texaswaterjournal.org

An online, peer-reviewed journal published in cooperation with the Texas Water Resources Institute and the Bureau of Economic Geology

# Texas Water Journal

Volume 15 Number 1 | 2024

# Texas Water Journal

Volume 15, Number 1
2024
ISSN 2160-5319

texaswaterjournal.org


THE TEXAS WATER JOURNAL is an online, peer-reviewed, and indexed journal devoted to the timely consideration of Texas water resources management, research, and policy issues. The journal provides in-depth analysis of Texas water resources management and policies from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. It also provides updates on key state legislation and policy changes by Texas administrative agencies.

For more information on the Texas Water Journal as well as our policies and submission guidelines, please visit texaswaterjournal.org. As a 501(c)(3) nonprofit organization, the Texas Water Journal needs your support to provide Texas with an open-accessed, peer-reviewed publication that focuses on Texas water. Please consider donating.




The Texas Water Journal is published in cooperation with the Texas Water Resources Institute, part of Texas A&M AgriLife Research, the Texas A&M AgriLife Extension Service, and the College of Agriculture and Life Sciences at Texas A&M University and the Bureau of Economic Geology in the Jackson School of Geosciences at The University of Texas at Austin.

The Texas Water Journal is indexed by Scopus, Google Scholar, and the Directory of Open Access Journals.


*Cover photo:*
The Narrows on the Blanco River.

**Texas Water Journal**
Volume 15, Number 1, February 27, 2024
Pages 1-33

# A Hydro-Economic Approach for Quantifying Well Performance Thresholds and Recoverable Groundwater Yields in Texas

Justin C. Thompson[1] and Michael H. Young[1]

**Abstract:** Groundwater overdraft may increase the depth-to-water over time, reducing the potentiometric head available to support well operation and increasing the cost of pumping. These hydro-economic impacts create well failure thresholds. Understanding these impacts and thresholds is a critical issue for groundwater management, but tools to assess them are not widely available or established. Therefore, an analytical model developed in this study quantifies changes in well performance with depth-to-water, calculates well failure thresholds, and estimates feasible yields for variable uses, wells, and aquifers. The model is developed and tested using both a single well and a regional analysis of the Carrizo-Wilcox Aquifer in Texas, United States, where a contemporary groundwater dataset is available, and management is depth-to-water-based. Results reveal how storage conditions drive well performance and suggest that performance in shallow and unconfined settings may be most limited by operational thresholds, while performance in deep and confined settings may be most limited by affordability thresholds. At the tested parameters for a single well, failure to account for drawdown under pumping would overestimate operationally feasible yields by 98–108% and economically feasible yields by 24%. The model could directly support manager, stakeholder, and policymaker consideration of desired future conditions.

**Keywords:** well performance, well optimization, pumping costs, depth-to-water, recoverability

[1] Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas.
* Corresponding author: justin.thompson@utexas.edu

Received 7 June 2023, Accepted 20 October 2023, Published online 27 February 2024.

Citation: Thompson JC, Young MH. 2024. A Hydro-Economic Approach for Quantifying Well Performance Thresholds and Recoverable Groundwater Yields in Texas. Texas Water Journal. 15(1):1-33. Available from: https://doi.org/10.21423/twj.v15i1.7160.

## Terms used in paper

| Acronym/Initialism | Descriptive Name |
|---|---|
| AFT | affordability failure threshold |
| AMSL | above mean sea level |
| CWA | Carrizo-Wilcox Aquifer |
| DFC(s) | desired future condition(s) |
| DTW | depth-to-water |
| GCD(s) | groundwater conservation district(s) |
| HELPER | Hydro-Economic welL PERformance model |
| OFT | operational failure threshold |
| POSGCD | Post Oak Savannah Groundwater Conservation District |
| TERS | total estimated recoverable storage |
| TWDB | Texas Water Development Board |
| WTP | willingness-to-pay |

## INTRODUCTION

Groundwater overdraft, or mining, is characterized by a net loss to the volume of water stored in an aquifer over time. Global groundwater resources have not been sustainably managed historically, and overdraft is occurring in the United States, India, the People's Republic of China, Mexico, Iran, Pakistan, Kenya, and Tanzania (Döll et al. 2014; Feng et al. 2013; Joodaki et al. 2014; Nanteza et al. 2016; Wada et al. 2010). The consequences of groundwater overdraft are numerous and include reductions to hydrologically connected surface water flows (Barlow and Leake 2012), subsidence of the land surface (Smith et al. 2017), and degraded water quality (Barlow and Reichard 2010; Smith et al. 2018).

Groundwater overdraft may also increase the static[1] depth of the water table or potentiometric surface, also known as depth-to-water (DTW), over time. As DTW increases, the cost of extracting groundwater rises (Domenico et al. 1968), the potentiometric head available to support well operation declines (Gailey et al. 2019; Gailey et al. 2022; Jasechko and Perrone 2021), and, in some settings, the ability of the aquifer to transmit water to wells (transmissivity) is reduced. Thus, increasing DTW drives hydro-economic impacts that create well failure thresholds; at some DTW the well can no longer physically operate (it "goes dry") or it is no longer affordable to pump. DTW is a key metric by which many groundwater resources are tracked and managed, but these well performance thresholds may not be consistently understood or applied by groundwater policymakers, managers, and stakeholders. This is partly due to the lack of a unified approach to quantifying hydro-economic well performance that has the flexibility to model a range of groundwater uses, storage conditions, and well designs.

### Groundwater Management in Texas

Groundwater in Texas is managed at the local level by approximately 100 groundwater conservation districts (GCDs). GCDs work together within a management area to adopt desired future conditions (DFCs) for the groundwater resources within their jurisdiction (2 Tex. Water Code §36.108). DFCs are a defined aquifer state over a specified planning timeframe and take many forms (e.g., minimum spring flows and maximum subsidence impacts), but they are most commonly expressed as a change in DTW (i.e., *x* feet of increased DTW over *y* years; Thompson et al. 2020). Depending on the region of interest, DFCs for the same aquifer in proximal locations may differ substantially from one GCD to another. Once DFCs are adopted, the Texas Water Development Board (TWDB) integrates them with its aquifer flow and pumping models to estimate the volume of water that can be produced within those limitations (2 Tex. Water Code §36.108(b)). These volumes, known as modeled available groundwater, are used in state and regional water planning and may be considered by GCDs in permitting decisions.

Texas law requires GCDs to consider many issues in the process of proposing and adopting DFCs (2 Tex. Water Code §36.108(d)), including hydrologic conditions and total estimated recoverable storage (TERS), but does not specify how those issues should be assessed. TERS is defined 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" (31 Tex. Admin Code §356.10(23)). Thus, by definition, TERS provides only arbitrary benchmarks for recoverable groundwater yields that do not capture any of the hydro-economic limitations to groundwater pumping (Thompson et al. 2020).

Under the current framework, GCDs lack a common method for determining the hydro-economic impacts of planned DTW changes and what potential recoverable groundwater yield limits might be before adopting management plans. The agency of individual groundwater users to participate in groundwater planning is diminished by the lack of a consistent approach for describing hydro-economic impacts and performance thresholds for their specific wells and uses.

### Hydro-Economic Well Performance

Three sets of factors work in concert to determine how a well responds to pumping under changes in DTW: aquifer characteristics, well infrastructure, and usage attributes. The principal physical response to groundwater pumping of interest in this study is the drawdown induced at the well over the given pumping period. In essence, drawdown under pumping describes how the water level within a well fluctuates locally over short periods. By contrast, DTW describes water levels at rest from pumping that change regionally over long periods. Thus, changes in DTW are related to, but often separate and distinct from, drawdown under pumping in both time and space.

Drawdown is a key driver of hydro-economic well performance in two important ways. Firstly, the water level within a well determines if and when a well experiences an operational failure. Secondly, some components of pumping costs are directly informed by lifting distance, which is the sum of DTW and drawdown. As lifting distance increases—driven by changes in DTW, drawdown, or a combination of both—pumping costs rise due to the increase in energy required to lift water to land surface.

However, many studies concerned with hydro-economic well performance (Domenico et al. 1968; Foster et al. 2016; de

[1] The term "static" here indicates that the depth of the water table or potentiometric surface is not under the influence of localized, short-term pumping. It does not indicate that this depth is immutable.

Frutos Cachorro et al. 2014; Gisser and Sanchez 1980; Jasechko and Perrone 2021; Kanazawa 1992; Provencher and Burt 1993; Reichard et al. 2010; Tsur and Zemel 2004; Turner et al. 2019; Zimmerman 1990) do not consider drawdown and, at most, evaluate changes in performance only with changes in DTW driven by overdraft, drought, or a combination of both. This may be because analytical solutions for drawdown are mathematically complex (requiring significant processing power for large datasets) or because the necessary aquifer characteristic, well infrastructure, and usage attribute parameters are not fully understood or known. Ultimately, by failing to account for drawdown, these studies inherently underestimate pumping costs and face errors in determining when operational failures may occur.

Some recent well performance studies (Gailey et al. 2019; Gailey et al. 2022; Thompson et al. 2020) do consider drawdown but calculate it from a fixed specific capacity value, which is frequently reported in units of volume produced per unit of time per unit of drawdown (such as gallons per minute per foot of drawdown). Specific capacity is determined from a pumping test of a specific well at a certain time and therefore has three important limitations when applied to calculate drawdown: (1) it does not capture prospective changes in storage conditions with changes in DTW (such as transmissivity variations); (2) it is a single, time-independent value that does not assess how drawdown increases over a pumping period; and (3) it cannot be used to estimate drawdown for a well of differing construction.

Additionally, we are unaware of a current approach to well design that is structured to maximize long-term groundwater yields based on quantifiable well performance thresholds. Instead, wells are designed to ensure they can meet immediate demand while minimizing the outlay and operational costs of the well at the time of drilling and installation (Misstear et al. 2017; Stoner et al. 1979). Ensuring the aquifer and well are capable of meeting pumping demand is frequently left to the discretion of the well driller, possibly only with guidance to screen the lower third to lower half of an aquifer (Sterret and Driscoll 2007). This logic and the lack of common methods for exploring feasible yield limits leads to a higher likelihood of wells that incur excess costs or physically fail to operate as DTW increases.

### Study Goals and Objectives

Our primary goal is to develop and demonstrate a new approach for quantifying well performance thresholds and related yields that specifically accounts for two key, interrelated hydro-economic impacts to pumping with changes in DTW. These impacts are: (1) the ability of an aquifer and well to satisfy pumping demand without physically failing to operate, and (2) the balance of pumping costs against what users are willing to pay for the water. The resulting analytical model, hereafter called the Hydro-Economic welL PERformance model (HELPER), may offer groundwater managers and stakeholders significant insight in managing DTW changes, calculating long-term feasible yields, and understanding how storage conditions drive well performance thresholds. Our study goal is supported by achieving three objectives:

- Quantifying interrelated physical and economic well performance thresholds using advanced pumping drawdown solutions to simulate water levels within a well;
- Maximizing feasible DTW and yields on either a physical or economic performance basis by optimizing well infrastructure design; and
- Testing and developing HELPER using a contemporary regional groundwater dataset and DTW-based planning and management regime.

HELPER is designed to simulate a single well, of any well screen interval and pump intake placement, pumping from any porous media aquifer. Therefore, while specific capacity drawdown solutions may be appropriate in some contexts, their limitations necessitate more advanced drawdown solutions to accomplish the goals of this study. HELPER can be applied to deterministic well infrastructure (i.e., existing or hypothetical wells) or well infrastructure optimized by the model for specified uses to maximize feasible DTW and yields. Other groundwater management concerns, such as water quality, groundwater–surface water interaction, and subsidence, are not considered.

## METHODS AND MATERIALS

Here we provide a general description of the HELPER framework and its key elements and assumptions. Additional details (e.g., descriptions of governing equations used to calculate drawdown, pumping costs, performance thresholds, and yields) are provided in the Supplemental Information. The source code for HELPER is also available via a public repository (*see* Open Research).

### Quantifying Well Performance Thresholds

HELPER numerically models the hydro-economic impacts of changes in DTW using a series of user-based, well-based, and aquifer-based parameters (Table 1). The initial DTW is provided by the user and then simulated to sequentially increase in 1-foot (0.3048-meter) increments. At each DTW, the model simulates a continuous and constant pumping session at the rate and period specified by the user. Well infrastructure and aquifer parameters are applied to analytical drawdown solutions to quantify how the water level in the well responds to pumping. The model uses the drawdown solutions to evaluate

**Table 1.** Input parameters supplied to HELPER by the user. Parameters required only for deterministic or model-optimized well infrastructure simulations are noted by "*" and "**", respectively. Elevations are in units above mean sea level (AMSL).

| Model parameters | Parameter units |
|---|---|
| User-based parameters: | |
| Units | Imperial or metric |
| Pumping rate | Gallons or liters per minute |
| Pumping period | Hours |
| Pumping sessions | Days per year |
| Price of pump power | Dollars per kilowatt-hour |
| Price of pump equipment | Dollars per horsepower or kilowatt |
| Price of well drilling and installation** | Dollars per foot or meter |
| Willingness-to-pay | Dollars per acre-foot or megaliter |
| Storage area providing yield | Acres or square kilometers |
| Well-based parameters: | |
| Wire-to-water well efficiency | Decimal percent |
| Well lifespan | Years |
| Pump lifespan | Years |
| Well loss coefficient | Seconds$^2$ per foot$^5$ or meter$^5$ |
| Well screen open area | Decimal percent |
| Well screen interval* | Feet or meters |
| Top of well screen elevation* | Feet or meters AMSL |
| Pump intake elevation* | Feet or meters AMSL |
| Cost of well drilling and installation* | Dollars |
| Well drilling diameter* | Feet or meters |
| Aquifer-based parameters: | |
| Land surface elevation | Feet or meters AMSL |
| Formation thickness | Feet or meters |
| Aquifer bottom elevation | Feet or meters AMSL |
| Initial depth-to-water elevation | Feet or meters AMSL |
| Horizontal hydraulic conductivity | Feet or meters per day |
| Vertical hydraulic conductivity | Feet or meters per day |
| Specific yield | None |
| Specific storage | Per foot or meter |

well performance at each DTW until it determines that well performance thresholds are reached.

Within this framework, HELPER calculates drawdown at a distance approximating the outer radius of the well screen gravel pack using the Theis (1935) and Hantush (1961a, 1961b) drawdown solutions (*see* Supplemental Information) in both confined and unconfined settings. The Theis (1935) solution is applied for fully penetrating wells, and a combination of the Theis (1935) and Hantush (1961a, 1961b) solutions is applied for partially penetrating wells. HELPER then evaluates whether or not sufficient potentiometric head is present to support pumping at each DTW. A limit, the operational failure threshold (OFT), is established at the DTW where the water level in the well (given as the DTW plus pumping drawdown at the end of the pumping period) reaches either the depth of the pump intake or the top of the well screen, whichever occurs first. Pumping beyond this limit may damage the well or pump (Smith and Comeskey 2010).

With drawdown estimated, HELPER next evaluates the affordability of pumping by calculating pumping costs on a dollars-per-volume basis (*see* Supplemental Information) and weighing them against the user's stated willingness-to-pay (WTP) for the water. A limit, the affordability failure threshold (AFT), is established at the DTW where pumping costs are equivalent to WTP.

WTP is by definition subjective and provided by the model user to establish the AFT. In this sense, the AFT is the DTW at which the user considers pumping unaffordable. For example, agricultural model users may know their WTP for particular crops or livestock, given local market conditions. Other model users may estimate their WTP. For another example, model users with a domestic water supply may wish to use the 2.5% of annual household income threshold for the affordability of water supply established by the U.S. Environmental Protection Agency (EPA 1998). Still other model users may wish to experiment with WTP to test a range of "what if" scenarios. In any case, the OFT and AFT are both provided by HELPER. Users who are uninterested in or insensitive to affordability constraints may simply choose to disregard AFT results.

HELPER considers three elements of pumping costs in units of dollars per volume: (1) the cost of energy required to lift water to land surface, (2) the cost of pump equipment, and (3) the cost of well drilling and installation. Delivering water beyond the well head at land surface bears additional energy and equipment costs that are unrelated to changes in DTW and not considered here. Both lifting and pump equipment costs are treated as functions of the lifting distance (i.e., the sum of the DTW and the drawdown calculated by HELPER). These costs are simulated to rise linearly with increasing DTW in confined settings (due to constant transmissivity and drawdown) and nonlinearly in unconfined settings (due to declining transmissivity and increasing drawdown). Well drilling and installation costs are related to the well infrastructure and are therefore unaffected by changes in DTW.

The energy cost to lift water to the land surface is calculated from the user-specified price of power and the HELPER-calculated lifting distance. The cost of lifting water per unit of distance is constant at a constant pumping rate, but the distance lifted is not because drawdown increases nonlinearly over the pumping period. Therefore, HELPER calculates lifting costs on a per-minute-of-pumping basis, sums them for the pumping period, and then divides the sum by the total production volume per pumping period. This calculated value represents the lifting cost in dollars per volume per pumping period at each tested DTW. User-specified pump equipment prices are given in units of dollars per energy unit to represent local market conditions, multiplied against the energy requirements of lifting, and distributed over the user-specified equipment lifespan and model-calculated aggregate pumping demand. The energy requirements for pumping equipment at each DTW are calculated from the maximum lifting distance at the final

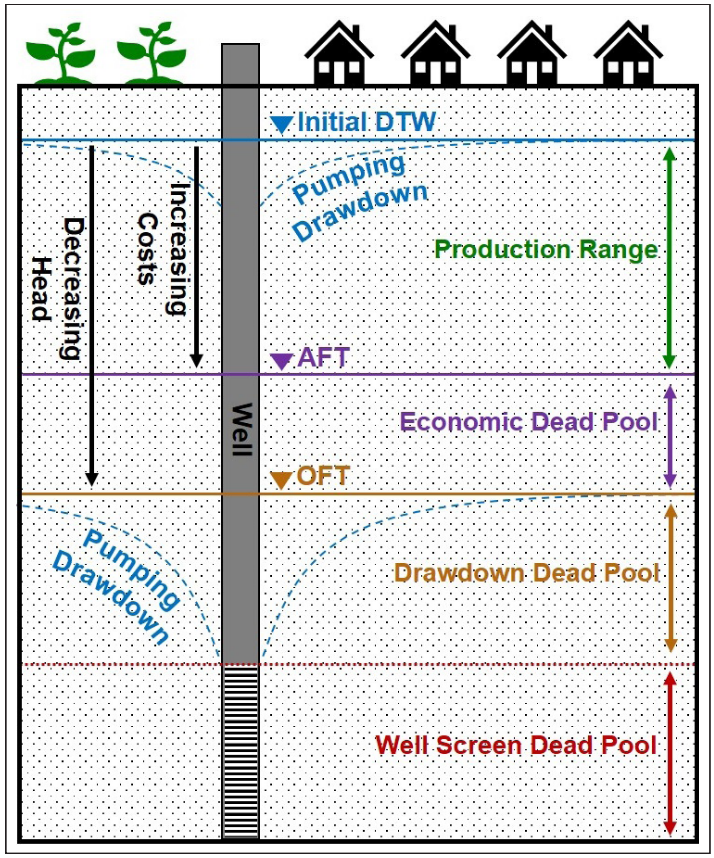


**Figure 1.** Conceptualization of the initial depth-to-water (DTW; blue line), pumping drawdown (dashed blue curve), the production range (green arrow), the affordability failure threshold (AFT; purple line), the economic dead pool (purple arrow), the operational failure threshold (OFT; orange line), the drawdown dead pool (orange arrow), and the well screen dead pool (red arrow) for an aquifer in the unconfined setting.

minute of the pumping period to ensure the pump is appropriately sized to support lifting water throughout the pumping period. The total cost of well drilling and installation—either user-specified for a deterministic well or generated by HELPER from user-specified drilling prices and model-optimized well infrastructure—is distributed over the user-specified well lifespan and the model-calculated aggregate pumping demand.

With the DTW of the operational and affordability thresholds established, we conceptualize the aquifer in four zones: the production range, the economic dead pool, the drawdown dead pool, and the well screen dead pool (Figure 1). The production range (the difference between the initial DTW and the shallower of either the OFT or the AFT) represents all potential DTW from which the well can produce without experiencing a hydro-economic well performance failure. The economic dead pool (the difference between the AFT and the OFT), if present, represents DTW at which pumping is not affordable at the user-specified WTP, but at which the well can physically operate without failure. The drawdown dead pool (the difference between the OFT and the shallower of the depth of the pump intake or the top of the well screen) represents the potentiometric head or saturated thickness that must be reserved from production to keep the well from failing to physically operate. The well screen dead pool is the saturated thickness of the aquifer reserved from production to support the well screen interval.

Finally, HELPER calculates a feasible local area storage yield at both the OFT and the AFT from the user-specified land surface area. This yield is given as the difference in the volume of water stored within the local area at the initial DTW and the volume stored at the well performance thresholds (*see* Supplemental Information). Recharge is not considered; yields represent only the volume of water produced from local storage if the aquifer were drained from the initial DTW to the well performance thresholds. If the AFT exceeds the OFT, the AFT yield is considered equivalent to the OFT yield. The land surface area component of the yield calculation is provided by the user and may therefore be tailored to the model user's needs. For example, a user may wish to calculate the land surface area from the well's radius of influence or on the basis of private property boundaries. These yields may be useful to regional yield planning and be particularly applicable in Texas or other jurisdictions that either consider in-situ groundwater to be owned by the overlying landowner (Edwards Aquifer Authority v. Day-McDaniel 2012) or that employ correlative groundwater rights regimes.

The input parameters supplied to HELPER to generate model results discussed below are provided in Table 2.

## Optimizing Well Design

An optimization scheme for HELPER is written to generate hypothetical well infrastructure that maximizes the OFT, AFT, and related yields. Parameters optimized include the depth of the well screen, the length of the well screen interval, the drilling diameter, and resultant pumping drawdown. Additional detail and a limited sensitivity analysis of a representative optimization solution is provided in the Supplemental Information.

To maximize the OFT, HELPER minimizes the sum of the drawdown dead pool and the well screen dead pool. To accomplish this, HELPER calculates a minimum well screen interval from well entry velocity limits (AWWA 2015), well up-flow velocity limits (Sterret and Driscoll 2007), and other factors. Next, HELPER calculates the optimal well screen interval by assessing how partial well penetration drawdown changes with variations in the well screen interval and by determining the configuration with the smallest combined drawdown dead pool and well screen dead pool. Concurrently, HELPER tests all possible placements of the screen interval within the saturated thickness of the aquifer to maximize the OFT. Thus, drawdown solutions that capture partially penetrating well effects, such as the Hantush (1961a, 1961b) solution, are crucial to the HELPER optimization logic.

Maximizing the AFT is similar but somewhat more complex. All three elements of pumping costs are related and evaluated simultaneously. HELPER first calculates pumping costs for a well configured to maximize the OFT. If those pumping costs are less than the user-specified WTP, the maximized AFT is considered equivalent to the maximized OFT. If not, HELPER calculates the least expensive well configuration with the ability to pump without experiencing an operational failure at the initial DTW. If these pumping costs exceed WTP, then no AFT is possible. If not, HELPER maximizes the AFT by conjunctively minimizing all three pumping cost elements at all possible well configurations.

## Integrating Regional Aquifer and Planning Data

To test and develop HELPER using a contemporary groundwater dataset and DTW-based planning regime, we evaluate model-optimized OFT and AFT yields for the Carrizo-Wilcox Aquifer (CWA) within the extent of the Post Oak Savannah Groundwater Conservation District (POSGCD; Figure 2). The term CWA is used to collectively describe four water-bearing formations. Those formations are, in order of increasing depth, the Carrizo Formation, Calvert Bluff Formation, Simsboro Formation, and Hooper Formation (Figure 2). CWA characteristics are derived and sourced from the Young et al. (2020) model developed for TWDB (*see also* Dutton et al. [2003]; Young et al. [2018]; Young and Kushnereit [2020]). Aquifer characteristics applied to this study include storage coefficients (specific yield and specific storage), hydraulic conductivity (horizontal and vertical), formation bottom depth, formation thickness, and initial (2010) DTW. A digital elevation model (NED 2013) is applied to this study area to represent the land surface.

We choose this study area for several key reasons. First, the CWA is Texas' largest aquifer by storage volume, with over 5.2 billion acre-feet (6.41 petaliters; Thompson et al. 2020) of groundwater stored close to growing population centers. Second, storage conditions for the CWA within the study area vary spatially, presenting unconfined conditions in shallow outcrop areas in the northwest and confined conditions in deep sub-crop areas in the southeast (Figure 2). Third, the groundwater flow model for the CWA (Young et al. 2020) is one of the more recent such models developed for TWDB. Fourth, the well field supplying water to San Antonio, Texas, via the Vista Ridge pipeline project, pumps from the CWA within the POSGCD, and the managed DTW in the area is anticipated to change significantly in the 2010–2069 planning period. To test and develop HELPER, we apply a representative managed

**Table 2.** The input parameters supplied to HELPER to demonstrate results. Elevations are provided in units above mean sea level (AMSL).

| Model parameter | Unconfined setting | Confined setting |
|---|---|---|
| User-based parameters: | | |
| Units | Imperial | Imperial |
| Pumping rate | 70 gallons per minute | 70 gallons per minute |
| Pumping period | 24 hours | 24 hours |
| Pumping sessions | 111 days per year | 111 days per year |
| Price of pump power | $0.10 per kilowatt-hour | $0.10 per kilowatt-hour |
| Price of pump equipment | $400 per horsepower | $400 per horsepower |
| Price of well drilling and installation | *see* Supplemental Information | *see* Supplemental Information |
| Willingness-to-pay | $100 per acre-foot | $100 per acre-foot |
| Storage area providing yield | 640 acres (1 square mile) | 640 acres (1 square mile) |
| Well-based parameters: | | |
| Wire-to-water well efficiency | 75% | 75% |
| Well lifespan | 50 years | 50 years |
| Pump lifespan | 10 years | 10 years |
| Nonlinear well loss coefficient | 5 seconds$^2$ per foot$^5$ | 5 seconds$^2$ per foot$^5$ |
| Well screen open area | 10% | 10% |
| Well screen interval | 40 feet | 40 feet |
| Top of well screen elevation | -120 feet AMSL | -820 feet AMSL |
| Pump intake elevation | -120 feet AMSL | -820 feet AMSL |
| Cost of well drilling and installation | $6,000 | $20,000 |
| Well drilling diameter | 0.5 feet | 0.5 feet |
| Aquifer-based parameters: | | |
| Land surface elevation | 100 feet AMSL | 100 feet AMSL |
| Formation thickness | 300 feet | 300 feet |
| Aquifer bottom elevation | -200 feet AMSL | -900 feet AMSL |
| Depth-to-water elevation | 100 feet AMSL | 100 feet AMSL |
| Horizontal hydraulic conductivity | 3 feet per day | 3 feet per day |
| Vertical hydraulic conductivity | 0.005 feet per day | 0.005 feet per day |
| Specific yield | 0.1 | 0.1 |
| Specific storage | 5 x 10$^{-6}$ per foot | 5 x 10$^{-6}$ per foot |

DTW change in the form of DFCs proposed for the POSGCD: Carrizo Formation +172 feet (+52 meters), Calvert Bluff Formation +179 feet (+55 meters), Simsboro Formation +336 feet (+102 meters), and Hooper Formation +214 feet (+65 meters; Westbrook 2021). Altogether, these factors highlight the importance of this section of the aquifer to regional water resources and establish that the model is tested from a wide variety of aquifer properties provided by an up-to-date dataset recently used for regional water planning that proposes significant DTW changes.

We provide two types of analyses of OFT- and AFT-based yields applying model-optimized well infrastructure for the extent of each geologic unit within the study area: (1) an analysis using the 2010 DTW (Young et al. 2020), and (2) an analysis where the DTW in each model grid cell is adjusted in accordance with the proposed DFCs (Westbrook 2021). In both analyses, we contemplate pumps set within the well screen interval. The depth of the top of the well screen is therefore applied as the limiting factor in OFT calculations. The first analysis is intended to demonstrate how HELPER could be useful to groundwater managers, planners, and stakeholders by identifying areas where spatially variable aquifer characteristics are or are not conducive to specified uses. The second analysis is intended to demonstrate how HELPER could be useful in

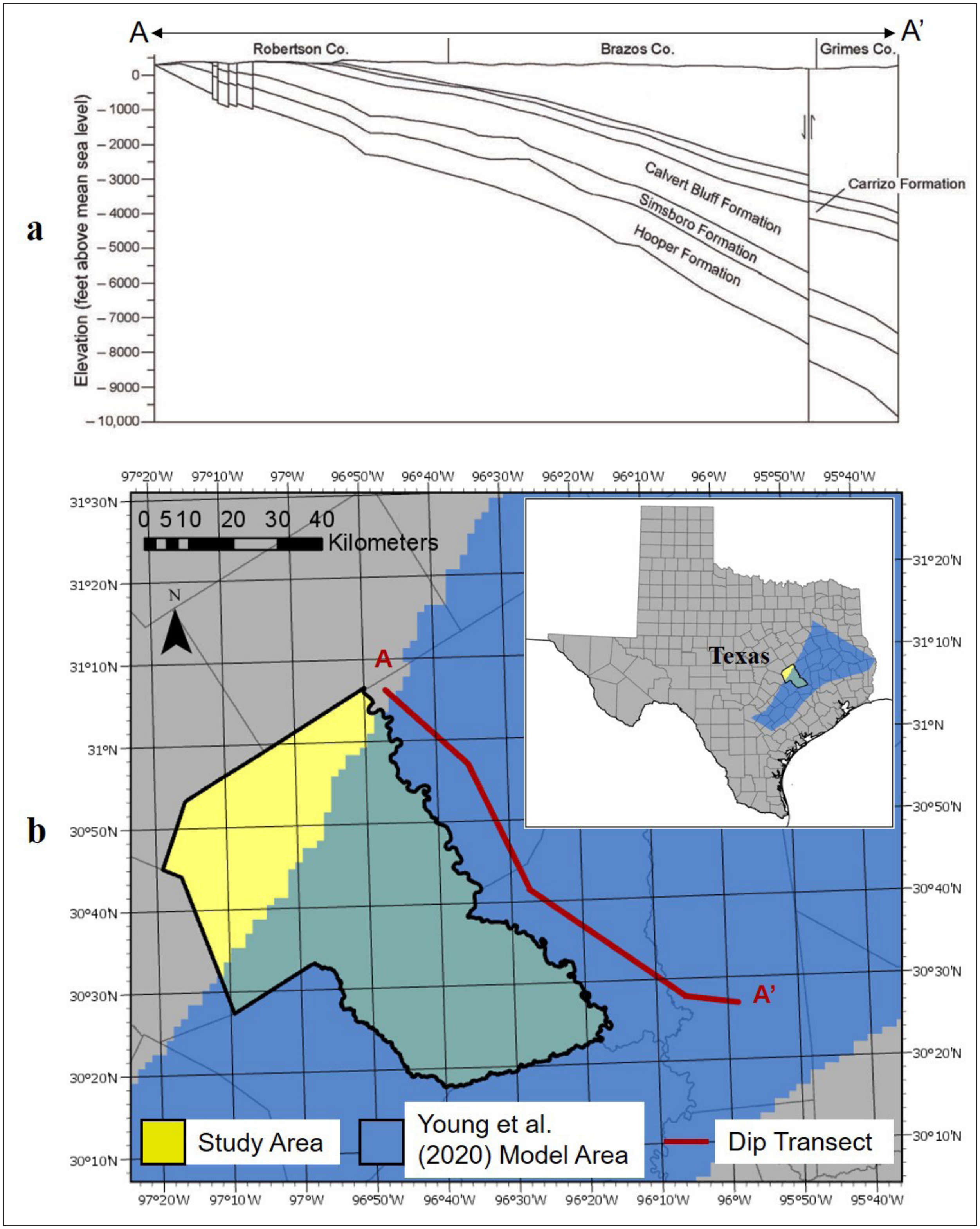


**Figure 2.** (a) Dip-oriented profile of the Carrizo-Wilcox Aquifer modified from Dutton et al. (2003). (b) A map of the study area showing the dip-oriented profile transect (red line, A to A') reproduced from Dutton et al. (2003), the extent of the Young et al. (2020) pumping and flow model for the Carrizo-Wilcox Aquifer (blue shading), and the extent of the Post Oak Savannah Groundwater Conservation District (yellow-shading with black outline).

evaluating how well performance may change with a planned change in DTW. In the latter analysis, we assume planned changes in DTW occur uniformly for every grid cell. However, proposed POSGCD DFCs discuss an average change in DTW throughout the study area (Westbrook 2021). Therefore, actual changes in DTW at any one location over the planning period may be less or greater than the average change in DTW considered by the proposed DFCs and this study.

In both analyses, we evaluate yields by simulating a single hypothetical well pumping from each grid cell. The parameters used in these regional HELPER analyses (Table 2) are the same as those applied to the single well approach discussed below, except that all aquifer-based parameters for both types of regional analysis are supplied on a cell-by-cell basis by the Young et al. (2020) flow model. The spatial resolution of grid cells demonstrated here is 1 square mile (2.59 square kilometers) to conform with the grid cell spatial resolution of the Young et al. (2020) flow model.

## Assumptions and Limitations

Where the initial DTW occurs above the depth of the aquifer (i.e., a confined aquifer state) but the final DTW falls below the top of the aquifer, HELPER considers the aquifer to "transition" to an unconfined state at the point where DTW is equivalent to the top of the aquifer. Upon transition, the relevant drawdown and yield coefficients are adjusted accordingly. The practicability and desirability of confined-to-unconfined aquifer transition, or any other DTW change, is not addressed by HELPER. The model simply assesses how well performance changes with changes in DTW.

We apply the Theis (1935) and Hantush (1961a, 1961b) unsteady-state drawdown solutions (*see* Supplemental Information) in both confined and unconfined settings. These drawdown solutions are imperfect, as neither was originally intended for use in unconfined settings. Therefore, HELPER may misstate drawdown and the OFT or AFT for some parameters (*see* Supplemental Information). However, these solutions demonstrate the utility of the HELPER approach in that they: (a) can be used to estimate pumping drawdown from a limited number of predefined aquifer and well characteristics; (b) capture the nonlinear increase in drawdown expected with increasing DTW in unconfined settings; (c) are unsteady-state solutions that by definition reflect the nonlinear increase in drawdown over any given pumping period; and (d) incorporate the partially penetrating well effects crucial to optimizing well design for maximizing performance thresholds and related yields. Alternative drawdown solutions that describe additional pumping dynamics (e.g., delayed gravity response of unconfined systems or leakage) could be similarly applied using the HELPER approach in future research.

We assume that DTW at the well fully recovers from pumping drawdown between pumping sessions; residual drawdown is not considered. This assumption would be invalid for a well that is pumped continuously. It may also result in the model overestimating the OFT and AFT because any well that does not fully recover from drawdown between pumping sessions and accumulates residual drawdown would begin the pumping session with well water levels that are deeper than simulated here. Future improvements to HELPER could quantify recovery between pumping sessions, but doing so would require users of the model to stipulate the resting period between each pumping session.

We assume that an appropriately sized pump is always available to the user (*see* Supplemental Information). The added costs of upgrading pumps before the end of a pump lifespan are not considered because the time between changes in DTW is not given. Additionally, there is a relationship between the pumping rate, pump equipment power, lifting distance, and pump efficiency. This relationship, typically described by a pump performance curve chart, shows that more energy is required as the lifting distance or pumping rate increases (Fipps 2015). Therefore, fluctuations in the pumping rate or pump efficiency may be expected for single-power pumps as the lifting distance increases under drawdown during the pumping period. HEPER does not account for these fluctuations; the pumping period, pumping rate, and wire-to-water well efficiency are specified by the user and assumed constant. Future research may seek to address this issue, but doing so may require the model user to specify pump performance curves for the full range of tested DTW, given that pump efficiency is a function of pump construction and cannot be determined analytically.

In determining the OFT, HELPER compares the water level within the well against the depth of the pump intake or the top of the well screen, whichever is shallower, to avoid damage to the well infrastructure and equipment. Pumping from well water levels beyond the depth of the pump intake cavitates the pump, and pumping from well water levels beyond the depth of the top of the well screen may cavitate the pump by inducing cascading flow or foul the well screen (Smith and Comeskey 2010). In either case, HELPER does not consider costs to repair or remediate the well. Therefore, HELPER evaluates the OFT by limiting the DTW such that no damage of any type or magnitude, regardless of whether it can be abided or remediated, occurs with the given well infrastructure. HELPER is also not designed for use with open-hole wells (i.e., wells that do not case or screen the saturated thickness of the aquifer). However, HELPER could be adapted and simplified to support open-hole well applications.

Further, HELPER does not consider how water levels within the well may be impacted by the drawdown of nearby wells. If drawdown from nearby wells influences water levels in the well simulated by HELPER, the model may overstate the OFT and

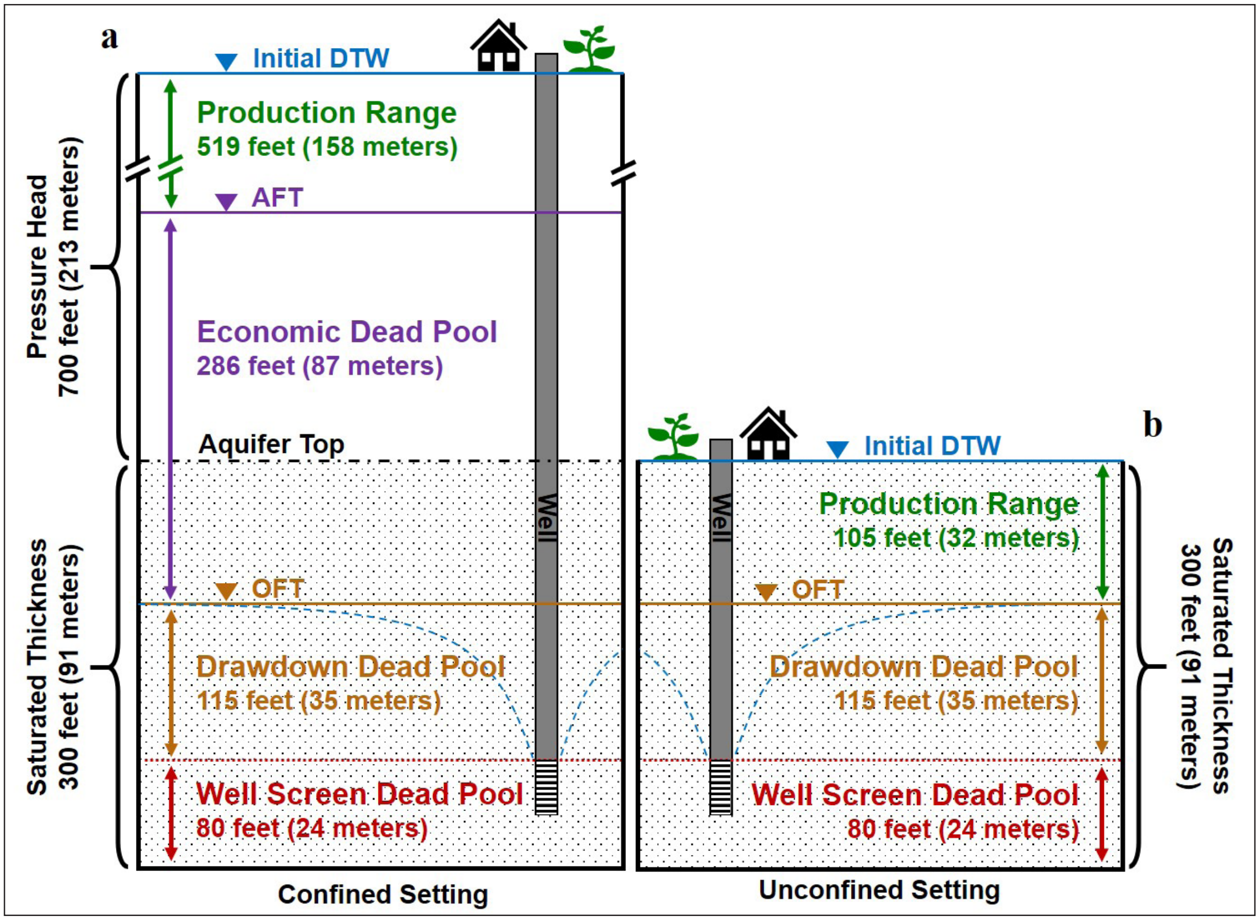


**Figure 3.** Depiction of hydro-economic well performance (HELPER) model results, showing the initial depth-to-water (DTW), affordability failure threshold (AFT), and operational failure threshold (OFT), for a well of determinative design (a) in a confined setting and (b) in an unconfined setting. Results are depicted to scale with two exceptions: there is a discontinuity in the potentiometric head of the confined setting (indicated by "//") for legibility, and the slope of the pumping drawdown curve is representational.

AFT. Future research is needed to adapt HELPER to address these impacts, but doing so will necessitate implementing mirror-well drawdown solutions that require the user to specify the spatial relationship of the wells, the timing of the pumping period for all relevant wells, and any relevant well water level recovery between pumping periods.

## RESULTS AND DISCUSSION

Two types of HELPER results are presented with accompanying discussion: (1) results for a single well of deterministic and optimized design in both confined and unconfined settings; and (2) results for model-optimized well infrastructure throughout the extent of the POSGCD at the 2010 and the proposed DFC DTW.

### Comparative Performance of a Single Well

To begin, we compare and contrast HELPER results for identical deterministic well infrastructure in both confined and unconfined settings (Figure 3) using comparable model parameters (Table 2). The saturated thickness in each setting is identical (300 feet or 91 meters) but occurs much deeper (+700 feet or +213 meters) in the confined setting. The initial DTW in both settings is also the same (land surface, a depth of 0 feet or meters). The deterministic well infrastructure for this simulation reflects an arbitrary well screen interval (40 feet or 12 meters) and well screen depth (terminating 40 feet or 12 meters above the bottom of the aquifer) to be a simple representation of a well that was not designed to maximize long-term well performance.

These results reveal important aspects of how well performance changes for a given use with changes in DTW. First, the OFT occurs within the saturated thickness at 195 feet (59 meters) above the bottom of the aquifer for both aquifer settings. This equivalency will necessarily be true unless the OFT in a confined setting occurs above the top of the aquifer, in which case the pumping rate in a comparable unconfined setting would not be possible without operational failure. The OFT equivalency occurs because a confined aquifer is considered transitioned to an unconfined state when DTW exceeds the top of the aquifer. In this sense, all aquifers are ultimately subject to the same operational limits created by the well screen dead pool and the drawdown dead pool, the latter of which increases nonlinearly with increasing DTW in unconfined or transitioned settings due to declining transmissivity (*see* Supplemental Information).

Second, while the OFT in the confined setting (805 feet or 245 meters) is 7.7 times deeper than the OFT in the unconfined setting (105 feet or 32 meters), the local area yield at the OFT in the confined setting (7,475 acre-feet or 9,220 megaliters) is only 10% larger than the same yield in the unconfined setting (6,803 acre-feet or 8,391 megaliters). This is because 87% of the change in DTW (from the initial DTW to the OFT) in the confined setting occurs within the confined pressure head, which yields water according to a confined storage coefficient of 0.0015. The unconfined storage coefficient, by contrast, is 0.10. This difference in storage coefficients means that the volume of water yielded for an equivalent change in DTW would be nearly two orders of magnitude greater in an unconfined setting than in a confined setting. Therefore, while the volume of water produced from the draining of pore space storage within the saturated thickness is the same in each setting (6,803 acre-feet or 8,391 megaliters), the volume produced by removing the full 700 feet (213 meters) of pressure head in the confined setting is only 672 acre-feet (829 megaliters).

Third, while the AFT in the confined setting (519 feet or 158 meters) is 4.9 times deeper than the AFT in the unconfined setting (which is constrained to be equivalent to the unconfined OFT of 105 feet or 32 meters), the local area yield at the AFT in the confined setting (498 acre-feet or 614 megaliters) is actually 93% less than the local area yield at the AFT in the unconfined setting (6,803 acre-feet or 8,391 megaliters). This difference in AFT yields between the two settings is again attributable to the applicable storage coefficients. In this simulation, where the confined setting AFT occurs within the confined pressure head of the system, all water yielded is from pressure head with none of the saturated thickness drained, whereas in the unconfined setting, the AFT occurs within the saturated thickness of the system.

Using these parameters (Table 2), a well performance analysis that does not consider drawdown and only evaluates an operational limit where DTW is equivalent to the top of the well screen would overestimate the OFT by 115 feet (35 meters) and the OFT yield by 7,347 acre-feet (9,062 megaliters) in both settings. Similarly, a well performance analysis that does not incorporate drawdown in calculating pumping costs would overestimate the AFT in the confined setting (wherein a binding economic limit applies) by 124 feet (38 meters) and the AFT storage area yield by 119 acre-feet (147 megaliters).

Comparing HELPER results for deterministic well infrastructure with results for optimized well infrastructure (using the same parameters, Table 2) demonstrates the significance of designing wells to maximize the OFT and AFT, particularly where performance thresholds fall within the saturated thickness of the aquifer. In the confined setting, HELPER-optimized well infrastructure increases the OFT by 8% (from 805 feet to 866 feet or 245 meters to 264 meters) and the corresponding yield by 53% (from 7,475 acre-feet to 11,412 acre-feet or 9,220 megaliters to 14,076 megaliters). An additional 61 feet (19 meters) of saturated thickness is recoverable at the optimized OFT. The AFT in the confined setting increases with HELPER-optimized well infrastructure by 19% (from 519 feet to 618 feet or 158 meters to 188 meters) and, given that both of the AFT limits occur within the confined pressure head of the aquifer, the corresponding yield also increases by 19% (from 498 acre-feet to 593 acre-feet or 614 megaliters to 731 megaliters).

In the unconfined setting, HELPER-optimized well infrastructure increases the OFT by 58% (from 105 feet to 166 feet or 32 meters to 51 meters) and the corresponding yield by 58% (from 6,803 acre-feet to 10,740 acre-feet or 8,391 megaliters to 13,248 megaliters). The AFT for both deterministic and model-optimized infrastructure in the unconfined setting is constrained to be equivalent to the OFT. As a result, the changes to the AFT and the local storage area yield at the AFT with optimized well infrastructure are equivalent to the depth and volume changes (+58%) at the OFT.

## Yield Performance Under Varied Regional Storage Conditions

POSGCD HELPER results at the 2010 DTW (Figure 4a–d) indicate that the principal driver of OFT yields is the saturated thickness of the aquifer (Figure 4e–h), not the amount of potentiometric head available. While deep and confined settings have more head available to support dead pools than shallow and unconfined settings, this relationship is only determinative of the OFT yield where the available head is insufficient to support pumping (where no yield is possible) or where the OFT falls within confined pressure head. Instead, the spatial variability in saturated thickness of each formation is more predictive of the spatial variability in OFT yields, due the importance of storage coefficients discussed above combined with the fact that 94% of the simulated OFT limits depict-

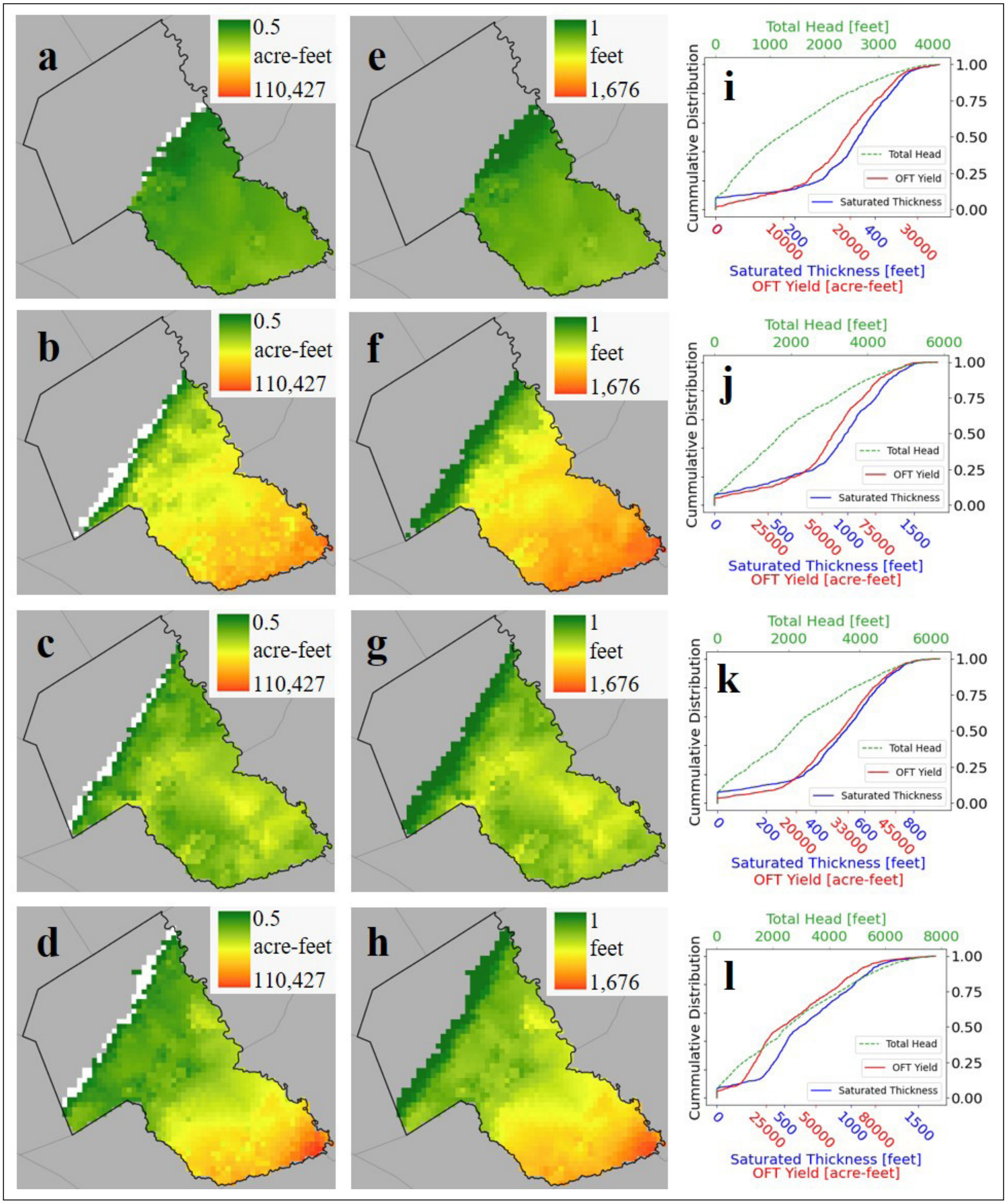


**Figure 4.** (a–d) Storage area yields at the operational failure threshold (OFT) for model-optimized well infrastructure, (e–h) saturated thickness, and (i–l) cumulative distribution functions for the (a, e, i) Carrizo Formation, (b, f, j) Calvert Bluff Formation, (c, g, k) Simsboro Formation, and (d, h, l) Hooper Formation. White cells (a–d) indicate that no OFT is possible at the given pumping rate.

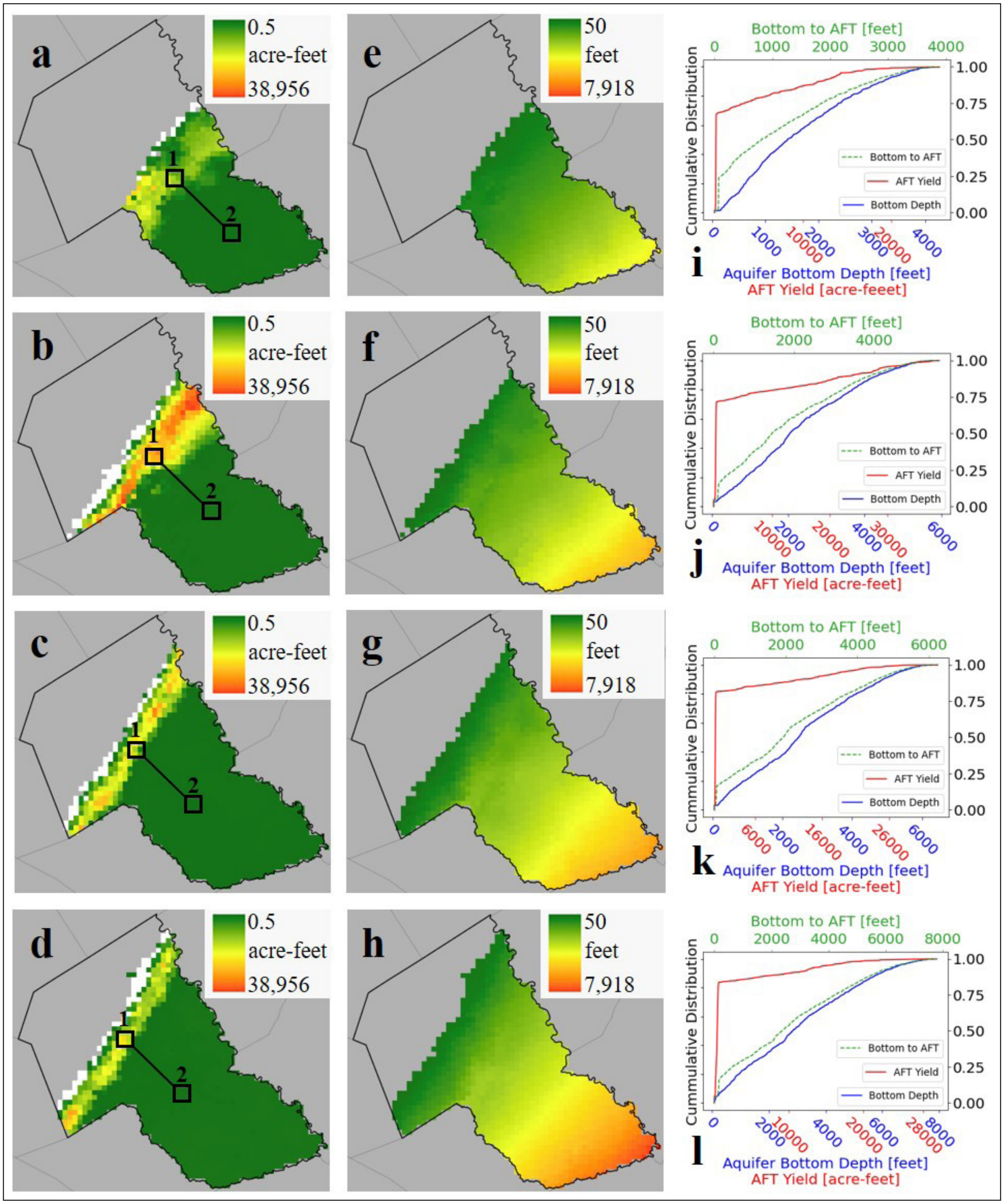


**Figure 5.** (a–d) Storage area yields at the affordability failure threshold (AFT) for model-optimized well infrastructure, (e–h) aquifer bottom depth, and (i–l) cumulative distribution functions for the: (a, e, i) Carrizo Formation, (b, f, j) Calvert Bluff Formation, (c, g, k) Simsboro Formation, and (d, h, l) Hooper Formation. White cells (a–d) indicate that no operational failure threshold is possible, and therefore no AFT is possible at the given pumping rate.

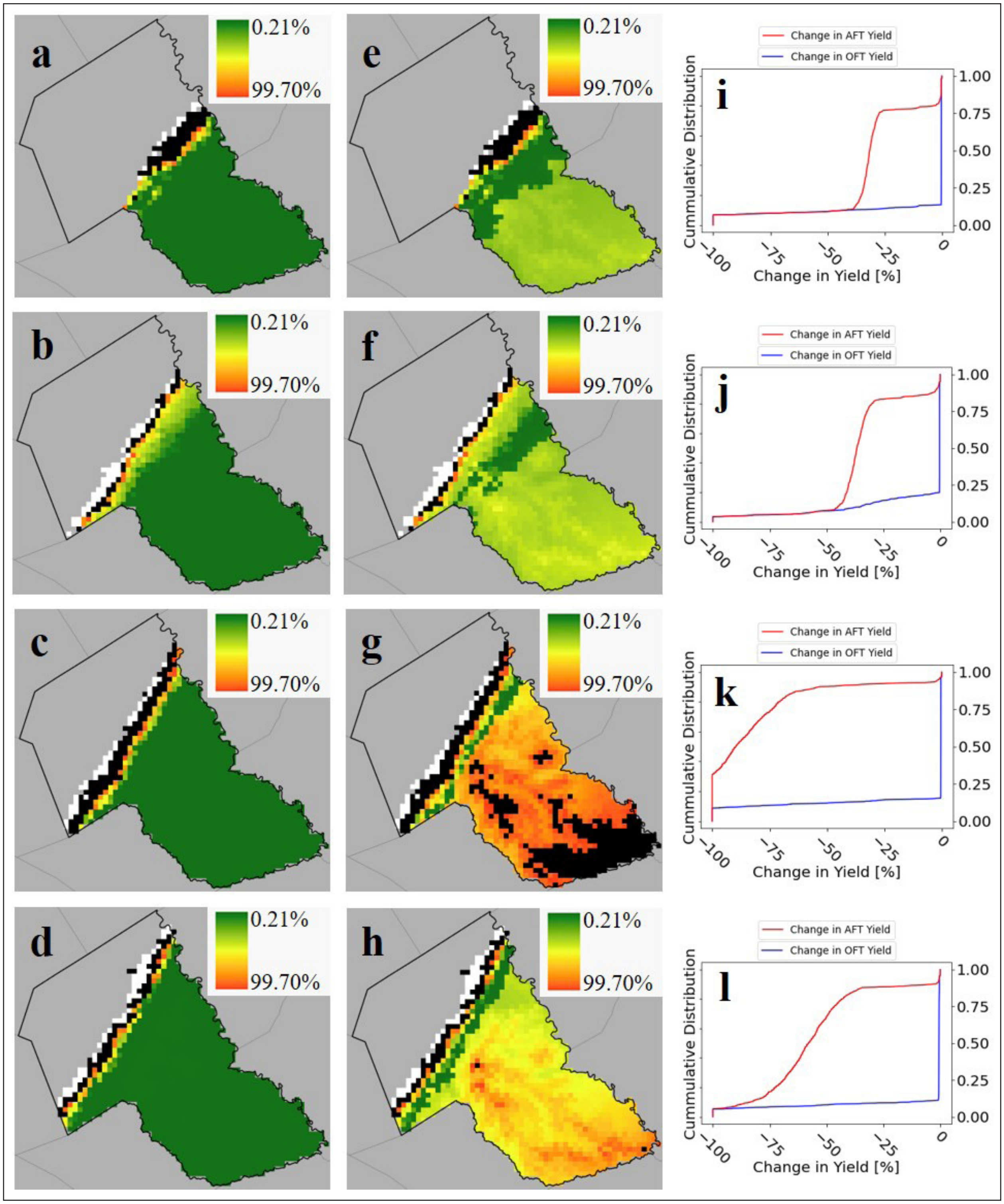


**Figure 6.** Percentage decline in storage area yields for model-optimized well infrastructure at the operational failure threshold (OFT; a–d) and affordability failure threshold (AFT; e–h) under the proposed change in depth-to-water (DTW) with cumulative density functions (i-l) for the (a, e, i) Carrizo Formation, (b, f, j) Calvert Bluff Formation, (c, g, k) Simsboro Formation, and (d, h, l) Hooper Formation. White cells indicate no OFT (or AFT) is possible at the 2010 DTW, and black cells indicate that either the OFT or AFT yield has declined by 100% (zero yield remaining) at the proposed change in DTW.

ed here fall within the saturated thickness. This causation is particularly visible in the Simsboro Formation (Figure 4c, 4g) and the Hooper Formation (Figure 4d, 4h), where deep and confined cells of comparable depth and available head present markedly different yields corresponding to differences in saturated thickness. Cumulative distribution functions of the OFT yield, saturated thickness, and available potentiometric head for each formation (Figure 4i–l) further demonstrate these relationships, showing a close correlation between yield and saturated thickness, not available head. These results suggest that to locate wells intended to maximize long-term yields, based on physical well operation, the relationship between the OFT and saturated thickness should be evaluated.

POSGCD HELPER results for the AFT at the 2010 DTW (Figure 5a–d) stand in almost direct contrast to comparable yields at the OFT. Here, the largest yields lie within a narrow, southwest to northeast trending band, where the AFT falls within the saturated thickness. Pumping from deep and confined cells in the southeast is economically feasible under these parameters; no cells report a yield of zero due to affordability limitations at the 2010 DTW. However, deep and confined yields in the southeast (where the AFT falls within the confined pressure head) are substantially less than those of unconfined or transitioned cells in the northwest (where the AFT falls within the saturated thickness). For instance, AFT yields for selected equivalent areas (9 square miles or 23 square kilometers) separated by only 11 miles (18 kilometers) in the Carrizo, Calvert Bluff, Simsboro, and Hooper formations are, respectively, 86, 97, 111, and 77 times greater in area one (northwest) than in area two (southeast; Figure 5a–d). These trends are largely driven by the costs of drilling and installation, which increase with aquifer depth (Figure 5e–h) from northwest to southeast, and the importance of yield storage coefficients discussed above. Cumulative distribution functions of the AFT yield, aquifer bottom depth, and the difference between the aquifer bottom depth and the AFT (Figure 5i–l) demonstrate that the AFT correlates strongly with the depth of the bottom of the aquifer. These results suggest that in deep and confined settings, subject to WTP, affordability constraints that consider aquifer and well infrastructure cost drivers may exert a greater influence on the feasibility of yields than physical operation constraints, and affordability may limit yields to production from confined pressure head. Furthermore, these results show that recoverability assessments that do not consider the hydro-economics of pumping (e.g., TERS) and related groundwater management structures, such as those proposed by Brady et al. (2016), may overstate recoverable groundwater in some settings where affordability is considered.

Finally, model results assessing the percentage change in the cell-by-cell local yield at the OFT and AFT, where DTW increases from the 2010 DTW pursuant to proposed DFCs (Figure 6), demonstrate important impacts. With respect to the OFT yield (Figure 6a–d), operational failures are identified in a narrow band of cells (representing 7%, 4%, 9%, and 5% of the surface area of the Carrizo, Calvert Bluff, Simsboro, and Hooper formations, respectively) trending from the southwest to the northeast; the feasible yield has decreased by 100%. No operational failures in cells immediately to the southeast of this trendline are identified, but yield at the OFT decreases by as much as 98% because the proposed DTW change and the OFT both occur within the saturated thickness of the cell. However, a relatively small percentage change in the OFT yield occurs within most of each formation in the study area (Figure 6i–l), because the proposed change in DTW occurs within the confined pressure head, while the OFT occurs within the saturated thickness of the aquifer.

The percent change in AFT yields (Figure 6e–h) provides important similarities to and differences from the changes in OFT yields. In this case, we see the same narrow, southwest to the northeast trending area of cells that experience a physical operation failure and similar yield impacts in areas immediately to the southeast of this trendline (up to a 98% decline in AFT yield). However, moving further to the southeast, two new trend groups that differ from the OFT yield results are apparent. First, a change in the AFT yield of 10% or less are identified in a band of cells (representing 19%, 10%, 4%, and 6% of the surface area of the Carrizo, Calvert Bluff, Simsboro, and Hooper formations, respectively), indicating that the AFT for these cells fall within the saturated thickness, while the proposed changes in DTW occur within the confined pressure head. All cells southeast of this band experience a decrease in the AFT yield ranging 11–100%, with notable impacts to the Simsboro Formation (Figure 6g), indicating that the AFT and the proposed change in DTW both occur within the confined pressure head of these cells. The cumulative distribution functions of changes to the OFT and AFT yields (Figure 6i–l) indicate that economic impacts of the proposed change in DTW are more pervasive than operational impacts.

Overall, these POSGCD OFT and AFT yield results indicate that locating and designing wells for maximized long-term production requires careful consideration of operational and economic factors. They suggest that the feasibility of yields for wells in shallow and unconfined (or transitioned) settings may be more limited by operational thresholds and less limited by affordability thresholds, while wells pumping from deep and confined settings may be limited in the opposite manner (Figures 4a–d, 5a–d). Similarly, OFT-based yields may be more sensitive to changes in DTW in shallow and unconfined, or transitioning, settings (Figure 6a–d), while AFT-based yields may be more sensitive in deep and confined settings (Figure 6e–g), particularly where the AFT and DTW change both occur within the pressure head of the aquifer.

## CONCLUSIONS

HELPER provides a new means for quantifying the interrelated hydro-economic impacts to pumping with planned or unplanned changes in DTW. The model applies physical laws and relationships to user-defined parameters describing aquifer storage conditions, pumping characteristics, and economic variables. Therefore, the model can generate results describing both the physical and economic limitations and impacts to production for any aquifer, well, and use case anywhere in the world, provided that the physical and economic parameters can be defined. As such, while this study focuses on and is contextualized within Texas, HELPER may provide insight and value to other, globally significant groundwater systems faced with current or future changes in DTW. Potential aquifer system candidates for study include but are not limited to the Central Valley in California, the North China Plains, the Indus-Ganges-Brahmaputra-Meghna in India, and the Great Artesian Basin in Australia. Some satellite systems (e.g., the Gravity Recovery and Climate Experiment) could point HELPER users toward groundwater resources that are chronically under threat, though we acknowledge that the spatiotemporal resolutions of most satellite systems are not well suited to determining how DTW is changing on a well-by-well basis.

HELPER improves on existing methods for evaluating well performance and related yields in two important ways. First, the model quantifies the short-term drawdown within a pumping well, the affordability of pumping, and the inherent linkages between the two. Other methods that do not fully explore these issues may overestimate hydro-economic performance thresholds. Second, by employing advanced drawdown solutions that account for partially penetrating well infrastructure, the model can optimize well designs to maximize the DTW from which the well can pump without failing, on either an operational or affordability basis.

HELPER results can be generated for existing infrastructure and could be used to answer questions such as: "Which wells will experience operational failures if DTW increases by *x*?" and "How much will pumping costs for current users rise if DTW increases by *x*?" HELPER answers to these questions could help groundwater managers and policymakers in jurisdictions that govern their resources using DTW-based metrics (such as DFCs) make better informed decisions as metrics are proposed, discussed, and adopted. For example, the socioeconomic impacts of DTW-based DFCs in Texas are currently largely unknown because no quantitative framework for assessing them has been available or established (GMA 8 2021; GMA 9 2021; GMA 13 2022; GMA 14 2022; GMA 15 2021). Future research using HELPER could also be leveraged by policy and economic interventions intended to mitigate the hydro-economic impacts of planned or unplanned changes in DTW by providing a quantified estimate of what those impacts might be. Similarly, stakeholders could use the HELPER framework to understand how their water supply, perhaps serving irrigation or domestic needs, may be impacted by a planned or potential change in DTW.

HELPER can also generate well infrastructure optimized to maximize the DTW from which the well can pump without experiencing a hydro-economic performance failure. These results could be used to answer questions such as: "Where is a supply of groundwater affordable or not?" and "What is the maximum feasible yield for a given use at this location?" These results could help a potential home buyer, real estate developer, or well owner to better understand their prospective access to groundwater prior to making financial commitments. HELPER could also be adapted by groundwater managers and policymakers considering DFCs in Texas for use in a manner like TERS, providing a range of feasible yield scenarios that account for hydro-economic well performance for any given aquifer, infrastructure, and use parameters. Additionally, the capacity of HELPER to provide optimized well infrastructure allows model users to explore the limits of feasible yields by effectively removing the constraints of well infrastructure upon yields and allowing model users to evaluate yield scenarios driven only by aquifer and use characteristics.

In its current form, use of HELPER requires some measure of access to technical information (in supplying the model with the requisite parameters) and technical skill (in downloading and executing the model code and interpreting results). Additionally, while the model has been designed to utilize multi-core processing for multi-well analyses *(see* Open Research), generating results for a large number of wells requires significant computational processing power. However, HELPER could be operationalized by deploying it to a web-based platform and, if needed, high-performance computing centers. Moreover, technical information barriers could be reduced by offering users the ability to populate certain well and aquifer parameters by linking the platform to existing public databases. A representative hydrostratigraphic column depicting aquifer geometries and well performance thresholds, or a similar visualization approach, could ease the interpretation of model results.

## ACKNOWLEDGMENTS

This work was supported by the University of Texas – Bureau of Economic Geology, Planet Texas 2050 (a University of Texas grand challenge), the State of Texas Advanced Resource Recovery (STARR) program, and the University of Texas – Bureau of Economic Geology Excellence Fund for Water Research and Policy. The opinions, findings, and conclusions of this work are those of the authors and do not necessarily reflect the views of supporting organizations. The authors wish to thank the anonymous reviewers and editor for their thoughtful comments and suggestions as well as author Justin C. Thompson's doctoral dissertation committee, Jay Banner, Sheila Olmstead, and Daniella Rempe, for their guidance and internal reviews.

## OPEN RESEARCH

Aquifer characteristics applied to this study for the central CWA are derived and sourced from the geodatabase provided by TWDB and associated with the groundwater flow model for the central portion of the Sparta, Queen City and Carrizo-Wilcox Aquifers (Young et al. 2020). The flow model is available from https://s3.amazonaws.com/gw-models/czwx-_c_qcsp_v3.02.7z, and the methods and details are described by Dutton et al. (2003), Young et al. (2018), and Young and Kushnereit (2020). The digital elevation model applied to this study is the 2013 National Elevation Dataset available from https://www.usgs.gov/core-science-systems/ngp/tnm-delivery/gis-data-download?qt-science_support_page_related_con=0#.

A repository hosted by the Texas Data Repository and located at https://doi.org/10.18738/T8/Z4QT6Q contains the following data:

1. The source code for HELPER (previously known as the Well Performance Model) in Python 3 format originally authored in Jupyter Notebooks in two forms:
   a. A form for generating results for a single well with the option to apply user-specified well infrastructure or model-optimized well infrastructure generated by HELPER (Thompson 2021a).
   b. A form for generating regional results using multicore processing on a cell-by-cell basis using model-optimized well infrastructure generated by HELPER (Thompson 2021b).
2. The parameter tables applied to HELPER for simulations discussed in this work.
3. The aquifer characteristics extracted and processed from the Young et al. (2020) groundwater flow and pumping model.

## REFERENCES

[AWWA] American Water Works Association. 2015. Standard for Water Wells. Denver, CO: American Water Works Association. https://doi.org/10.12999/AWWA.A100.15.

Barlow, Paul M., and Stanley A. Leake. 2012. Streamflow Depletion by Wells: Understanding and Managing the Effects of Groundwater Pumping on Streamflow. Reston, VA: U.S. Geological Survey. https://pubs.usgs.gov/circ/1376/pdf/circ1376_barlow_report_508.pdf.

Barlow, Paul M, and Eric G. Reichard. 2010. "Saltwater Intrusion in Coastal Regions of North America." Hydrogeology Journal 18: 247–260. https://doi.org/10.1007/s10040-009-0514-3.

Bradley, Robert G. 2016. Aquifer Assessment 16-01: Supplemental Report of Total Estimated Recoverable Storage for Groundwater Management Area 10. Austin, TX: Texas Water Development Board. https://www.twdb.texas.gov/groundwater/docs/AA/AA16-01_TERS.pdf.

Brady, Ross, Wayne Beckerman, Amber Capps, Braden Kennedy, Peyton McGee, Kayla Northcut, Mason Parish, Abdullilah Qadeer, Shuting Shan, and James Griffin. 2016. Reorganizing Groundwater Regulation in Texas. College Station, TX: Texas A&M University. https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/187041/2016%20Final%20Report%20Reorganizing%20Groundwater%20Regulation%20in%20Texas%20%283%29.pdf?sequence=1&isAllowed=y.

de Frutos Cachorro, Julia, Katrin Erdlenbruch, and Mabel Tidball. 2014. "Optimal Adaptation Strategies to Face Shocks on Groundwater Resources." Journal of Economic Dynamics and Control 40: 134–153. https://doi.org/10.1016/j.jedc.2014.01.005.

Döll, Petra, Hannes Müller Schmied, Carina Schuh, Felix T. Portmann, and Annette Eicker. 2014. "Global-scale Assessment of Groundwater Depletion and Related Groundwater Abstractions: Combining Hydrological Modeling with Information from Well Observations and GRACE Satellites." Water Resources Research 50 (7): 5698–5720. https://doi.org/10.1002/2014WR015595.

Domenico, P. A., D. V. Anderson, C. M. Case. 1968. "Optimal Ground-Water Mining." Water Resources Research 4 (2): 247–255. https://doi.org/10.1029/WR004i002p00247.

Dutton, Allan R., Bob Harden, Jean-Philippe Nicot, and David O'Rourke. 2003. Groundwater Availability Model for the Central Part of the Carrizo-Wilcox Aquifer in Texas. Austin, TX: Bureau of Economic Geology, the University of Texas at Austin. http://www.twdb.texas.gov/groundwater/models/gam/czwx_c/czwx_c_full_report.pdf.

Edwards Aquifer Authority v. Day-McDaniel, 08-0964 (Tex. Feb. 24, 2012). https://caselaw.findlaw.com/tx-supreme-court/1595644.html.

[EPA] U.S. Environmental Protection Agency. 1998. Information for States on Developing Affordability Criteria for Drinking Water. Washington, DC: U.S. Environmental Protection Agency Office of Water. https://nepis.epa.gov/Exe/ZyPDF.cgi/2000272B.PDF?Dockey=2000272B.PDF.

Feng, Wei, Min Zhong, Jean-Michel Lemoine, Richard Biancle, Hou-Tse Hsu, and Jun Xia. 2013. "Evaluation of Groundwater Depletion in North China Using the Gravity Recovery and Climate Experiment (GRACE) Data and Ground-based Measurements." Water Resources Research 49 (4): 2110–2118. https://doi.org/10.1002/wrcr.20192.

Fipps, Guy. 2015. Calculating Horsepower Requirements and Sizing Irrigation Supply Pipelines. College Station, TX: Texas Agricultural Extension Service, Texas A&M University. https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/87739/pdf_669.pdf?sequence=1&isAllowed=y.

Foster, Timothy, Nicholas Brozović, and Adrian P. Butler. 2016. "Effects of Initial Aquifer Conditions on Economic Benefits from Groundwater Conservation." Water Resources Research 53 (1): 744–762. https://doi.org/10.1002/2016WR019365.

Gailey, Robert M., Jay R. Lund, and Josué Medellín-Azuara. 2019. "Domestic Well Reliability: Evaluating Supply Interruptions from Groundwater Overdraft, Estimating Costs and Managing Economic Externalities." Hydrogeology Journal 27: 1159–1182. https://doi.org/10.1007/s10040-019-01929-w.

Gailey, Robert M., Jay R. Lund, and Jon R. Phillip. 2022. "Domestic-well Failure Mitigation and Costs in Groundwater Management Planning: Observations from Recent Groundwater Sustainability Plans in California, USA." Hydrogeology Journal 30: 417–428. https://doi.org/10.1007/s10040-021-02431-y.

Gisser, Micha, and David A. Sánchez. 1980. "Competition Versus Optimal Control in Groundwater Pumping." Water Resources Research 16 (4): 638–642. https://doi.org/10.1029/WR016i004p00638.

[GMA 8] Groundwater Management Area 8. 2021. Groundwater Management Area 8 Desired Future Conditions Explanatory Report. Austin, TX: Texas Water Development Board. https://www.twdb.texas.gov/groundwater/dfc/docs/2021/GMA8_DFCExpRep_2021.pdf?d=3609.

[GMA 9] Groundwater Management Area 9 Joint Planning Committee. 2021. Groundwater Management Area 9 2021 Explanatory Report for Desired Future Conditions for Major and Minor Aquifers. Austin, TX: Texas Water Development Board. https://www.twdb.texas.gov/groundwater/dfc/docs/2021/GMA9_DFCExpRep_2021.pdf?d=3609.

[GMA 13] Groundwater Management Area 13 Joint Planning Committee. 2022. 2021 Joint Planning Desired Future Conditions Explanatory Report. Austin, TX: Texas Water Development Board. https://www.twdb.texas.gov/groundwater/dfc/docs/2021/GMA13_DFCExpRep_2021.pdf?d=3609.

[GMA 14] Groundwater Conservation Districts in Groundwater Management Area 14. 2022. Desired future conditions explanatory report. Austin, TX: Texas Water Development Board. https://www.twdb.texas.gov/groundwater/dfc/docs/2021/GMA14_DFCExpRep_2021.pdf?d=3609.

[GMA 15] Groundwater Management Area 15 Joint Planning Committee. 2021. 2021 Joint Planning Desired Future Conditions Explanatory Report. Austin, TX: Texas Water Development Board. https://www.twdb.texas.gov/groundwater/dfc/docs/2021/GMA15_DFCExpRep_2021.pdf?d=3609.

Hantush, Mahdi S. 1961a. "Drawdown Around a Partially Penetrating Well." Journal of the Hydraulics Division 87 (4): 83–98. https://doi.org/10.1061/JYCEAJ.0000633.

Hantush, Mahdi S. 1961b. "Aquifer Tests on Partially Penetrating Wells." Journal of the Hydraulics Division 87 (5): 171–194. https://doi.org/10.1061/JYCEAJ.0000639.

Jacob, C. E. 1947. "Drawdown Test to Determine Effective Radius of Artesian Well." Transactions of the American Society of Civil Engineers 112 (1): 1047–1064. https://doi.org/10.1061/TACEAT.0006033.

Jasechko, Scott, and Debra Perrone. 2021. "Global Groundwater Wells at Risk of Running Dry." Science 372 (6540): 418–421. https://doi.org/10.1126/science.abc2755.

Joodaki, Gholamreza, John Wahr, and Sean Swenson. 2014. "Estimating the Human Contribution to Groundwater Depletion in the Middle East, from GRACE Data, Land Surface Models, and Well Observations." Water Resources Research 50 (3): 2679–2692. https://doi.org/10.1002/2013WR014633.

Kanazawa, Mark T. 1992. "Econometric Estimation of Groundwater Pumping Costs: a Simultaneous Equations Approach." Water Resources Research 28 (6): 1507–1516. https://doi.org/10.1029/92WR00198.

Michael, A. M., S. D. Khepar, and S. K. Sondhi. 2008. Water Wells and Pumps – 2nd Edition. New Delhi, India: Tata McGraw-Hill Publishing Company Ltd.

Misstear, Bruce, David Banks, and Lewis Clark. 2017. Water Wells and Boreholes, 2nd Edition. Chichester, West Sussex, UK: John Wiley & Sons Ltd.

Nanteza, Jamiat, Caroline R. de Linage, Brian F. Thomas, and James S. Famiglietti. 2016. "Monitoring Groundwater Storage Changes in Complex Basement Aquifers: an Evaluation of the GRACE Satellites over East Africa." Water Resources Research 52 (12): 9542–9564. https://doi.org/10.1002/2016WR018846.

[NED] Nation Elevation Dataset. 2013. 10 Square Meter Resolution. U.S. Geological Survey. https://www.usgs.gov/core-science-systems/ngp/tnm-delivery/gis-data-download?qt-science_support_page_related_con=0#.

Neuman, Shlomo P. 1972. "Theory of Flow in Unconfined Aquifers Considering Delayed Response of the Water Table." Water Resources Research 8 (4): 1031–1045. https://doi.org/10.1029/WR008i004p01031.

Neuman, Shlomo P. 1974. "Effect of Partial Penetration on Flow in Unconfined Aquifers Considering Delayed Gravity Response." Water Resources Research 10 (2): 303–312. https://doi.org/10.1029/WR010i002p00303.

Olsthoorn, Theo. 2016. Transient Groundwater Flow 1.0.1 Analytical Solutions Documentation. Delft, Netherlands: IHE Delft Institute for Water Education. https://olsthoorn.readthedocs.io/en/latest/index.html.

Provencher, Bill, and Oscar Burt. 1993. "The Externalities Associated with the Common Property Exploitation of Groundwater." Journal of Environmental Economics and Management 24: 139–158. https://doi.org/10.1006/jeem.1993.1010.

Reichard, Eric G., Zhen Li, and Caroline Hermans. 2010. "Emergency User of Groundwater as a Backup Supply: Quantifying Hydraulic Impacts and Economic Benefits." Water Resources Research 46 (9). https://doi.org/10.1029/2009WR008208.

Smith, Stuart A., and Allen E. Comeskey. 2010. Sustainable Wells: Maintenance, Problem Prevention, and Rehabilitation. Boca Raton, FL: CRC Press.

Smith, Ryan G., Rosemary Knight, Jingyi Chen, Jessica A. Reeves, Howard A. Zebker, Thomas Farr, and Zhen Liu. 2017. "Estimating the Permanent Loss of Groundwater Storage in the Southern San Joaquin Valley California." Water Resources Research 53 (3): 2133–2148. https://doi.org/10.1002/2016WR019861.

Smith, Ryan G., Rosemary Knight, and Scott Fendorf. 2018. "Overpumping Leads to California Groundwater Arsenic Threat." Nature Communications 9. https://doi.org/10.1038/s41467-018-04475-3.

Sterret, Robert J., and Fletcher G. Driscoll. 2007. Groundwater & Wells, 3rd Edition. New Brighton, MN : Johnson Screens.

Stoner, R. F., D. M. Milne, and P. J. Lund. 1979. "Economic Design of Wells." Quarterly Journal of Engineering Geology 12 (2): 63–78. https://doi.org/10.1144/GSL.QJEG.1979.012.02.01.

Theis, Charles V. 1935. "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage." American Geophysical Union Transactions 16: 519–524. https://doi.org/10.1029/TR016i002p00519.

Thompson, Justin C. 2021a. "Jupyter Notebook WPM (Version 1.0)." Texas Data Repository. https://doi.org/10.18738/T8/Z4QT6Q.

Thompson, Justin C. 2021b. "Jupyter Notebook WPM_RegionLauncher (Version 1.0)." Texas Data Repository. https://doi.org/10.18738/T8/Z4QT6Q.

Thompson, Justin C., Charles W. Kreitler, and Michael H. Young. 2020. "Exploring Groundwater Recoverability in Texas: Maximum Economically Recoverable Storage." Texas Water Journal 11 (1): 152–171. https://doi.org/10.21423/twj.v11i1.7113.

Tsur, Yacov, and Amos Zemel. 2004. "Endangered Aquifers: Groundwater Management under Threats of Catastrophic Events." Water Resources Research 40 (6). https://doi.org/10.1029/2003WR002168.

Turner, Sean W. D., Mohamad Hejazi, Catherine Yonkofski, Son H. Kim, and Page Kyle. 2019. "Influence of Groundwater Extraction Costs and Resource Depletion Limits on Simulated Global Nonrenewable Water Withdrawals over the Twenty-First Century." Earth's Future 7 (2): 123–135. https://doi.org/10.1029/2018EF001105.

Wada, Yoshihide, Ludovicus P. H. van Beek, Cheryl M. van Kempen, Josef W. T. M. Reckman, Slavek Vasak, and Marc F. P. Bierkens. 2010. "Global Depletion of Groundwater Resources." Hydrology and Land Surface Studies 37 (20). https://doi.org/10.1029/2010GL044571.

Westbrook, Gary. 2021. Letter to Groundwater Conservation Districts Located in Groundwater Management Area 12 Regarding Proposed Desired Future Conditions (DFCs). Milano, TX: Post Oak Savannah Groundwater Conservation District. https://posgcd.org/wp-content/uploads/2021/06/GMA-12-Proposed-DFCs_v2.pdf.

Williams, Dennis E. 1985. "Modern Techniques in Well Design." Journal - American Water Works Association 77 (9): 68–74. https://doi.org/10.1002/j.1551-8833.1985.tb05608.x.

Young, Steven, Marius Jigmond, Toya Jones, and Tom Ewing. 2018. Final Report: Groundwater Availability Model for the Central Portion of the Sparta, Queen City, and Carrizo-Wilcox Aquifers. Austin, TX: INTERA Incorporated. https://www.twdb.texas.gov/groundwater/models/gam/czwx_c/czwx_c.asp.

Young, Steven, and Ross Kushnereit. 2020. GMA 12 Update to the Groundwater Availability Model for the Central Portion of the Sparta, Queen City, and Carrizo-Wilcox Aquifers. Austin, TX: INTERA Incorporated. https://www.twdb.texas.gov/groundwater/models/gam/czwx_c/czwx_c.asp.

Young, Steven, Marius Jigmond, Toya Jones, Tom Ewing, and Ross Kushnereit. 2020. Geodatabase Associated with the Groundwater Availability Model for the Central Portion of the Sparta, Queen City, and Carrizo-Wilcox Aquifers, version 3.02. Austin, TX: INTERA Incorporated. https://s3.amazonaws.com/gw-models/czwx_c_qcsp_v3.02.7z.

Zimmerman, W. R. 1990. "Finite Hydraulic Conductivity Effects on Optimal Groundwater Pumping Rates." Water Resources Research 26 (12): 2861–2864. https://doi.org/10.1029/WR026i012p02861.

# Supplemental Information

## INTRODUCTION

This supplemental information contains a detailed description of the mathematical solutions (Equations 1–28) employed by the Hydro-Economic welL PERformance model (HELPER) to calculate the operational failure threshold *(OFT)*, the affordability failure threshold *(AFT)*, and related yields. Even greater detail can be obtained by consulting the HELPER code found in the data repository associated with this study (*see* Open Research). Also included are a limited sensitivity analysis of key parameters for a representative simulation; a description of how certain model parameters were pre-processed prior to being supplied to HELPER; and a table of well drilling and installation prices sourced by a survey of Texas licensed water well drillers conducted by the authors in 2020.

### Modeling Methods

Certain equations described below are derived for imperial units. Please note however that the version of HELPER available from the data repository (*see* Open Research) accepts either metric or imperial units for model parameters and returns results in the same form.

HELPER numerically simulates the hydro-economic impacts of changes in depth-to-water *(DTW)* using a series of user-based, well-based, and aquifer-based parameters supplied by the model user. The user-given initial *DTW* is simulated to increase in 1-foot (0.3048-meter) increments until well performance thresholds are reached. HELPER assesses how well performance responds in the event that the increased *DTW* were to occur by simulating drawdown (the short-term fluctuations in water levels occurring within a well over a pumping period) and pumping costs.

*DTW* is the depth of the potentiometric surface. It is the depth that would be recorded by a monitoring well or in a well that has been locally rested from pumping. In unconfined settings, the aquifer is not pressurized, and *DTW* is also known as the water table. In confined settings, the weight of overlying formations combined with a relatively impermeable barrier at the top of the aquifer, or confining layer, pressurizes the aquifer. This pressure results in a *DTW* that occurs above the depth of the aquifer itself or even above the land surface, a condition also known as "artesian." *DTW* changes regionally over time and is related to, but often separate and distinct from, drawdown. Where *DTW* increases, the water produced from a confined setting results from reducing the aquifer pressure, the aquifer itself remains fully saturated. In an unconfined setting, the water produced from increasing *DTW* results from decreasing the saturated thickness of the aquifer, which is also known as "dewatering."

The pumping rate *(Q)*, in units of volume per minute, is given by the model user. HELPER assumes *Q* is constant throughout the pumping period. Therefore, the effect of changes in pump efficiency on *Q* as water levels within the well change over the course of a pumping period are not considered. HELPER calculates pumping period demand as:

$$Demand = Q\ Period\ 60 \tag{1}$$

where *Demand* is the total volume produced by each pumping period, *Period* is the user-specified time period for each pumping session in units of hours, and 60 is minutes per hour.

### Operational Well Performance

HELPER calculates pumping period drawdown at the well on a minute-by-minute basis at each simulated *DTW* in two forms to determine the *OFT.* First, HELPER calculates drawdown for a fully penetrating well in the transient state using the Theis (1935) solution (Equations 2 and 3). Theis (1935) drawdown assumes the full saturated thickness of the aquifer is screened by the well and therefore flow to the well screen is horizontal. The solution is given to HELPER as:

$$s_T = \frac{Q}{4\,\pi\,T}\int_u^\infty \frac{e^{-y}}{y}\,dy \tag{2}$$

$$u = \frac{r^2 \, S}{4 \, T \, t} \tag{3}$$

where $s_T$ is Theis (1935) pumping drawdown in units of length; $T$ is the transmissivity of the aquifer in units of length squared per day; $r$ is the radial distance from the center of the well to the point of drawdown calculation in units of length (given to HELPER as a distance approximating the outer radius of the well screen gravel pack, estimated as twice the drilling radius); $S$ is the dimensionless storage coefficient (specific yield in unconfined settings and storativity in confined settings); and $t$ is the time of pumping expressed in fractions of days for each minute of pumping.

Drawdown in unconfined settings may exhibit a delayed gravity response wherein the drawdown curve (i.e., drawdown over time) exhibits three distinct phases (Figure SI 1): an early time phase where drawdown conforms to the Theis (1935) solution, where $S$ is storativity; a middle time phase where drawdown becomes relatively constant; and a late time phase where drawdown conforms to the Theis (1935) solution, where $S$ is specific yield. Many factors, including aquifer anisotropy, the measure of $r$ (Figure SI 1), and the length of $t$, determine the particular impact of delayed gravity response upon the drawdown curve (Neuman 1972). HELPER does not employ drawdown solutions specifically designed to capture a delayed gravity response. Instead, in unconfined settings, the Theis (1935) solution is applied, where $S$ is given as specific yield. HELPER users may evaluate anticipated delayed gravity response and select a value for the "specific yield" parameter employed by HELPER in unconfined settings (Table 1) that meets their needs. To generate results for this study, a specific yield value of 0.1 (Table 2), not a storativity value, is applied. An analysis of drawdown generated using the commercial software package Aqtesolv and the Neuman (1974) solution for delayed gravity response indicates that for the parameters applied here (Table 2), the Theis (1935) solution employing specific yield (0.1) for $S$ closely approximates the delayed gravity response solution (Figure SI 2).

Second, because this study is interested in evaluating partially penetrating wells and minimizing the drawdown and well screen dead pools in model-optimized wells, HELPER calculates the additional partial penetration drawdown arising from non-horizontal flow near the well screen (Equation 4). Partial penetration drawdown applied here employs a modified Bessel function, second order, and therefore overstates partial penetration drawdown in early pumping time in the unconfined setting. HELPER also assumes the well screen interval is continuous and is therefore not designed for intermittent well screen intervals. The HELPER solution for partial penetration drawdown is adapted from a Python implementation developed by Olsthoorn (2016), which is derived from Hantush (1961a, 1961b) as:

$$s_H = \frac{Q}{2\,\pi\,T}\,\frac{2\,B}{\pi\,d}\,\sum_{n=1}^{\infty}\frac{1}{n}\left[\sin\left(\frac{n\,\pi\,a}{B}\right) - \sin\left(\frac{n\,\pi\,b}{B}\right)\right]\,\cos\left(\frac{n\,\pi\,z}{B}\right)\,K_0\left(\frac{n\,\pi\left(\frac{Kz}{Kx}\right)r}{B}\right) \tag{4}$$

where $s_H$ is Hantush (1961a, 1961b) partially penetrating well drawdown in units of length; $B$ is the saturated thickness of the aquifer in units of length; $a$ is the difference from the top of the aquifer (in the confined setting) or from $DTW$ (in the unconfined setting) to the bottom of the well screen in units of length; $b$ is the difference from the top of the aquifer (in the confined setting) or from $DTW$ (in the unconfined setting) to the top of the well screen in units of length; $z$ is the difference from the top of the aquifer (in the confined setting) or from $DTW$ (in the unconfined setting) to the point of drawdown measure in units of length; $K_0$ is the Bessel function; $Kz$ is the vertical hydraulic conductivity in units of length per time; and $Kx$ is the horizontal hydraulic conductivity in units of length per time. HELPER limits $n$ in accordance with an iteration limit, given here as 500, and an accuracy tolerance threshold, given here as 0.001 feet, in order to limit the computational power required to arrive at a result (*see* Open Research for the full model code). These limits may be adjusted by the HELPER user as needed or desired.

The contribution of turbulent flow well friction losses to pumping drawdown is captured by the Jacob (1947) solution as:

$$s_J = C\,Q^2 \tag{5}$$

where $C$ is the nonlinear (turbulent) well loss coefficient in units of time squared over length to the fifth power.

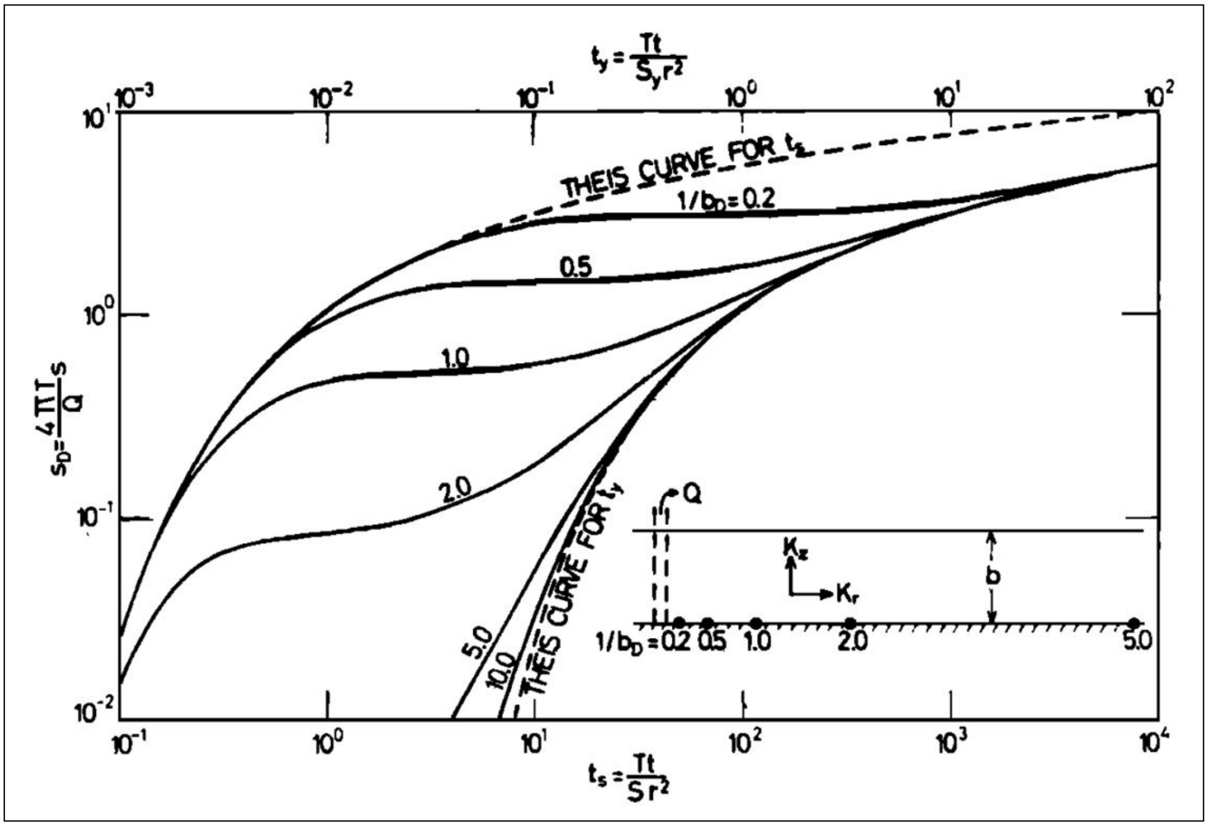


**Figure SI 1.** Dimensionless drawdown (y-axis) versus dimensionless time (x-axis) showing the significance of *r* upon delayed gravity response in comparison to Theis (1935) solutions, where *S* is storativity (denoted by "ts" in the figure) and where *S* is specific yield (denoted by "ty" in the figure) storage coefficients.

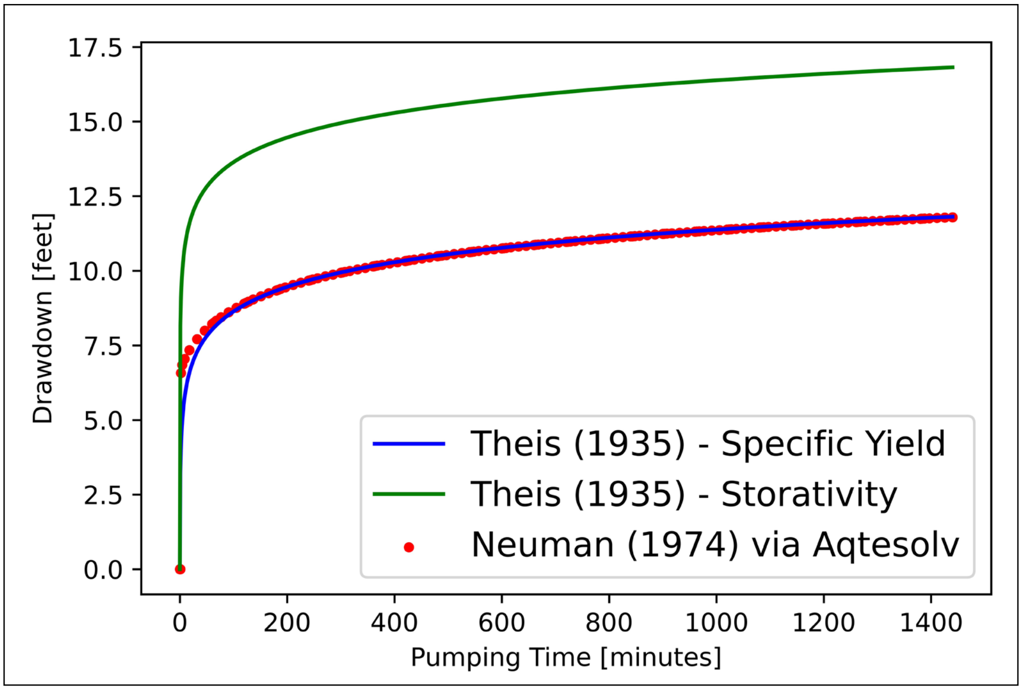


**Figure SI 2.** Drawdown for the study parameters (Table 2) generated using the commercial software package Aqtesolv and the Neuman (1974) solution for delayed gravity response (red scatter plot); HELPER employing the Theis (1935) solution, where *S* is storativity (green curve); and HELPER employing the Theis (1935) solution, where *S* is specific yield (blue curve).

In unconfined settings, HELPER recalculates *T,* the product of the saturated thickness of the aquifer and the user-given horizontal hydraulic conductivity of the aquifer, at each simulated, hypothetical $DTW$ because saturated thickness declines with increasing $DTW$. Therefore, $s_T$ and $s_H$ are both functions of $DTW$ and increase nonlinearly with increasing $DTW$ in these settings. Thus, HELPER estimates total pumping drawdown *(s)* at the well at each minute of pumping for fully penetrating wells (Equation 6) and partially penetrating wells (Equation 7) as a function of $DTW$ as:

$$s(DTW) = s_T + s_J \tag{6}$$

$$s(DTW) = s_T + s_J + s_H \tag{7}$$

HELPER establishes the $OFT$ (Equation 8) at the simulated, hypothetical $DTW$ where the maximum *s,* which occurs at the final minute of the user-given pumping period, is equivalent to the distance between the simulated, hypothetical $DTW$ and the depth of the pump intake or the top of the well screen, whichever is shallower. The $OFT$ is therefore defined by HELPER as:

$$OFT = Bar - \max\ s(DTW) \tag{8}$$

where *Bar* is the depth, in units of length, of the shallower of the pump intake or the top of the well screen.

It is necessary to maintain a certain distance between the water level occurring within the pumping well (i.e., $DTW$ + max *s(DTW)*) and the depth of the pump intake to avoid vortexing that may damage the pump or well. This distance is known as net positive suction head required. Net positive suction head required is not relevant to HELPER for performance optimized wells (*see* Operational Performance Maximization). For deterministic well infrastructure, the net positive suction head required, if known for the given *Q,* may be functionally addressed by the HELPER user by reducing the depth of the given pump intake by the relevant net positive suction head required distance.

Note that when calculating *s* and the *OFT,* HELPER assumes that water levels at the well fully recover to the simulated, hypothetical *DTW* between pumping sessions. This assumption would not be appropriate for wells that are pumped continuously and may result in HELPER underestimating s in wells wherein the *DTW* does not fully recover between pumping periods. Additionally, HELPER does not consider the potential impact of drawdown induced by nearby pumping wells (i.e., well interference) to simulated well water levels.

## Affordability Well Performance

HELPER calculates pumping costs on a dollars-per-volume basis. Pumping costs considered by the model are comprised of three components: (1) lifting costs, (2) pump equipment costs, and (3) well drilling and installation costs.

The total lifting distance (Equation 9) necessary to bring water to land surface is expressed in length on a per-minute-of-pumping basis and incorporates the drawdown calculations given above as it is calculated by HELPER as:

$$Lift = DTW + s(DTW) \tag{9}$$

*Lift* does not consider pressure requirements at the discharge point.

Lifting costs (*LC;* Equation 10), or the energy costs of lifting the water at the given pumping rate to land surface, are expressed in dollars per volume. *LC* is derived from water horsepower (Fipps 2015) and *Lift* on a per-minute-of-pumping basis and given to HELPER as:

$$LC = \left(\sum_{n=1}^{\max t} \frac{Lift\ Q\ 745.7\ P_{pwr}}{3960\ Eff}\right) / \ Demand \tag{10}$$

where *Q* is expressed in units of gallons per minute; 3960 is a conversion constant from feet-gallons per minute to horsepower; *Eff* is the user-given wire-to-water well efficiency in units of decimal percent; 745.7 is a conversion constant from horsepower to watts; $P_{pwr}$ is the user-given price of power in units of dollars per watt-minute; and *Demand* is expressed in the same volumetric units as the pumping rate (in this case, gallons).

Pump equipment costs (*EC;* Equation 11) are expressed in dollars per volume. *EC* is derived from the user-given equipment price in units of dollars per unit of power and *Lift* and then distributed over the production lifespan of the equipment. *EC* is given to HELPER as:

$$EC = \frac{\max Lift\ Q\ P_{Eq}}{3960\ Eff\ Life_p\ Days\ Demand} \tag{11}$$

where $Q$ is expressed in units of gallons per minute; $P_{Eq}$ is the user-given price of pump equipment in the user's local market in units of dollars per horsepower; $Life_P$ is the user-given lifespan of the pump equipment in units of years; *Days* is the user-given number of pumping sessions in units of days per year; and *Demand* is expressed in the same volumetric units as the pumping rate (in this case gallons).

Well drilling costs (*DC;* Equation 12) are considered by HELPER to be fully inclusive of all drilling and installation costs with the exception of pump equipment costs (e.g., drilling, casing, screening, discharge pipe, gravel pack, grout, backfill, and wellhead pad). *DC* is expressed in dollars per volume, distributed over the production lifespan of the well, and given to HELPER as:

$$DC = \frac{WC}{Life_W\ Days\ Demand} \tag{12}$$

where *WC* is the user-given total cost of well drilling and installation in dollars, and $Life_W$ is the user-given lifespan of the well in units of years.

Altogether, pumping costs (*PC;* Equation 13) are considered by HELPER to be the sum of *LC, EC,* and *DC.* Both *LC* and *EC* incorporate *Lift,* which is derived from *s(DTW)* and *DTW.* Therefore, *PC* is a function of *DTW* and is given in units of dollars per volume as:

$$PC(DTW) = LC + EC + DC \tag{13}$$

HELPER establishes the *AFT* (Equation 14) at the simulated, hypothetical *DTW* where *PC(DTW)* is equivalent to the user-given willingness-to-pay *(WTP)* for the water pumped. The *AFT* is therefore defined by HELPER as:

$$PC(DTW) = WTP \rightarrow AFT = DTW \tag{14}$$

where *WTP* is expressed in the same units of dollars per volume as *PC(DTW).*

Additionally, because HELPER does not consider well remediation costs that might be generated where water levels in the well under pumping exceed the *OFT,* HELPER constrains the *AFT* in relation to the *OFT* as:

$$AFT \leq OFT \tag{15}$$

## Performance Optimized Wells

HELPER is designed to quantify well performance for existing or hypothetical well infrastructure specified by the user. In those cases, the following model parameters are specified by the user and considered fixed: the length of the well screen interval, the elevation of the top of the well screen, the elevation of the pump, well drilling and installation costs, and the well drilling radius. However, HELPER is also designed to simulate a hypothetical well whose infrastructure is optimized by the model to maximize the *OFT, AFT,* and related yields. In that case, parameters which are otherwise user-specified are estimated by means of additional HELPER calculations and new model inputs, the well screen open area and the price of well drilling and installation, are introduced for that purpose.

## Operational Performance Maximization

HELPER begins by calculating the well screen radius (Equation 16) from the pumping rate and common limits on well up-flow velocity to reduce friction losses in the well casing pipe (Sterret and Driscoll 2007), which is generally the same size as the well screen (Michael et al. 2008), as water travels to the pump intake. The well screen radius is assumed to be at least 2 inches (5.08 centimeters) and is calculated as:

$$Screen_r = \frac{12\sqrt{\frac{\frac{4\,Q}{V_{up}}}{\pi}}}{2} \geq 2 \qquad (16)$$

where $Screen_r$ is the well screen radius expressed in inches; 12 is a conversion constant from feet to inches; $Q$ is expressed in units of cubic feet per second; and $V_{up}$ is the limit on the well up-flow velocity, given here as 5 feet per second (Sterret and Driscoll 2007).

HELPER then uses the well screen radius to calculate the minimum well screen interval (Equation 17) from the pumping rate and common limits on well entrance velocity to reduce turbulent flow. This calculation is modified from Williams (1985) and given to HELPER as:

$$Screen_m = \frac{Q\,V_{enter}\,Screen_r\,Open}{235} \qquad (17)$$

where $Screen_m$ is the minimum well screen interval expressed in feet; 235 is a conversion constant; $V_{enter}$ is the limit on the well entrance velocity in feet per second, given here as 0.1 feet per second (AWWA 2015); $Q$ is expressed in units of gallons per minute, and *Open* is the user-given well screen open area in decimal percent.

HELPER then optimizes the length of the well screen interval (Equation 18) by evaluating changes in the length of the well screen interval against changes in the partial penetration drawdown (Equation 4) to minimize the combined well screen dead pool and pumping range dead pool and thereby maximize the production range. To do this, HELPER assumes the well screen begins at the bottom of the aquifer and calculates $s_H$, which is a function of the length and placement of the screen interval, at initial *DTW* conditions for well screen interval lengths ranging from the minimum well screen interval to a maximum of full penetration (screening the entire saturated thickness of the aquifer) by iteratively increasing the well screen interval length in 1-foot (0.3048-meter) increments. Where HELPER determines that adding 1 foot (0.3048 meters) of well screen reduces partial penetration drawdown by more than 1 foot (0.3048 meters), it considers the greater well screen interval length preferable and continues to iterate increased well screen interval lengths until this balance is no longer true. The well screen interval length that provides the smallest combined well screen interval length and $s_H$ is considered optimal and is applied to the remainder of OFT-related calculations as the optimized well screen interval length, or:

$$Screen_l = \min\left(s_H(DTW_0; Screen_l) + Screen_l\right) \qquad (18)$$

where $Screen_l$ is the optimized length of the well screen interval, and $DTW_0$ is the initial *DTW* provided by the model user.

Similarly, because $s_H$ is also a function of the placement of the well screen interval within the aquifer, HELPER also evaluates where $Screen_l$ placement within the aquifer minimizes the sum of $s_H$ and the saturated thickness of the aquifer reserved by the screen by iteratively decreasing the depth of the bottom of the well screen interval from the bottom of the aquifer in 1-foot (0.3048-meter) increments as:

$$Screen_{opt} = \min s_H(DTW; Screen_l; Screen_{opt}) \qquad (19)$$

where $Screen_{opt}$ is the optimized depth of the bottom of the well screen.

For model-optimized well infrastructure, HELPER assumes that the depth of the pump intake occurs within the well screen interval, and therefore the maximized *OFT* for model-optimized well infrastructure is given as:

$$OFT' = Screen_{opt} - Screen_l - \max\, s(DTW) \qquad (20)$$

**Table SI 1.** Market prices for well drilling and installation based on the diameter of the drilled well (*x*), which are applied to HELPER affordability calculations for model-optimized wells and which may be adjusted by the user to reflect local market prices.

| Drilling diameter (*x*) | Drilling price |
|---|---|
| 6 in (15.24 cm) (assumed minimum) = *x* | \$20/ft (\$6.10/m) |
| 6 in (15.24 cm) < *x* < 8 in (20.32 cm) | \$40/ft (\$12.19/m) |
| 8 in (20.32 cm) <= *x* < 10 in (25.40 cm) | \$60/ft (\$18.29/m) |
| 10 in (25.40 cm) <= *x* < 12 in (30.48 cm) | \$80/ft (\$24.38/m) |
| 12 in (30.48 cm) <= *x* < 12 in (35.56 cm) | \$100/ft (\$30.48/m) |
| 14 in (35.56 cm) <= *x* < 16 in (40.64 cm) | \$120/ft (\$36.58/m) |
| 16 in (40.64 cm) <= *x* < 18 in (45.72 cm) | \$150/ft (\$45.72/m) |
| 18 in (45.72 cm) <= *x* < 20 in (50.80 cm) | \$200/ft (\$60.96/m) |
| 20 in (50.80 cm) <= *x* | \$250/ft (\$76.20/m) |

## Affordability Performance Maximization

For a model-optimized well, HELPER estimates well drilling and installation costs using a series of calculations and parameters. The well drilling diameter (Equation 21) is estimated as 1.5 times the calculated well screen diameter and is assumed to be a minimum of 6 inches (15.24 centimeters). It is given to HELPER in inches as:

$$Drill_{diam} = Screen_r \; 2 \; 1.5 \geq 6 \tag{21}$$

where $Drill_{diam}$ is the estimated drilling diameter expressed in units of inches, and 2 is a conversion constant from radius to diameter.

Well drilling and installation costs are then estimated (Equation 22) based on the calculated drilling diameter, the model-calculated drilling depth (i.e., $Screen_{opt}$), and user-given prices inclusive of all drilling and installation costs. Drilling and installation prices are user-given on a dollars-per-unit-distance basis for a range of drilling diameters and are estimated here from a limited survey of well drillers in Texas conducted in 2020 by the authors (SI Table 1), which may be adjusted by users to reflect local market prices. Estimated well drilling and installation costs for model-optimized wells *(DC')* are given to HELPER in units of dollars per volume as:

$$DC' = \frac{P_{drill}(Drill_{diam})\; Screen_{opt}}{Life_W \; Days \; Demand} \tag{22}$$

where $P_{drill}$ is the market price of drilling and installation expressed on a dollars-per-unit-distance basis.

To maximize the *AFT* for model-optimized well infrastructure, HELPER calculates pumping costs for model-optimized well infrastructure *(PC')* in a similar manner as described above (Equations 10–13). But because *LC, EC,* and *DC'* are all functions of the model-optimized well infrastructure (because *LC* and *EC* are functions of $s_H$), HELPER evaluates *PC'* where $Screen_{opt}$ is simulated at depths decreasing in 1-foot (0.3048-meter) increments until $Screen_{opt} – Screen_l$ is equivalent to the top of the aquifer in confined settings or until an operational failure occurs. Thus, HELPER minimizes *PC'* as:

$$\min PC' = \min LC(DTW; Screen_{opt}; Screen_l) + EC(DTW; Screen_{opt}; Screen_l) + DC(DTW; Screen_{opt}; Screen_l) \tag{23}$$

HELPER establishes the *AFT* for model-optimized well infrastructure at the deepest simulated, hypothetical *DTW* and well infrastructure where minimized *PC'* is equivalent to *WTP.* The *AFT* for model-optimized well infrastructure is therefore defined by HELPER as:

$$\min PC(DTW; Screen_{opt}; Screen_l) = WTP \rightarrow AFT' = DTW \tag{24}$$

and

$$AFT' \leq OFT' \tag{25}$$

## Yield Calculation

HELPER considers *OFT* and *AFT* (or *OFT'* and *AFT'*) to calculate feasible yield volumes based on those limits and the user-defined area of interest. The yield calculation methods (Equations 26–28) are adapted from those provided by the Texas Water Development Board in its reports on total estimated recoverable storage (Bradley 2016) and vary based on the aquifer storage conditions:

$$Unconfined\ Yield = Area\ (DTW_0 - Limit)\ Sy \tag{26}$$

$$Confined\ Yield = Area\ (DTW_0 - Limit)\ St \tag{27}$$

$$Transitioned\ Yield = Area\ (DTW_0 - Top)\ St + Area\ (Top - Limit)\ Sy \tag{28}$$

where *Unconfined Yield* is the yield volume produced by an aquifer presenting unconfined storage conditions; *Area* is the land surface area of the aquifer producing the yield in length squared; *Limit* is the depth of the *OFT* or the *AFT* (or the depth of the *OFT'* or *AFT'*) in length; *Sy* is the specific yield storage coefficient of the aquifer (dimensionless); *Confined Yield* is the yield volume produced by an aquifer presenting confined storage conditions; *St* is the confined storativity storage coefficient (dimensionless); *Transitioned Yield* is the yield volume produced wherein *Limit* appears within the saturated thickness of an aquifer initially presenting confined conditions; and *Top* is the depth of the top of the aquifer initially presenting confined storage conditions in length.

## Sensitivity Analysis of Model Parameters

To evaluate the sensitivity of the *OFT* and *AFT* in an unconfined setting for a model-optimized well, we test combinations of key parameters, holding all other parameters (Table 2) constant. For the *OFT,* we test *Q* values ranging from 1 gallon (3.79 liters) per minute to 500 gallons (1,892 liters) per minute in 50 equal increments and horizontal hydraulic conductivity *(Kx)* values ranging from 1 foot (0.3048 meters) per day to 10 feet (3.048 meters) per day in 10 equal increments. For the *AFT,* we test *Q* values ranging from 1 gallon (3.79 liters) to 100 gallons (379 liters) per minute in 50 equal increments and *WTP* ranging from $25 per acre-foot ($20.27 per megaliter) to $50 per acre-foot ($40.54 per megaliter) in 10 equal increments.

To calculate the numerical sensitivity of the *OFT* and *AFT* to the relevant tested range of *Q, Kx,* and *WTP* parameters, we fit planar curves to data generated by HELPER (Figure SI 3). Planar curve solutions are generated using the commercial software package TableCurve 3D (version 4.0), and the solutions chosen are selected on the basis of balancing maximized R-squared *($R^2$)* values, minimized fitted standard error, and a minimized number of fitting coefficients. For both the *OFT* and *AFT,* we then proceed to take the partial derivatives for each of the tested parameters: *Q* and *Kx* for the *OFT,* and *Q* and *WTP* for the *AFT.* Where the absolute value of one partial derivative exceeds the other, we conclude that HELPER results for *OFT* and *AFT* are more sensitive to that model parameter.

The planar curve solution chosen to mathematically describe the *OFT* results generated by HELPER for the sensitivity analysis presented in this study is given as:

$$OFT = \frac{(a + b \times \ln(x) + c \times \ln(y))}{(1 + d \times \ln(x) + e \times \ln(y))} \tag{29}$$

where the value of *a* is 92.013458; the value of *b* is -12.914434; the value of *c* is 11.487508; the value of *d* is -0.1112429; the value of *e* is 0.094929013; *x* is the tested *Q;* and *y* is the tested *WTP.* When fitted to the *OFT* sensitivity analysis data generated by HELPER for this study, the $R^2$ value is 0.9958, and the fitted standard error is 1.3669.

The partial differential equation solution to Equation 29 with respect to *x* (which is *Q)* is given as:

$$\frac{\partial OFT}{\partial x} = \frac{a\,d - e\,b\ln(y) - b + c\,d\ln(y)}{x\,(1 + d\ln(x) + e\ln(y)\,)^2} \tag{30}$$

The partial differential equation solution to Equation 29 with respect to *y* (which is *Kx)* is given as:

$$\frac{\partial OFT}{\partial y} = \frac{(c\,d - e\,b)\,\ln(x) + c - e\,a}{y\,(1 + d\,\ln(x) + e\,\ln(y))^2} \tag{31}$$

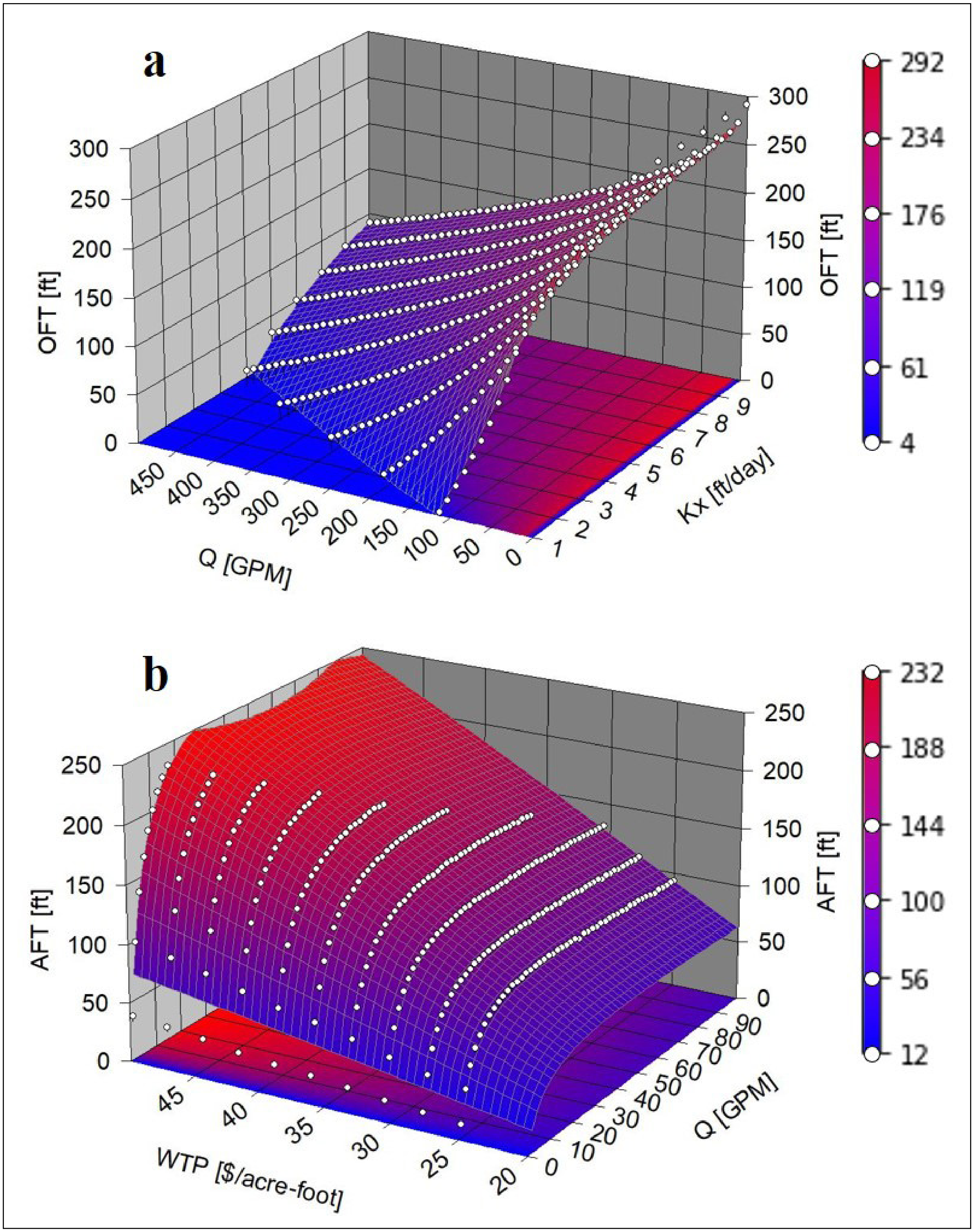


**Figure SI 3.** Planar curves fitted to data generated by HELPER using the sensitivity analysis parameter space for (a) the *OFT* and (b) the *AFT* using the TableCurve 3D commercial software package. Hot colors (reds) indicate high *OFT/AFT* values, and cool colors (blues) indicate low *OFT/AFT* values. White circles indicate *OFT/AFT* data generated by HELPER.

The planar curve solution chosen to mathematically describe the *AFT* results generated by HELPER for the sensitivity analysis presented in this study is given as:

$$AFT = e^{a + b\,x + \frac{c}{\sqrt{x}} + \frac{d}{\sqrt{y}}} \tag{32}$$

where the value of *a* is 7.2569169; the value of *b* is -0.0009633605; the value of *c* is -5.0936216; the value of *d* is -14.799013; *x* is the tested *Q;* and *y* is the tested *WTP.* When fitted to the *AFT* sensitivity analysis data generated by HELPER for this study, the $R^2$ value is 0.9972, and the fitted standard error is 0.6847.

The partial differential equation solution to Equation 32 with respect to *x* (which is *Q)* is given as:

$$\frac{\partial AFT}{\partial x} = \frac{e^{\frac{a\sqrt{x}\,\sqrt{y} + c\,\sqrt{y} + d\,\sqrt{x} + b\,x^{\frac{3}{2}}\sqrt{y}}{\sqrt{x}\,\sqrt{y}}}\left(2\,b\,x^{\frac{3}{2}} - c\right)}{2\,x^{\frac{3}{2}}} \tag{33}$$

The partial differential equation solution to Equation 32 with respect to *y* (which is *WTP)* is given as:

$$\frac{\partial AFT}{\partial y} = \frac{e^{\frac{a\sqrt{x}\,\sqrt{y} + c\,\sqrt{y} + d\,\sqrt{x} + b\,x^{\frac{3}{2}}\sqrt{y}}{\sqrt{x}\,\sqrt{y}}}\,d}{2\,y^{\frac{3}{2}}} \tag{34}$$

The results of our sensitivity analysis of the *OFT* (Figure S1 4) reveal that throughout the entire parameter space tested, the *OFT* is more sensitive to *Kx* than *Q*. Sensitivity to *Kx* decreases nonlinearly with increasing *Kx,* and sensitivity to *Kx* increases nonlinearly with increasing *Q* (Figure S1 4b). For example, where *Q* is 256 gallons (968 liters) per minute, the sensitivity of the *OFT* to *Kx* declines nonlinearly as *Kx* increases over the tested range by two orders of magnitude from 524.19 to 6.76. By comparison, the sensitivity of the *OFT* to *Q* over the same parameter space (Figure S1 4a) is 2,759–338 times smaller as it decreases by one order of magnitude from -0.19 to -0.02. These results suggest that accurate aquifer characterization is critical to predicting the operational limitations at high *Q,* particularly at low *Kx.* For example, at a *Q* of 256 gallons (968 liters) per minute, a 25% mischaracterization of *Kx* (e.g., 4 feet or 1.2192 meters per day versus 3 feet or 0.9144 meters per day) would result in an *OFT* that is 49% shallower than would be expected from HELPER results. However, where *Q* is only 1 gallon (3.79 liters) per minute, the same 25% mischaracterization of *Kx* would result in an *OFT* that is only 1% shallower than would be expected. Thus, the *OFT* for low *Q* (such as is expected for domestic users) is less sensitive to and constrained by spatially variable *Kx* than high *Q* (such as is expected for irrigation and municipal supply users).

The results of our sensitivity analysis of the *AFT* (Figure SI 5) reveal that the *AFT,* in the tested parameter space, is more sensitive to *WTP* than *Q* at high *Q*. However, the relative sensitivity of the *AFT* to *WTP* decreases as *Q* decreases (Figure SI 5a) because pumping costs in this parameter space decrease at a slower rate than the rate of change in *Q*. For example, at *WTP* of $50 per acre-foot ($40.54 per megaliter), a 67% decrease in *Q* from 3.02 gallons (11.43 liters) per minute to 1 gallon (3.79 liters) per minute results in only a 0.07% decline in pumping costs. This trend is driven principally by drilling costs. In addition, at an identical *WTP* ($50.00 per acre-foot or $40.54 per megaliter) and decrease in *Q* (67%), drilling costs, which represent 87% of pumping costs at the lower *Q,* have increased by 27%, even though the depth of drilling has decreased by 58%. *AFT* sensitivity to *WTP* (Figure SI 5b) tells a similar story through a different lens. Increasing *WTP* increases the *AFT* in a nearly linear fashion and, consequently, the sensitivity surface of the *AFT* to *WTP* is almost flat at all *Q* parameter spaces. Meanwhile, *AFT* sensitivity to *WTP* across the *Q* parameter space reflects changes in pumping costs with changes in *Q*. In the low *Q* parameter space, changes in *WTP* are offset by the changes in drilling costs, resulting in low sensitivity to *WTP.* However, in higher *Q* parameter space, lifting costs and drilling costs begin to equalize, and total pumping costs become relatively flat and ultimately fall slightly with increasing *Q*. *AFT* sensitivity to *WTP,* being approximately linear, follows this same trend. Thus, in summary, the *AFT* for low *Q* (such as is expected for domestic users) is more sensitive to and constrained by *WTP* due primarily to drilling costs, while high *Q* (such as is expected for irrigation and municipal supply users) are more sensitive to *WTP,* which varies almost uniformly with *Q*.

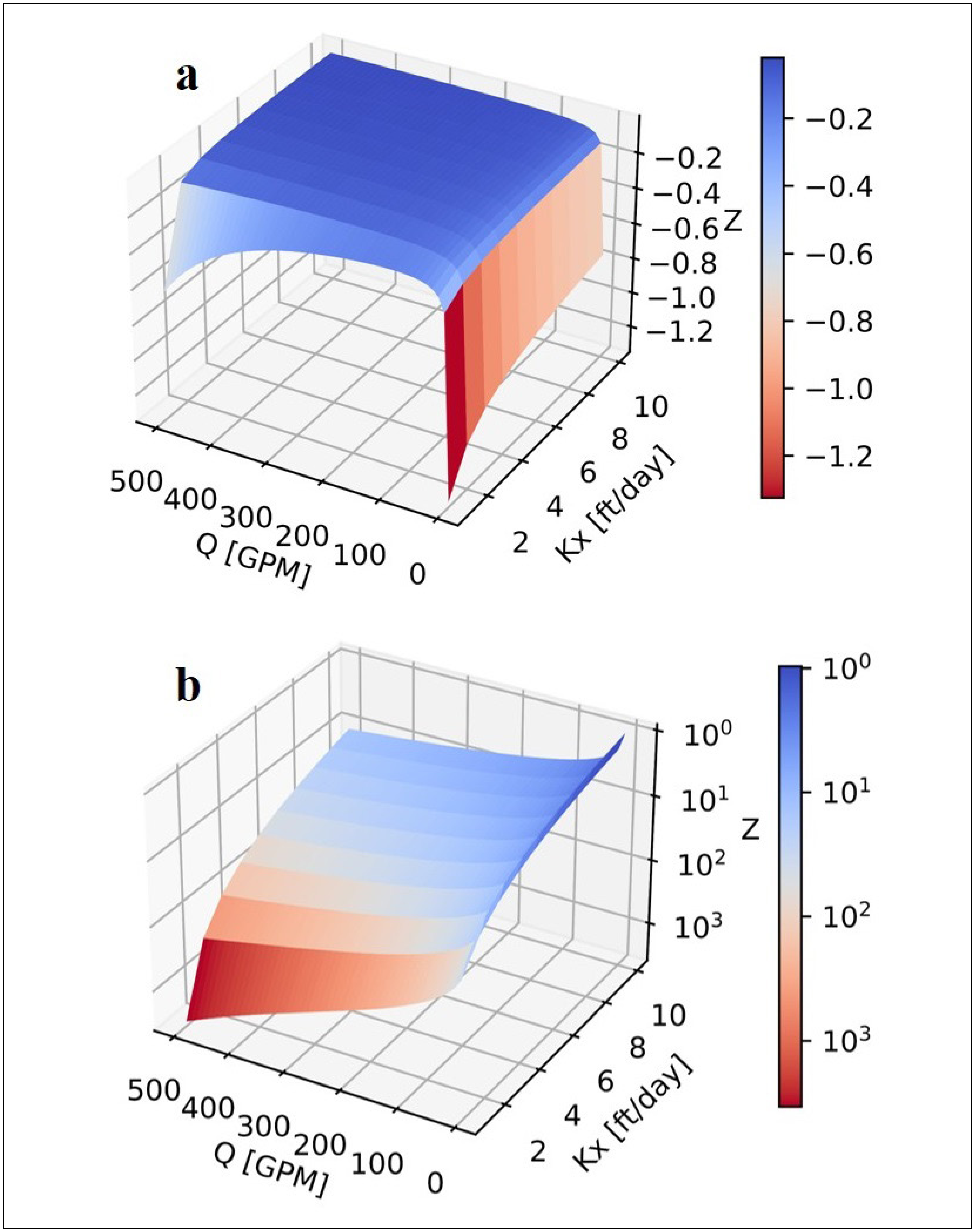


**Figure SI 4.** The surface of *z*, the sensitivity of the *OFT*, with respect to (a) *Q* and (b) *Kx*. Hot colors (reds) indicate high sensitivity, and cool colors (blues) indicate low sensitivity.

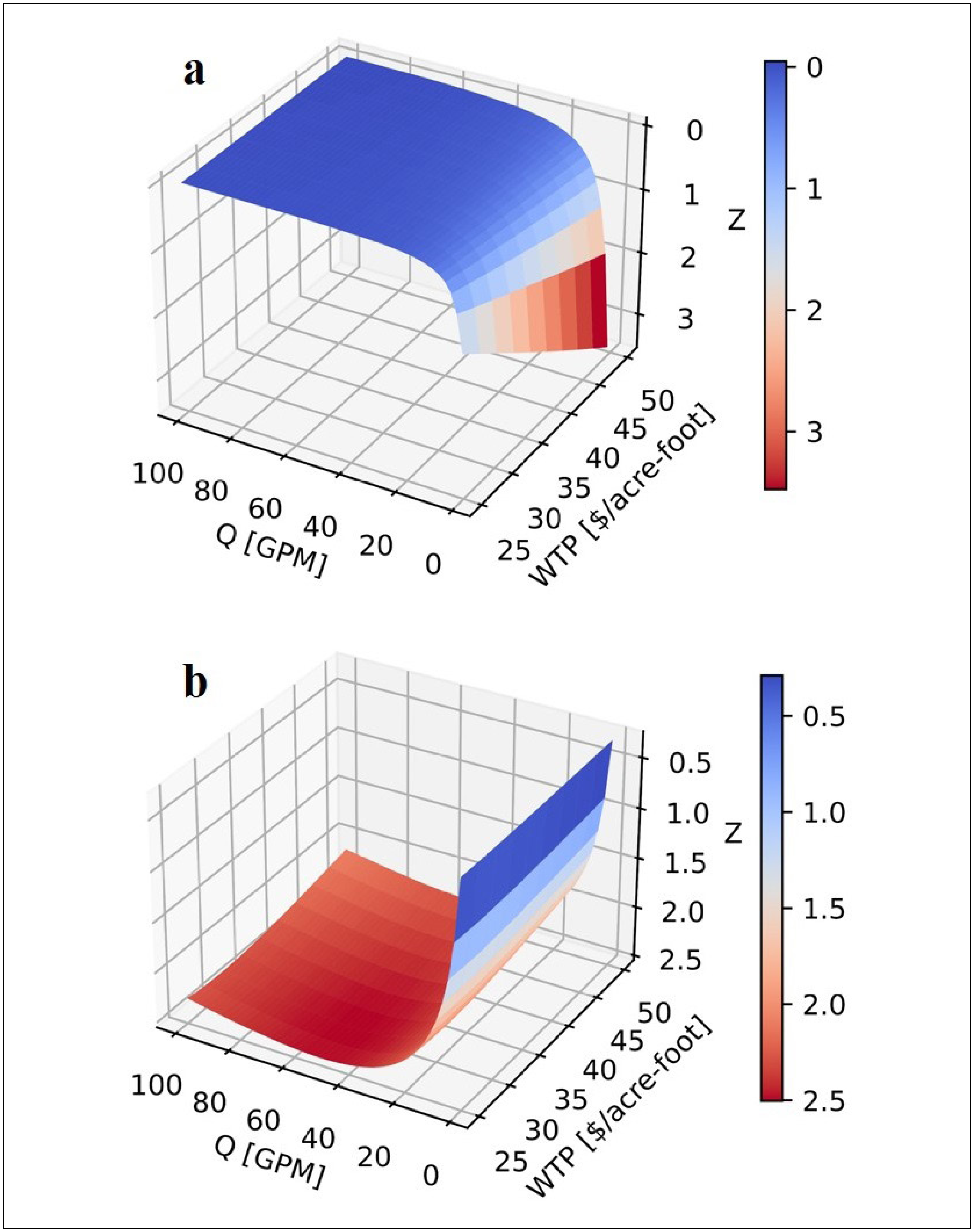


**Figure SI 5.** The surface of *z*, the sensitivity of the *AFT*, with respect to (a) *Q* and (b) *WTP*. Hot colors (reds) indicate high sensitivity, and cool colors (blues) indicate low sensitivity.

### Aquifer Parameters for the Study Area

Where necessary, aquifer characteristics (Young et al. 2020) and the digital elevation model (NED 2013) are processed using geographic information systems to make preliminary calculations and bring the data points into a common, 1 square mile (2.59 square kilometer), rasterized framework. Notably, aquifer formation thicknesses are calculated as the difference between the given depth of the bottom of the formation and the given depth of the bottom of the overlying formation; calibrated hydraulic conductivity pilot points are interpolated (bilinear); and 2010 water levels are converted from the topography to a raster using the relevant tool provided by ArcGIS Pro. All elevations are recalculated to depths from land surface by use of the digital elevation model (NED 2013), which was resampled (bilinear) from a 10 square meter resolution to a 1 square mile (2.59 square kilometer) resolution. Finally, aquifer characteristic data are exported from ArcGIS Pro in American Standard Code for Information Interchange (ASCII) format for processing by HELPER in a Python computational environment (i.e., Jupyter Notebooks).