hydrogeologic and economic constraints. The maximum yield a well can physically produce is limited by the relationship between the aquifer, well, and pumping rate. We anticipate that aquifer and pumping characteristics introduce capacity constraints where demand is constant. We further expect some percentage of saturated thickness to be unavailable for production (a groundwater "dead pool") at any given pumping rate, and a relationship to exist between the pumping rate and the saturated thickness available for production. In terms of economics, increasing depth-to-water increases pumping costs where other factors are held constant. We expect these changes can be significant to agricultural and other uses. Therefore, we address two hypotheses in this study:

- H1: In shallow and unconfined settings, physical constraints related to the capacity of the aquifer and well to meet demand, not economic constraints, will limit groundwater recoverability.
- H2: In deep and confined settings, economic constraints, not physical constraints, will limit groundwater recoverability for some uses, restricting them to producing from confined, pressurized storage.

## Groundwater management in Texas

Groundwater in Texas is managed at the local level by approximately 100 groundwater conservation districts (GCD(s)). However, in 2005, the 79th Texas Legislature enacted House Bill 1763, which amended the Texas Water Code (TWC) to regionalize groundwater availability decision making under groundwater management areas (GMA(s)).

House Bill 1763 further instructs GCDs within a GMA on how they should cooperate with each other and the Texas Water Development Board (TWDB) to determine groundwater volumes available for permitting. Chapter 36 §108 of the TWC states that "[GCDs] shall propose for adoption desired future conditions for the relevant aquifers within the [GMA]." Desired future conditions (DFC(s)) are further defined by Title 31, Part 10, §356.10(6) of the Texas Administrative Code to be "the desired, quantified condition of groundwater resources (such as water levels, spring flows, or volumes) within a [GMA] at one or more specified future times as defined by participating [GCDs] within a [GMA] as part of the joint planning process." Our evaluation of currently adopted DFCs shows that, while spring flow and saturated thickness metrics are common, groundwater in Texas is most commonly managed as a function of depth-to-water over time (i.e., x feet of drawdown over y years).

Once DFCs are adopted, Chapter 36 §108(b) of the TWC requires the TWDB to calculate values for the volume of modeled available groundwater (MAG) that comply with the adopted DFC given the hydrologic properties of the aquifer in question. Finally, Chapter 16 §053(e)(3) of the TWC requires that GCDs honor MAG volumes in their groundwater management plans. In this way, the DFCs adopted by GCDs create a regulatory target or cap for groundwater extraction in the form of the derived MAG volumes provided by the TWDB (Mace et al. 2008).

## 2017 State Water Plan: Water for Texas

The latest iteration of the Texas state water plan, 2017's "Water for Texas," predicts a deficit of total water supplies under drought-of-record conditions in the amount of 4.8 and 8.9 million acre-feet by the year 2020 and 2070, respectively, resulting from an anticipated 70% increase in the population concurrent with an 11% projected decline in total water supplies (TWDB 2016). The plan further estimates that, if left unresolved into 2070, these deficits would result in approximately $151 billion of annual economic losses and roughly a third of the projected population having less than half the projected municipal water demand (TWDB 2016). The plan considers drought-of-record conditions. Under unprecedented drought driven by climate change (Nielsen-Gammon et al. 2020), supply deficits and economic losses may be even higher. Even without this consideration, the plan findings establish a central theme: demonstrating the necessity of responsive water development financing while sounding a call to action for policymakers.

But how were these conclusions reached? What key assumptions were made?

First, an important distinction should be noted between water resource *availability* and water resource *supply* as those terms are defined by the plan. Section 6.1 of the plan clarifies:

> "Water availability refers to the maximum volume of raw water that could be withdrawn annually from each source (such as a reservoir or aquifer) during a repeat of the drought of record. **Availability does not account for whether the supply is connected to or legally authorized for use by a specific water user group**. Water availability is analyzed from the perspective of the source and answers the question: **How much water from this source could be delivered to water users as either an existing water supply or, in the future, as part of a water management strategy?** […] [Then], planning groups evaluate the subset of the water availability volume that is already connected to water user groups. **This subset is defined as existing supply**." (TWDB 2016, p. 61 [**emphasis** added])

Recognizing this distinction, the plan reveals a projected 20% decline in available groundwater (from 12.3 million to 9.8 million acre-feet) and a 24% decline in groundwater supply (from 7.2 million to 5.5 million acre-feet) over the planning period (2020 through 2070) "… due primarily to reduced availability from the Ogallala Aquifer, based on its managed depletion, and the Gulf Coast Aquifer, based on regulatory limits aimed at reducing long-term groundwater pumping to limit land surface subsidence" (TWDB 2016, p. 70).

Indeed, reductions in groundwater supply considered by the plan account for 95% of the anticipated 11% decline in total water supply (TWDB 2016). If the impacts of population growth are assumed valid and held constant (i.e., only the decline in total supply is considered), the total water resource

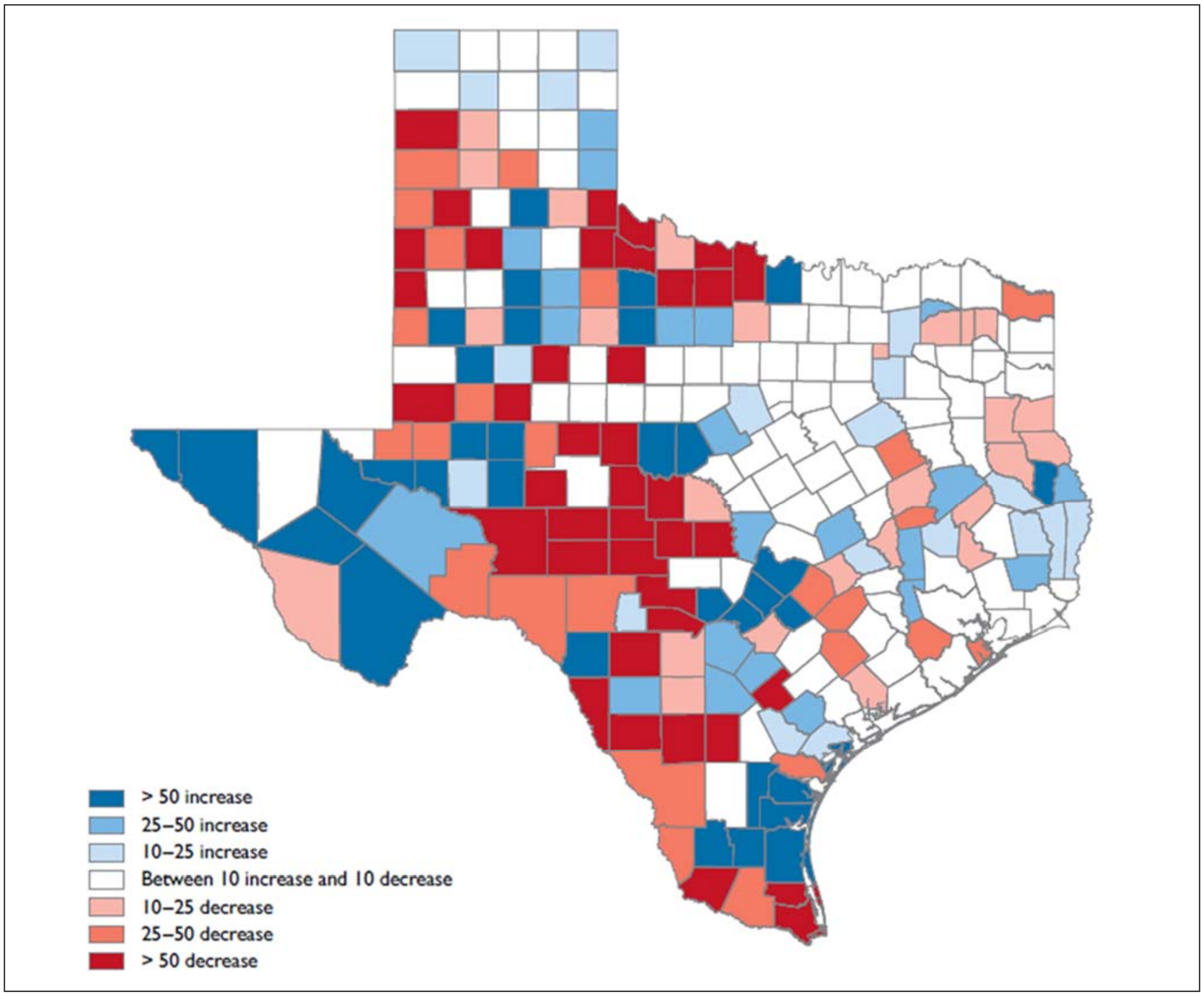


**Figure 1.** Change in groundwater availability by county from the state water plan in 2012 to 2017 (TWDB 2016).

deficits portended by the plan are driven almost entirely by anticipated declines in groundwater availability.

Second, we note that this water plan determines, for the first time, groundwater availability volumes as the sum of the MAG volumes provided by the TWDB in accordance with the DFCs adopted by GCDs (TWDB 2016). This change in accounting methodology from the previous state water plan (2012) to the current plan (2017) has produced significant changes in regional groundwater availability estimates, in many jurisdictions increasing or decreasing volume by 50% or more (TWDB 2016) (Figure 1).

However, MAG volumes derived from DFCs do not strictly adhere to the definition of availability given by the plan. Specifically, MAG volumes from DFCs are the total volume of groundwater that is "legally authorized for use" (TWDB 2016, p. 61).

## TOTAL ESTIMATED RECOVERABLE STORAGE

Prior to adopting a DFC, Chapter 36 §108(d)(3) of the TWC requires GCDs to consider, among nine potentially conflicting issues, the total estimated recoverable storage (TERS) volumes provided by the TWDB for each area aquifer. TERS is defined by Rule §356.10.23 of the Texas Administrative Code as "the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25% and 75% of the porosity-adjusted aquifer volume."

Given the statutory definition of TERS and the statutory definition of total storage provided in Chapter 36 §001(24) of the TWC as "the total calculated volume of groundwater that an aquifer is capable of producing," the TWDB has developed a working definition of TERS as a two-step calculation.

In the first step, the hydrologic properties and geometries of the aquifer (such as transmissivity, water levels, and storage coefficients) are established according to the relevant TWDB groundwater availability model (where available). Those values are then used to derive total storage (Bradley 2016). The calculation differs among confined and unconfined aquifers and is provided by the TWDB (Bradley 2016) as:

$$\textit{total unconfined storage} = \textit{area} \times (\textit{water level} - \textit{bottom}) \times Sy \tag{1}$$

$$\textit{total confined storage} = (\textit{area} \times (\textit{water level} - \textit{top}) \times St) + (\textit{area} \times (\textit{top} - \textit{bottom}) \times Sy) \tag{2}$$

where *total unconfined storage* is the storage volume of water released due to water draining from an unconfined setting (i.e., dewatering); *area* is the land surface area of the aquifer; *water level* is the depth of potentiometric head; *bottom* is the depth of the bottom of the aquifer; *Sy* is the specific yield storage coefficient; *total confined storage* is the storage volume of water released due to the elastic properties of the aquifer, plus the volume of water released due to dewatering; *top* is the depth of the top of the aquifer; and *St* is the confined storativity storage coefficient.

In the second step, the calculated total storage is multiplied by 25% and 75% to "account for recovery scenarios that range between 25% and 75% of the porosity-adjusted aquifer volume" (Wade and Shi 2014b., p. 4) and thereby arrive at final TERS volumes.

We are unaware of any rationale provided in the public record for why 25% and 75% were chosen to represent the limits of potentially recoverable groundwater in TERS. We therefore assume these bounds are arbitrary reference points and that none of the potential physical and economic constraints and limitations associated with the recoverability of groundwater extraction are captured by TERS.

The total storage component of TERS is the state's closest approximation of groundwater availability, or "the maximum volume of raw water that could be withdrawn" (TWDB 2016, p. 61), as it incorporates depth-to-water and spatially variable aquifer characteristics. Thus, we compile total storage volumes (Tables 1 and 2), published by the TWDB as of April 2018 for the nine major aquifers of the state within each GMA (Figure 2). Note that total storage data are not available for the Hueco-Mesilla Bolsons Aquifer and GMA 5 because no GCDs administer this area. The Carrizo-Wilcox Aquifer and the Gulf Coast Aquifer reported the largest total storage volumes at 5.227 and 4.163 billion acre-feet (respectively) and together constitute 81% of the sum total volume of water in storage for all nine major aquifers, calculated at 11.575 billion acre-feet. By contrast, the Seymour, Edwards (Balcones Fault Zone), and Edwards-Trinity (Plateau) Aquifers reported the smallest total storage volumes at 5.128, 24.951, and 45.491 million acre-feet, respectively. The total storage volume for the Ogallala Aquifer is reported to be 380.544 million acre-feet, representing only 3% of the total volume of water in storage for all nine major aquifers.

Even at the 25% TERS metric, the TERS volume reported for the Carrizo-Wilcox Aquifer alone (1.306 billion acre-feet) is far more than sufficient to satisfy the 2070 deficits projected by the 2017 state water plan (8.9 million acre-feet by 2070). The difference between these volumes could mean that, while the state is projecting water supply deficits, it is ignoring significant reserves of recoverable groundwater.

We are not the first to acknowledge TERS volumes in light of potential future deficits. A 2016 report by Brady et al. (2016), addressed to the Texas Comptroller of Public Accounts, criticized the current groundwater management approach as reverse-engineered and politicized, resulting in a "regulation-induced [groundwater] shortage" (Brady et al. 2016, p. 2). They recommended that the approach be revised in favor of more objective, economic constraints and presumably greater volumes of groundwater available for production. The report "assumes that prudent aquifer management would allow the TERS in each GCD to be drawn down by 5% over a 50-year period—or .1% of TERS annually" (Brady et al. 2016, p. 9) and proposes that such a metric replace the MAG from DFC volume regulations mandated by the current form of the TWC. TERS estimates report significant volumes of groundwater in storage that could potentially be available to meet the deficits projected by the state water plan. However, this critique disregards the apparently arbitrary recoverability constraints of TERS (25% and 75% of total storage).

## SIMULATING RECOVERABILITY

To test H1 and H2 and quantitatively evaluate the physical and economic impacts to groundwater recoverability associated with changes in depth-to-water, we develop a simplified, single-cell pumping simulation using numerical processors to generate MERS. This is done through a linear convex optimization constrained by hydrogeology, pumping dynamics from given well specifications and pumping demand, and the given agricultural value of the water pumped over derived pumping costs. The MERS model is applied to a variety of user inputs and hydrogeologic conditions but was conceptualized for a single well pumping for agricultural uses.

**Table 1.** Total storage and total estimated recoverable storage (25% and 75%) of the nine major aquifers of Texas in GMA 1-8. Source: Boghici et al. 2014, Jones et al. 2013a., Jones et al. 2013b., Kohlrenken et al. 2013a., Kohlrenken et al. 2013b., Kohlrenken 2015, Shi et al. 2014.

| TWDB major aquifers | | Aquifer (million acre-feet) | Groundwater management area (million acre-feet) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1 (Kohlrenken 2015) | 2 (Kohlrenken et al. 2013a.) | 3 (Jones et al. 2013a.) | 4 (Boghici et al. 2014) | 6 (Kohlrenken et al. 2013b.) | 7 (Jones et al. 2013b.) | 8 (Shi et al. 2014) |
| Carrizo - Wilcox | Total storage | 5,227.077 | | | | | | | |
| | 25% | 1,306.769 | | | | | | | |
| | 75% | 3,920.308 | | | | | | | |
| Gulf Coast | Total storage | 4,163.507 | | | | | | | |
| | 25% | 1,040.877 | | | | | | | |
| | 75% | 3,122.630 | | | | | | | |
| Trinity | Total storage | 1,405.166 | | | | | 0.471 | 0.523 | 1,359.625 |
| | 25% | 351.292 | | | | | 0.118 | 0.131 | 339.906 |
| | 75% | 1,053.875 | | | | | 0.353 | 0.392 | 1,019.719 |
| Ogallala | Total storage | 380.545 | 232.700 | 139.210 | 0.010 | | 2.285 | 6.340 | |
| | 25% | 95.136 | 58.175 | 34.803 | 0.002 | | 0.571 | 1.585 | |
| | 75% | 285.408 | 174.525 | 104.408 | 0.007 | | 1.714 | 4.755 | |
| Pecos Valley | Total storage | 323.860 | | 2.000 | 309.000 | 1.490 | | 11.370 | |
| | 25% | 80.965 | | 0.500 | 77.250 | 0.373 | | 2.843 | |
| | 75% | 242.895 | | 1.500 | 231.750 | 1.118 | | 8.528 | |
| Edwards - Trinity (Plateau) | Total storage | 45.491 | | 0.142 | 0.390 | 3.780 | | 38.821 | |
| | 25% | 11.373 | | 0.036 | 0.098 | 0.945 | | 9.705 | |
| | 75% | 34.118 | | 0.107 | 0.293 | 2.835 | | 29.116 | |
| Edwards (BFZ) | Total storage | 24.952 | | | | | | | 0.095 |
| | 25% | 6.238 | | | | | | | 0.024 |
| | 75% | 18.714 | | | | | | | 0.071 |
| Seymour | Total storage | 5.128 | 0.001 | 0.057 | | | 5.070 | 0.001 | |
| | 25% | 1.282 | 0.000 | 0.014 | | | 1.268 | 0.000 | |
| | 75% | 3.846 | 0.001 | 0.043 | | | 3.803 | 0.000 | |
| | Gross storage | 11,575.726 | 232.701 | 141.409 | 309.400 | 5.270 | 7.826 | 57.055 | 1,359.625 |
| | 25% Gross storage | 2,893.932 | 58.175 | 35.352 | 77.350 | 1.318 | 1.957 | 14.264 | 339.906 |
| | 75% Gross storage | 8,681.795 | 174.526 | 106.057 | 232.050 | 3.953 | 5.870 | 42.791 | 1,019.719 |

**Table 2.** Total storage and total estimated recoverable storage (25% and 75%) of the nine major aquifers of Texas in GMA 9-16. Source: Jigmund and Wade 2013, Jones and Bradley 2013, Jones et al. 2013c., Wade and Anaya 2014, Wade and Bradley 2013, Wade et al. 2014, Wade and Shi 2014a., Wade and Shi 2014b.

| TWDB major aquifers | | Aquifer (million acre-feet) | Groundwater management area (million acre-feet) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 9 (Jones and Bradley 2013) | 10 (Jones et al. 2013c.) | 11 (Wade and Shi 2014a.) | 12 (Wade and Shi 2014b.) | 13 (Wade and Bradley 2013) | 14 (Wade et al. 2014) | 15 (Wade and Anaya 2014) | 16 (Jigmund and Wade 2013) |
| Carrizo - Wilcox | Total storage | 5,227.077 | | | 2,061.633 | 1,019.320 | 1,951.720 | 19.804 | 69.900 | 104.700 |
| | 25% | 1,306.769 | | | 515.408 | 254.830 | 487.930 | 4.951 | 17.475 | 26.175 |
| | 75% | 3,920.308 | | | 1,546.225 | 764.490 | 1,463.790 | 14.853 | 52.425 | 78.525 |
| Gulf Coast | Total storage | 4,163.507 | | | 1.447 | 0.450 | 2.460 | 2,776.000 | 368.800 | 1,014.350 |
| | 25% | 1,040.877 | | | 0.362 | 0.113 | 0.615 | 694.000 | 92.200 | 253.588 |
| | 75% | 3,122.630 | | | 1.085 | 0.338 | 1.845 | 2,082.000 | 276.600 | 760.763 |
| Trinity | Total storage | 1,405.166 | 5.280 | 23.057 | 0.500 | 11.100 | 4.705 | | | |
| | 25% | 351.292 | 1.320 | 5.764 | 0.125 | 2.775 | 1.176 | | | |
| | 75% | 1,053.875 | 3.960 | 17.293 | 0.375 | 8.325 | 3.529 | | | |
| Ogallala | Total storage | 380.545 | | | | | | | | |
| | 25% | 95.136 | | | | | | | | |
| | 75% | 285.408 | | | | | | | | |
| Pecos Valley | Total storage | 323.860 | | | | | | | | |
| | 25% | 80.965 | | | | | | | | |
| | 75% | 242.895 | | | | | | | | |
| Edwards - Trinity (Plateau) | Total storage | 45.491 | 2.358 | | | | | | | |
| | 25% | 11.373 | 0.590 | | | | | | | |
| | 75% | 34.118 | 1.769 | | | | | | | |
| Edwards (BFZ) | Total storage | 24.952 | 0.261 | 22.878 | | | 1.718 | | | |
| | 25% | 6.238 | 0.065 | 5.719 | | | 0.430 | | | |
| | 75% | 18.714 | 0.196 | 17.158 | | | 1.289 | | | |
| Seymour | Total storage | 5.128 | | | | | | | | |
| | 25% | 1.282 | | | | | | | | |
| | 75% | 3.846 | | | | | | | | |
| | Gross storage | 11,575.726 | 7.899 | 45.935 | 2,063.580 | 1,030.870 | 1,960.603 | 2,795.804 | 438.700 | 1,119.050 |
| | 25% Gross storage | 2,893.932 | 1.975 | 11.484 | 515.895 | 257.718 | 490.151 | 698.951 | 109.675 | 279.763 |
| | 75% Gross storage | 8,681.795 | 5.924 | 34.451 | 1,547.685 | 773.153 | 1,470.453 | 2,096.853 | 329.025 | 839.288 |

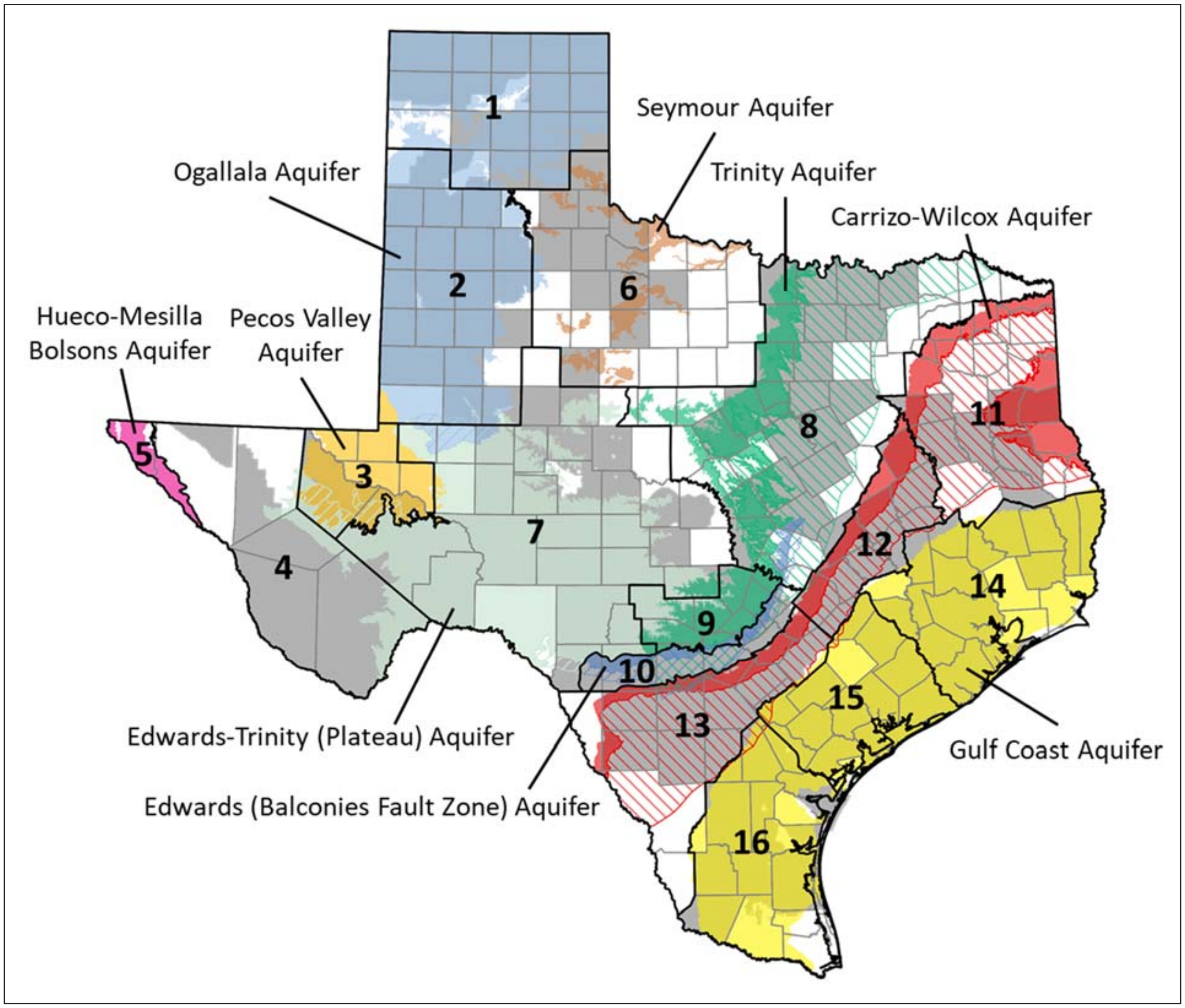


**Figure 2.** Map of the state's 16 Groundwater Management Areas (numbered) and nine major aquifers (colored). Solid aquifer colors indicate outcrop areas (the part of an aquifer that lies at the land surface) and hatched aquifer colors indicate sub-crop areas (the part of an aquifer that lies or dips below other formations). Gray areas indicate areas regulated by groundwater conservation and subsidence districts. Gray outlines indicate Texas counties. Map generated by ArcGIS with data available from the TWDB at: https://www.twdb.texas.gov/mapping/gisdata.asp.

## Methods

To test and develop the MERS model we simulate hydrogeologic characteristics and approximate conditions in the central section of the Carrizo-Wilcox Aquifer under confined and unconfined conditions. This area was selected in part because the Carrizo-Wilcox Aquifer, with the largest total storage in the state, is in close proximity to development corridors and population centers, and in part because much of its water is stored at significant depths under confined conditions. Similarly, hypothetical well characteristics (presumably available to stakeholders and managers applying these methods but estimated here) were derived from representative agricultural demand and approximated aquifer characteristics.

Carrizo-Wilcox Aquifer characteristics were estimated from the literature to represent a simplified version of the generalized conditions present in Bastrop, Burleson, Caldwell, Gonzales, Guadalupe, Lee, Milam, and Wilson counties located within GMA 12 (four counties) and GMA 13 (four counties). Due to limitations in the scope of this study, we assume that the Carrizo-Wilcox Aquifer is both homogenous and isotropic within the study area and this construction is characterized by

**Table 3.** Hydrogeologic properties assumed for the study area simulation.

| Property | Setting | Value | Source |
|---|---|---|---|
| Depth to aquifer bottom | Unconfined | 350 feet | (Dutton et al. 2003) |
| Depth to aquifer bottom | Confined | 2,000 feet | |
| Depth to aquifer top | Confined | 1,650 feet | |
| Initial saturated thickness | All | 350 feet | |
| Specific yield | All | 0.15 | |
| Storativity | Confined | $10^{(-3.52)}$ | (Mace et al. 2000) |
| Hydraulic conductivity | All | 7 feet per day | (Dutton et al. 2003) |

the above idealized and simplified hydrogeological properties (Table 3).

### *Key assumptions*

The limitations of this MERS analysis are akin to those applied to TERS; no consideration is given to subsidence, surface water interaction, or water quality. These are all clearly important issues for groundwater managers and must be considered when adopting DFCs pursuant to Chapter 36 §108(d) of the TWC.

We simulate agricultural uses because this economic sector generally returns the smallest monetized benefit per volumetric unit of water consumed. When compared to industrial or municipal/domestic uses, the volumes demanded are comparatively high and the economic value of the product (crops) is comparatively low (Aylward et al. 2010; Young and Loomis 2014). We therefore assume agricultural users may be considered the most sensitive of all users to prospective changes in recoverability driven by increasing depth-to-water. Additionally, we assume that agricultural users represent a substantial proportion of groundwater ownership under Texas law (which links groundwater ownership to the area of owned overlying land and historical use—see *Edwards Aquifer Authority v. Day-McDaniel*) and therefore those users have significant agency in DFC adoption.

We also assume that agricultural daily water demand is constant, cannot be deferred during the growing season, and cannot be satisfied by alternative sources. We calculate constant daily demand as a function of the irrigated area and the requisite irrigation depth as follows:

$$demand = \left(\left(\frac{irdepth}{12}\right) \times irarea \times 325851\right) \div t \qquad (3)$$

where *demand* is in units of gallons per minute, *irdepth* is the target daily irrigation depth in units of inches (simulated here as 0.5 unless otherwise noted), *irarea* is the area to be irrigated in units of acres (simulated here as 100), 325,851 is the conversion constant from acre-feet to gallons, and $t$ is the time of pumping in units of minutes (assumed here to be 1440 minutes, or one day, in all cases).

Reference agricultural harvest values in units of dollars per acre per year are assumed in this simulation to be inclusive of any relevant subsidies and net of all costs external to pumping (such as fertilizer, labor, machinery). Reference harvest values are given by Shaw (2005) as: alfalfa = $440, onions = $778, tomatoes = $1,018, grains = $1,153, and potatoes = $2,792. These values are likely overestimates of the actual net value of all costs unrelated to pumping, but such crop-specific data are difficult to obtain. Thus, we assume that groundwater managers and agricultural users will input this key variable to the MERS model with more precise values for local uses.

Well efficiency, or the energy loss of the well due to friction, is given as a user input to the model and held constant. As most modern pumps have an efficiency of between 50% and 85% (Stringman 2013),depending upon the age of the system, the type of construction, accumulated well screen fouling, the type of power plant, and other factors, we hold operational well efficiency constant at 75% for all calculations.

Finally, we assume that where hypothetical depth-to-water in the confined setting falls below the depth of the top of the aquifer, the groundwater system fully transitions to the unconfined setting. In this way, the same demand-capacity constraints that are applied to the unconfined setting also apply to the confined setting but occur at greater depth. Furthermore, the depth of the bottom of the aquifer in the confined setting is assumed to be the depth of the base of potable water, approximately 2,000 feet in our study area (Dutton et al. 2003).

### *Aquifer and well performance*

Here we use specific capacity to capture the hydrogeologic limitations to production at a given well. Specific capacity has units of length squared per time but is frequently reported in units of volume per time per length of drawdown. For example, a specific capacity of 5 square feet per minute may be reported as 37.4 gallons per minute per foot of drawdown, where the conversion from one form to the other is accomplished by multiplying square feet per minute by the constant 7.48052 gallons per cubic foot. A relationship between specific capacity and pumping dynamics was developed from the Theis (1935) non-equilibrium solution by Theis (1963) and is presented in this form in Mace et al. (2000):

$$specific\ capacity = (4 \times \pi \times T) \div [\ln((2.25 \times T \times t) \div (r^2 \times S))] \quad (4)$$

where *specific capacity* is in units of length squared per time (such as feet squared per minute), $T$ is the transmissivity of the aquifer in units of length squared per time (also equal to the product of hydraulic conductivity and saturated thickness), $t$ is the time of pumping (one day or 1440 minutes), $r$ is the well radius (simulated here as 1 foot to include the gravel pack), and $S$ is the dimensionless storativity of the aquifer ($Sy$ in the unconfined setting and $St$ in the confined setting).

As we are interested in increasing depth-to-water over time (as might occur under DFCs), we iteratively calculate specific capacity by applying transmissivities that decrease as a function of declining saturated thickness (in single foot increments here) to simulate planned and potential changes in depth-to-water.

A representative depth of the top of the well screen (the depth of the bottom of the aquifer minus the length of the well screen interval) is calculated for this MERS simulation from demand and the well screen intake capacity. A representative well screen intake capacity is estimated from the maximum well entry velocity (assumed here at 0.1 feet per second) and the well screen open area (i.e. slot size) derived from grain size distribution of the Carrizo-Wilcox Aquifer which is estimated from hydraulic conductivity using the Hazen (1893) approximation. Here we simulate the smallest well screen interval capable of supporting demand in order to minimize the well screen dead pool.

We then iteratively calculate the maximum pumping rate supported by the hydrogeologic and well characteristics (at all possible depths-to-water) as a function of the specific capacity and the available saturated thickness as:

$$maximum\ pumping\ rate = specific\ capacity \times s\_max \quad (5)$$

where *maximum pumping rate* is in units of volume per time (such as gallons per minute), *specific capacity* is in units of volume per time per unit of drawdown (such as gallons per minute per foot) as converted from Equation 4, and *s_max* is the maximum possible drawdown given available saturated thickness, simulated here as the difference, in length, between the iterated depth-to-water and the top of the well screen.

Note that where maximum pumping rate values are significantly greater than demand the results may not be plausible with the given well screen (due to well entry velocity and other factors) and are provided for reference only. The maximum pumping rate declines with declining transmissivity and available *s_max* associated with hypothetical dewatering (decreasing saturated thickness) occurring in the unconfined or transitioned setting over time. To avoid pumping air, a certain amount of saturated thickness must be reserved from production to support the well screen interval dead pool and the pumping period drawdown (*s,* which is assumed here equivalent to *s_max* where the maximum pumping rate equals demand). Thus, where the maximum pumping rate equals demand a binding constraint is applied to the MERS model; beyond this depth-to-water, defined here as *h_max*, the aquifer and well can no longer satisfy demand (Figure 3).

While it is possible to pump beyond *h_max* (i.e., where the top of the well screen is exposed), the MERS model does not allow such over pumping as we assume the introduction of air to the system has significant impacts to efficiency and may damage the well. The difference between the initial depth-to-water and *h_max* is defined here as the production range (Figure 3). Within the production range, the aquifer and the well have the physical capacity to satisfy demand. Similarly, we dub the saturated thickness required to support pumping period drawdown which is variable with pumping rate and well characteristics the pumping range (Figure 3). Importantly, the production range and pumping range vary significantly with demand.

### Pumping costs

Pumping costs at the well head (or marginal extraction costs) are identified here as the hypothesized binding constraint for agricultural users in deep and confined settings. These are defined as the energy costs required to pump water to the surface at the given hydrogeologic, well and demand conditions. Fixed costs are not considered in this study.

*Water horsepower*, or the amount of horsepower required to do the work of lifting the given output of water to the discharge point if the well was 100% efficient (Fipps 2015), is defined as:

$$water\ horsepower = (h \times demand) \div 3960 \quad (6)$$

where $h$ is the iterated hypothetical depth-to-water in feet and 3,960 is the conversion constant to horsepower.

However, because no well is 100% efficient, the wire-to-water efficiency of the pumping system must adjust water horsepower to calculate the true horsepower applied to run the pump at the observed pumping rate. The pumping rate demand, as adjusted for well efficiency losses, is then directly relatable to dollar costs per unit of pumping time to meet the given demand volume by introducing an applicable power cost rate for the study area to calculate a pumping cost rate at depth-to-water as:

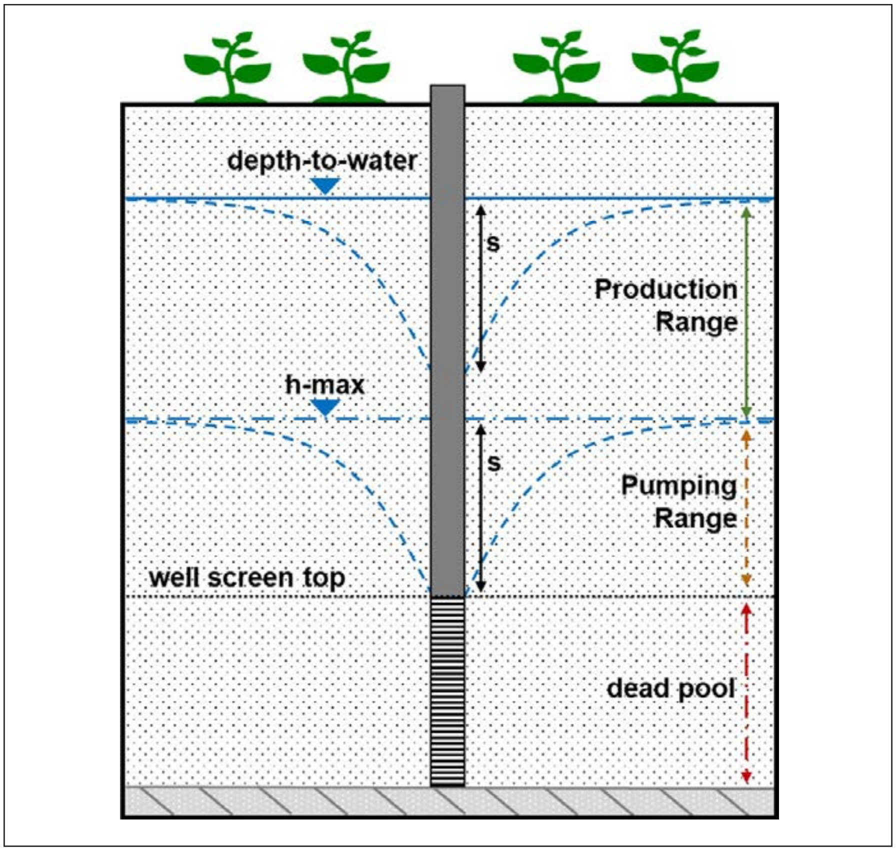


**Figure 3.** Representation of the aquifer and well constraints associated with pumping applied to the simulation in order to generate demand-capacity constraints.

$$pumping\ cost\ rate = \left(\frac{water\ horsepower}{well\ efficiency}\right) \times 745.7 \times power\ cost\ rate \quad (7)$$

where *pumping cost rate* is in units of dollars per minute, 745.7 is the conversion constant from horsepower to watts, and power cost rate is the applicable *power cost rate* in dollars per watt-minute (assumed \$0.07 per kilowatt-hour here).

We can then simplify the pumping cost rate at depth-to-water and demand to dollars per gallon, a form we refer to here as recoverability:

$$recoverability = pumping\ cost\ rate \div demand \quad (8)$$

Pumping costs in the MERS model is then expressed in dollars per pumping period as a function of demand and recoverability as:

$$pumping\ costs = (demand \times t) \times recoverability \quad (9)$$

While we choose to express depth-to-water as all possibilities between the land surface and the aquifer bottom for this study, the range of *h* may be adjusted by the user to evaluate any relevant range of potential depth-to-water changes (such as existing or proposed DFCs).

### Depth maximization

Given that most of the simplified relationships evaluated by this simulation are functionally linear, we modify an analytical solution (originally developed by Domenico 1972) for linear optimization of groundwater yields to implement the limitations associated with an aquifer bottom and declines in transmissivity associated with increasing depth-to-water over time. We define *value* as the estimated daily dollar value of irrigation as:

$$value = (harvest\ value \times irarea) \div irrigation\ days \quad (10)$$

where *harvest value* is in units of dollars per area of agricultural production per year (such as dollars per acre per year, a common metric), *irarea* is the user defined area to be irrigated (100 acres simulated here), and *irrigation days* is the number of days in the annual growing season to be irrigated (simulated here as

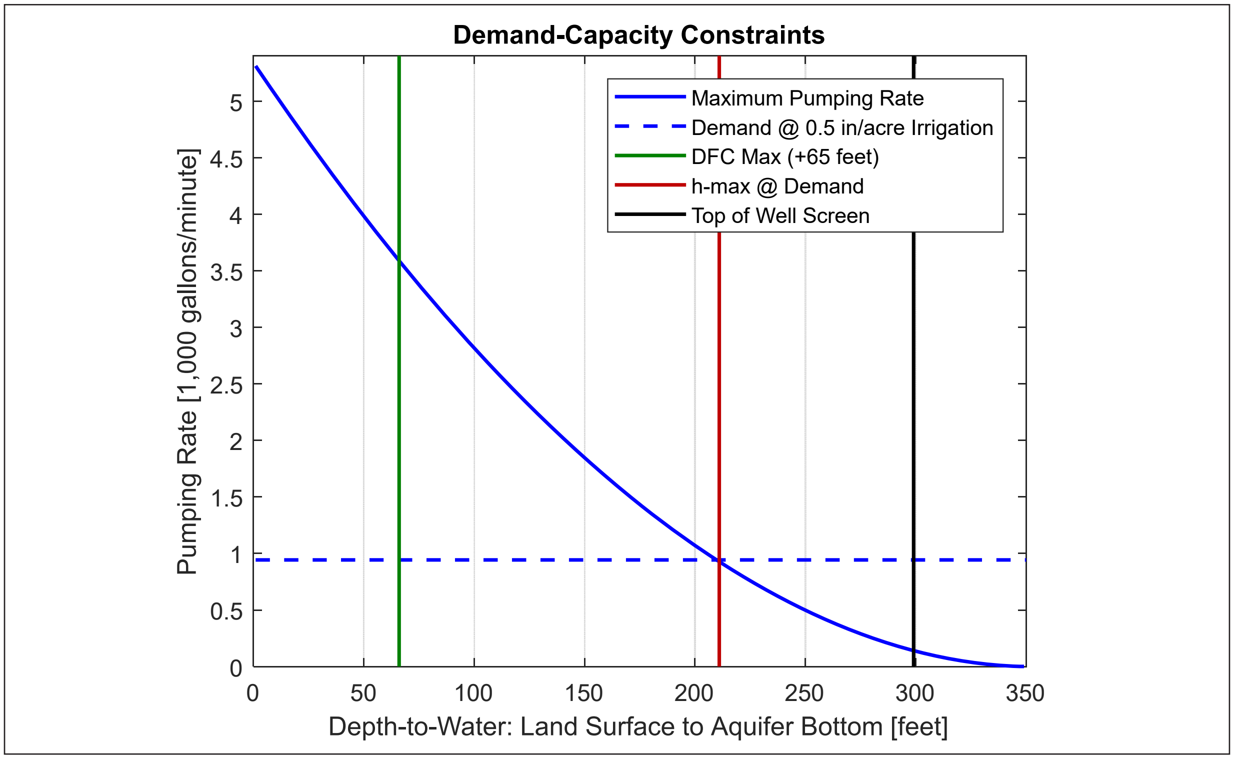


**Figure 4.** Relationship between maximum pumping rate, demand, and depth-to-water in the unconfined setting given input aquifer, well, and use parameters. The (solid blue) curve is the maximum pumping rate. The only horizontal line (dashed blue) is demand at the given irrigation rate. From left to right: The first vertical line (solid green) is the deepest depth-to-water based DFC found in the representative study area of the Carrizo-Wilcox Aquifer (+65 feet), the second vertical line (solid red) represents *h_max*, the third vertical line (solid black) indicates the top of the well screen. Note that where maximum pumping rate values are significantly greater than demand the results may not be plausible with the depicted well screen interval due to well entry velocity and other factors. Simulation generated by MATLAB.

111 days per year = 37 growing season weeks per year multiplied by 3 irrigation days per week).

With pumping costs and value determined we are able to generate a simple profit function in terms of dollars per irrigation day:

$$profit = value - pumping\ costs \tag{11}$$

Because *value* is constant here and *pumping costs* increase linearly with increasing depth-to-water, *profit* falls linearly to zero where *pumping costs* are equivalent to *value*. Beyond this point the irrigator is theoretically losing money if pumping continues and, if no other constraint is limiting, this constraint is binding on the MERS model. This ensures a global solution to the optimization problem and creates an objective limit to economic recoverability.

Altogether, the MERS simulation applies three key limitations as constraints upon recoverability: (1) saturated thickness screened by the well, (2) the saturated thickness necessary to accommodate drawdown at demand, and (3) the depth-to-water at which value is equivalent to pumping costs. The smallest depth-to-water value (i.e., the most constraining limitation) is then applied to derive the maximum recoverable depth-to-water.

## Results

### *Shallow and unconfined storage (addressing H1)*

Two factors limit physical yield capacity: (1) dewatering (increasing depth-to-water which reduces saturated thickness), and (2) variability in pumping rates. In effect, the well screen dead pool and the pumping range together serve to simulate an effective aquifer bottom and thereby introduce physical constraints on yields in the form of production capacity.

As the saturated thickness of the aquifer decreases, the maximum pumping rate supported by the well and aquifer decreases non-linearly (Figure 4). The DFC with the largest increase

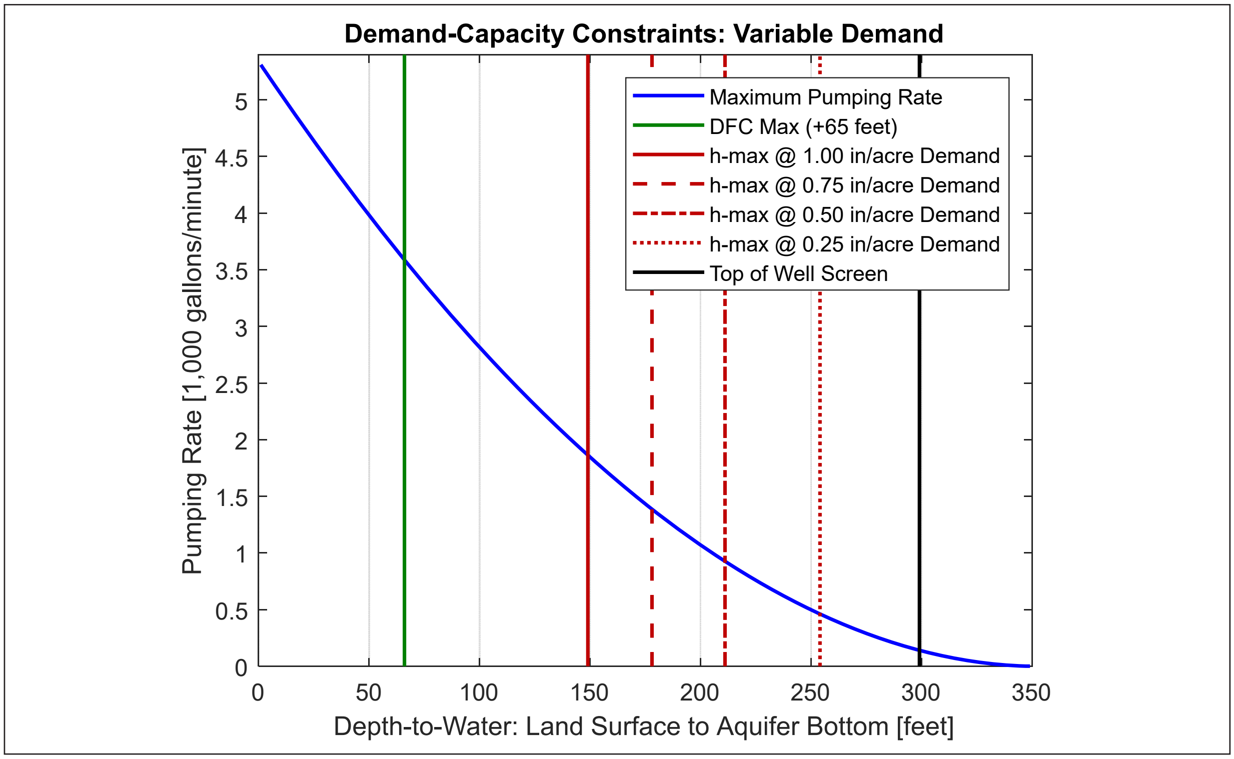


**Figure 5.** Relationship between maximum pumping rate, varying demand, and depth-to-water in the unconfined setting given input aquifer, well, and use parameters. The (solid blue) curve is the maximum pumping rate. From left to right: The first vertical line (solid green) is the deepest depth-to-water based DFC found in the representative study area of the Carrizo-Wilcox Aquifer (+65 feet), the four red vertical lines indicate *h_max* at irrigation demand of 1.00 inches per acre per day (solid), 0.75 inches (dashed), 0.50 inches (dash-dot), and 0.25 inches (dotted), and the fifth vertical line (solid black) indicates the top of the well screen (generated for demand at 0.5in/acre irrigation). Simulation generated by MATLAB.

in depth-to-water within the simulated study area is 65 feet of drawdown over 50 years (in Burleson and Milam counties, GCD #71) and provided for reference. Specific capacity, the first component of the maximum pumping rate, falls with declines in transmissivity (Equation 3), which in turn falls with declining saturated thickness. Similarly, the maximum distance between the initial depth-to-water and the top of the well screen (i.e., *s_max*), the second component of maximum pumping rate, falls linearly with declining saturated thickness. Thus, at some depth-to-water, the transmissivity and available pumping range are insufficient to support the demanded pumping rate and resultant drawdown under pumping. Here a binding constraint is applied to the model: beyond this depth (*h_max*) the aquifer and well do not have sufficient capacity to meet irrigation demand.

The higher the pumping rate demanded is, the greater the drawdown under pumping and resultant pumping range are. Naturally, where the pumping range increases, the production range decreases as additional saturated thickness is reserved from production to accommodate the increased drawdown. Importantly, our results indicate that impacts to the pumping and production ranges are significant within the potential range of irrigation demand for various crops. Here we simulate irrigation depths (which drive demand) from 0.25 inches per acre per day to 1.00 inch per acre per day to evaluate the changes in the pumping range (Figure 5). When irrigation demand is 0.25 inches, *h_max* is over 250 feet (over 80% of the unscreened saturated thickness is physically recoverable); but when the irrigation demand is 1.00 inch, *h_max* is less than 150 feet (approximately 50% of the unscreened saturated thickness is physically recoverable). Thus, smaller pumping rates may extract from greater depths than larger pumping rates before reaching the demand-capacity constraints of the well and aquifer.

Simulated pumping costs increase linearly with depth-to-water to a maximum of $33.41 per acre-foot at the aquifer bot-

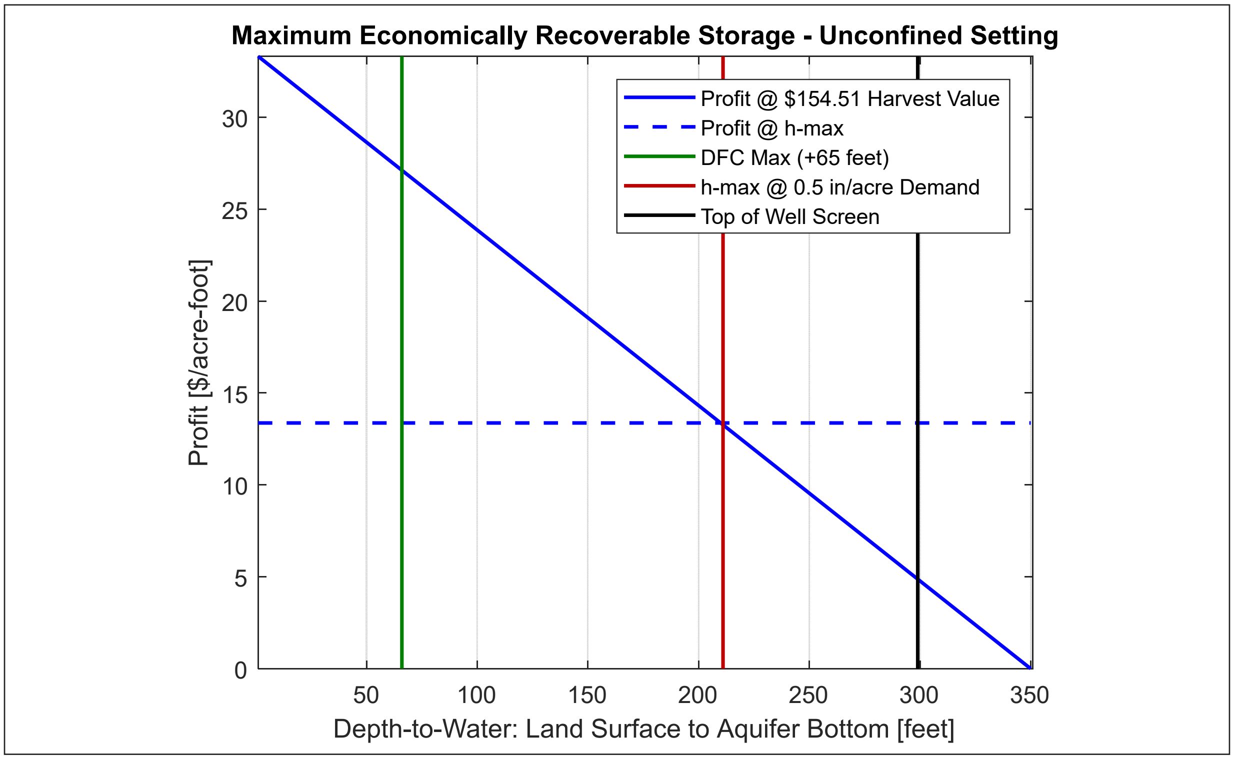


**Figure 6.** Maximum economically recoverable storage where harvest value is $154.51 per acre per year and irrigation demand is 0.5 inches per acre per day in the unconfined setting. The (solid blue) diagonal line reflects the linear change in profit as pumping costs increase with depth-to-water. The only horizontal line (dashed blue) is profit at the binding demand-capacity constraint (*h_max*). From left to right: The first vertical line (solid green) is the deepest depth-to-water based DFC found in the representative study area of the Carrizo-Wilcox Aquifer (+65 feet), the second vertical line (solid red) represents *h_max* (binding here), and the third vertical line (solid black) indicates the top of the well screen. Simulation generated by MATLAB.

tom (a depth of 350 feet) while profit falls linearly with increasing depth-to-water. The harvest value point at which profit is equivalent to pumping costs at the depth of the bottom of the aquifer (350 feet) is found to be $154.51 per acre per year. At this harvest value, profit is $13.27 per acre-foot of groundwater pumped at the above *h_max* depth of 211 feet—less than 40% of the initial value.

Importantly, a $154.51 harvest value falls well below even the lowest reference harvest value considered here, which is alfalfa at the price of $440 per acre per year. This suggests that many or all harvest values may be sufficient to dewater the full production range before profit falls to zero in shallow and unconfined settings.

Thus, where irrigation demand is 0.50 inches per acre per day, the irrigated area is 100 acres, and the harvest value is $154.51 per acre per year, the binding MERS constraint in the unconfined setting is the demand-capacity constraint (*h_max*), simulated at a maximum depth of 211 feet or 71% of the unscreened saturated thickness (Figure 6). The demand-capacity constraint (*h_max*) simulated here in the unconfined setting exceeds this maximum DFC depth by over 140 feet.

These results confirm H1: simulated recoverability is constrained by demand-capacity limitations in shallow and unconfined settings for all irrigation demand rates and harvest values. However, the reference harvest values noted here are estimates and may not represent true agricultural values net of all costs beyond those explicitly considered here. Moreover, pumping costs are not insignificant to agricultural users. Determining what reduction in profit irrigators are willing to accept as pumping costs rise is another matter not considered here beyond the economically inefficient limit of profit = 0.

### *Deep and confined storage (addressing H2)*

The methods for calculating MERS in the confined setting have several important distinctions from the methods used in

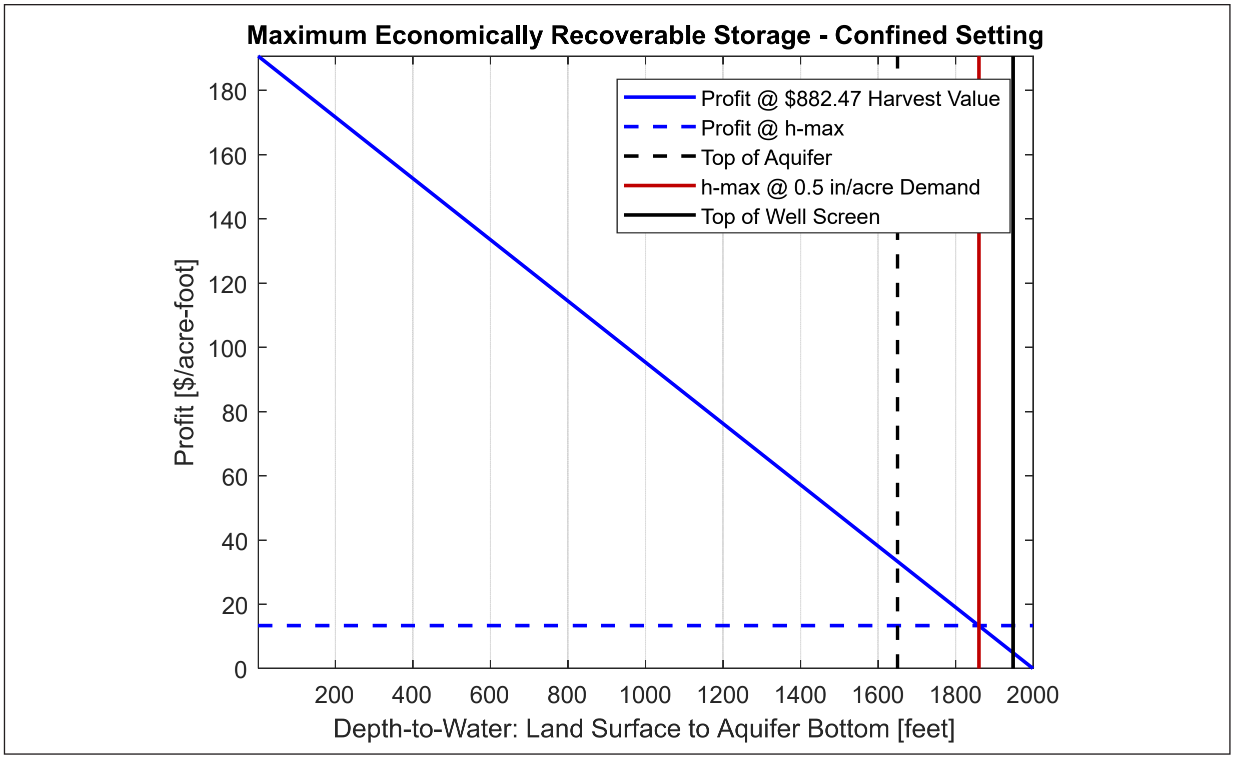


**Figure 7.** Maximum economically recoverable storage where harvest value is $882.47 per acre per year and irrigation demand is 0.5 inches per acre per day in the confined setting. The (solid blue) diagonal line reflects the linear change in profit as pumping costs increase with depth-to-water. The only horizontal line (dashed blue) is profit at the binding demand-capacity constraint (*h_max,* binding here). From left to right: The first vertical line (dashed black) is the depth of the top of the aquifer, the second vertical line (solid red) represents *h_max* (binding here), and the third vertical line (solid black) indicates the top of the well screen. Simulation generated by MATLAB.

the unconfined setting. In this construct of the Carrizo-Wilcox Aquifer the simulated depth to the bottom of the aquifer is much deeper in the confined setting (2,000 feet) than the unconfined setting (350 feet). The depth to the top of the aquifer (1,650 feet) is introduced as a new variable to create a distinction between the pressurized storage of the aquifer and pore space storage. Accordingly, the well screen and pumping range occur at significant depth (within the saturated thickness of the aquifer). Thus, the demand-capacity constraint considered by the MERS model is also at great depth (Figure 7) and, while present, may not be binding in light of economic impacts.

Pumping cost impacts to recoverability within the production range are significant in deep and confined settings. Pumping costs at the depth of the bottom of the aquifer (2,000 feet) reflect the increased depth and are found to be $190.90 per acre-foot, or roughly 5.71 times the $33.41 pumping costs at the aquifer bottom in the shallower, unconfined case (350 feet). Similarly, the harvest value point where profit = 0 at the depth of the bottom of the aquifer (2,000 feet) is found to be $882.47 per acre per year; again, this is 5.71 times the comparable $154.51 harvest value above as changes in pumping costs are linear (5.71 is equivalent to the change in depth, 2,000 feet / 350 feet). Where harvest value is $882.47 per acre per year, profit is $13.27 per acre-foot of groundwater pumped at the *h_max* depth of 1,860 feet—less than 7% of the initial value.

Agricultural users experience much greater changes in pumping costs over the full production range in the confined setting because the range of depths is greater, and those changes are sufficient to make a clear difference in recoverability among crop types (Figure 8). For example, alfalfa harvest values are insufficient to allow positive profit long before depth-to-water reaches the top of the aquifer (and transitions it from the confined to the unconfined state), but tomato harvest values are sufficient to reach the demand-capacity constraint (Figure 8). Note that demand is constant at an irrigation rate of 0.5 inches per acre per day for all simulated harvest values shown here (Figure 8), but higher value crops may require greater irrigation demand than lower value crops. Additionally, simulated harvest values are likely overestimates of the actual net value of all costs unrelated to pumping (see key assumptions).

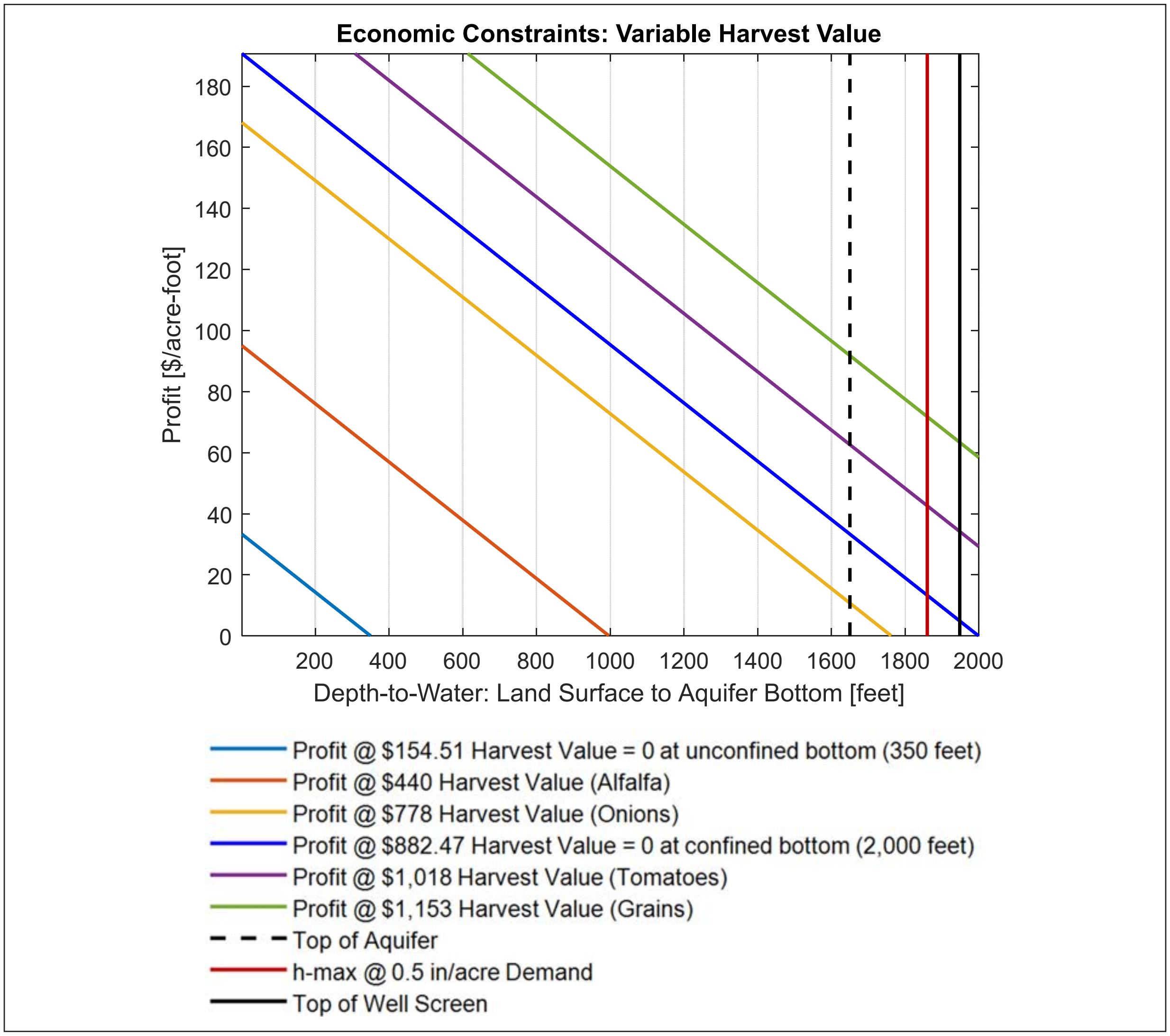


**Figure 8.** Profit function over increasing depth-to-water in the confined setting for a range of reference and representative harvest values. The diagonal lines reflect the linear changes in profit as pumping cost increases with depth-to-water for given harvest values. From left to right: The first vertical line (dashed black) is the depth of the top of the aquifer, the second vertical line (solid red) represents *h_max* (where irrigation demand is 0.5 inches per acre), and the third vertical line (solid black) indicates the top of the well screen. Simulation generated by MATLAB.

These results confirm H2, that simulated recoverability in deep and confined settings is constrained by economic limitations for some uses (harvest values) at all irrigation (demand) rates, restricting them to producing from pressurized storage.

## DISCUSSION

Whether Texas is running out of groundwater or experiencing a regulation-induced shortage depends upon how one assesses groundwater availability. At the same time, there is no universal groundwater availability assessment method for the state as availability is a function of many, potentially conflicting management objectives. The methods developed here define MERS as a simplified simulation of the physical and economic limitations to groundwater recoverability; key elements of availability common to all human groundwater demand absent from total storage and TERS.

Our results indicate that recoverability is a function of use, aquifer characteristics, and well infrastructure. Here we show the capacity of an aquifer to meet demand is a function of transmissivity where transmissivity declines with increasing depth-to-water. Together with well screen limitations and drawdown under pumping, a maximum depth-to-water with the capacity to satisfy the demanded pumping rate is established as a binding constraint. While simple in concept, these constraints are absent from many publications in the literature that assume a bottomless aquifer of infinite areal extent. This demand-capacity constraint is found to be binding in shallow and unconfined settings simulated here and exceeds maximum established DFCs for all agricultural uses. Changes in pumping costs are shown to be significant to agricultural users and directly associated with changes in depth-to-water in both the confined and unconfined settings. Indeed, while the capacity of deep and confined aquifers to meet demand is high, the costs associated with reaching the depth-to-water necessary to extract much of that storage may be economically prohibitive for some uses. In all cases, users are economically incentivized to minimize pumping costs (and thereby depth-to-water) irrespective of confined or unconfined setting.

Critically, our results further suggest that storage-based estimates that do not incorporate the physical and economic constraints of pumping (such as TERS, at either percentile benchmark) may overestimate groundwater availability in deep and confined settings by orders of magnitude due to the change in storage coefficient assumed when an aquifer transitions from confined to unconfined state (Equation 2). This manifests for uses where pumping from depth-to-water at or below the top of the confined aquifer is infeasible.

For example, the local total storage volume for a 100-acre farm pumping in deep and confined settings, where the initial depth-to-water is 350 feet above land surface (artesian), would be 5,313.25 acre-feet (Equation 2 and Table 3). Related TERS volumes would be 3,984.93 acre-feet (at 75% of local total storage) and 1,328.31 acre-feet (at 25% of local total storage). However, if we apply the above conditions and assumptions to an alfalfa farm, we see that the MERS model constrains the maximum recoverable depth-to-water to the depth where profit = 0 at approximately 1,000 feet (Figure 8). We can then calculate the local MERS volume by integrating this simulated depth-to-water recoverability limit with the relevant elements of the total storage calculation (Equation 2). The MERS model would thus estimate that only 42.69 acre-feet is recoverable for this use, about 0.8% of the local total storage or 1.1% and 3.2% of comparable TERS estimates.

Thus, while the Carrizo-Wilcox Aquifer stores 5.227 billion acre-feet of water, or 45% of the total 11.575 billion acre-feet stored by all major aquifers of the state (Tables 1 and 2), the overwhelming majority of that storage may be unrecoverable, by these standards, for some uses and locations due to the change in depth necessary to transition the aquifer from the confined to unconfined state.

Importantly, while we choose to simulate agricultural uses operating in the central section of the Carrizo-Wilcox Aquifer, the MERS model may be applied to any aquifer and any use to estimate groundwater recoverability where demand and the economic value generated by pumped groundwater are known and effectively constant. Moreover, the MERS model is deliberately designed to be calculable with commonly held data (such as specific capacity) without the need for advanced computing and mathematics, perhaps increasing accessibility.

We suggest that groundwater policymakers, managers, and producers consider including MERS (or a similar metric) along with TERS and the other considerations of Chapter 36 §108(d)(3) of the TWC, especially in jurisdictions operating under a depth-to-water based DFC. Even a simple estimate of how groundwater recoverability changes with depth-to-water for variable uses, such as when certain pumping demands become infeasible for various crop or other use values, may prove useful. Failure to account for demand-capacity constraints and the economic impact to pumping costs arising from prospective changes in depth-to-water may result in overestimates of groundwater availability.

## CONCLUSION

We conclude that Texas groundwater managers, stakeholders, and policymakers assessing groundwater availability need an alternate approach for estimating recoverability. The current metrics employed by the state for estimating groundwater storage and recoverability, total storage and TERS, are highly limited in scope and function. Irrespective of the name, TERS values do not scientifically account for many of the physical and none of the economic constraints upon groundwater recoverability, as noted by the TWDB (Bradley 2016).

The system of equations described above, which constitute the MERS model, represents one method for estimating the limits of groundwater recoverability that accounts for some of the physical and economic constraints upon yields. These constraints can be significant and may limit recoverability to as little as 1% of local storage (or 1.1% and 3.2% of comparable TERS estimates) in deep and confined settings. This suggests that the majority of water stored in the Carrizo-Wilcox Aquifer (45% of major aquifer storage in Texas) may not be economically recoverable for some agricultural uses. Conversely, recoverability of water stored in shallow and unconfined settings may be limited only by the capacity of the well and aquifer to meet demanded pumping rates.

Future studies expanding on these methods may refine drawdown estimates by replacing specific capacity estimates with drawdown solutions that account for partial well penetration, though the analyses would become more complex. These or similar methods could also be integrated with the TWDB groundwater availability model and groundwater database data to estimate local recoverability for any use and aquifer.

Ultimately, what is recoverable for a microchip manufacturer may not be the same as what is recoverable for a farmer, and what is recoverable for an alfalfa farmer may not be the same as what is recoverable for a tomato farmer. Moreover, the limits to what is economically recoverable for any user are not economically efficient and pumping costs increase for all users in all cases where depth-to-water increases. Nonetheless, quantifying planned and potential changes to groundwater recoverability using scientific methods with known assumptions, conditions, and infrastructure provides important information for Texas policymakers and stakeholders looking to the future.

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