Groundwater

Impacts of Groundwater Pumping for Hydraulic Fracturing on Aquifers Overlying the Eagle Ford Shale

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Abstract

Hydraulic fracturing (HF) events consume high volumes of water over a short time. When groundwater is the source, the additional pumping by rig/frack supply wells (RFSWs) may impose costs on owners of other sector wells (OSWs) by lowering the hydraulic head. The Carrizo–Wilcox aquifer in south Texas is the main source of water for HF of the Eagle Ford Shale (EFS) Play. The objectives are to assess the impacts of groundwater pumping for HF supply on: (1) hydraulic heads in OSWs located nearby an RFSW and (2) volumetric fluxes between layers of the regional aquifer system compared to a baseline model without the effect of RFSW pumping. The study area spans the footprint of the EFS Play in Texas and extends from 2011 to 2020. The pumping schedules of 2500 RFSWs were estimated from reported pumped water volumes to supply 22,500 HF events. Median annual drawdowns in OSWs ranged from 0.2 to 6.6 m, whereas 95th percentile annual drawdowns exceeded 20 m. The magnitudes of drawdown increased from 2011 to 2020. Of the four layers that comprise the Carrizo–Wilcox aquifer, the upper Wilcox was the most intensively pumped for HF supply. During the peak HF year of 2014, the net flux to the upper Wilcox was 292 Mm^3 compared to the baseline net flux for the same year of 278 Mm^3—a relative gain of 14 Mm^3. Pumping for HF supply has the potential to negatively impact nearby OSWs by capturing water from adjacent aquifer layers.

Introduction

At the end of the 20th century, engineers working to satisfy America's demand for energy developed hydraulic fracturing (HF) by leveraging new techniques of directional drilling to extract gas and oil from tight shale formations in the Barnett Shale in north Texas (Gold 2014; Nicot et al. 2014). HF requires large volumes of water. Much of this water is lost within the producing formation while some of the injected water and formation brines flow back to the surface in a highly contaminated form. This water must be treated or injected into deep geologic formations (Scanlon et al. 2014a). Pumping from aquifers to supply water to initiate the HF of shale rocks contributes to the consumption of fossil groundwater supplies in semi-arid and arid regions. Globally, 31% of all shale plays that could be exploited for oil and gas through HF are located in regions that are currently experiencing or are vulnerable to water stress (Rosa et al. 2018). Many of these regions have already suffered a significant depletion of stored groundwater. Agriculture is the sector most commonly responsible for that depletion (Scanlon et al. 2012; Bhattarai et al. 2021; Graham et al. 2021); 30% of all shale plays are located under irrigated lands (Rosa et al. 2018). Thus, water availability and the cost-effectiveness of treating, recycling, or disposing of the flowback are major limitations on the regional sustainability of HF, especially in semi-arid and arid regions that are highly dependent on groundwater (Vengosh et al. 2014; Scanlon et al. 2014b; Scanlon et al. 2020).

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To identify gaps in the literature that analyzes the impacts of water withdrawal for HF supply on groundwater resources, we searched for the key words "hydraulic fracturing" AND "water resources" AND "groundwater" in Title/Keywords/Abstracts in Web of Science Core Collection. This retrieved 299 references. Screening of the titles revealed that only 96 of these were related to HF and water resources. Many of these studies analyzed the risks to shallow aquifer water quality from cross-formational flow and poorly disposed toxic flowback water (Vengosh et al. 2014; McIntosh and Ferguson 2019). Only 17 studies performed detailed analyses of the past or future impacts of water demand for HF on groundwater resources. One study was a review paper (Saha and Quinn 2020a). The remaining primary research articles were subdivided into those that quantified the impacts of past water extraction for HF supply and those that considered the future impacts from HF development. All in the former group used data-driven approaches (Horner et al. 2016; Arciniega-Esparza et al. 2017; Lin et al. 2018; Rosa and D'Odorico 2019; Unruh et al. 2021; Scanlon et al. 2022). Future impact studies used both data-driven (Hernandez-Espriu et al. 2019; Karim et al. 2020) and numerical modeling approaches (Best and Lowry 2014; Duda 2014; Saha and Quinn 2020b). None of the studies explicitly modeled the local impacts of groundwater extraction for HF supply in the regional aquifer system.

Although the annual volume of water utilized for HF over a region that is defined by the extents of the shale play ranges from small (<1%) to moderate (~10–20%) compared to total consumptive use (Nicot and Scanlon 2012; Horner et al. 2016; Lin et al. 2018; Rosa and D'Odorico 2019), the local impacts may nonetheless be large. These local impacts are obscured in three ways: (1) a lack of public reporting of the source water to supply individual HF events; (2) the erratic pumping schedules from rig/frack supply wells (RFSWs) which are not explicitly modeled in regional groundwater models used for planning purposes (Horner et al. 2016); and (3) an insufficient density of public water level monitoring wells to detect the formation of local cones of depression (Scanlon et al. 2020). This lack of data, tools, and observations to account for the local impacts of rapid water withdrawals from the aquifer fails to address concerns among land owners that rapidly expanding cones of depression may cause well water levels to fall below pump intake levels in wells (Bajaras 2011; Brantley et al. 2014; Vengosh et al. 2014). This risk has not been systematically assessed.

We studied the short-term impacts of groundwater pumping for HF supply on other sector wells (OSWs) screened within the four major units that comprise the Carrizo–Wilcox aquifer; the principal aquifer supplying water for HF of the Eagle Ford Shale (EFS) Play. Since the start of HF in the EFS in 2008, hydraulic heads have declined by 6 to 60 m in the confined Carrizo sand layers (Scanlon et al. 2020). This decline was partly caused by the single most severe drought-of-record year for Texas in 2011 (Nielsen-Gammon et al. 2020). This drought year depleted groundwater storage volumes in the confined Carrizo–Wilcox aquifer owing to high irrigation pumping to compensate for the lack of rainfall (Li et al. 2020; Gyawali et al. 2022). Exploring the local impacts of groundwater pumping for HF supply should be useful to regions that have shale gas but have not yet exploited it (Scanlon et al. 2014b; Horner et al. 2016; Hernandez-Espriu et al. 2019).

Texas state law treats the groundwater beneath a property as a private resource. Nevertheless, because groundwater is fluid, pumping of this private resource impacts the aquifer for surrounding landowners. To manage the Common Pool Resource through communicating the past, present, and future conditions of the aquifer, hydrologists working for the Texas Water Development Board (TWDB) develop regional numerical groundwater models (called groundwater availability models or GAMs) to assess the long-term and aggregated impacts of pumping of the aquifer. Annual permitted pumped volumes for both existing and proposed wells are allocated over 365 days. This is referred to herein as annualized pumping rates. Unlike OSWs, the high density of RFSWs across the EFS suggests that pumping for HF supply is performed "on-demand" over short time intervals (weeks). The median distance between a HF well and a RFSW is less than 2 km (Brien 2021). The median distance between HF wells and domestic water wells across the United States is also less than 2 km (Jasechko and Perrone 2017). The GAMs use coarse grid spacing at 2.59 km^2 (1 $mile^2$) with annualized pumping rates, making the GAMs unsuitable to estimate the lateral extent of cones of depression from short-lived pumping for HF supply. This pumping may impose additional energy costs on owners of nearby wells to lift water to the surface, or to repair or replace damaged pumps from when water levels fall below the pump intake level (Bajaras 2011).

Therefore, the first objective of this study is to quantify drawdown at a daily time interval in OSWs screened within the four hydrostratigraphic units of the Carrizo–Wilcox aquifer owing to pumping for HF supply between 2011 and 2020. An analytical equation is used to predict drawdown at high spatial resolution and daily pumped volumes are input into the model to predict drawdown at the same frequency. Drawdown magnitudes and durations are then translated into additional energy costs for lifting water to the surface and the probability of damaging pumps. The second objective is to calculate the additional cross-formational volumetric fluxes between the four model layers of the Carrizo–Wilcox aquifer owing to RFSW pumping. This is important because this flux can draw brackish water into freshwater aquifers (Fogg et al. 1983). Furthermore, pumping from brackish groundwater zones, which is increasingly being done to supply water for HF, can deplete the hydraulic heads of connected freshwater aquifers (McMahon et al. 2016; Karim et al. 2020).

Methods

The FracFocus database was used to determine the location of OGWs that were hydraulically fractured and the water volume reported for each HF event. These volumes were attributed to the closest existing RFSW that was registered in the Submitted Drillers Reports (SDR) database of TWDB over the duration of the HF event. The wells included in the SDR include all wells drilled after 2002. As many of the wells in operation over the study period would be older than 2002, the analysis presented is an underestimate of the number of OSWs impacted. From this information, daily pumping schedules were created for each RFSW (Obkirchner 2019; Brien 2021). Drawdowns in OSWs from transient RFSW pumping schedules were predicted with an analytical model.

To assess the impact of RFSW pumping on layer-to-layer volumetric fluxes, two numerical groundwater model simulations were generated for each year of the study period (2011–2020). These were created using the existing GAM for the Carrizo–Wilcox, Queen City, and Sparta aquifers (Deeds et al. 2003; Kelley et al. 2004; Schorr et al. 2021). A baseline simulation was generated to calculate annual volumetric fluxes without pumping from RFSWs. Then a simulation was generated by entering the daily pumping schedules for RFSWs. The difference between the baseline and RFSW simulations in hydraulic heads and volumetric fluxes among the aquifer layers was calculated to assess the impacts from pumping for HF supply.

Study Area

The EFS is in south-central Texas. The Texas portion of the EFS extends from the Texas–Mexico border 650 km to the northeast and underlies 26 counties in Texas (Figure S1). The formation is approximately 80 km wide from northwest to southeast with an aerial footprint of 5.2×10^4 km^2 (Railroad Commission of Texas 2020). Its depth ranges from 1220 to 3658 m below land surface and has a typical thickness of 76 m. HF has been performed on the EFS since 2008. There are three production areas in the EFS that produce oil, wet gas/condensate, and dry gas (U.S. EIA 2014). The total estimated volumes of recoverable oil and natural gas are approximately 540 Mm^3 (3.4×10^9 barrels) and 5.9×10^5 Mm^3 (2.1×10^{13} ft^3), respectively (IER 2016).

From 2010 to 2011, oil and gas production from the EFS accounted for 85% of growth in production across Texas. During 2011 alone, more than 5.7 Mm^3 (3.6×10^7 barrels) of oil was extracted (Institute for Energy Research 2016). The flowback water from a given HF event in the EFS returns approximately 15% of water injected during the first 6 months after completion (Kondash et al. 2017). The typical well requires approximately 18.6 m^3 of water per meter of horizontal length (Ikonnikova et al. 2017).

Approximately 90% of the water used for the oil and gas industry to supply HF in the EFS is sourced from fresh groundwater aquifers (Nicot et al. 2012). The remaining 10% is sourced from fresh surface water and brackish groundwater. Brackish water is defined herein as water with total dissolved solid values (TDS) between 1000 and 10,000 mg/L (Arnett et al. 2014).

The water demanded for HF supply in central Texas has the potential to increase competition for groundwater. Irrigation-fed farming is widespread, and the region hosts 6 out of 15 of the fastest growing cities in the United States (U.S. Census Bureau 2020). Although pumped volumes for irrigation and municipal supply greatly exceeds pumping for HF supply at the regional scale, the nature of pumping for HF supply is unique; large volumes are pumped over short time periods from groundwater wells that are widely distributed and frequently pumped from confined aquifers (Scanlon et al. 2020). Whereas cones of depression in unconfined aquifers have limited spatial extent and form slowly (weeks), in confined aquifers these expand quickly (days) to cover much larger areas. This rate of expansion is controlled by aquifer diffusivity, which is defined as the aquifer's hydraulic conductivity (K) divided by its specific storage (S_s) (Jacob 1950; Ferris 1951).

The majority of water in south-central Texas is supplied by the Carrizo–Wilcox aquifer. This aquifer spans from inside of Mexico to Louisiana (Figure S2). It outcrops over an area of 2.9×10^4 km^2 along its northwest edge but is confined to the southeast along its dip direction over an area of 6.6×10^4 km^2 (TWDB 2016). The Carrizo–Wilcox aquifer contains approximately 6.4×10^6 Mm^3 of stored water. The GAM used in this study includes layers that represent minor aquifers and aquitards that overly the Carrizo and Wilcox sand layers. From youngest to oldest, the aquifer system contains the Sparta Aquifer, Weches Aquitard, Queen City Aquifer, Reklaw Aquitard, Carrizo Aquifer, upper Wilcox Aquifer, middle Wilcox Aquifer, and lower Wilcox Aquifer.

The same aquifers that are pumped for HF supply are the principal source of water supply for municipal and irrigation use across central and east Texas. The EFS spans six Groundwater Conservation Districts (GCDs) (Figure S1) and six regional water planning groups (Figure S3). Region L is the focus of this study since it is the main region that overlays the EFS. Total water use in 2017 within Region L was 1190 Mm^3/year and approximately three quarters of this was sourced from groundwater (South Central Texas Regional Water Planning Group 2020). Municipal water use comprised 47% of the total (558 Mm^3/year). Agriculture (irrigation and livestock) water use comprised 30% (360 Mm^3/year). Mining water use, which is mostly used for HF supply, comprised 7% (79 Mm^3/year). For comparison, in the early years of HF in the EFS only 18 Mm^3 of water was consumed to develop tight shale OGWs over the three-year period of 2009 through 2011 (Nicot and Scanlon 2012).

Starting in 2012, oil and gas operators were required to publicly report the water volumes consumed for each HF event to a national chemical disclosure registry called FracFocus. This database reports that more than 22,500 HF events were performed in the EFS from 2011 to 2020.

The water to perform HF was mostly supplied by 2500 RFSWs. Over this period large changes in crude oil prices drove water demand for HF (Figure S4).

The climate in the watersheds overlying the EFS ranges from semi-arid to arid (Figure S5). The state of water stress in the watersheds overlying the EFS ranges from high to severe according to the Texas Baseline Water Stress Index (Freyman 2014). This index is calculated using: (1) the ratio of annual water withdrawn to total available water; (2) intra- and interannual variation in water supply; (3) severity of floods and droughts; (4) storage and depletion of groundwater and rivers; (5) return flow; and (6) environmental regulations, such as instream flow regulations that prevent water from being removed from a stream if it would reduce the volume of water below a set threshold (Gassert et al. 2013).

Data Acquisition

The principal data sources used in this study were obtained from FracFocus, TWDB, and the Energy Information Administration (EIA). Each dataset was organized and cleaned before combining to derive new information such as RFSW pumping schedules which were then input into the models (Figure S6). The FracFocus database discloses chemicals and water volumes used in the HF process (FracFocus 2021). For each hydraulically fractured well this study utilized the following information from FracFocus: (1) HF job start and end dates; (2) well name; (3) American Petroleum Institute number; (4) county; (5) GPS coordinates including the map projection; and (6) total water volume injected. FracFocus lists the total volume of water consumed for a job but not its source. In this study, all water consumed by a HF event was assumed to be sourced from the nearest RFSW (Obkirchner 2019).

Water well construction and water use information for both RFSWs and OSWs were obtained from the SDR database (TWDB 2021). This included: (1) the proposed use of the water well; (2) drilling completion date; (3) borehole depth; (4) well report tracking number; (5) latitude and longitude; (6) plugging report number if the well was plugged; (7) screen depth interval; (8) pump intake elevation; (9) pumping rate and the dynamic drawdown during the pumping test; and (10) target aquifer in which the well was screened. Target aquifer was rarely available in the individual well installation reports. To assign wells to an aquifer well top elevations were extracted in ArcMap using "Extract Values to Points Tool" and their reported lengths were subtracted from this to determine the bottom elevation. Then the well screen depth intervals were converted to elevations. If a well contained multiple screened intervals, the screen was treated as continuous. A well was assigned to an aquifer if its screened interval lay within the upper and lower boundary of the aquifer.

Estimating Pumping Schedules of RFSWs

To estimate the volume and timing of water pumped from RFSWs to supply water for HF events, each event listed in FracFocus was assigned to the nearest RFSW by utilizing ARC GIS Pro (version 2.7.0, ESRI, Redlands, California). Once the location of the HF events performed on specific OGWs were mapped, all HF events outside of the EFS footprint, defined by the shape file provided by U.S. EIA (U.S. EIA 2014) were removed using the intersect tool in ArcMap. The remaining HF events were then organized into 10 groups based on year (2011–2020). The start and end dates of each HF event were included in the ArcMap database. The average duration of an HF event was 18 days. This resulted in 10 new feature layers containing RFSW pumping schedules for each year of the study. A small number of abandoned RFSWs were removed from the ArcMap database in the year they were abandoned.

Once HF events and screen locations of RFSWs were organized by year in ArcMap, the nearest RFSW to each hydraulically fractured OGW was identified using Theissen polygons (Figure 1) (Obkirchner 2019; ESRI 2021). The ID number of each RFSW was cross-referenced to the ID of each OGW that was hydraulically fractured in that year as well as the distance between the two wells. The pumping rates for RFSWs were then estimated from the reported volumes of water used for the duration of each HF event. Approximately 1% of entries in FracFocus did not report the volume of water consumed. In such cases the average volume per HF event for that year was substituted. Estimated pumping rates from RFSWs that exceeded 631 L/s (around 5% of wells experienced this at some point) were limited to that rate since rates higher than this for a single well were unrealistic and prevented the numerical model from converging since it dried out cells within the model. This was an artifact caused by multiple HF events occurring within the same Theissen polygon "catchment" area for which all water for HF supply was assumed to be sourced from a single RFSW. In such a situation, the water for HF supply would likely have been sourced from multiple nearby wells. It was relatively common for more than one OGW to be located within a single Theissen polygon for a RFSW.

Modeling Drawdown in OSWs

The change in the water level in an OSW is a function of the RFSW's pumping rate, duration, and aquifer transmissivity (T) and storativity (S) (Theis 1935). To assess the drawdown in specific OSWs that were located within 3 km of an actively pumped RFSW, the Theis analytical equation (Theis 1935) was solved (Equation 1):

$$s = \frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \ldots\right] \quad (1)$$

where

$$u = \frac{r^2 S}{4Tt} \quad (2)$$

and Q is volumetric discharge (m^3/s) (pumping rate) from the RFSW and r is the straight-line distance between the RFSW and the paired OSW screened in the

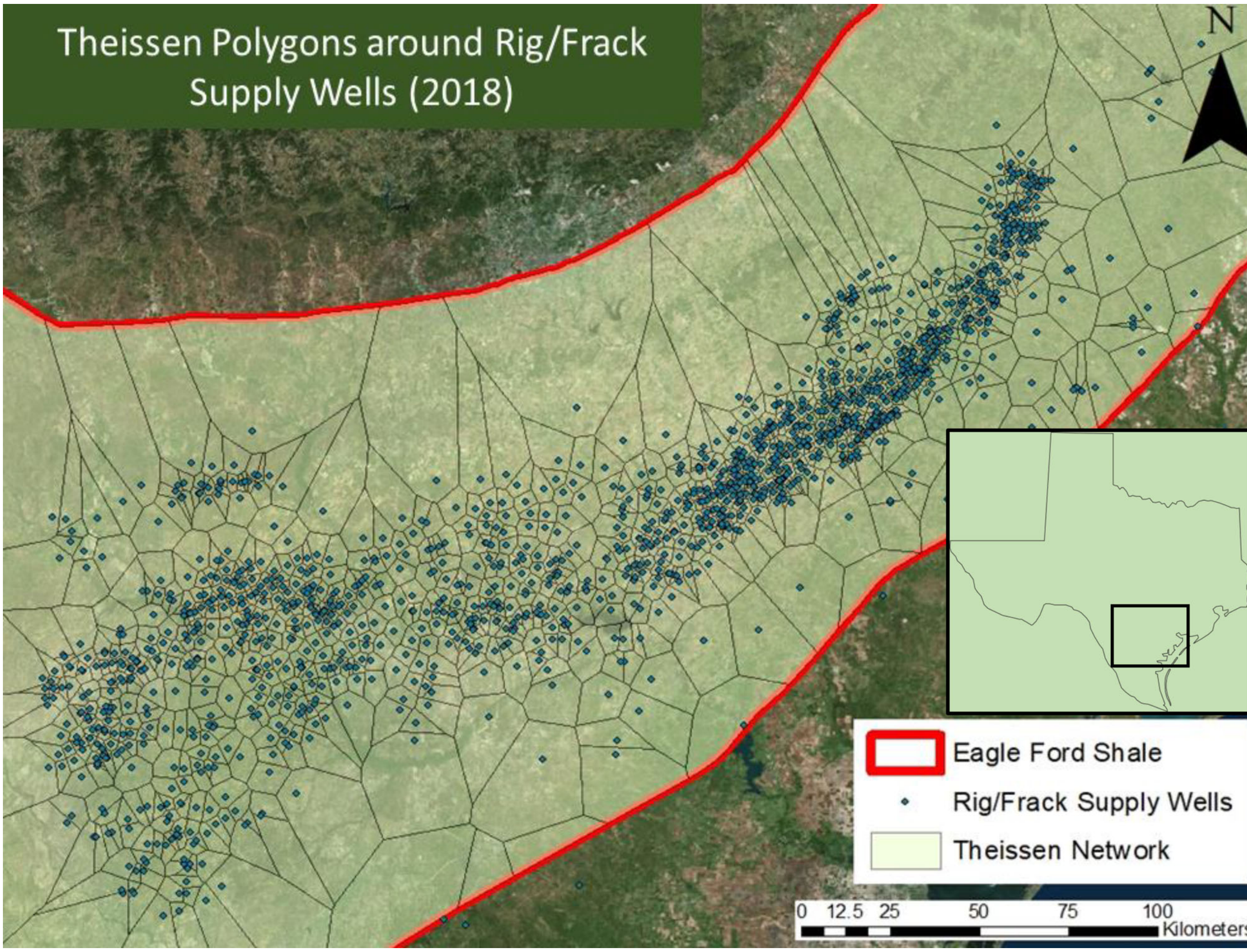

Figure 1. Locations of RFSWs and the surrounding Theissen polygons. The inset shows the location of the study area in the black outlined box within the state of Texas.

same hydrostratigraphic unit with a vertically overlapping screened interval, and t is the duration of pumping (s). OSWs tended to have shorter screen lengths than RFSWs with 5th, 50th, and 95th percentile screen lengths of 6, 18, and 91 m. The RFSWs had corresponding percentile screen lengths of 24, 71, and 210 m, respectively. The four layers that comprise the Carizo–Wilcox aquifer have high internal vertical hydraulic anisotropy ranging from a K_h/K_v of 1000 to 10,000 (Fogg et al. 1983; Ryder 1988) and thus only pumping from wells with vertically overlapping screens are likely to impact the hydraulic heads in nearby wells (Hantush 1961). Since the RFSW have long screens that spanned a significant proportion of the target aquifer, the local aquifer T obtained from the GAM was used. Equations 1 and 2 were implemented in MATLAB (version 2021a, Natick, Massachusetts) (Codes S1 and S2 in Appendix S1) (Obkirchner 2019).

An OSW was determined to have experienced drawdown only if its magnitude was equal to or greater than 0.01 m. The number of days an OSW experienced drawdown is referred to herein as drawdown-days. For example, if two wells experienced drawdowns of 365 and 91 days over a 365-day study period, then this group of wells experienced at total of 456 drawdown-days out of 730 possible drawdown-days (Equation 3):

$$\text{Possible drawdown days} = n_w * \text{Study days} \quad (3)$$

where n_w is the number of wells and study days is the time frame of the analysis.

Calculating Volumetric Fluxes Between Aquifer Layers

Numerical Model

Large-scale simulations of drawdown from pumping by all wells in the Carrizo–Wilcox, Queen City, and Sparta aquifer systems within the region were performed using the GAM developed for the TWDB (Deeds et al. 2003; Kelley et al. 2004). This GAM represents the southern portion of the aquifer system and is used by local regulators to inform water management in the region (e.g., Wade 2017). This GAM, referred to here as the "standard GAM," was originally constructed to represent the period from 1980 to 2050. Predevelopment steady-state conditions as well as the transient hydraulic head conditions observed from 1980 through 1989 were used to calibrate the model. The model was then verified by comparing predicted to observed heads from 1990 through 1999 (Kelley et al. 2004). The model structure and data inputs are currently being updated as part of the TWDB's water planning cycle. Since this process is not yet complete, we used the existing version of the model (version 2.01) but supplement it with the new data that has been developed for it, such as pumping rates after the year 2000 (Schorr et al. 2021).

The standard GAM encodes the following information: (1) spatial extents of each aquifer; (2) S and K values which were obtained from field investigations; (3) starting hydraulic heads in 1980; (4) the locations and screened intervals of OSWs; and (5) annualized pumped volumes for each well. The GAM runs in MODFLOW-2000 (Harbaugh et al. 2000) and the software Groundwater Modeling System visual pre- and postprocessor was used for data management and analysis (GMS version 10.4.10, Aquaveo, Provo, Utah). The model has a grid scale of 2.59 km^2 (1 $mile^2$), stress periods of 1 year, and 10 computational timesteps per stress period. The model represents the aquifer system as eight layers (from youngest to oldest): the Sparta Aquifer, Weches Aquitard, Queen City Aquifer, Reklaw Aquitard, Carrizo Aquifer, upper Wilcox Aquifer, middle Wilcox Aquifer, and lower Wilcox Aquifer. Cross-formational flow is allowed between each, and recharge, discharge, and river-aquifer fluxes are allowed in locations where a formation outcrops. The model has no-flow boundaries at its southwestern and northeastern extents, which represent the groundwater divides formed by the Rio Grande and the Red River, respectively. A no-flow boundary is also implemented at the bottom of layer 8, and a general head boundary condition is present above the subcrop areas of layer 1. Streams flowing within the model are generally treated as head-dependent flow boundaries and springs as drains, both based on historical gaging data. Recharge is a calibrated parameter, initially estimated based on the difference between evapotranspiration and precipitation.

The GAM was originally calibrated by Kelley (Kelley et al. 2004) using measured K and S data as initial estimates (e.g., Mace et al. 2000; Mace and Smyth 2003) and adjusting these values such that the model predictions matched existing hydraulic head and stream flow measurements. Both spatially and temporally distributed calibration data were used, and "best fit" parameter values were determined by minimizing the root mean square error (RMSE). The RMSE for the calibration period ranged from approximately 7–10 m for the different layers of the Carrizo–Wilcox aquifer with a low bias (mean error < 3 m) (Kelley et al. 2004). Over the Carrizo–Wilcox aquifer the average values of transmissivity (T) and storativity (S) were reported to be 27.9 m^2/d and 0.0003, respectively (Mace and Smyth 2003). However, the calibrated values of T and S are higher, with averages (and 5th to 95th percentiles) of 234.7 (1.9–1105) m^2/d and 0.0017 (0.0001–0.0045), respectively. Further details of the calibration process may be found in Kelley et al. (2004).

The RFSW simulation represented pumping from RFWS as a certain volume pumped over the duration of the HF event as recorded in FracFocus. The stress periods in the GAM were reduced to 5 days over the study period (2011–2020). This means that the total pumped volume of water for an HF event needed to be spread evenly over the closest time period to the reported length of the event that was divisible by 5. The baseline simulation represented only the annualized pumping schedules stored in the standard GAM.

These simulations were initialized based on the hydraulic head values found at the end of the 2010 predictive period in the standard GAM. Pumping rates for the years from 2011 to 2020 were then incorporated using values found in the recent TWDB documentation (Schorr et al. 2021). The model for these simulations needed to be adapted from the original to accommodate the "flashy" character of the pumping schedules from the RFSWs in two ways: the model timestep had to be shortened from monthly to daily increments and the stress periods had to be shortened from 1 year to 5 days.

Differences in gross and net volumetric fluxes among aquifer layers between the baseline and RFSW numerical models were calculated using the zone budget tool within GMS. This permitted calculating the additional volumetric fluxes that occurred between hydrostratigraphic units (herein referred to as layers) of the aquifer system owing to pumping for HF supply. Volumetric fluxes were only calculated among the layers of the Carrizo–Wilcox aquifer system (Carrizo, upper Wilcox, middle Wilcox, and lower Wilcox).

Calculating Additional Costs of Pumping Groundwater for OSWs

Pumping groundwater requires energy to lift water from an aquifer to the surface. Energy requirements increase as the hydraulic head of the aquifer drops. To calculate the total energy E (kWh) required to operate OSWs over each day of the study, the following equation (Equation 4), which is based on the extended Bernoulli equation (Weiner and Matthews 2003), was used:

$$E = \frac{\frac{\gamma}{\eta} Q h_{\mathrm{L}} t}{366{,}508} \tag{4}$$

where γ is specific weight of water (1000 kg/m^3), h_{L} is lift height (m), Q is volumetric discharge (m^3/s), η is pump efficiency (−) (typically 0.6–0.7 at optimal operation), and t is the time the pump is on (hours). For the analytical model, additional lift height was simply the calculated drawdown from the RFSW pumping well. The additional electricity cost to well owners was calculated using published electricity rates. Public supply wells are charged commercial rates, domestic wells are charged residential rates, and agricultural, livestock, and industrial wells are all charged industrial rates (Electricity Local 2018).

Estimating OSWs at Risk of Pump Failure

Pump failure is likely to occur if the hydraulic head falls below the pump intake elevation. Pump intake elevations were calculated using the SDR database when their depths were available. Pump elevations were subtracted from the hydraulic head calculated with the baseline numerical model for each year of the study to obtain the standing water height above the pump intake unperturbed by pumping for HF supply. Next, calculated drawdown from the analytical Theis equation determined if the hydraulic head fell below the pump intake elevation, thereby putting the pump at risk for damage or causing the overheated pump to melt the polyvinyl chloride casing in some cases. The cost of replacing a damaged pump depends on the price of a new pump, as well as labor, wiring, and pipe. Replacement costs for domestic and livestock wells range from \$2500 to \$4000 whereas the cost of a new pump for an irrigation well ranges from \$20,000 to \$30,000. Costs of replacing pumps installed in industrial and municipal wells range from \$30,000 to \$50,000 (Brien 2021). The higher costs correspond to the horsepower rating of the pump.

Results and Discussion

Water Demand for HF Supply

The number of actively pumped RFSWs (Figure 2a) and water demand for HF supply rose steeply from 2011 through 2014 (Figure 2b). Then following the crash in oil and gas prices in 2014 (Figure S4), water demand fell through 2015 and 2016. The years 2014 and 2016 represent maximum and minimum water demand years, respectively. Irrespective of the year, the upper Wilcox layer (dark orange bars) supplied the most water for HF, followed by the Carrizo (blue) and the middle Wilcox layers (light orange) (Figure 2b).

Drawdown in Wells Attributed to Groundwater Pumping for HF

Predicted drawdown in OSWs in the Carrizo–Wilcox aquifer caused by pumping from RFSWs was generally less than 5 m (Figures 3 and S7). Median annual drawdowns calculated with the analytical model ranged from 0.21 to 6.55 m across all four layers (Table S1). However, extreme drawdowns reaching 25 m or higher were predicted in all layers of the Carrizo–Wilcox during multiple years.

The predicted drawdowns in 2014 were log-normally distributed whereas in 2016 they were more evenly distributed (Figure S8). In 2014, of the 30 OSWs that experienced drawdown in the middle Wilcox, the predicted median drawdown was 0.64 m. The predicted 95th percentile drawdown (three wells), however, was 19.02 m and the 99th percentile (one well) was 42.85 m (Table S1). Drawdown occurred on 1138 of 10,220 possible drawdown-days in the wells that were susceptible to drawdown (10% of the time) (Table S1).

In 2016, the median predicted drawdown of the 25 impacted OSWs in the middle Wilcox was 2.75 m (Figure S7). The 95th percentile (five wells) drawdown was 15.95 m and the 99th (four wells) was 24.75 m. Drawdown was predicted to have occurred in the middle Wilcox layer on 974 of 9150 possible drawdown-days in the wells that were susceptible (11% of the time).

Additional Energy Costs from Increased Lift Heights

The additional energy costs to owners of OSWs from lifting water to the surface was calculated using the drawdown in hydraulic head predicted by the analytical model owing to pumping for HF supply. The additional head was substituted into the extended Bernoulli equation (Equation 4) to determine the additional annual energy requirements for all impacted wells (Brien 2021). Predicted costs incurred by individual OSW owners in

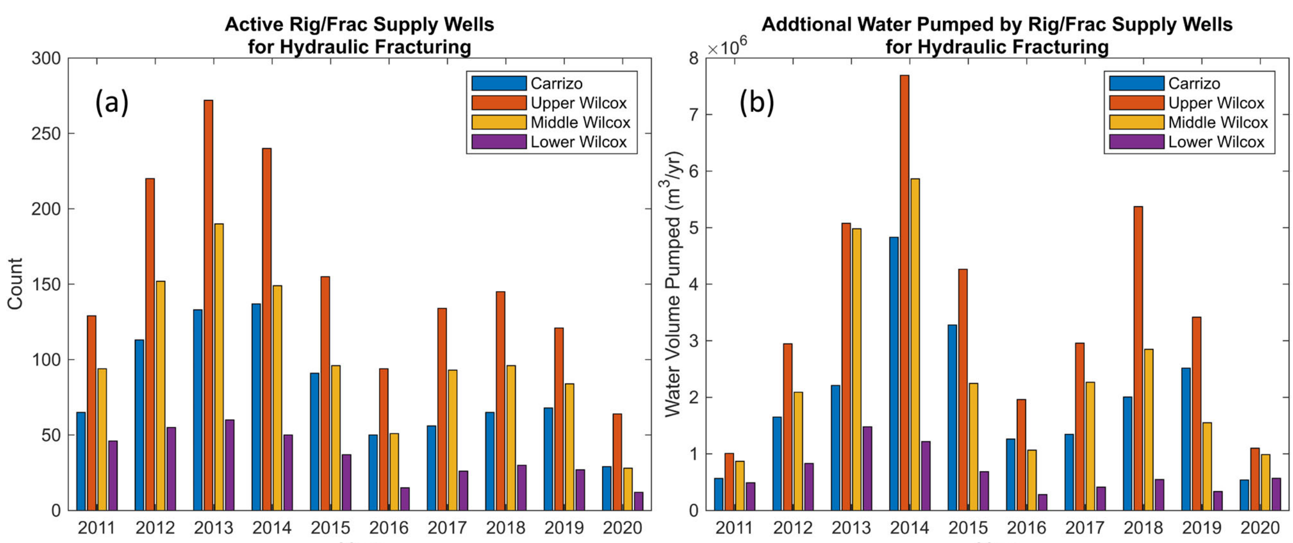

Figure 2. (a) Number of actively pumped RFSWs for HF supply in each hydrostratigraphic unit of the Carrizo–Wilcox aquifer. (b) Annual pumped volume of water from RFSWs in each unit from 2011 to 2020.

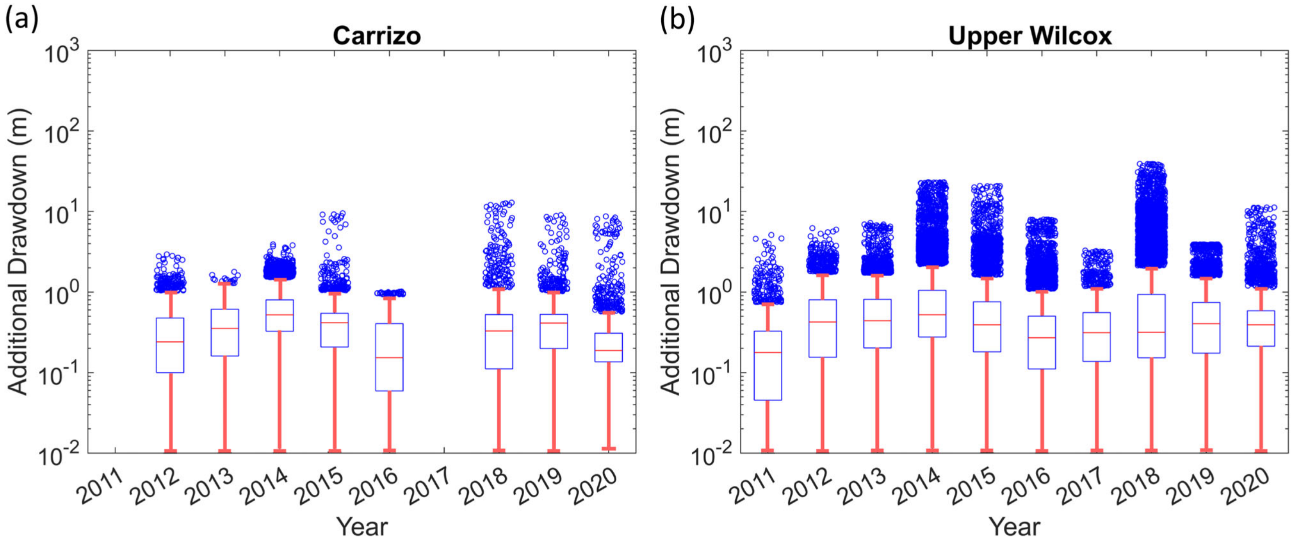

Figure 3. Daily drawdowns owing to pumping for HF supply predicted by the analytical model in the upper two layers of the Carrizo–Wilcox aquifer: (a) Carrizo and (b) upper Wilcox. The central line corresponds to the median drawdown (second quartile or Q2), and the lower and upper bounds of the box correspond to the first (Q1) and third (Q3) quartiles. The lower whisker is equal to Q1 − 1.5 × IQR (interquartile range or Q3–Q1), and the upper whisker is equal to Q3 + 1.5 × IQR (Tukey 1977). The outliers (blue circles) have been jittered for better visualization.

the Carrizo–Wilcox tended to remain under \$10.0/year (Table S2). Predicted pumping cost incurred by owners of 30 OSWs that were susceptible to drawdown in the middle Wilcox during 2014 had a median, 95th and 99th percentile costs of \$0.1/year, \$7.2/year (two wells), and \$103.2/year (one well), respectively.

Risk of Damaged Pumps from Erratic Water Levels

The drawdown calculated by the analytical model was used to assess the risk of pump failure in OSWs owing to water levels falling below the pump intake level. In the Carrizo–Wilcox Aquifer system, 250 OSWs had overlapping screened intervals within 3 km of an RFSW. Pump intake elevations were reported for 86 (34%) of those wells in the SDR database. Of these, two were at risk of pump failure according to the maximum predicted drawdown in those wells. One well was a domestic supply well that was screened in the middle Wilcox and experienced only 1 day of hydraulic head below the intake elevation in 2018. The other well was an industrial supply well that was screened across the upper and middle Wilcox and experienced 68 and 6 days when hydraulic head fell below the pump elevation in 2018 and 2019, respectively. For the remaining 164 wells without known pump intake elevations, these elevations were estimated by substituting the average standing water height above pump intake for each sector. When this was done, an additional 10 wells were estimated to have been at risk of pump failure.

Impact of Pumping for HF Supply on Groundwater Fluxes Between Layers

Gross Volumetric Fluxes

Additional gross volumetric fluxes between layers in the Carrizo–Wilcox aquifer system owing to pumping for HF supply were calculated by subtracting fluxes in the baseline model from the RFSW model. This was done for each year of the study for the four layers that comprise the system. The three layers of the Wilcox group were predicted to have experienced similar increases in volumetric fluxes owing to pumping for HF supply over the study period (Figure S9). The temporal increase in gross volumetric fluxes to and from each layer in both the baseline and RFSW models was partly caused by an overall increase in groundwater pumping in the region, which increased by 3.3% between 2011 and 2020.

The greatest increases in gross volumetric fluxes owing to pumping for HF supply occurred in the upper two layers: the Carrizo and the upper Wilcox. In the maximum water demand year of 2014, the additional daily influx into the upper Wilcox from the Carrizo and middle Wilcox layers was predicted to have been 13,061 and 1126 m^3/d, respectively (Figure 4a, right side). During the same year, the daily additional efflux from the upper Wilcox to the Carrizo and middle Wilcox was predicted to have been 2007 and 1255 m^3/d, respectively (Figure 4a, left side). Thus, pumping for HF supply increased both influx to, and efflux from the upper Wilcox layer.

In the lowest water demand year of 2016, the additional daily influx into the upper Wilcox from the Carrizo and middle Wilcox was predicted to have been 5141 and 719 m^3/d, respectively (Figure 4c, right side). During the same year, additional daily efflux from the upper Wilcox to the Carrizo and the middle Wilcox was predicted to have been 1592 and 210 m^3/d, respectively (Figure 4c, left side).

Net Volumetric Fluxes

The Carrizo is the only layer that experienced an increase in net water efflux (Figure 5a). The baseline

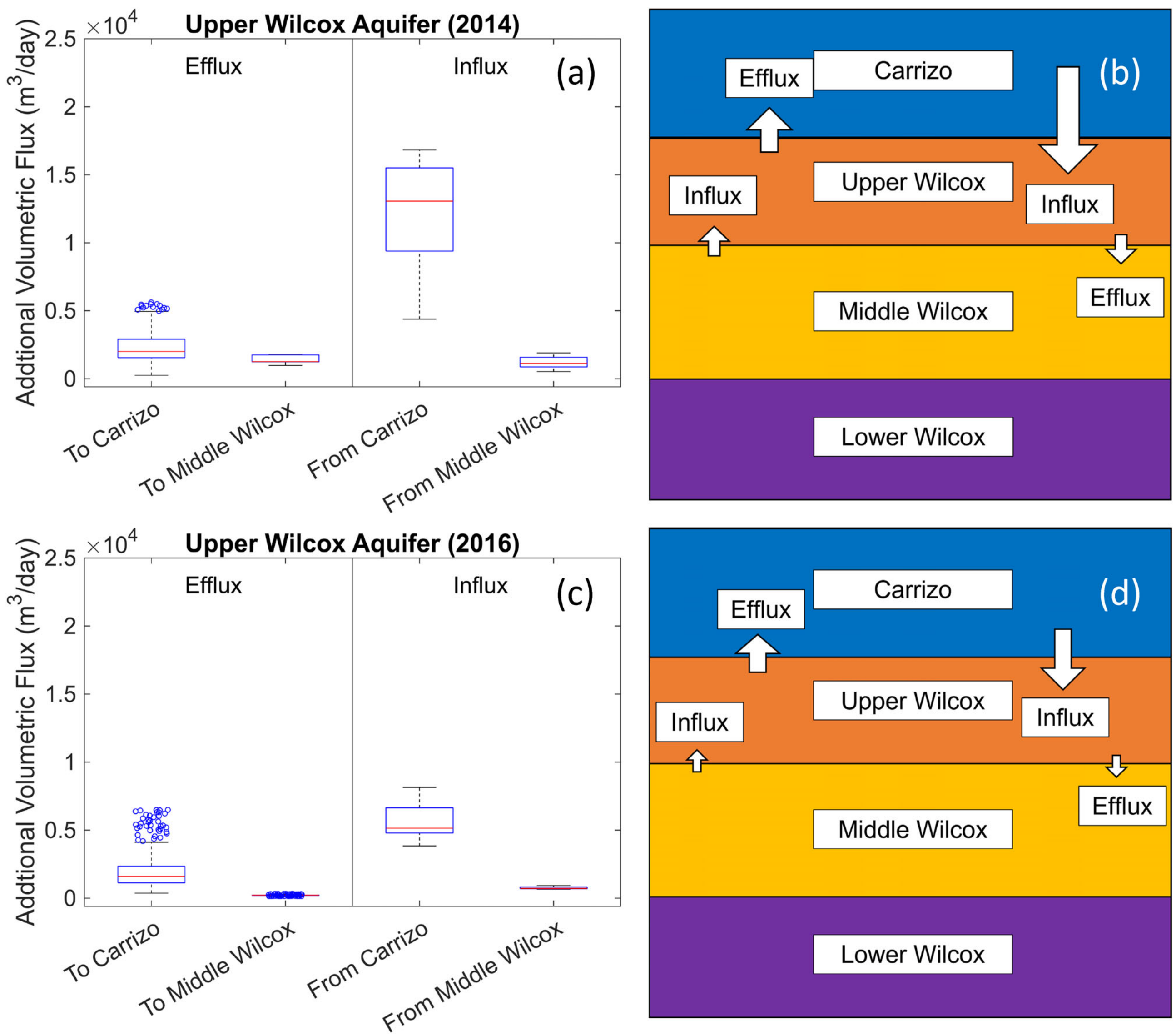

Figure 4. Change in daily gross volumetric fluxes driven by pumping for HF supply to and from the upper Wilcox hydrostratigraphic unit in maximum (2014) (a) and minimum HF demand (2016) (c). Panels (b) and (d) are conceptual diagrams that depict the approximate magnitude and directions of fluxes in 2014 and 2016, respectively.

model predicted a net negative flux for 2011–2013 (Figure 5a, solid orange line), whereas the RFSW model predicted net negative fluxes for 2011–2014 (Figure 5a, dashed orange line) (Table S3). To determine the additional net volumetric flux (influx − efflux) driven by pumping for HF supply, the baseline net volumetric flux was subtracted from the RFSW net flux for each layer. This was done for each year of the study. In the Carrizo layer, an increase in net flux was predicted for the years 2015, 2016, 2019, and 2020 (positive values in column 4 of Table S3) (Figure 5a, blue bars). During these years, both the baseline and RFSW models predicted a net positive flux; however, the RFSW model predicted a net flux that was 85.6 Mm^3 (57%) less. The smallest difference in the magnitude of net flux between the two models is predicted to have occurred in 2015 with an increase in net influx of 11.2 Mm^3 (13%).

Influx to the upper Wilcox layer exceeded efflux for both the baseline (Figure 5b, solid orange line) and RFSW model (Figure 5b, dashed orange line) for each year (Table S2). The greatest difference in net volumetric influx between the baseline and RFSW models in this layer was predicted to have occurred in 2015 with an increase of 218 Mm^3 (7%). This maximum increase in predicted net volumetric influx to the upper Wilcox lagged the peak water demand year of 2014 by 1 year. The smallest differences in predicted net flux occurred in 2011 with an increase in net flux of 7.26×10^6 m^3 (<1%).

Impacts of Uncertainties and Biases on Findings

Several assumptions in this study were made regarding oil and gas activities, well owners, and the accuracy and completeness of databases. The following three assumptions led to an underestimation of total drawdown in OSWs owing to pumping for HF supply: (1) all OSWs

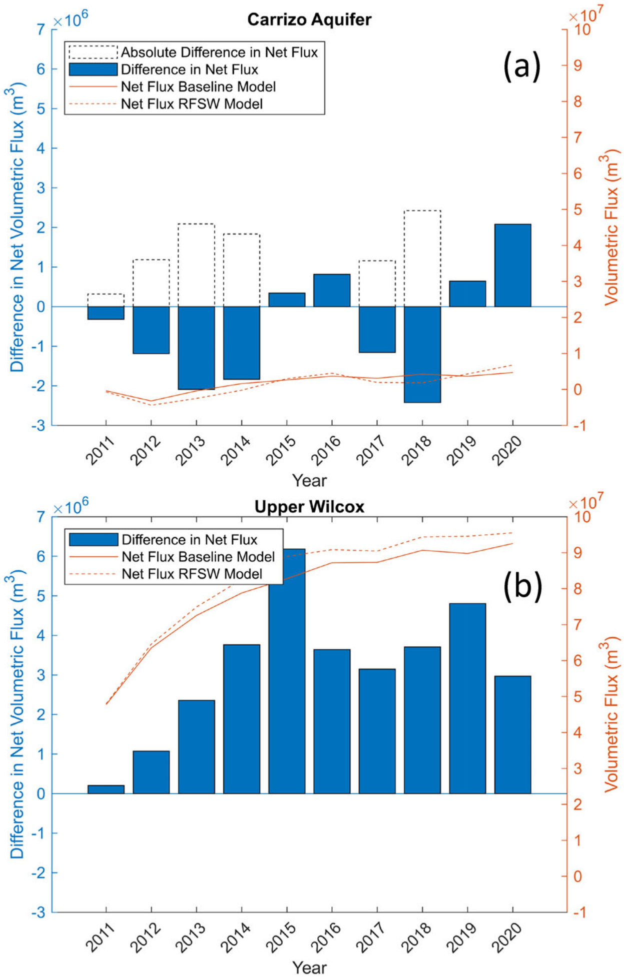

Figure 5. Differences in annual net influx (positive blue bars) and efflux (negative blue bars) to and from two layers that were most impacted by pumping for HF supply. The differences are calculated from net fluxes of the baseline and RFSW models which are indicated by solid and dashed orange lines, respectively. Absolute flux differences are depicted by positive dashed outlines. (a) Carrizo sand. (b) Upper Wilcox.

were reported in the SDR database. This is not the case as some well's construction predates 2001, when the construction details of all new wells were required to be reported. Information on many of these pre-2001 OSWs can be found on the TWDB Groundwater Database. When we searched this database for wells located within 3 km of a RFSW in this study (for any year), we found 34 wells in the Carrizo–Wilcox aquifer (13 public supply, 10 domestic, 6 irrigation, and 5 stock). Many of these wells would not be screened in the same layer as a given RFSW. Therefore, the number of wells registered in the TWDB Groundwater Database that were potentially impacted by RFSW pumping that were not included in this study is much lower than 34. This is comparatively a much smaller number than the 250 OSWs registered in the SDR as installed in the Carrizo–Wilcox aquifer system with overlapping screened intervals and located within 3 km of an RFSW. Future work should include as many registered OSWs as is possible; (2) OSWs and RFSWs were no longer operational from the year they were abandoned, not after plugging was completed. This may have distributed HF pumping in the models away from what were indeed active RFSWs; and (3) this study does not explicitly model the additive effects of drawdown from pumping for HF supply and pumping from the at-risk well (Reilly et al. 1984). It is assumed that the OSW is not currently being pumped.

The following three assumptions led to an overestimation of additional drawdown: (1) all water utilized for HF comes from groundwater. In fact, approximately 10% of water for HF is supplied by surface water (Nicot et al. 2012); (2) OSWs and RFSWs were operational beginning the year a well was drilled, not once drilling was completed. This may have distributed HF pumping to RFSWs that were not yet active; (3) one RFSW supplied all the water for each HF event. If water for a single HF event was sourced from multiple RFSWs the impacts on OSWs would have been less severe but more widespread. Service companies that supply water to oil and gas companies in shale plays will source their water in different ways which will impact the temporal and spatial distribution of groundwater pumping.

Implications of Enhancing Mixing of Water across Hydrostratigraphic Units

Net volumetric influx to the upper Wilcox was predicted to be higher in the RFSW model than the baseline model during all years of the study. Most of this additional water captured from adjacent layers came from the overlying Carrizo. When compared to the total volume of water used for HF supply by year and layer, the difference in net layer to layer volumetric flux followed trends in additional water consumption added from RFSW pumping, but with a 1-year lag (Figures 2b and 5b).

In contrast to the upper Wilcox, predicted net volumetric influx to the Carrizo layer was typically less under the influence of the additional pumping for HF supply. The Carrizo sand typically contains fresher water than the underlying Wilcox layers (Klemt et al. 1976). Pumping from freshwater aquifers can encourage underlying brackish water from a hydraulically connected aquifer to upwell thereby deteriorating the water quality of the pumped aquifer (Bredehoeft and Pinder 1973; Fogg et al. 1983). Here we show that pumping for HF supply contributes to inducing vertical flow across layers. As with any intensive and widespread pumping, this has the potential to disturb the chemical stratification of the aquifer system and thereby limit future fresh water supplies (Fogg et al. 1983; McMahon et al. 2016). This is one of the ways that HF may impose external costs to present and future generations by limiting the supply of high-quality potable water.

Conclusions

Globally, many shale plays are located underlying groundwater-dependent, semi-arid, and arid regions (Rosa et al. 2018). At the regional scale, water extracted for HF is commonly a small fraction of annual total extractions. However, this study suggests that the short-lived nature of these extractions will lead to drastic local drawdowns which impact neighboring wells. RFSWs pump large volumes of water while operating but do not operate continuously as public supply wells do. To accurately calculate the drawdown caused by pumping for HF supply, models must calculate those drawdowns over fine temporal and spatial resolution on the order of days and meters, respectively, rather than years and kilometers. This was achieved using an established analytical model. Neither a numerical nor analytical model are sufficient to assess the comprehensive impacts from pumping for HF supply that is distributed across a large area. A combined modeling approach is necessary; the numerical model can predict changes in layer-to-layer volumetric fluxes and the analytical model can predict drawdowns.

Modeling alone is not enough, however, to address the concerns of stakeholders. To improve the model accuracy, the timing and volumes of water sourced from aquifers should be reported for all HF operations. To verify the predicted impacts from these improved models so that stakeholders can gain confidence that the pumping for HF supply is not causing their wells to go dry, real-time water levels should be measured in a subset of OSWs near RFSWs and reported to a public website.

In the present study, calculated drawdowns exceeding 20 m placed some OSWs at risk of pump failure. However, of the OSWs that had pump intake elevations listed in the SDR, only two wells in the analytical model were predicted to be at risk of pump failure. If this study were conducted for a shale play underlying aquifer formations with less thickness or lower storativity, the impact could have been much greater with more wells at risk of failure.

Layer-to-layer flux predicted by the numerical model provides insight into how the layers of the Carrizo–Wilcox were likely impacted by additional HF supply pumping. Understanding the direction water is moving in the system can help determine which layers of the Carrizo–Wilcox are at risk of water quality degradation. However, future work is needed to test the impact that layer to layer flux has on water quality in the Carrizo–Wilcox aquifer. One way to do this would be by using TDS values determined by past studies (Hamlin et al. 2017) and a MODFLOW transport model to track water quality changes caused by additional RFSW pumping.

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Authors' Note

The authors do not have any conflicts of interest or financial disclosures to report.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Table S1. Additional drawdown in OSWs calculated with the analytical model. Well count (N_w) is the number of sector wells impacted by additional drawdowns.

Table S2. Additional pumping costs at OSWs by sector for the middle Wilcox calculated predicted by the analytical model during 2014. These costs were estimated using additional drawdowns and the Bernoulli equation with energy costs. Median costs are per well, and total costs are per sector.

Table S3. Additional net layer to layer volumetric flux in the Carrizo and Upper Wilcox from 2011 through 2020. The signs − represents net efflux and + represents net influx.

Figure S1. Map of Eagle Ford Shale with County and Groundwater Conservation District data.

Figure S2. Hydrostratigraphic cross-sections of the Carrizo–Wilcox aquifer and overlying strata.

Figure S3. Map of Eagle Ford Shale with Texas Water Planning Groups.

Figure S4. Daily spot prices of crude oil from 2010 to 2020.

Figure S5. Average total annual precipitation across Texas. The region with the solid-red line outline represents the extent of the Eagle Ford Shale play.

Figure S6. Sources of data and project workflow.

Figure S7. Daily drawdowns owing to pumping for HF supply predicted by the analytical model in the lower two layers of the Carrizo–Wilcox aquifer which are the Middle Wilcox and the Lower Wilcox. n_e is drawdown-days.

Figure S8. Additional drawdown predicted by the analytical model in OSWs in the middle Wilcox analytical model owing to pumping from RFSWs. (a) 2014 drawdowns. (b) 2016 drawdowns in. n_w is other sector wells. n_e is drawdown-days.

Figure S9. Gross annual volumetric fluxes to and from each layer of the Carrizo–Wilcox aquifer. (a) Volumetric fluxes into/out of Carrizo. (b) Volumetric flux fluxes into/out of the upper Wilcox. (c) Volumetric fluxes into/out of the middle Wilcox. (d) Volumetric fluxes into/out of the lower Wilcox.

Appendix S1. Computer codes written in MATLAB to generate RFSW pumping schedules and calculate drawdown.

References

Arciniega-Esparza, S., J.A. Brena-Naranjo, A. Hernandez-Espriu, A. Pedrozo-Acuna, B.R. Scanlon, J.P. Nicot, M.H. Young, B.D. Wolaver, and V.H. Alcocer-Yamanaka. 2017. Baseflow recession analysis in a large shale play: Climate variability and anthropogenic alterations mask effects of hydraulic fracturing. *Journal of Hydrology* 553: 160–171.

Arnett, B., K. Healy, Z. Jiang, D. LeClere, L. McLaughlin, J. Roberts, and M. Steadman. 2014. Water use in the Eagle Ford Shale: An economic and policy analysis of water supply and demand, report for the Texas Railroad Commission by the Bush School of Government and Public Service, Texas A&M University. https://hdl.handle.net/1969.1/151989

Bajaras, M. 2011. Texas fracking critics tour the Eagle Ford as complaints of contamination surface. *San Antonio Current*, San Antonio, TX. June 21.

Best, L.C., and C.S. Lowry. 2014. Quantifying the potential effects of high-volume water extractions on water resources during natural gas development: Marcellus Shale, NY. *Journal of Hydrology-Regional Studies* 1: 1–16.

Bhattarai, N., A. Pollack, D.B. Lobell, R. Fishman, B. Singh, A. Dar, and M. Jain. 2021. The impact of groundwater depletion on agricultural production in India. *Environmental Research Letters* 16, no. 8.

Brantley, S.L., D. Yoxtheimer, S. Arjmand, P. Grieve, R. Vidic, J. Pollak, G.T. Llewellyn, J. Abad, and C. Simon. 2014. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. *International Journal of Coal Geology* 126: 140–156.

Bredehoeft, J.D., and G.F. Pinder. 1973. Mass-transport in flowing groundwater. *Water Resources Research* 9, no. 1: 194–210.

Brien, J.A. 2021. Impacts of groundwater pumping for hydraulic fracturing on other sector wells in aquifers overlying the Eagle Ford Shale of Texas. Master of science thesis, Water Management and Hydrologic Sciences Program, Texas A&M University, College Station, Texas. https://doi.org/10.2139/ssrn.4203523

Deeds, N., V. Kelley, D. Fryar, T. Jones, A.J. Whallon, and K.E. Dean. 2003. *Groundwater Availability Model for the Southern Carrizo-Wilcox Aquifer*. Austin, Texas: Prepared for Texas Water Development Board.

Duda, R. 2014. Assessment of disposable groundwater resources for hydraulic fracturing of gas shales in the Lublin Basin (eastern Poland). *Gospodarka Surowcami Mineralnymi-Mineral Resources Management* 30, no. 4: 79–96.

Electricity Local. 2018. Local electricity rates & statistics. https://www.electricitylocal.com/ (accessed August 1, 2021).

ESRI. 2021. *Thiessen Polygons*. Environmental Systems Research Institute, Online.

Ferris, J.G. 1951. Cyclic fluctuations of a water level as a basis for determining aquifer transmissivity. *International Association of Scientific Hydrology Publication* 33: 148–155.

Fogg, G.E., S.J. Seni, and C.W. Kreitler. 1983. *Three-Dimensional Ground-Water Modeling in Depositional Systems, Wilcox Group, Oakwood Salt Dome Area, East Texas*. Austin, Texas: Bureau of Economic Geology, University of Texas. https://doi.org/10.23867/RI0133D

FracFocus. 2021. FracFocus chemical discloser registry, online. https://fracfocus.org/ (accessed August 1, 2021).

Freyman, M. 2014. *Hydraulic fracturing & water stress: Water demand by the numbers—Shareholder, lender & operator guide to water sourcing*. Boston, Massachusetts: Ceres. www.ceres.org

Gassert, F., M. Landis, M. Luck, P. Reig, and T. Shiao. 2013. Aqueduct global maps 2.0, World Resources Institute, Working Paper. http://pdf.wri.org/aqueduct_metadata_global.pdf

Gold, R. 2014. *The Boom: How Fracking Ignited the American Energy Revolution and Changed the World*. New York: Simon & Schuster, Inc.

Graham, N.T., G. Iyer, M.I. Hejazi, S.H. Kim, P. Patel, and M. Binsted. 2021. Agricultural impacts of sustainable water use in the United States. *Scientific Reports* 11, no. 1: 17917.

Gyawali, B., D. Murgulet, and M. Ahmed. 2022. Quantifying changes in groundwater storage and response to hydroclimatic extremes in a coastal aquifer using remote sensing and ground-based measurements: The Texas Gulf Coast aquifer. *Remote Sensing* 14, no. 3: 612.

Hamlin, H.S., B.R. Scanlon, R.C. Reedy, D.A. Banerji, S.C. Young, M. Jigmond, and J. Harding. 2017. *Fresh, Brackish, and Saline Groundwater Resources in the Carrizo-Wilcox, Queen City and Sparta Aquifers in Groundwater Management Area 13—Location, Quantification, Producibility, and Impacts*. Austin, Texas: Prepared by Bureau of Economic Geology and INTERA Inc. for Texas Water Development Board. TWDB Contract No. 1548301855.

Hantush, M.S. 1961. Drawdown around a partially penetrating well. *Journal of the Proceedings of the American Society of Civil Engineers* 87, no. 4: 83–98.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000: U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process. U.S. Geological Survey Open-File Report 00-92. https://doi.org/10.3133/ofr200092

Hernandez-Espriu, A., B. Wolaver, S. Arciniega-Esparza, B.R. Scanlon, M.H. Young, J.P. Nicot, S. Macias-Medrano, and J.A. Brena-Naranjo. 2019. A screening approach to improve water management practices in undeveloped shale plays, with application to the transboundary Eagle Ford Formation in northeast Mexico. *Journal of Environmental Management* 236: 146–162.

Horner, R.M., C.B. Harto, R.B. Jackson, E.R. Lowry, A.R. Brandt, T.W. Yeskoo, D.J. Murphy, and C.E. Clark. 2016. Water use and management in the Bakken Shale Oil Play in North Dakota. *Environmental Science & Technology* 50, no. 6: 3275–3282.

Ikonnikova, S.A., F. Male, B.R. Scanlon, R.C. Reedy, and G. McDaid. 2017. Projecting the water footprint associated with shale resource production: Eagle Ford Shale case study. *Environmental Science & Technology* 51, no. 24: 14453–14461.

Institute for Energy Research. 2016. Eagle Ford Shale fact sheet, Washington, DC. http://www.instituteforenergyresearch.org/ (accessed August 1, 2021).

Jacob, C.E. 1950. Flow of ground water. In *Engineering Hydraulics*, ed. H. Rouse, 321–386. New York: Wiley.

Jasechko, S., and D. Perrone. 2017. Hydraulic fracturing near domestic groundwater wells. *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 50: 13138–13143.

Karim, A., M.G. Cruz, E.A. Hernandez, and V. Uddameri. 2020. A GIS-based fit for the purpose assessment of brackish groundwater formations as an alternative to freshwater aquifers. *Water* 12, no. 8: 2299.

Kelley, V.A., N. Deeds, D.G. Fryar, J.P. Nicot, T.J. Jones, A.R. Dutton, G. Bruehl, T. Unger-Holtz, and J.L. Machin. 2004. *Groundwater Availability Models for the Queen City and Sparta Aquifers*. Austin, Texas: INTERA Inc. and

The University of Texas at Austin, Bureau of Economic Geology, prepared for Texas Water Development Board.
Klemt, W.B., G.L. Duffin, and G.R. Elder. 1976. *Ground-Water Resources of the Carrizo Aquifer in the Winter Garden Area of Texas. Texas Water Development Board Report 210, 2 vols*. Austin, Texas: Texas Water Development Board.
Kondash, A.J., E. Albright, and A. Vengosh. 2017. Quantity of flowback and produced waters from unconventional oil and gas exploration. *Science of the Total Environment* 574: 314–321.
Li, Y., J.H. Hernandez, M. Aviles, P.S.K. Knappett, J.R. Giardino, R. Miranda, M.J. Puy, F. Padilla, and J. Morales. 2020. Empirical Bayesian kriging method to evaluate inter-annual water-table evolution in the Cuenca Alta del Rio Laja aquifer, Guanajuato, Mexico. *Journal of Hydrology* 582, no. 124517.
Lin, Z.L., T. Lin, S.H. Lim, M.H. Hove, and W.M. Schuh. 2018. Impacts of Bakken Shale oil development on regional water uses and supply. *Journal of the American Water Resources Association* 54, no. 1: 225–239.
Mace, R.E., and R.C. Smyth. 2003. *Hydraulic Properties of the Carrizo-Wilcox Aquifer in Texas: Information for Groundwater Modeling, Planning, and Management*. Austin, Texas. Report of Investigations No. 269: Bureau of Economic Geology. https://doi.org/10.23867/RI0269D
Mace, R.E., R.C. Smyth, L. Xu, and J. Liang. 2000. *Transmissivity, Hydraulic Conductivity, and Storativity of the Carrizo-Wilcox Aquifer in Texas*. Austin, Texas: Texas Water Development Board. Texas Water Development Board Contract No. 99-483-279, Part 1.
McIntosh, J.C., and G. Ferguson. 2019. Conventional oil-the forgotten part of the water-energy nexus. *Groundwater* 57, no. 5: 669–677.
McMahon, P.B., J.K. Bohlke, K.G. Dahm, D.L. Parkhurst, D.W. Anning, and J.S. Stanton. 2016. Chemical considerations for an updated national assessment of brackish groundwater resources. *Groundwater* 54, no. 4: 464–475.
Nicot, J.P., B.R. Scanlon, R.C. Reedy, and R.A. Costley. 2014. Source and fate of hydraulic fracturing water in the Barnett Shale: A historical perspective. *Environmental Science & Technology* 48, no. 4: 2464–2471.
Nicot, J.P., R.C. Reedy, R.A. Costley, and P.E. Huang. 2012. *Oil & Gas Water Use in Texas: Update to the 2011 Mining Water Use Report*, 117. Austin, Texas: Bureau of Economic Geology, The University of Texas at Austin.
Nicot, J.P., and B.R. Scanlon. 2012. Water use for shale-gas production in Texas, US. *Environmental Science & Technology* 46, no. 6: 3580–3586.
Nielsen-Gammon, J.W., J.L. Banner, B.I. Cook, D.M. Tremaine, C.I. Wong, R.E. Mace, H.L. Gao, Z.L. Yang, M.F. Gonzalez, R. Hoffpauir, T. Gooch, and K. Kloesel. 2020. Unprecedented drought challenges for Texas water resources in a changing climate: What do researchers and stakeholders need to know? *Earths Future* 8, no. 8: e2020EF001552.
Obkirchner, G.E. 2019. Evaluating the economic impacts of groundwater pumping for hydraulic fracturing on aquifer stakeholders in the Eagle Ford Shale. Master of science thesis, Water Management and Hydrologic Sciences Program, Texas A&M University, College Station, Texas.
Railroad Commission of Texas. Eagle Ford Shale: Information and Statistics. 2020. https://www.rrc.state.tx.us/oil-and-gas/major-oil-and-gas-formations/eagle-ford-shale/ (accessed August 1, 2021).
Reilly, T.E., O.L. Franke, and G.D. Bennett. 1984 The principle of superposition and its application in ground-water hydraulics.U.S. Geological Survey Open-File Report 84-459. https://pubs.usgs.gov/of/1984/0459/report.pdf
Rosa, L., and P. D'Odorico. 2019. The water-energy-food nexus of unconventional oil and gas extraction in the Vaca Muerta Play, Argentina. *Journal of Cleaner Production* 207: 743–750.
Rosa, L., M.C. Rulli, K.F. Davis, and P. D'Odorico. 2018. The water-energy nexus of hydraulic fracturing: A global hydrologic analysis for shale oil and gas extraction. *Earths Future* 6, no. 5: 745–756.
Ryder, P.D. 1988. Hydrogeology and predevelopment flow in the Texas Gulf Coast aquifer system. U.S. Geological Survey Water Resource Investigations Report 87-4248.
Saha, G.C., and M. Quinn. 2020a. Assessing the effects of water withdrawal for hydraulic fracturing on surface water and groundwater—A review. *Meteorology Hydrology and Water Management-Research and Operational Applications* 8, no. 2: 52–59.
Saha, G.C., and M. Quinn. 2020b. Integrated surface water and groundwater analysis under the effects of climate change, hydraulic fracturing and its associated activities: A case study from northwestern Alberta, Canada. *Hydrology* 7, no. 4: 70.
Scanlon, B.R., R.C. Reedy, and B.D. Wolaver. 2022. Assessing cumulative water impacts from shale oil and gas production: Permian Basin case study. *Science of the Total Environment* 811, no. 152306: 152306.
Scanlon, B.R., S. Ikonnikova, Q. Yang, and R.C. Reedy. 2020. Will water issues constrain oil and gas production in the United States? *Environmental Science & Technology* 54, no. 6: 3510–3519.
Scanlon, B.R., R.C. Reedy, and J.P. Nicot. 2014a. Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil. *Environmental Science & Technology* 48, no. 20: 12386–12393.
Scanlon, B.R., R.C. Reedy, and J.P. Nicot. 2014b. Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays? *Environmental Research Letters* 9, no. 12: 124011.
Scanlon, B.R., C.C. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, and P.B. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 24: 9320–9325.
Schorr, S., M. Zivic, S. Panday, W.R. Hutchison, and J. Rumbaugh. 2021. *Conceptual Model Report: Update to the Groundwater Availability Model for Southern Portion of the Carrizo-Wilcox, Queen City, and Sparta Aquifers*. Austin, Texas: Texas Water Development Board. Contract No. 1948312321.
South Central Texas Regional Water Planning Group. 2020. 2021 South Central Texas Regional Water Plan (Region L). https://www.regionltexas.org/current-planning-effort/5th-cycle-2021/2021-regional-water-plan/
Theis, C.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.
Tukey, J.W. 1977. *Exploratory Data Analysis*. Reading, Massachusetts: Addison-Wesley.
TWDB. 2021. *Texas Water Development Board Submited Drillers Reports*. Austin, Texas: Texas Water Development Board. Database. https://www.twdb.texas.gov/groundwater/data/drillersdb.asp
TWDB. 2016. *Texas Aquifers Study*. Austin, Texas: Texas Water Development Board. Special Legislative Report for 85th Texas Legislature.
Unruh, H., E.H. Habib, and D. Borrok. 2021. Impacts of hydraulic fracturing on surface and groundwater water resources: Case study from Louisiana. *Journal of Water Resources Planning and Management* 147, no. 10: 05021017.

U.S. Census Bureau. 2020. *Southern and Western Regions Experienced Rapid Growth This Decade*. Press Release No. CB20-78. Washington, DC: U.S. Census Bureau.

U.S. Energy Information Administration. 2014. *Updates to the EIA Eagle Ford Play Maps*. Washington, DC: U.S. Department of Energy.

Vengosh, A., R.B. Jackson, N. Warner, T.H. Darrah, and A. Kondash. 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology* 48, no. 15: 8334–8348.

Wade, S.C. 2017. *GAM Run 17-027 MAG: Modeled Available Groundwater for the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson Aquifers in Groundwater Management Area 13*. Austin, Texas: Texas Water Development Board.

Weiner, R.F., and R.A. Matthews. 2003. *Environmental Engineering*. New York, NY: Butterworth-Heinemann.