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## LETTER

# Dry groundwater wells in the western United States

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Supplementary material for this article is available [online](#)

## Abstract

Declining groundwater levels are common in parts of the western US, but their impact on the ability of wells to pump groundwater is not known. Here we collate groundwater well records for the western United States and present the recorded locations, depths, and purposes of more than two million groundwater wells constructed between 1950 and 2015. We then use the well records to estimate the percentage of wells that were dry during the years 2013–2015. During the two year period, dry wells were concentrated in rural areas with high agricultural productivity, such as parts of the California Central Valley and the High Plains. Our results support anecdotal evidence that wells used for domestic purposes are more susceptible to drying than wells used for agricultural purposes throughout California's Central Valley because the former tend to be shallower. However, this is not the case in all regions. Our findings suggest that declining groundwater levels are threatening drinking water reliability and agricultural productivity, and consequently, have key implications for both domestic and agricultural water security. Ongoing reductions to groundwater storage are drying groundwater wells in the western US, and this manifestation of water scarcity warrants innovative groundwater management transcending status quos.

## Introduction

Unsustainable groundwater pumping, enabled by limited long-term water management, is depleting many western US groundwater aquifers [1–6]. Changes in climate and infiltration can reduce groundwater recharge, also impacting groundwater storage [7]. Excessive groundwater pumping and reductions in groundwater recharge can cause loss of groundwater storage capacity [8], land subsidence [9], stream-flow depletion [10], ecosystem harm [11], sea-level rise [12], and seawater intrusion [13]. Although many of the undesirable impacts linked to depletion and the reduction in groundwater recharge have been evaluated, the prevalence of dry wells has not yet been assessed. Mapping dry wells is important because dry wells threaten drinking water

access, agricultural yields, and industrial productivity. Furthermore, dry wells interfere with a well owner's legal right to withdraw water, because the well owner is no longer guaranteed a reliable water supply [14].

In the western United States (US)—where 60% of national groundwater withdrawals occur [15]—there is anecdotal evidence that wells are going dry or becoming less productive due to declining water tables (e.g. [16–18]). In California, there is also anecdotal evidence that wells used for domestic purposes are more susceptible to drying than wells used for agricultural purposes [19, 20], because domestic wells are shallower than agricultural wells. Nevertheless, it is unclear if this pattern holds across the western 17 states. If confirmed, such a pattern would raise important questions about groundwater management, because domestic well users tend to withdraw less groundwater than

agricultural well users, and because domestic water use for drinking, sanitation, and hygiene is seen as a basic right [21, 22].

Unfortunately, dry wells are not recorded or reported comprehensively in the western US. The lack of well construction information and water level measurements across jurisdictions makes it difficult to assess which wells have been impacted by declining water levels. Well completion records are collated at the county or state scale, but the records are rarely stitched together across jurisdictional boundaries. To our knowledge, the last characterization of groundwater wells at the continental scale was published nearly three decades ago [23]. Consequently, the modern-day spatial density of groundwater wells, their depths and purposes, and the number that have become dry due to declining groundwater levels are unknown.

The objectives of our study are to (i) identify the locations, depths, and purposes of groundwater wells constructed in the western US between 1950 and 2015, (ii) estimate the number of wells that were dry during years 2013–2015 due to declines in local groundwater levels, and (iii) test if domestic groundwater wells are shallower—and, therefore, more vulnerable to drying should groundwater levels decline—than agricultural wells across the western US.

## Methods

To meet our first objective, we compiled western US groundwater well data. To meet our second objective, we estimated 2013–2015 well water levels in flatter areas of the western US; identified wells that were likely dry during years 2013–2015; and assessed the sensitivity of our calculation approach. To meet our third objective, we completed practical and statistical significance testing on agricultural and domestic well depths.

### Compilation of western USA groundwater well data

We compiled groundwater well construction reports from databases in 17 western states; we refer to this as our constructed well database henceforth. We surveyed state groundwater experts to ensure that we correctly interpreted notation in each database (supplementary information section S2, table S1, available at [stacks.iop.org/ERL/12/104002/mmedia](http://stacks.iop.org/ERL/12/104002/mmedia)). We screened our data for quality (supplementary information section S3), using only wells designed for domestic (domestic, municipal), agricultural (irrigation, livestock), and industrial (commercial, thermoelectric production, primary energy production) uses.

### Estimating 2013–2015 well water levels

We analysed water-level data from three sources: (i) US Geological Survey (USGS) (<http://groundwaterwatch.usgs.gov/Net/OGWNetworkLTN.asp?ncd=ltm&a=1&d=1>), (ii) measured water levels from our constructed

well database, and (iii) California's Groundwater Ambient Monitoring and Assessment Program (GAMA) (<https://data.ca.gov/dataset/water-data-library-groundwater-level-measurements>; supplementary information section S4, figure S7(a)).

We used water level measurements made between 1 January 2013–31 December 2014 from wells with depth information to estimate the 2013–2015 water level. To develop a single water level value for monitoring wells with data available for both the 2013 and 2014 calendar years we: (i) averaged well water level measurements made in 2013; (ii) averaged water level measurements made in 2014; and (iii) averaged values obtained in (i) and (ii). The approach attempted to weight 2013 and 2014 water levels equally.

Well water level measurements made during or after the construction of a new well may not represent equilibrium conditions. To address this concern, we compared 2013–2015 constructed well water level measurements to nearby ( $<1$  km) monitoring well water level measurements in USGS and GAMA monitoring wells with similar well depths ( $\pm 10$  m). Constructed well water levels are similar to nearby USGS and GAMA monitoring well water levels (figure S7(b)), suggesting that constructed well water levels are of reasonable quality for use in our analysis.

We only analysed water level measurements made in wells located in flatter areas (topographic grades  $<3\%$ ). To identify flatter areas, we analysed the CGIAR-CSI SRTM v4.1 digital elevation model (<http://cgiar-csi.org>). We calculated maximum slopes for each grid cell using elevations of the eight surrounding grid cells. The digital elevation model's grid size ( $\sim 75$  m) is not too coarse to miss local variability, but also not too fine to contain 'noise' or hinder data processing [24].

We estimated the 2013–2015 water table in flatter areas (slopes  $<3\%$ ) by interpolating well water level measurements using an approach common to our field (inverse distance weighting) [4]; we focused our analysis on flatter areas in order to increase the likelihood that a water level measurement provides a plausible estimate of the water level at a nearby ( $<1$ – $10$  km) location. By interpolating measurements of the depth below land surface to water in a well, rather than water table elevations, we implicitly assumed that the water table follows topography between the interpolated points in low gradient areas [25]. This approach introduced limitations to our analysis because western US water tables do not follow topography in some places [26], and because our compilation of piezometric measurements were not spatially continuous (supplementary information section S5). Our estimate of the 2013–2015 groundwater table may be improved by incorporating more piezometric data (e.g. river stage variations and impacts on water tables along river corridors) or by testing other water table elevation estimation approaches (e.g. groundwater models informed by actual piezometric measurements).

Applying alternate approaches to estimate water tables could also help assess dry well abundances in steep areas excluded from this analysis.

We used only water level measurements made in wells screened in the shallowest portion of the crust in an effort to exclude wells perforated in confined aquifers, which are likely poor estimates of water table depths. We assumed wells constructed within 100 m of the land surface represent unconfined conditions as applied in the past [27]. To assess the sensitivity of the assumption that wells shallower than 100 m represent unconfined conditions [27] we completed two additional water level measurement interpolations using measurements made in wells (i) shallower than 50 m and (ii) shallower than 150 m (supplementary information sections S4 and S5). Hydraulic heads vary with depth below the water table in many areas, meaning that water level measurements made in deeper wells likely differ from those made in nearby shallower wells (figure S8). If 3D hydrogeological data were available we would quantify depths to semi-confined and confined systems and account for vertical hydraulic gradients. Unfortunately, existing publically-available, continental-scale lithological data only reports alluvial thicknesses up to 50 m [28]. Alluvial thicknesses are imperfect proxies of unconfined aquifer systems (e.g. alluvial aquifers can be (semi)confined). Furthermore, a 50 m thickness cut-off is too shallow to be useful in multiple deep alluvial aquifers critical to our analysis (e.g. California Central Valley, parts of the High Plains).

### Identifying dry wells

To estimate which wells have gone dry, we subtracted each groundwater well's depth (from subsection entitled Compilation of western USA groundwater well data) from our calculated 2013–2015 depth to groundwater (from subsection entitled Estimating 2013–2015 well water levels); i.e. [pressure head] = [well depth] – [2013–2014 groundwater level depth]. We only calculate pressure heads in wells where at least one groundwater level measurement has been made between 2013 and 2015 within a 1–10 km radius of the groundwater well (supplementary information section S5). This step is important to constrain our use of the interpolated water table solely to wells located nearby at least one water level measurement; i.e. we only analyse wells nearby one or more control points used in our water table depth interpolation. We use the pressure head to identify dry wells in flat areas: negative values suggest that the well is dry (negative pressure heads are zero in reality), and high positive values indicate that the bottom of the well is much deeper than its modern water level (figure S9). We report fractions of groundwater wells in 10 km by 10 km grids that have gone dry for all grids containing at least  $n = 20$  constructed wells.

### Statistical sensitivity analysis of dry well estimates

Our analysis included three key assumptions: (i) water level measurements made in wells shallower than 50–150 m represent unconfined conditions (supplementary information section S5.1, figure S10; tables S21 and S22), (ii) wells with a pressure head of less than zero meters are dry (supplementary information section S5.2), and (iii) water level measurements made within 1–10 km are useful estimates of the water level at the well site (supplementary information section S5.3). In supplementary information section S5.4 we highlight the impacts of these assumptions on our results.

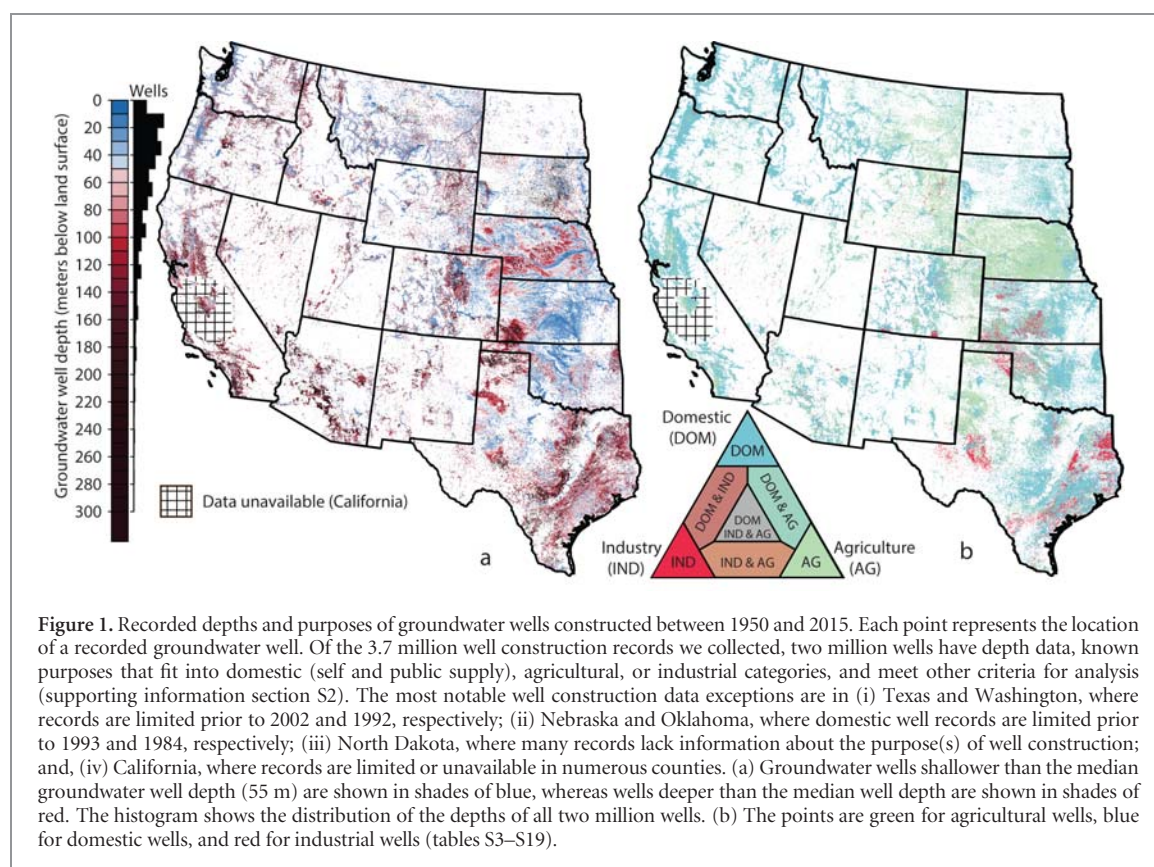
### Agricultural and domestic well depth differences

To test if domestic wells are shallower, and therefore more vulnerable to drying, than agricultural wells, we compared agricultural and domestic groundwater well depth distributions within each 10 km by 10 km grid that contains  $n_{\text{agricultural\_wells}} \geq 10$  and  $n_{\text{domestic\_wells}} \geq 10$ . We compared medians rather than means, because well depths are not normally distributed (supplementary information section S6, figure S13).

We performed statistical significance testing on grids with practical significance: more than 10 m differences among median agricultural and median domestic well depths. We used the two-sided Wilcoxon rank sum test to test the null hypothesis that agricultural and domestic groundwater well depth distributions are from continuous distributions with equal medians, against the alternative hypothesis that agricultural and domestic wells are not from distributions with equal medians. Because our statistical hypothesis testing is performed on thousands of grids ( $n_{\text{grids}} = 3487$ ), we estimate the  $q$ -value [29] (supplementary information section S6, table S23);  $q < 0.01$  suggests that 1% of tests will result in false discovery.

We map differences between median agricultural well depths and median domestic well depths at 10 km by 10 km grids, and we select six areas to show grid-aggregated histograms of well depths for all wells, agricultural wells, and domestic wells. For each grid-aggregated area, we (i) provide median values to communicate practical significance, (ii) test the null hypothesis that agricultural and domestic groundwater well depth distributions are from continuous distributions with equal medians, against the alternative hypothesis that agricultural and domestic wells are not from distributions with equal medians (supplementary information section S6, table S24), and (iii) present the  $p$ -value;  $p < 0.01$  rejects the null hypothesis at the 0.01 significance level, suggesting that agricultural and domestic wells are not from distributions with equal medians.





**Figure 1.** Recorded depths and purposes of groundwater wells constructed between 1950 and 2015. Each point represents the location of a recorded groundwater well. Of the 3.7 million well construction records we collected, two million wells have depth data, known purposes that fit into domestic (self and public supply), agricultural, or industrial categories, and meet other criteria for analysis (supporting information section S2). The most notable well construction data exceptions are in (i) Texas and Washington, where records are limited prior to 2002 and 1992, respectively; (ii) Nebraska and Oklahoma, where domestic well records are limited prior to 1993 and 1984, respectively; (iii) North Dakota, where many records lack information about the purpose(s) of well construction; and, (iv) California, where records are limited or unavailable in numerous counties. (a) Groundwater wells shallower than the median groundwater well depth (55 m) are shown in shades of blue, whereas wells deeper than the median well depth are shown in shades of red. The histogram shows the distribution of the depths of all two million wells. (b) The points are green for agricultural wells, blue for domestic wells, and red for industrial wells (tables S3–S19).

## Results

### Groundwater wells in the West

Recorded well depths average 72 m, have an upper and lower quartile range of 30 m to 92 m, a 5th–95th percentile range of 12 m to 186 m, and a median of 55 m (figure 1(a)). Most wells (96%) have total construction depths that are within 200 m of the land surface. Deep wells (>200 m) are concentrated where confined aquifers and thick alluvial deposits exist, and shallow wells are common on floodplains (figure 1(a)).

The prevalence of domestic, agricultural, and industrial groundwater wells varies across the western US (figure 1(b)). Domestic wells comprise 73% of wells in our dataset and are common in mountainous regions and deserts. Agricultural wells comprise 23% of the total wells in our dataset and are concentrated in key food producing regions. The remaining wells in our dataset (4%) are for industrial purposes and are common in oil-and-gas-rich areas such as the Permian, Fort Worth, East Texas, and Anadarko Basins in Texas, Oklahoma, or Kansas.

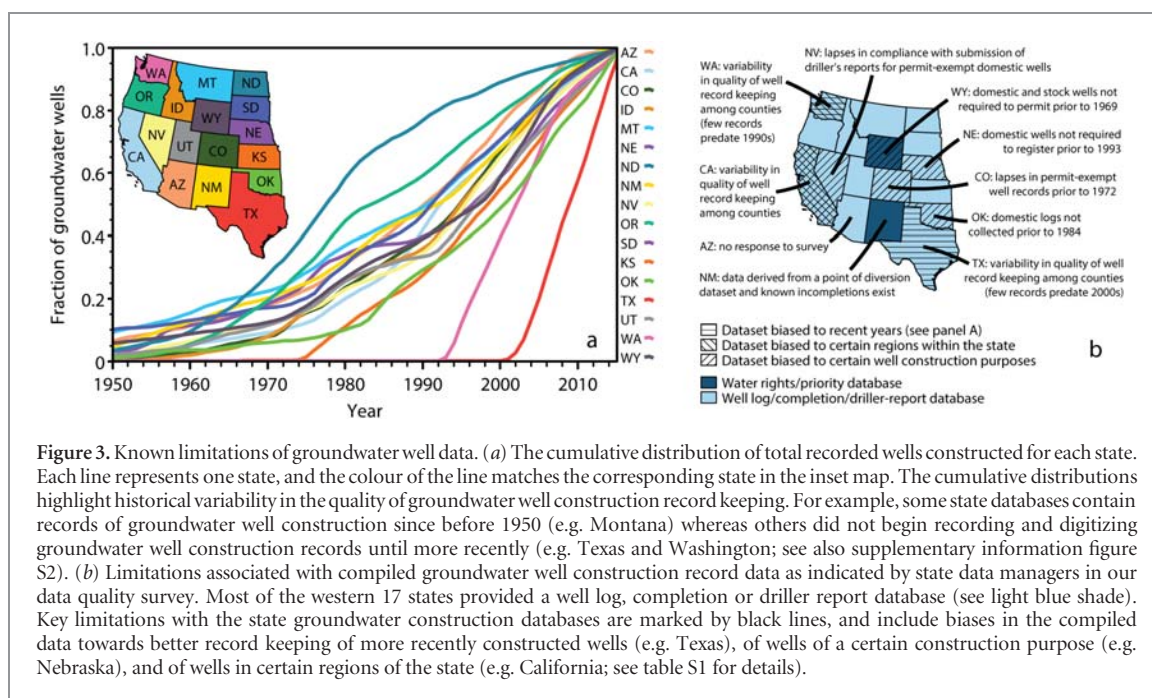
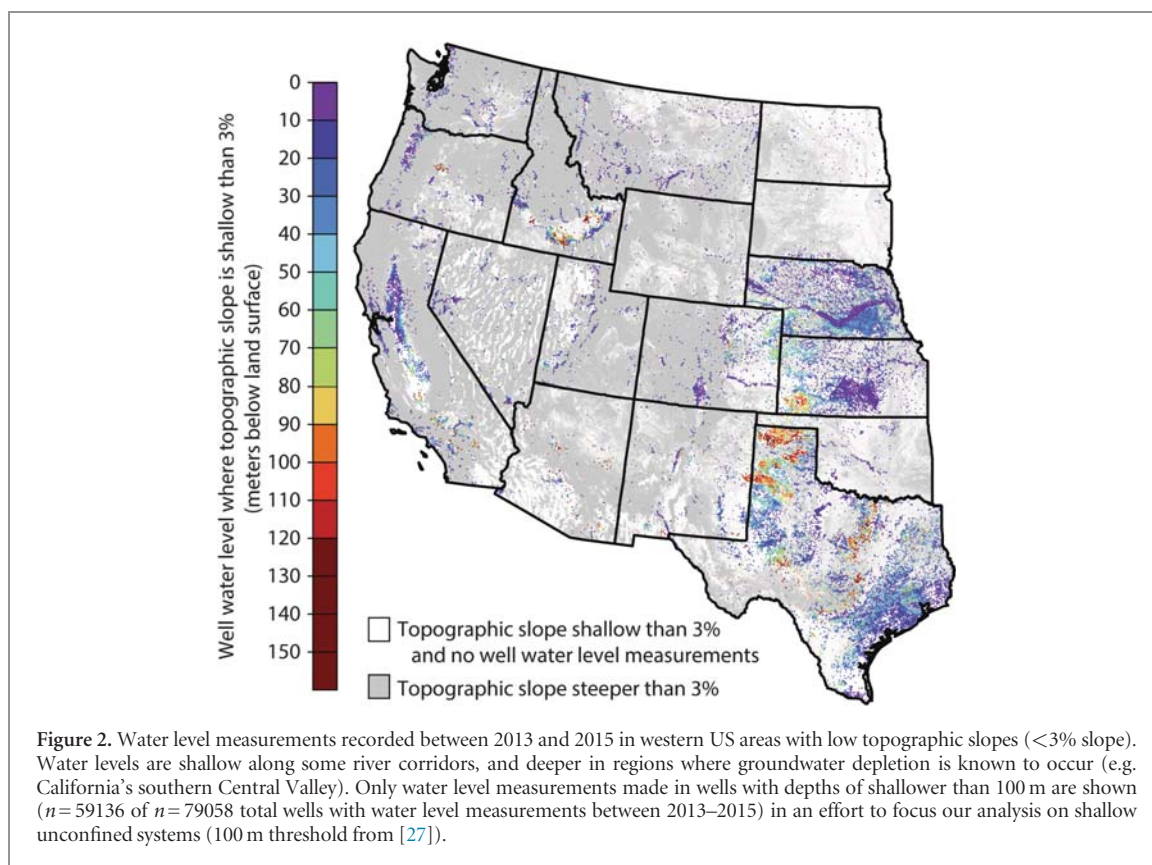
Measured water levels in groundwater wells shallower than 100 m have an upper and lower quartile range of 5.3 m to 24.4 m, a 5th–95th percentile range of 2.1 m to 50.5 m, a median of 11.3 m and an average of 17.1 m (figures 2 and S8). Measured well water levels are often shallow close to river corridors (figure 2), where the wells themselves tend to be shallow (figure 1(a)) and where local and regional groundwater flows often support shallow water tables. Well water

levels are generally deeper in mountainous regions and where unsustainable pumping has depleted aquifer storage, such as in western Kansas and in California's southern Central Valley.

Our compilation efforts show that most of the western 17 states have been recording well construction data for at least 40 years through (i) well log, well completion or driller reports, or (ii) water rights and priority databases, but exceptions exist (figure 3; supplementary information sections S2). The most notable well construction data limitations, as indicated by survey responses provided by each state's data manager, are in (i) Texas and Washington, where records are limited prior to 2002 and 1992, respectively (figure 3(a)); (ii) Nebraska and Oklahoma, where domestic well records are limited prior to 1993 and 1984 (figure 3(b)), respectively; (iii) North Dakota, where many records lack purpose information (figure 3(b)); and (iv) California, where records are limited or unavailable in numerous counties (figure 1; figure 3(b); table S1).

### Hotspots of dry wells

By subtracting each well's depth (figure 1) from our estimated groundwater level (figure 2), we estimate the bottoms of 3.3% (uncertainty range: 2.1%–5.5%) of western US wells constructed between 1950 and 2015 are shallower than nearby 2013–2015 water level measurements, implying these 1-in-30 groundwater wells were dry between 2013 and 2015 (figure 4). Our estimate of 3.3% is based on water level measurements



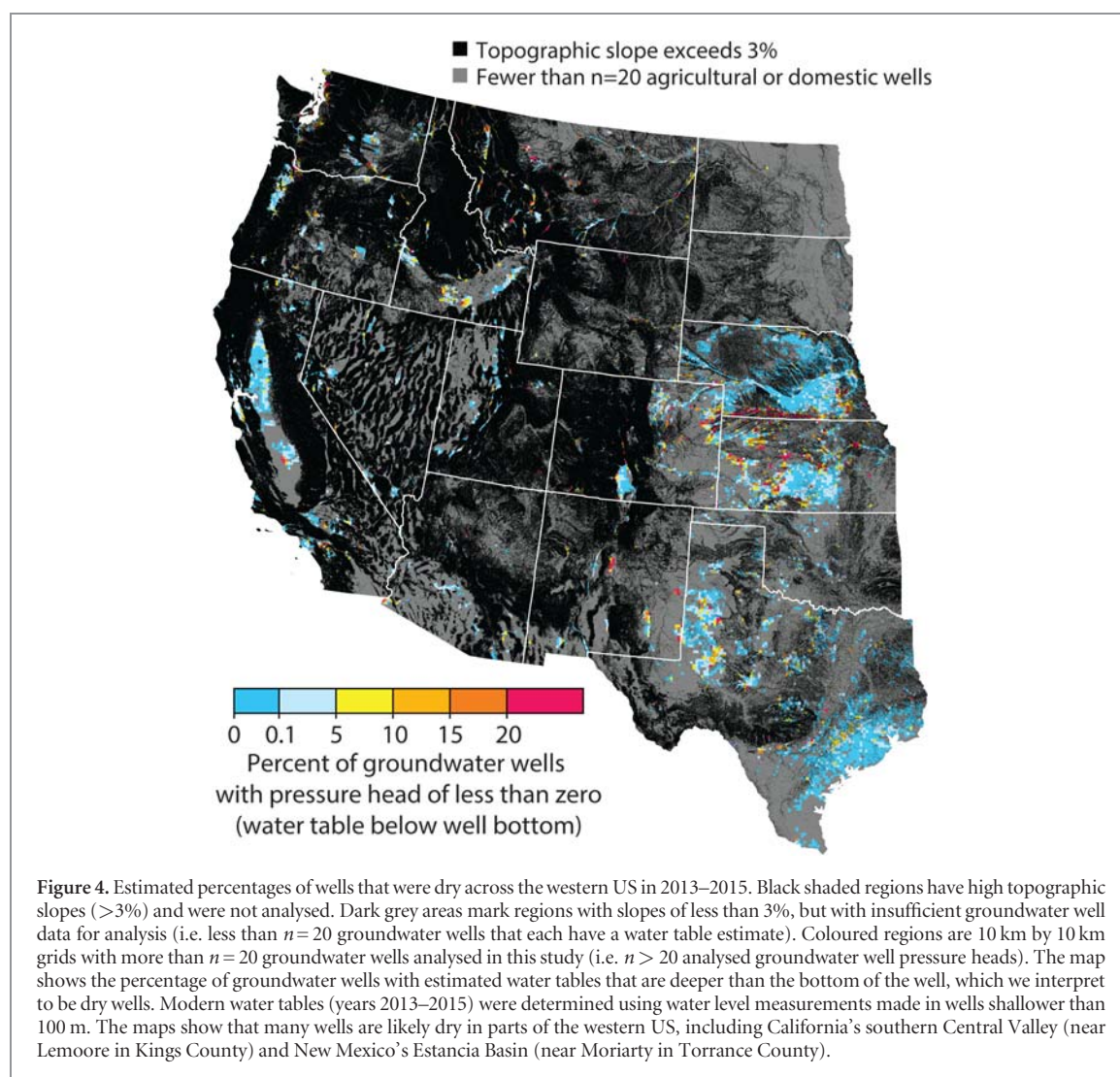
made in nearby wells with depths shallower than 100 m, and the uncertainty range represents wells with a total depth that is within  $\pm 2.5$  m of our estimated 2013–2015 water level. Applying a range of sensitivity analyses, we find that numerous regions in the western US show high prevalence of dry wells (figures S10–S12; table S21).

Across the western US, we estimate that 3.5% (2.3%–5.9%) of domestic wells were dry during

2013–2015, but only 2.8% (1.8%–4.6%) of agricultural wells were dry, implying domestic wells go dry disproportionately often due to their shallower depths in areas where groundwater levels have declined (table S22).

Dry groundwater wells are concentrated in rural regions, many of which are key to agricultural production (figure 4). Across our studied 10 km by 10 km grids, we estimate that more than 1-in-20 wells were





dry in  $18.8\%$  ( $12.9\%$ – $29.1\%$ ) of grids and that more than 1-in-10 wells were dry in  $10.9\%$  ( $7.0\%$ – $17.6\%$ ) of grids. Some of the areas where dry wells are common are located where groundwater depletion is widespread and where anecdotal evidence (table S25) suggests wells are drying up, such as near Wilcox in southeast Arizona [30], near Portales in eastern New Mexico [31], and near Lemoore in southern California [32].

### Domestic and agricultural well depths

Our comparison of agricultural versus domestic well depths shows that the differences between the median agricultural well depths and the median domestic well depths are practically significant (i.e.  $>10\text{ m}$ ) in  $47\%$  of our  $10\text{ km}$  by  $10\text{ km}$  study grids ( $n_{\text{practically\_significant}} = 1628$  of  $n_{\text{total}} = 3487$ ). Of the grids with practical significance,  $60\%$  are statistically significant (rank sum test,  $q < 0.01$ ). Of the grids with practical significance, most ( $72\%$ ) have deeper median agricultural well depths than median domestic well depths ( $n_{\text{deeper\_agricultural}} = 1165$  of  $n_{\text{practically\_significant}} = 1628$ ).

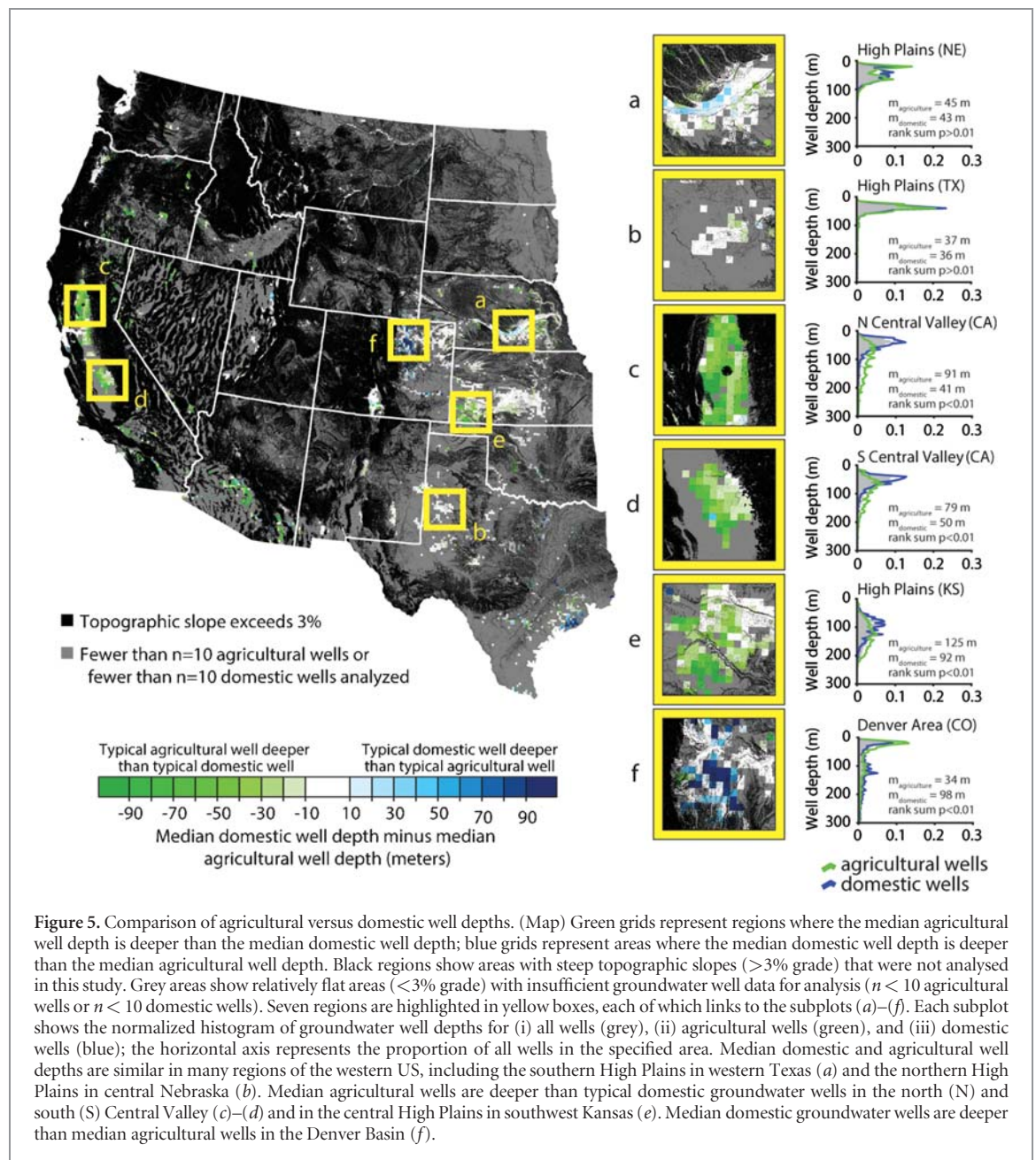
We select six areas to show grid-aggregated distributions of well depths (figures 5(a)–(f)). No practical

or statistical significant difference was found between agricultural and domestic well depths in the northern High Plains of Nebraska nor the southern High Plains of west Texas (rank sum,  $p > 0.01$ ; figures 5(a) and (b)). Agricultural well depths are significantly (practically and statistically) deeper than domestic well depths in the northern California Central Valley, southern California Central Valley and the High Plains aquifer of southwest Kansas (rank sum test,  $p < 0.01$ ; figures 5(c)–(e)). By contrast, domestic wells are deeper (practically and significantly) than agricultural wells in the Denver area (rank sum test,  $p < 0.01$ ; figure 5(f)).

## Discussion

### Groundwater wells in the West

Our constructed well database compilation highlights existing data gaps among state databases (figures 1–3) that have implications for groundwater management. Because some wells have productive lifespans exceeding  $40$  years, absent well construction data for older wells may impede metering and reporting efforts, possibly undercutting the effectiveness of



groundwater management. In some states, domestic wells were not initially required to submit well construction reports. Missing information about domestic wells could make it difficult for groundwater managers to assess withdrawals and groundwater sustainability in the region, especially as land-uses change. The current lack of groundwater well depth data may also inhibit assessments of groundwater users' vulnerability to contaminants. The lack of publicly available well records in parts of California impedes efforts to decipher which communities could benefit most from emergency funding designed to relieve water stress [32]. Unfortunately, areas in central and southern California with anecdotal evidence of well drying are also areas where well construction data are unavailable (figure 1).

These aforementioned limitations provide a glimpse into the evolution of strategic groundwater

policies—or lack thereof—associated with each state. Mapping wells may lead to better understanding of where groundwater is being extracted [33], and could be used to refine groundwater-fed irrigation maps [34]. Well data are valuable to demand-side planning efforts, such as identifying areas to reform and improve regulations, focus conservation campaigns, or tailor economic incentives. Groundwater well locations and depths can be vital for mapping the impacts of groundwater pumping on surface waters [10]. On the supply-side of groundwater management, well locations can help target optimal areas for managed aquifer recharge projects.

### Hotspots of dry wells

We show that a considerable percentage of western US groundwater wells were dry during 2013–2015. In addition to the 3.3% (2.1%–5.5%) of wells that we



estimate to be dry during the period 2013–2015, we estimate that 6.3% of well bottoms are still submerged but have pressure heads between zero and five meters, and that 17.5% of wells have pressure heads between zero and ten meters.

The existence of many wells with pressure heads of only a few meters (figure S10) implies that water table declines of only several meters ( $<10$  m) has the potential to dry or reduce the productivity of many wells. It is possible that some of these wells may already be dry at intra-annual or inter-annual timescales, as year-to-year well water levels can vary several meters. In reality, wells go dry when the water table drops below the pump intake, which rests above the bottom of the well. Because the depth to the pump is shallower than the well bottom, our estimates of dry well abundance are likely conservative. Furthermore, well productivity can be impacted even where the water table has not dropped below the pump intake, because groundwater pumping induces a localized drawdown of the water table known as the cone of depression. Estimating the cone of depression at each well would require continental-scale information about groundwater pumping, aquifer transmissivity and storativity—data unavailable at continental scales.

The prevalence of dry wells highlights yet another undesirable impact associated with groundwater storage declines. In cases where a well's useful lifespan has been exhausted due to well drying, a well owner could consider a number of adaptive responses, some of which include: (i) drilling deeper wells, (ii) receiving delivered water via truck, (iii) connecting to centralized water systems, (iv) conserving groundwater where groundwater is being depleted. (i) Constructing deeper wells can burden well owners and municipalities with the high cost of constructing a new well. Moreover, groundwater users in some regions likely face other impediments to deeper well construction, including less transmissive aquifers and saline groundwater at deeper depths. Well depth patterns (figure 1) indicate that well construction may be constrained to shallow depths in some regions by local lithology, water quality, or socioeconomics (i.e. expense of drilling new well for rural well owners), while groundwater users in other regions may be able to adapt by drilling deeper wells. Even in regions where deep aquifers contain fresh groundwater [35], constructing deeper wells is not a panacea to groundwater depletion. Groundwater depletion has other consequences, such as streamflow deprivation and impacts to groundwater dependent ecosystems, which should be considered when managing groundwater resources. (ii) Programs to deliver bulk water by truck have been used in parts of California, but these programs are likely unsustainable long-term solutions. (iii) Connecting to centralized water systems, can burden water users and municipalities with the high costs of constructing new distribution infrastructure. (iv) Conserving water in households and on farms may be achievable in many regions, but

requires sustained efforts from the larger community of groundwater users. Overall, drying of groundwater wells caused by groundwater level declines can lead to costly or challenging scenarios.

### Domestic and agricultural well depths

We show that median agricultural well depths differ from median domestic well depths by more than 10 m (i.e. practical significance) in 47% of our study grids; the majority of these differences occur because agricultural wells are deeper than domestic wells. Our results support anecdotal evidence that wells used for domestic purposes are more susceptible to drying than wells used for agricultural purposes throughout California's Central Valley. Agricultural wells, however, are not significantly deeper than domestic wells in all regions. In more than half of the grids we analysed median domestic and agricultural well depths are similar. This finding suggests that, all else equal, declining groundwater levels will impact domestic and agricultural wells proportionately in these areas. Consequently, our analysis of dry wells in western US aquifers has key implications for both domestic and agricultural water security.

Our results show that dry wells tend to be concentrated in rural areas, where domestic self-supply wells are common (figure 4). Unfortunately, rural communities often bear the brunt of the impacts of groundwater depletion [22, 32], because these communities are isolated from urban infrastructure and more likely to rely solely on groundwater [36]. Furthermore, rural communities often have limited ability to diversify their economies [37], and constructing new wells can be costly [38]. Although individuals and communities in rural and low-income brackets are eligible for Department of Agriculture grants and loans to drill wells or to connect to public water systems, the accessibility and effectiveness of these programs has yet to be studied extensively (e.g. Rural Repair and Rehabilitation Loan and Grant (section 504) Program, Rural Housing Direct Loan (section 502) Program, Emergency Community Water Assistance Grant Program; [www.rd.usda.gov/files/CA-DroughtAssistance.pdf](http://www.rd.usda.gov/files/CA-DroughtAssistance.pdf)). Rural communities without public supply or surface water options may be most vulnerable to the impacts of dry wells, but communities that rely on groundwater as part of their public water supply are also impacted by drying wells [22]. For each urban supply well that goes dry, it is possible that hundreds or thousands of people may be affected either by curtailed water supplies or requirements to access alternate water sources (e.g. [31]).

Dry groundwater wells also have implications for US agriculture. Groundwater supplies more than 40% of water used for US irrigated agriculture and is often used as a buffer when surface waters are limited (e.g. drought [39]). In 2010, groundwater supplied 36% [15] of the water used for western US irrigated agriculture, and this fraction is likely greater during droughts

[6, 7, 40]. Crop yields from irrigated lands often exceed yields from non-irrigated farmlands [41]; it is possible that agricultural productivity may decline where agricultural wells dry up, should producers switch to dryland farming [6, 42].

### Implications for groundwater management

Our main findings—(i) there are a range of data gaps among the various state well construction databases, (ii) 1-in-30 wells constructed between 1950–2015 were likely dry during 2013–2015, and (iii) when agricultural well distributions and domestic well distributions differ significantly, domestic wells are usually shallower, and therefore, disproportionately vulnerable to drying—underscore society's need to improve groundwater management. Groundwater is a public interest resource, meaning that it is publicly owned, in most western states (e.g. Idaho § 42–203A; Kansas § 82a–711(a); Utah § 73–3–8). Consequently, effective groundwater management is important to sustainably serve the public by meeting domestic and agricultural water demands.

Our analysis provides the first continental-scale study of groundwater wells in nearly three decades [23], and represents the first continental-scale examination of groundwater infrastructure impacted by declines in groundwater levels. Dry wells in the United States are not recorded, reported, or analysed comprehensively or across jurisdictional boundaries. For instance, California has a system with publicly available information about water shortages [16], but this system is new as of 2014 and relies on voluntary reporting by households. Some state well construction databases include information about plugged or abandoned wells, but the comprehensiveness of these inventories is unclear [43], and the details about why the wells were plugged or abandoned are often unavailable.

Western US groundwater is a strategic resource used for drinking, sanitation, and hygiene by nearly 10 million people through self-supply wells (data from [15]). Groundwater is also critical to irrigated agriculture, increasing the resilience of agricultural production to drought [7]. It is possible that water users will become more dependent on groundwater as climate warms and the timing and fluxes of river discharges change [37]. If current groundwater management follows 'business-as-usual' scenarios, groundwater resources may not be available to effectively aid climate change adaptation efforts. Groundwater regulation has lagged behind surface water regulation, likely because of the difficulty in characterizing aquifers [44]. Early groundwater legislation, such as common law, focused on 'safe yield', a phrase outdated both in its science and its ability to promote sustainability [45, 46]. Although there has been a widespread movement towards more comprehensive regulatory approaches, one of which is groundwater withdrawal permitting [47], the effectiveness of these approaches is unclear. What is clear, however, is that declining

groundwater levels are interfering with well owners' legal rights to withdraw groundwater in many areas across the western US, because the well owner is no longer guaranteed reliable water supplies [14]. Overall, water table declines are drying up groundwater wells, and this manifestation of water scarcity warrants innovative groundwater management transcending status quos.

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### References

- [1] Castle S L, Thomas B F, Reager J T, Rodell M, Swenson S C and Famiglietti J S 2014 Groundwater depletion during drought threatens future water security of the Colorado River basin *Geophys. Res. Lett.* **41** 5904–11
- [2] Famiglietti J S, Lo M, Ho S L, Bethune J, Anderson K J, Syed T H, Swenson S C, Linage C R D and Rodell M 2011 Satellites measure recent rates of groundwater depletion in California's Central Valley *Geophys. Res. Lett.* **38** L03403
- [3] Konikow L F and Kendy E 2005 Groundwater depletion: a global problem *Hydrol. J.* **13** 317–20
- [4] McGuire V L 2014 *Water-level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011–13* (Reston, VA: US Geological Survey)
- [5] Scanlon B R, Faunt C C, Longuevergne L, Reedy R C, Alley W M, McGuire V L and McMahon P B 2012 Groundwater depletion and sustainability of irrigation in the US high plains and Central Valley *Proc. Natl Acad. Sci.* **109** 9320–5
- [6] Steward D R, Bruss P J, Yang X, Staggenborg S A, Welch S M and Apley M D 2013 Tapping unsustainable groundwater stores for agricultural production in the high plains aquifer of Kansas, projections to 2110 *Proc. Natl Acad. Sci.* **110** E3477–86
- [7] Taylor R G *et al* 2013 Ground water and climate change *Nat. Clim. Change* **3** 322–9
- [8] Smith R G, Knight R, Chen J, Reeves J A, Zebker H A, Farr T and Liu Z 2017 Estimating the permanent loss of groundwater storage in the Southern San Joaquin Valley, California *Water Resour. Res.* **53** 2133–48
- [9] Galloway D, Jones D R and Ingebritsen S E 1999 Land subsidence in the United States *US Geological Survey Circular 1182* (Reston, VA: United States Geological Survey)
- [10] Barlow P M and Leake S A 2012 Streamflow depletion by wells—understanding and managing the effects of groundwater pumping on streamflow *US Geological Survey Circular 1376* (Reston, VA: United States Geological Survey)
- [11] Perkin J S, Gido K B, Falke J A, Fausch K D, Crockett H, Johnson E R and Sanderson J 2017 Groundwater declines are linked to changes in great plains stream fish assemblages *Proc. Natl Acad. Sci.* **114** 7373–8
- [12] Konikow L F 2011 Contribution of global groundwater depletion since 1900 to sea-level rise *Geophys. Res. Lett.* **38** L17401
- [13] Ferguson G and Gleeson T 2012 Vulnerability of coastal aquifers to groundwater use and climate change *Nat. Clim. Change* **2** 342–5

- [14] California Legislature 2014 Sustainable Groundwater Management Act *California Water Code* § 10720–10720.9
- [15] Maupin M A, Kenny J F, Hutson S S, Lovelace J K, Barber N L and Linsey K S 2014 Estimated use of water in the United States in 2010 *US Geological Survey Circular 1405* (Reston, VA: United States Geological Survey)
- [16] California Department of Water Resources 2017 State of California household water supply shortage reporting system (<https://mydrywatersupply.water.ca.gov/report>)
- [17] Miller R D, Buchanan R and Brosius L 1998 *Measuring Water Levels in Kansas* (Lawrence, KS: Kansas Geological Survey) ([www.kgs.ku.edu/Publications/pic12/pic12\\_1.htm](http://www.kgs.ku.edu/Publications/pic12/pic12_1.htm))
- [18] Parker L 2016 *What Happens to the US Midwest When the Water's Gone?* (Washington, DC: National Geographic Magazine) ([www.nationalgeographic.com/magazine/2016/08/vanishing-midwest-ogallala-aquifer-drought/](http://www.nationalgeographic.com/magazine/2016/08/vanishing-midwest-ogallala-aquifer-drought/))
- [19] Richtel M 2015 *California Farmers Dig Deeper for Water, Sipping Their Neighbors Dry* (The New York Times) ([www.nytimes.com/2015/06/07/business/energy-environment/california-farmers-dig-deeper-for-water-sipping-their-neighbors-dry.html?mcubz=3](http://www.nytimes.com/2015/06/07/business/energy-environment/california-farmers-dig-deeper-for-water-sipping-their-neighbors-dry.html?mcubz=3))
- [20] Khokha S 2014 As their wells run dry *California Residents Blame Thirsty Farms* (Washington, DC: National Public Radio) ([www.npr.org/2014/10/19/357273445/as-their-wells-run-dry-california-residents-blame-thirsty-farms](http://www.npr.org/2014/10/19/357273445/as-their-wells-run-dry-california-residents-blame-thirsty-farms))
- [21] Gleick P H 1998 The human right to water *Water Policy* **1** 487–503
- [22] Feinstein L, Phurisamban R, Ford A, Tyler C and Crawford A 2017 *Drought and Equity in California* (Oakland, CA: Pacific Institute) (<http://pacinst.org/publication/drought-equity-california/>)
- [23] Hindall S M and Eberle M 1989 National and regional trends in water-well drilling in the United States, 1964–84 *US Geological Survey Circular 1029* (Reston, VA: United States Geological Survey)
- [24] Sharma A, Tiwari K N and Bhadoria P B S 2011 Determining the optimum cell size of digital elevation model for hydrologic application *J. Earth Syst. Sci.* **120** 573–82
- [25] Tóth J 1963 A theoretical analysis of groundwater flow in small drainage basins *J. Geophys. Res.* **68** 4795–812
- [26] Gleeson T, Marklund L, Smith L and Manning A H 2011 Classifying the water table at regional to continental scales *Geophys. Res. Lett.* **38** L05401
- [27] Fan Y, Li H and Miguez-Macho G 2013 Global patterns of groundwater table depth *Science* **339** 940–3
- [28] Pelletier J D, Broxton P D, Hazenberg P, Zeng X, Troch P A, Niu G-Y, Williams Z, Brunke M A and Gochis D 2016 A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling *J. Adv. Model. Earth Syst.* **8** 41–65
- [29] Storey J D and Tibshirani R 2003 Statistical significance for genomewide studies *Proc. Natl Acad. Sci.* **100** 9440–5
- [30] Arizona Department of Water Resources 2014 *Preliminary Results of ADWR's Survey of Well Conditions in the Willcox Basin Area* (Phoenix, AZ: Arizona Department of Water Resources) ([www.azwater.gov/azdwr/PublicInformationOfficer/documents/WellSurveyResults.pdf](http://www.azwater.gov/azdwr/PublicInformationOfficer/documents/WellSurveyResults.pdf))
- [31] Wilson C R 2013 City of Portales review of water supply options ([www.portalesnm.gov/egov/documents/1386182798\\_59198.pdf](http://www.portalesnm.gov/egov/documents/1386182798_59198.pdf))
- [32] Hanak E, Mount J, Chappelle C, Lund J, Medellín-Azuara J, Moyle P and Seavy N 2015 *What if California's Drought Continues?* (San Francisco, CA: Public Policy Institute of California) ([www.ppic.org/publication/what-if-californias-drought-continues/](http://www.ppic.org/publication/what-if-californias-drought-continues/))
- [33] Ekdahl E 2016 Challenges in using large datasets for state water board groundwater regulatory activities *Groundwater Data Workshop Series: Groundwater Data in the SGMA Context Workshop* ed T Moran (Stanford, CA: Stanford University)
- [34] Siebert S, Burke J, Faures J M, Frenken K, Hoogeveen J, Döll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory *Hydrol. Earth Syst. Sci.* **14** 1863–80
- [35] Kang M and Jackson R B 2016 Salinity of deep groundwater in California: Water quantity, quality, and protection *Proc. Natl Acad. Sci.* **113** 7768–73
- [36] Moore E, Matalon E, Balazs C, Clary J, Firestone L, De Anda S, Guzman M, Ross N and Luu P 2011 *The Human Costs of Nitrate-Contaminated Drinking Water in the San Joaquin Valley* (Oakland, CA: Pacific Institute) (<http://pacinst.org/publication/human-costs-of-nitrate-contaminated-drinking-water-in-the-san-joaquin-valley/>)
- [37] Melillo J M, Richmond T C and Yohe G W 2014 *Climate Change Impacts in the United States: The Third National Climate Assessment* (Washington, DC: US Global Change Research Program)
- [38] Famiglietti J S 2014 The global groundwater crisis *Nat. Clim. Change* **4** 945–8
- [39] Hanak E, Escrivá-Bou A, Howitt R, Lund J, Burt C, Harter T, Medellín-Azuara J, Parker D, Sumner D and Zoldoske D 2016 *California's Water: Water for Farms* (San Francisco, CA: Public Policy Institute of California) ([www.ppic.org/publication/californias-water-water-for-farms/](http://www.ppic.org/publication/californias-water-water-for-farms/))
- [40] Chappelle C, Hanak E and Harter T 2017 *Groundwater in California. Just the FACTS* (San Francisco, CA: Public Policy Institute of California) ([www.ppic.org/content/pubs/jtf/JTF\\_GroundwaterJTF.pdf](http://www.ppic.org/content/pubs/jtf/JTF_GroundwaterJTF.pdf))
- [41] Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42
- [42] Torell L A, Libbin J D and Miller M D 1990 The market value of water in the Ogallala aquifer *Land Econ.* **66** 163–75
- [43] Wiley J 2015 Groundwater issues, interview with Todd Jarvis *Water Rep.* **137** 10–1
- [44] Alley W M, Beutler L, Campana M E, Megdal S B and Tracy J C 2016 Groundwater visibility: the missing link *Groundwater* **54** 758–61
- [45] Konikow L F and Leake S A 2014 Depletion and capture: Revisiting the source of water derived from wells *Groundwater* **52** 100–11
- [46] Alley W M and Leake S A 2004 The journey from safe yield to sustainability *Groundwater* **42** 12–6
- [47] Nelson R and Perrone D 2016 The role of permitting regimes in Western United States groundwater management *Groundwater* **54** 761–4