California’s Central Valley Groundwater Wells Run Dry During Recent Drought

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Abstract Declining water tables are causing wells to run dry in California, but the prevalence and spatial distribution of wells that have run dry are not known beyond anecdotal and voluntary reports. Here, we apply a new, simple, and measurement-driven method to calculate a localized water table; we show, for the first time using observations, that up to one-in-five wells now runs dry in California’s Central Valley. The spatial distribution of wells identified as having dried up replicates hot spots of wells identified as having run dry in a voluntary reporting system, while also capturing impacts on groundwater wells that have not reportedly run dry. We assess the rates of drilling throughout the Central Valley and find, surprisingly, that domestic wells are being drilled deeper at a rate that exceeds agricultural wells across much of the central Central Valley. Because new groundwater wells are costly (i.e., $10,000 to $100,000), we suggest explicitly considering dry wells in groundwater sustainability planning to protect homes and farms from the loss of access to reliable water supplies in the future.

Plain Language Summary Anecdotal evidence suggests that groundwater level declines are causing wells to run dry in California’s Central Valley, threatening access to reliable water supplies. Here we show with observational data that thousands of wells ran dry at the peak of the recent drought, especially in the southeastern Central Valley. We use groundwater well construction data to show that domestic water wells ran dry in disproportionate numbers, because typical domestic wells are shallower than typical agricultural wells. The results of this work can be used as water agencies are considering current and future impacts of groundwater depletion on groundwater users.

1. Introduction

Groundwater provides the primary source of drinking water to several million individuals and supplies 40% of the water used for irrigated agriculture in California’s Central Valley. Large groundwater withdrawals, combined with minimal oversight (Chappelle et al., 2017; Nelson & Perrone, 2016), have led to aquifer overdraft and concomitant groundwater depletion (Boyle et al., 2012; Famiglietti et al., 2011; Faunt et al., 2009; Konikow, 2014; Marston & Konar, 2017; Miro & Famiglietti, 2018; Scanlon et al., 2012; Xiao et al., 2017). Identifying where wells have run dry is particularly timely, because ongoing policy development will have implications for future groundwater supplies and demands.

Previous attempts to assess how many wells have run dry and calculate which kinds of groundwater users are impacted most have been hindered by the lack of groundwater well completion reports across a large swath of the Central Valley where groundwater depletion has been documented (Perrone & Jasechko, 2017). That is, to date, no peer-reviewed study has systematically evaluated the prevalence of dry wells throughout the entire Central Valley using only observations. Much of what we do know about groundwater wells derives from hearsay, newspaper reports (supporting information Table S12) or a voluntary reporting system. The voluntary reporting system, also known as the Household Water Supply Shortage Reporting System, was developed in 2014 by the Department of Water Resources (California Department of Water Resources, 2018). This system corroborates newspaper reports that wells are running dry but likely under-represents the actual number of wells that have run dry (California Department of Water Resources, 2018). Many reported water shortages were filed on behalf of water users by county health officials, with some counties being more proactive than others (California Department of Water Resources, 2018).

Recently, the Department of Water Resources published well completion reports for the parts of the Central Valley that previously lacked well completion data. These well completion reports, combined with the
development of a novel method to calculate water table elevations that we present here (section 2), provide an opportunity to (a) estimate how many groundwater wells went dry in recent years; (b) map where these dry wells are clustered and crosscheck the hot spots with voluntary reports of dry wells; and (c) identify areas where groundwater wells have been drilled deeper, possibly in an effort to stave off the loss of access to groundwater induced by groundwater level declines and concomitant well drying.

The three objectives of our study are to (i) calculate a localized water table using a new measurement-driven method designed for non-hydrostatic aquifer systems with vertical hydraulic gradients, (ii) compare locally relevant, observation-based water table elevations to groundwater well depths to identify wells that ran dry sometime during the most recent California drought (2013–2018), and (iii) quantify the rates of change in well drilling depths to understand vulnerabilities of different kinds of groundwater users to well drying.

2. Methods

2.1. Well Completion Data Compilation and Quality Control

Well construction data were provided by the California Department of Water Resources (Figures 1a and 1b; personal communication; water.ca.gov/Programs/Groundwater-Management/Wells). We completed six quality control procedures designed to exclude well construction records that (a) have unclear construction dates, (b) are replicated in the database, (c) do not correspond to the construction of a well, (d) lack well depth information, (e) have an unrealistic recorded location, or (f) may have been constructed for a purpose other than domestic, agricultural, or industrial use (supporting information sections S1.1 to S1.6 and Table S1). We focused on wells constructed after 1975 because wells typically have 40–50 year life spans (e.g., Harding et al., 1947).

2.2. Well Water Level Data

We amassed well water level measurements from (a) the United States Geological Survey (Figure 1c; water.usgs.gov/ogw/data.html); (b) California’s groundwater monitoring program (waterboards.ca.gov/gama); and (c) water level measurements made in constructed wells (section 2.1). Water levels recorded in well completion reports are of suitable quality for use in our analysis, as supported by our comparison of water level measurements reported in well drilling reports versus those measured in monitoring wells, when these measurements have been made at a similar time (supporting information section S2).

2.3. Vertical Hydraulic Gradient Calculation

We completed regression analyses of well water level elevation values and well bottom elevation values to quantify vertical hydraulic gradients throughout the Central Valley. Our analysis of well water level observations confirms that hydraulic gradients are downward-oriented throughout much of the Central Valley. Where non-zero vertical hydraulic gradients exist, no single well water level measurement necessarily represents the local water table.

2.4. Water Table Elevation Calculation Accounting for Vertical Hydraulic Gradients

To quantify water table elevations in a way that accounts for vertical hydraulic gradients, we completed a regression-based methodology that uses many well water level measurements to estimate the elevation of the water table (Figure 2a). For each pumping well (see depiction in Figure 2), we estimated the local water table elevation through linear least squares regression analyses, calculating the y-intercept (and associated standard error) for all recent well water level measurements made near a pumping well that met our criteria for analysis. All analyzed well water levels are from wells that were not being pumped when the measurements were made (i.e., “static” water levels). We completed regressions of well water level elevation minus well bottom elevation plotted against well bottom elevation (Figure 2b). The method is designed to account for the non-zero vertical hydraulic gradients that are widespread in the Central Valley (e.g., Figures 2c and 3a).

We calculated water table elevations at the locations of each constructed well (i.e., “pumping well”) meeting quality control criteria (section 2.1). We ran a suite of sensitivity analyses that included three components (see supporting information section S3). The first component included adjusting minimum dates of well water level measurements. Analyses were completed using only well water level measurements made from 2013 to 2018, only measurements made from 2014 to 2018, and only measurements made from 2015 to 2018.
The second component included adjusting the maximum distance from a pumping well to a well water measurement (i.e., “radius” in Figure 2a; “radius” distance ranged 3 to 10 km across our sensitivity analyses; supporting information section S3). The third component included uncertainty in the land surface elevation at the wellhead (e.g., excluded wells with more than 10 m or more than 20 m uncertainty in wellhead land surface elevation; uncertainty in land surface elevations arises because constructed wells locations are uncertain to ±1.6 km).

2.5. Department of Water Resources’ Self-Reported Dry Wells Data Set

California’s Department of Water Resources’ database of voluntarily reported water supply shortages was provided via a Public Records Request fulfilled on 9 February 2019 (mydrywatersupply.water.ca.gov/report/publicpage). We map solely those records with a recorded “Shortage Type” of “Dry well (groundwater).” We analyzed records with a “Water Issues” value indicative of a dry well (Table S8). To test our method (Figure 2), we excluded Household Water Supply Shortage Reporting System records lacking well...
depth data or that identified uncertainty in recorded well depths (e.g., excluded records with well depths: “maybe 160,” “Possibly 170,” “Think it’s at 105”). If more than one depth was reported, we selected the deeper depth to be more conservative. The Department of Water Resources’ Household Water Supply Shortage Reporting System dataset redacts personal information; as a result, latitude and longitude data are only available to the nearest township‐range‐section (±1.6 km). Uncertainty in Household Water Supply Shortage Reporting System report locations creates uncertainty in land surface elevations at wellheads (supporting information section S4).

We completed identical analyses for \( n = 461 \) wells (i.e., from Household Water Supply Shortage Reporting System) to that completed for all pumping wells; this includes the suite of sensitivity analyses outlined in section 2.4. We then compared estimated water table elevations to elevations of well bottoms and show that our method adequately identifies wells (i.e., from Household Water Supply Shortage Reporting System) reported to have run dry (supporting information section S4).

2.6. Drilling Depth Variations Through Time

We completed linear regressions of drilling date (x‐axis) and well depth (y‐axis) for wells located in 10 km by 10 km grids throughout the Central Valley. We used only the constructed wells meeting our quality assurance criteria (supporting information). We analyzed the trends for the time interval 1950–2018. We present regression slopes in Figure 5 only if all of the following criteria were met: (a) at least \( n = 10 \) recorded constructed wells exist in the 100 km² area that met our criteria for analysis, (b) at least one recorded constructed well was completed in the 1950s, and (c) at least one recorded constructed well was completed after January 1, 2010.

3. Results

3.1. Water Table Elevations at Pumping Wells

We find that most areas in the Central Valley have a downward‐oriented vertical hydraulic gradient (Figure 3a). We compare water table elevations (Figure 3b) and well bottom elevations (Figure 1b) in California’s Central Valley and find that thousands of wells constructed between 1975 and 2018 have likely...
run dry (Figure 3c). Pumping wells that have run dry are concentrated in the southeastern part of the Central Valley (Figure 3c).

Among all sensitivity analysis scenarios, we estimate that (a) 1.6% to 6.7% of pumping wells have a water table that is deeper than their well bottom during 2013–2018, (b) 5.4% to 11.6% of pumping wells have a water table that overlies but is within 10 m of their well bottom, and (c) 14.5% to 22.4% of wells have a water table that overlies but is within 20 m of their well bottom (supporting information section S3).

3.2. Water Table Elevations Where Wells Have Reportedly Run Dry

We analyze water table elevations for wells reported to have run dry in the Household Water Supply Shortage Reporting System (Figure 3d). We find that, for the great majority of these wells (84% to 95%), run dry (Figure 3c). Pumping wells that have run dry are concentrated in the southeastern part of the Central Valley (Figure 3c).

Figure 3. Geospatial analysis of vertical hydraulic gradients, water table depth, pumping wells estimated to have run dry, and wells reported to have run dry. (a) Calculated vertical hydraulic gradients at each pumping well, based on regression analyses (see Figure 2c). (b) The depth to the local water table, determined through regression analyses (see Figure 2b). (c) Estimated differences between water table elevations and well depths; positive values imply a local water table that overlies the bottom of the well. Results exclude well water level measurements (i) made more than 10 km from the pumping well, (ii) made prior to 2013 or after 2018, (iii) made in wells deeper than 1 km, and (iv) made in wells where the range of possible land surface elevations at the wellhead was more than 10 m (this uncertainty arises from the poor precision of latitudes and longitudes for constructed wells). (d) The California’s Department of Water Resources voluntarily reported instances of water supply shortages in the Central Valley. Yellow circles are reported dry wells used to validate our method; red circles are other reported dry wells that did not meet our criteria for use in method validation (e.g., lack of well depth information; see also supporting information Figure S8). (a–c) Pumping wells and reported wells are recorded at township-range-section centroids; a small amount of dispersion was used to for display purposes only so that points were not hidden beneath each other.
our estimated water table is either deeper than the well bottom or overlies the bottom of the well by less than 20 m (supporting information section S3 and Table S9), implying our method adequately identifies wells that have run dry.

3.3. Proportions of Domestic Wells and Agricultural Wells Running Dry

We present frequency plots to explore differences in elevation between domestic and agricultural well bottoms and water table elevations (Figures 4a and 4b). Whereas 6% of agricultural wells have well bottom elevation that either overlies the water table or extends no more than 20 m below the water table; by contrast, only 6% of agricultural wells meet the same criteria. (c) Differences between median agricultural wells depths and median domestic well depths. Each square’s color represents the difference between the depth of the median agricultural well and the median domestic well within a 10 km by 10 km area. We only plot 10 km by 10 km areas if they contain at least five agricultural wells and at least five domestic wells. Median agricultural well depths exceed median domestic well depths in nearly all areas (94%; n = 587 of n = 625).

Figure 4. Comparison of water table elevations and well bottom elevations for agricultural (green) and domestic (blue) wells constructed from 1975 to 2018. (a) Frequency distribution of water table elevation minus well bottom elevation values. (b) Cumulative distribution of water table elevation minus well bottom elevation values. Nineteen percent of domestic wells have a well bottom elevation that either overlies the water table or extends no more than 20 m below the water table; by contrast, only 6% of agricultural wells meet the same criteria. (c) Differences between median agricultural wells depths and median domestic well depths. Each square’s color represents the difference between the depth of the median agricultural well and the median domestic well within a 10 km by 10 km area. We only plot 10 km by 10 km areas if they contain at least five agricultural wells and at least five domestic wells. Median agricultural well depths exceed median domestic well depths in nearly all areas (94%; n = 587 of n = 625).

We determine differences between domestic and agricultural well depths in 10 km by 10 km areas throughout the Central Valley (n = 625 areas; Figure 4c). Among all studied 100 km² areas containing at least five agricultural wells and five domestic wells in the Central Valley, the median agricultural well depth exceeds the median domestic well depth in 94% of areas (Figure 4c). The median agricultural well depth exceeds the median domestic well depth by at least 10 m in 84% of study areas, by at least 20 m in 71% of areas, by at least 50 m in 39% of areas, and by more than 100 m in 11% of study areas. Our finding that domestic wells are typically shallower than agricultural wells (Figure 4c) is consistent with our finding that domestic wells run dry disproportionately often relative to agricultural wells (Figures 4a and 4b; supporting information section S5).
We conclude that the rates that agricultural and domestic wells are being drilled deeper vary systematically across the Central Valley, with the rate that agricultural wells are being drilled deeper in the middle section of the Central Valley exceeding the rate that domestic wells are being drilled deeper across much of the southern Central Valley. The rate that domestic wells are being drilled deeper outpaces the rate that agricultural wells are being drilled deeper in the northern Central Valley. A construction depth rate of change over time (Figure 5d). We show that the rate that agricultural wells are being drilled deeper through time across the majority of the Central Valley (Table 1). Across all grids meeting our criteria for analyses, n = 535 (85%) have linear least squares regression slopes consistent with well deepening over time (well depth vs. time slope coefficients exceeding zero; Figure 5a). When we examine only significant (p-value < 0.05) trends, our conclusion that wells are being drilled deeper in the great majority of the Central Valley becomes even stronger (96% of all studied areas with significant trends; see second column in Table 1). Further, among all high-magnitude slopes (absolute value exceeding 1 m/year), we find that well deepening prevails in the vast majority of areas (see third and fourth columns in Table 1). Well deepening trends are apparent when we analyze drilling date versus well depth trend analyses for only domestic wells and for only agricultural wells (Table 1).

Sufficient well data exist in n = 332 study areas to juxtapose domestic versus agricultural groundwater well construction depth rates of change over time (Figure 5d). We show that the rate that agricultural wells are being drilled deeper exceeds the rate that domestic wells are being drilled deeper across much of the southern Central Valley and northern Central Valley. The rate that domestic wells are being drilled deeper outpaces the rate that agricultural wells are being drilled deeper in the middle section of the Central Valley. We conclude that the rates that agricultural and domestic wells are being drilled deeper vary systematically in space (Figure 5d).

### Table 1

| Well type | Well construction depth trends consistent with well deepening over time for 1950–2018 in 10 km by 10 km grids | Well construction depth trends with slopes exceeding 1 m/year consistent with well deepening over time for 1950–2018 in 10 km by 10 km grids |
|-----------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| All domestic, agricultural, and industrial wells | n<sub>deep</sub> = 535 of n<sub>all</sub> = 627 (85%) n<sub>deep-sig</sub> = 393 of n<sub>sig</sub> = 411 (96%) | n<sub>deep</sub> = 177 of n<sub>all</sub> = 194 (91%) n<sub>deep-sig</sub> = 163 of n<sub>sig</sub> = 173 (94%) |
| Only domestic wells | n<sub>deep</sub> = 411 of n<sub>all</sub> = 433 (95%) n<sub>deep-sig</sub> = 333 of n<sub>sig</sub> = 338 (99%) | n<sub>deep</sub> = 100 of n<sub>all</sub> = 102 (98%) n<sub>deep-sig</sub> = 98 of n<sub>sig</sub> = 99 (99%) |
| Only agricultural wells | n<sub>deep</sub> = 412 of n<sub>all</sub> = 482 (85%) n<sub>deep-sig</sub> = 266 of n<sub>sig</sub> = 276 (95%) | n<sub>deep</sub> = 177 of n<sub>all</sub> = 193 (92%) n<sub>deep-sig</sub> = 158 of n<sub>sig</sub> = 168 (94%) |

Note. n<sub>all</sub> = total number of grids meeting our criteria for analyses; n<sub>deep</sub> = grids with well construction depth trend consistent with well deepening (i.e., Pearson regression slope coefficient > 0); n<sub>sig</sub> = total number of grids meeting our criteria for analyses and with a significant trend (Pearson p-value <0.05); n<sub>deep-sig</sub> = grids with well construction depth trend consistent with significant well deepening (i.e., Pearson regression slope coefficient > 0 and also a Pearson p-value < 0.05).

### 3.4. Deeper Well Drilling

Wells are being drilled deeper through time across the majority of the Central Valley (Table 1). Across n = 627 study areas (10 km by 10 km) that meet our criteria for analyses (section 2), n = 535 (85%) have linear least squares regression slopes consistent with well deepening over time (well depth vs. time slope coefficients exceeding zero; Figure 5a). When we examine only significant (p-value < 0.05) trends, our conclusion that wells are being drilled deeper in the great majority of the Central Valley becomes even stronger (96% of all studied areas with significant trends; see second column in Table 1). Further, among all high-magnitude slopes (absolute value exceeding 1 m/year), we find that well deepening prevails in the vast majority of areas (see third and fourth columns in Table 1). Well deepening trends are apparent when we analyze drilling date versus well depth trend analyses for only domestic wells and for only agricultural wells (Table 1).

Sufficient well data exist in n = 332 study areas to juxtapose domestic versus agricultural groundwater well construction depth rates of change over time (Figure 5d). We show that the rate that agricultural wells are being drilled deeper exceeds the rate that domestic wells are being drilled deeper across much of the southern Central Valley and northern Central Valley. The rate that domestic wells are being drilled deeper outpaces the rate that agricultural wells are being drilled deeper in the middle section of the Central Valley. We conclude that the rates that agricultural and domestic wells are being drilled deeper vary systematically in space (Figure 5d).

### 4. Discussion

#### 4.1. Water Table Elevations at Pumping Wells

We estimate that at least one-in-thirty wells constructed between 1975 and 2018 ran dry between 2013 and 2018; wells that have run dry are concentrated in the southeastern Central Valley (Figure 3c). The southeastern part of the Central Valley is characterized by not only high-magnitude downward hydraulic gradients (Figure 3a) and deep water tables (Figure 3b) but also some relatively shallow wells (Figure 1b; e.g., Kings and Tulare Lake Basins—supporting information section S7). The combination of moderate-to-deep water tables and relatively shallow wells in the southeastern Central Valley creates conditions conducive to wells running dry.

Because we analyze elevations of well bottoms rather than the top of perforated intervals (see section 4.4), we likely underestimate the abundance of wells that have run dry. The ability to pump water from a well can be impaired before the water table declines below the bottom of the well (Gailey et al., 2019; Pauloo et al., 2020). Wells may run dry even when water tables overlie well bottoms for two reasons.

First, pumping draws down the water level in the well, meaning wells can run dry even before the water table drops below well perforations. The difference between the static (i.e., non-pumping) water level and the water level during pumping can be several meters. For example, the total drawdown reported
Groundwater wells are being drilled deeper in California’s Central Valley. Panels (a–c) present the slope of a linear least squares regression of well completion depth over time in 10 km by 10 km areas for (a) all wells meeting our criteria for analyses, (b) only domestic wells, (c) only agricultural wells (see section 2). Red shades mark areas where the linear regression of well depth and time yields a positive slope coefficient, consistent with deeper well completion depths over time (i.e., more recent wells constructed deeper than older wells). The great majority of well completion depth time series suggest that wells have been drilled deeper over time; specifically, among the \( n = 627 \) 10 km by 10 km areas we analyzed, \( n = 535 \) (i.e., 85% of studied areas) have regression slope coefficients exceeding zero, consistent with well deepening over time (see Table 1 for complete statistics). Panel (d) compares the slope coefficients for domestic versus agricultural well depth trends through time (i.e., comparison of values in panels (b) and (c)). Yellow shades mark areas where the slope coefficient for the linear regression of well depth versus drilling date for agricultural wells exceeds that for domestic wells; light blue shades are areas where the slope coefficient for domestic wells exceeds that for agricultural wells. Panel (e) presents an example of the linear regression for all wells in one 10 km by 10 km area (see dashed line from panel (b) to study location in map in panel (a)). Blue circles represent the completion of a domestic or municipal supply well; orange circles represent the completion of an agricultural well. The blue and orange lines are linear least squares regressions for only domestic wells (blue line—corresponding to values presented in panel (a)) and only agricultural wells (orange line—corresponding to values presented in panel (b)). The thick black line is the linear least squares regression for domestic and agricultural wells, represented by the slope coefficient 1.09 (consistent with well deepening over time) and the \( y \)-intercept coefficient \(-2,075\).
during pumping tests among completed wells in California has a median value of 30.5 m (Figure S28). While pumping rates during these tests can commonly be in excess of actual pumping rates during the wells life span, these data show that meters or tens-of-meters of drawdown during pumping is not uncommon.

Second, well pumping rates are susceptible to decline when the water table reaches the top of the perforated interval; in our study, we analyze the depth of wells rather than the depth to the top of perforations, because only half of all Central Valley records in the Department of Water Resources' well completion database report perforated interval data. Among wells meeting our criteria for analysis that report perforated interval(s), the offset from the top of the perforated interval to the bottom of the well has a median of 18 m, a lower-upper quartile range of 8 to 43 m, and a 5th–95th percentile range of 5 to 116 m. The existence of perforations 18 m above well bottoms in half of our pumping wells implies, again, that using the base of the well as a threshold water table depth for wells to run dry likely underestimates the number of wells with reduced yields induced by declining water tables.

If we assume that wells with bottoms that are below but within 20 m of the water table may also be dry—similar to the median offset from the well bottom to the top of the perforated interval—we estimate that about one fifth (14.5% to 22.4%) of wells constructed since 1975 ran dry.

4.2. Water Table Elevations Where Wells Have Reportedly Run Dry

Our method suggests that the water table is at or near the bottom of wells reported as dry in the Household Water Supply Shortage Reporting System (supporting information section S4). Because our approach identifies wells that have run dry within the Water Supply Shortage Reporting System database implies that our method is useful for mapping wells that have likely run dry (Figures S8–S25). This is especially critical for places where voluntary data are not available or are incomplete.

The method used to estimate water table elevations is, to the best of our knowledge, novel in that it provides a purely empirical approach to estimating water table elevations in a way that accounts for the existence of vertical hydraulic gradients. Most previous estimates of the spatial distribution of water tables implicitly assume no vertical hydraulic gradient exists or rely on hydrologic models, themselves often calibrated and validated against well water levels under the implicit assumption that these well water levels represent water table elevations. The approach described here demonstrates that (a) well water levels are unlikely representative of water table elevations for the great majority of areas, as non-zero vertical hydraulic gradients are expectedly widespread in actual aquifer systems, and (b) water table elevations can be estimated empirically without relying on a multi-parameter hydrologic model using only observations of hydrologic conditions (Figure 3). The latter may be especially important for agencies with limited resources to invest in hydrologic modeling.

4.3. Proportions of Domestic Wells and Agricultural Wells Running Dry

Our analysis of domestic and agricultural wells has ramifications for agricultural production and water access in the Central Valley. We estimate that, among all basins in the Central Valley, a larger proportion of domestic wells have likely run dry compared to the proportion of agricultural wells that have run dry, since domestic wells tend to be shallower than agricultural wells (Figure 4; supporting information section S5). The U.S. Geological Survey’s groundwater pumping estimates for 2015 suggest that county-scale agricultural groundwater pumping is 1.1 to 232 times higher than domestic and municipal groundwater pumping (1.1 to 232 is the range among counties that overlap at least partially with the Central Valley; supporting information section S10; data from Dieter et al., 2018; see also review of water use data: Perrone et al., 2015).

Drilling new wells is expensive and may exclude those who cannot afford new infrastructure, such as some rural homeowners. A comprehensive database of costs to construct new wells or deepen existing wells is, to the best of our knowledge, unavailable. Instead, we review dozens of media reports across California and find that (a) new domestic wells typically cost tens-of-thousands of dollars, (b) new agricultural wells typically cost hundreds-of-thousands of dollars, and (c) new municipal wells typically cost close to one million dollars (supporting information section S6 and Figure 6). Because of the high costs of new well construction, we conclude that strategic groundwater sustainability planning will consider the
4.4. Limitations to Our Analyses

Our analyses have limitations, four of which pertain to (1) uncertainty in wellhead locations, (2) uncertainty in the timing that wells first went dry, (3) simplifying assumptions about hydrogeologic conditions, such as aquifer formations, and (4) impacts of pumping-induced drawdown.

1. The Department of Water Resources’ well completion reports and water supply shortage reports redact personal information. As a result, the reports provide latitude and longitude data accurate only to the nearest township-range-section (about 1.6 km). This uncertainty in well locations translates to uncertainty in land surface elevations at the wellheads. More precise well location data can provide for more robust analyses for Groundwater Sustainability Agencies seeking to identify dry wells, especially where the topography changes substantially within township-range-section areas.

2. We emphasize that our analysis estimates wells that ran dry during the 2013–2018 time interval; some wells may have first run dry prior to this 5-year interval. Our maps of wells that ran dry during 2013–2018 are likely valuable to groundwater sustainability planning because they provide baseline information about the number of wells that have run dry.

3. Our proposed methodology to estimate water table elevations using well water level measurements simplifies actual hydrogeologic conditions. Fluvial deposits and the Corcoran Clay formation create semi-confining conditions in parts of the Central Valley. Our approach assumes that vertical hydraulic gradients remain constant with depth within the study area (see radius in Figure 2). This assumption oversimplifies actual hydrogeologic conditions because of the three-dimensional nature of groundwater flows under natural conditions (Tóth, 1963), non-equilibrium hydraulic heads induced by groundwater pumping (Fetter, 2000), and heterogeneity and anisotropy in aquifer system hydraulic conductivity that induces refraction in flow paths (Fetter, 2000). Further, the lack of widespread screen interval data for wells where we have water level data limits us to using the total well depth rather than the depth to the top or middle of the screened interval. Imperfections in some of our assumptions are likely captured in the scatter of the data points (e.g., Figures 2b and 2c) and therefore embedded in standard errors of regression coefficients. The proposed methodology goes beyond previous approaches (Perrone & Jasechko, 2017) that implicitly assume hydrostatic conditions by interpolating well water levels without considering how well depths correlate with well water levels.

4. Groundwater pumping induces a localized drawdown of the water table near each pumping well known as a cone of depression. Unfortunately, we do not have information about actual pumping rates from wells, meaning we cannot estimate the drawdown at pumping wells in our analysis. However, because our methodology uses well water level data from non-pumping wells, we stress that our results may, if

Figure 6. Groundwater well completion costs reported in news media (data compiled by D. Nguyen). Each bar represents the range of reported costs for well construction (see supporting information section S6): Municipal supply wells (n = 2 reports of well completion costs) are represented by the uppermost bar, agricultural wells (n = 6 reports) are represented by the middle bar, and domestic wells (n = 26 reports) are represented by the lowermost bar.
anything, underestimate the actual number of dry wells because we do not explicitly estimate pumping-induced drawdown (which serves to cause wells to run dry even when the water table overlies their bottom).

4.5. Managing California’s Groundwater for the Future

Currently, groundwater storage losses via pumping and discharges exceed inputs via recharge (Faunt et al., 2016), leading to storage declines in some basins. “Business as usual” projections suggest that groundwater storage will continue to decline for several decades in the absence of changes to groundwater inputs or losses (Massoud et al., 2018). Stabilizing or increasing groundwater storage will likely require considering both supply and demand management. Supply-side opportunities include water transfers (Jenkins et al., 2004), conjunctive use (Christian-Smith, 2013; Scanlon et al., 2016), and the intentional recharge of aquifers ("managed aquifer recharge") (Beganskas & Fisher, 2017). Potential exists to “bank” groundwater using storm water runoff, treated wastewater (Perrone & Rohde, 2016), or streamflow diverted when river discharges are high (Kocis & Dahlke, 2017). Augmenting water storage via managed aquifer recharge is often economically favorable relative to further dam construction (Perrone & Rohde, 2016). Demand-side options include, foremost, changes to agricultural water demands, as these are projected to be disproportionately important to storage stabilization relative to changes in domestic water demands (Massoud et al., 2018). Reductions to irrigated land areas are one mechanism that would expectedly reduce groundwater demands (Massoud et al., 2018). Hydroeconomic models suggest that lands growing less-profitable crops may be more likely to be fallowed during droughts, although decisions to fallow are complex and incorporate considerations beyond water availability (e.g., price expectations) (Medellín-Azuara et al., 2015).

In 2014, California passed the Sustainable Groundwater Management Act (California Water Code §10720-10737.8). The Act requires Groundwater Sustainability Agencies to develop plans that avoid six undesirable results of groundwater depletion. Communicating the proportion of groundwater wells whose pumping is impacted by water table declines provides a clear impression of an impact of groundwater depletion to the public. Consideration of dry groundwater wells in sustainability planning is straightforward to communicate, which is important when developing plans (Conrad et al., 2019).

One way to assess if the legislation is working is to use our findings as a baseline. A baseline has been difficult to assess for parts of the Central Valley, because there has yet to be a comprehensive analysis of wells that have run dry due to water table declines using observations. As sustainability plans are implemented, our baseline can be used to assess if the temporal and spatial patterns of dry wells change or if the impacts on domestic wells subside. In determining sustainability criteria, it will be important that minimum thresholds or objectives for groundwater levels support all beneficial users reliant on groundwater in the Central Valley.

5. Conclusion

Declining groundwater tables are driving wells to run dry in the Central Valley. This analysis provides information about the southern Central Valley, a subregion of the aquifer where groundwater use and depletion are considerable and where well construction reports were not previously available for a dry well analysis. Many, but not all, of the areas where wells are running dry are designated as critically overdrafted basins, where groundwater stores are declining (supporting information Figure S27). Balancing groundwater recharge and losses in these areas either through supply augmentation (e.g., “groundwater banking”) or reductions in pumping can reduce the number of wells that go dry in the future. Domestic wells are going dry disproportionately. More-explicit consideration for the potential for domestic and agricultural well water supplies to run dry as Groundwater Sustainability Agencies develop Groundwater Sustainability Plans can help to embed this important and undesirable impact of groundwater depletion.

Author Contributions

D. P. and S. J. contributed equally to this work. D. P. and S. J. compiled data and wrote the manuscript. S. J. developed the water table calculation method and completed geospatial analyses. D. P. oversaw compilation of articles reporting dry wells and well completion costs. D. P. and S. J. developed and ran code to calculate local water table elevations.
Acknowledgments

We thank D. Nguyen for assistance in compiling articles reporting dry wells and well completion costs (Table S12). Well completion data analyzed in this study are available from California’s Department of Water Resources (https://data.cnr.ca.gov/dataset/well-completion-reports). The authors declare no competing interests. The authors declare no funding for this work.

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