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Deeper well drilling an unsustainable stopgap to groundwater depletion

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Groundwater depletion is causing wells to run dry, affecting food production and domestic water access. Drilling deeper wells may stave off the drying up of wells—for those who can afford it and where hydrogeologic conditions permit it—yet the frequency of deeper drilling is unknown. Here, we compile 11.8 million groundwater-well locations, depths and purposes across the United States. We show that typical wells are being constructed deeper 1.4 to 9.2 times more often than they are being constructed shallower. Well deepening is not ubiquitous in all areas where groundwater levels are declining, implying that shallow wells are vulnerable to running dry should groundwater depletion continue. We conclude that widespread deeper well drilling represents an unsustainable stopgap to groundwater depletion that is limited by socioeconomic conditions, hydrogeology and groundwater quality.

Groundwater pumped from wells in the United States provides drinking water to about 120 million Americans, supplies nearly half of all irrigation by volume, and supports industrial activities[1,2]. Although groundwater is critical to domestic, agricultural and industrial activities, current withdrawals from some aquifers are unsustainable[3–5]. Groundwater depletion is occurring beneath large population centres, key food-producing regions and industrial hubs, including the following aquifers: Central Valley aquifer system of California[5–7], High Plains aquifer of the central United States[8,9], Mississippi embayment aquifer system[10,11], Northern Atlantic Coastal Plain aquifer system[12] and Floridan aquifer system[13]. Groundwater depletion can cause wells to run dry and disrupt access to reliable fresh water[14]. Constructing deeper wells as a means of adapting to such depletion[6] may be possible where hydrogeological and socioeconomic conditions support it. Nevertheless, the frequency with which deeper wells are being constructed is unknown.

Because of the decentralized nature of groundwater-well infrastructure, the construction of each new well provides insights into local hydrogeologic conditions and groundwater-user decision-making. Accordingly, understanding groundwater-well construction trends can inform groundwater management, which has long lagged behind surface-water management[15,16]. Yet, in contrast to curated surface-water infrastructure databases (for example, of canals or dams[17]), no groundwater infrastructure (that is, well) database exists. Consequently, locally relevant well location and depth data—critical to assessing how vulnerable groundwater infrastructure is to groundwater depletion—have remained unknown until now.

The objectives of this paper are fourfold: (1) analyse spatial patterns of groundwater-well depths and purposes (see Millions of groundwater wells in the United States), (2) quantify local groundwater-well construction depth changes over time (see Deeper well construction over time in most areas across the United States), (3) test for relationships among groundwater-level time-series trends and groundwater-well construction depth time-series trends (see Declining groundwater levels not always met by deeper drilling) and (4) juxtapose agricultural-versus-domestic groundwater uses with well depths to understand which users may be driving depletion and which are most vulnerable to well drying (see Agricultural wells deeper than domestic wells).

To meet our objectives we (1) performed quality control and analysis of recorded groundwater-well records compiled from 64 different state-, regional- or county-level groundwater-well data repositories; (2) quantified local well construction depth trends over time; (3) compared observed well water-level changes in time to recorded changes in well construction depths in time in the five aforementioned aquifers; and (4) juxtaposed agricultural-versus-domestic well depths with agricultural-versus-domestic groundwater withdrawals in the five aquifers.

Results

Millions of groundwater wells in the United States. We mapped and analysed constructed-groundwater-well locations, depths and purposes to quantify spatial patterns of groundwater infrastructure across the United States (Fig. 1). Most recorded groundwater wells are for domestic or municipal use (83%; Fig. 1a), some are for agricultural use (15%; Fig. 1a) and a small percentage is for industrial use (2%; Fig. 1a). Groundwater-well depths average 60 m below the land surface, with a median depth of 44 m, a lower-upper quartile range of 25 to 76 m, a 5th to 95th percentile range of 11 to 157 m and a 1st to 99th percentile range of 6 to 262 m (Fig. 1b).

Unsurprisingly, agricultural wells are most common in rural regions where groundwater-based irrigation is common, such as the Central Valley aquifer system, High Plains aquifer and Mississippi embayment aquifer system. Domestic wells dominate well purposes throughout the midwestern, northeastern and northwestern regions of the United States. Deeper wells are more widespread across the relatively arid western states, where deep water tables have been documented[18]. Deep wells are commonly constructed in the southern Central Valley aquifer system, the central and southern High Plains aquifer, aquifers underlying the Ozark Plateau, and sedimentary aquifers spanning central and eastern Texas (Fig. 1b and Supplementary Figs. 36 and 37).

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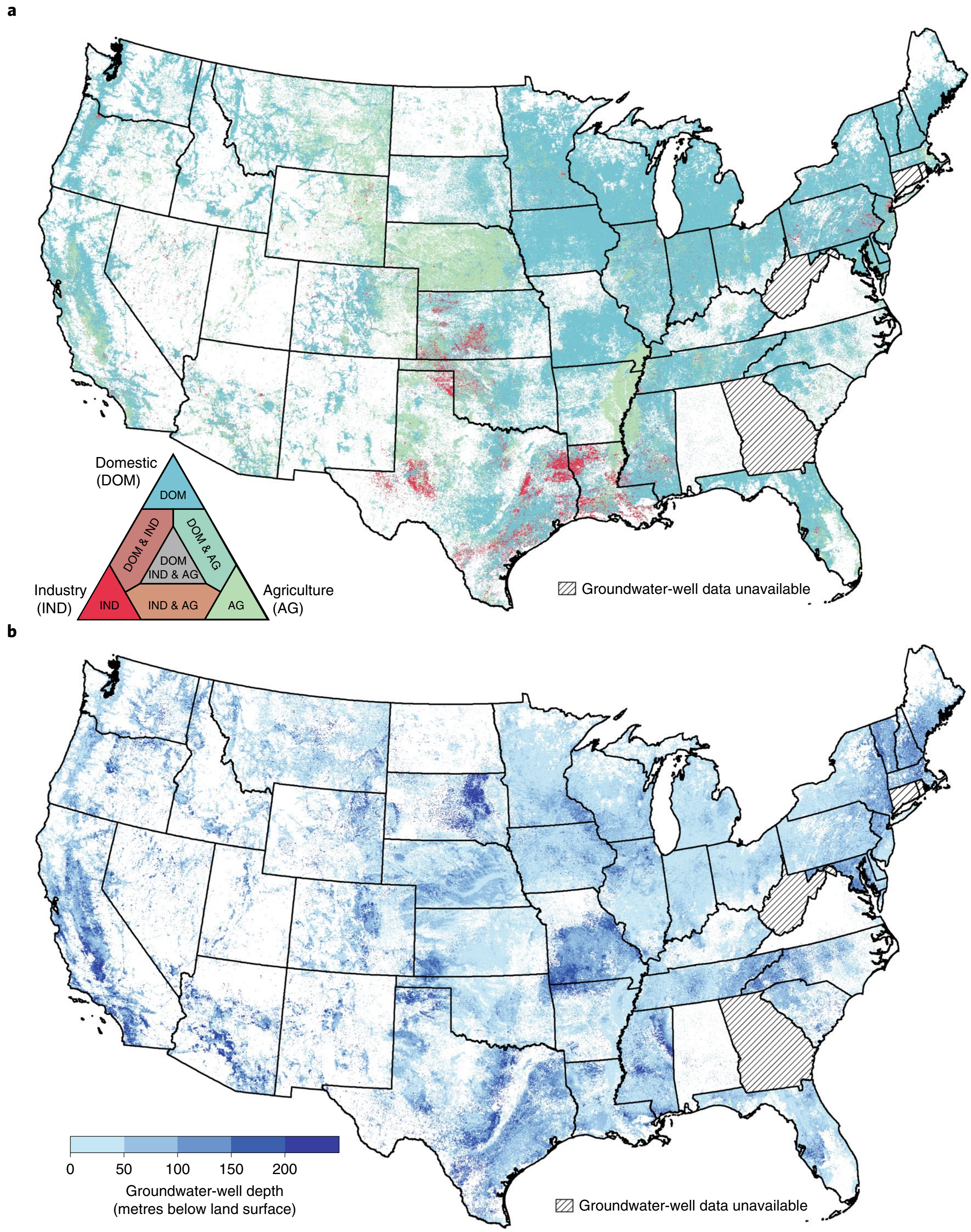


Fig. 1 | Groundwater wells across the United States. Each point on a map represents the recorded location of a well. **a**, The purpose for a well's construction; blue dots represent wells constructed for domestic or municipal supply, green dots for agriculture and red dots for industry. **b**, The depth of constructed wells; darker blues represent deeper wells and lighter blues represent shallower wells. Deep wells are common in California's southern Central Valley, parts of Texas and the Ozarks of Arkansas, Missouri and Oklahoma. Georgia, West Virginia, Rhode Island and Connecticut do not have publicly available groundwater-well datasets. Refer to Supplementary Information for data limitations.

Shallower wells are common throughout the Midwest and close to major rivers, where shallow water tables have been documented[18] (Fig. 1b).

Deeper well construction over time in most areas across the United States. Well construction depths vary not only in space (Fig. 1b), but also over time. We show that the depths to which groundwater wells are being constructed has increased over time across much of the United States (Fig. 2). This 'well deepening' has been documented in 72% of study areas for years 1950–1975, 63% of areas for years 1975–2000 and 59% of areas for years 2000–2015 (Table 1; positive Spearman rank correlation coefficient ($\rho > 0$) describing well completion depth versus well construction date, where 'areas' refer to 10 km × 10 km grids).

Regionally, groundwater wells are being constructed deeper with time in California's Central Valley (Fig. 2a–c), southwestern Kansas (Fig. 2b,c), western Texas (Fig. 2c), the Atlantic Coastal Plain (Fig. 2a,b) and portions of the Mississippi embayment (Fig. 2b,c). Well depth trends have shifted from deepening to shallowing in some areas; for example, well deepening dominated areas in the northern part of the High Plains aquifer from 1950 to 1975 as most groundwater levels declined (Supplementary Fig. 24), yet well shallowing was more common from 1975 to 2000 when most groundwater levels rose (Supplementary Fig. 25).

Our conclusion that well deepening is more common than well shallowing holds when we examine different time intervals and when we examine solely significant trends (that is, Spearman P value < 0.05). Well deepening characterizes 79% of areas for years 1950–2015 and 70% of areas for years 1975–2015 (Supplementary Section 38.1 and Supplementary Figs. 11 and 12). If we restrict our analysis to areas where groundwater-well construction depth trends are significant (Spearman P value < 0.05), well deepening characterizes 89% of areas for years 1950–1975, 79% of areas for years 1975–2000 and 72% of areas for years 2000–2015 (Table 1). Examining longer time intervals and solely areas with significant (Spearman P value < 0.05) trends yields well deepening in 90% of areas for years 1950–2015 and 85% of areas for years 1975–2015 (Table 1). In summary, well-deepening trends are 1.4 to 9.2 times (40% to 820%) more common than well-shallowing trends (Table 1).

Because we analysed areas where sufficient well completion data exist ($n \geq 10$ in 10 km × 10 km grids), our results should be interpreted as most representative among areas where groundwater-well completion data are available and where groundwater wells are densely distributed (Supplementary Section 35). To assess if our main findings are susceptible to sampling biases by area, we ran our analysis using polygons generated to attain about 100 wells per polygon (Supplementary Section 37). Our main findings remained unchanged (Supplementary Figs. 6–10): well-deepening trends are 1.6 to 10.0 times (60% to 900%) more common than well-shallowing trends (Supplementary Table 53).

Declining groundwater levels not always met by deeper drilling. To explore how often declining groundwater levels are met by the construction of deeper wells, we compared time-series trends of groundwater levels observed in monitoring wells for years 2000–2015 (y axes in Fig. 3) to time-series trends of depths of wells constructed near (<5 km) each monitoring well (x axes in Fig. 3; Supplementary Fig. 26). We focused on five aquifers, which were chosen for their importance and geographic distribution: the Central Valley aquifer system in California, the High Plains aquifer in the central United States, the Mississippi embayment aquifer system, the Northern Atlantic Coastal Plain aquifer system and the Floridan aquifer system.

In the Central Valley aquifer system of California—where most groundwater-level observations demonstrate declines from 2000 to 2015—groundwater wells are being constructed to greater depths in the vast majority of the analysed study sites (Fig. 3a–c, lower-right quadrant). The co-occurrence of groundwater-level declines and well deepening is evident in all three hydrologic subregions of the Central Valley aquifer system (Fig. 3a–c), but it is most common in the Tulare Lake subregion, where 89% of all sites demonstrate co-occurrence of well deepening and declining water levels. The

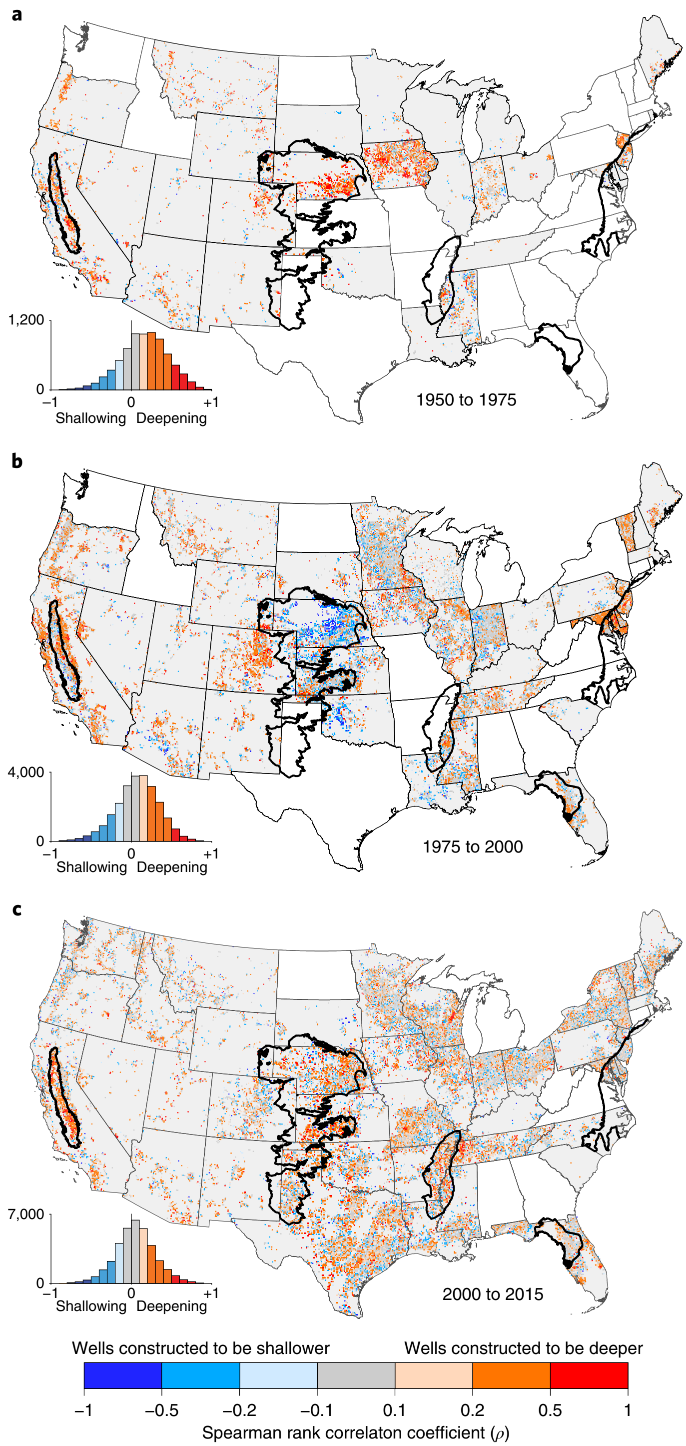


Fig. 2 | Groundwater-well construction depths vary over time. Each map presents the Spearman rank correlation coefficients (ρ) describing variations in well construction depths over time in 10 km × 10 km grids. **a–c**, Correlations for years 1950–1975 (**a**), for years 1975–2000 (**b**) and for years 2000–2015 (**c**). Orange-red shades are areas where groundwater-well depth trends are deepening over time (Spearman rank correlation coefficient $\rho > 0.1$). Blue shades are areas where groundwater-well depth trends are shallowing over time (Spearman rank correlation coefficient $\rho < -0.1$). The histogram in the lower left corner of each panel shows the distribution of ρ values; all three histograms demonstrate that most of the well construction depth trends are positive (that is, they are deepening over time). States with blank (white) backgrounds are those where no well construction data (or minimal data) were available. Thick black outlines mark the boundaries of five major aquifers; from west to east, these are (1) Central Valley aquifer system, (2) High Plains aquifer, (3) Mississippi embayment aquifer system, (4) Floridan aquifer system and (5) Northern Atlantic Coastal Plain aquifer system. Aquifer boundary credit: US Geological Survey.

Table 1 | Groundwater-well completion depth trends with time for wells in the United States

Time interval	Well construction depth trends in 10 km × 10 km grids	
	n_{all}, total number of grids (any Spearman P value) n_{deep}, grids with deeper well construction trends (Spearman ρ value > 0)	n_{sig}, grids with significant trends only (Spearman P value < 0.05) $n_{deep\text{-}sig}$, grids with significant, deeper well construction trends (Spearman P value < 0.05 and Spearman ρ value > 0)
1950–1975	n_{deep} = 5,343 of n_{all} = 7,381 (72%)	$n_{deep\text{-}sig}$ = 2,003 of n_{sig} = 2,258 (89%)
1975–2000	n_{deep} = 15,567 of n_{all} = 24,614 (63%)	$n_{deep\text{-}sig}$ = 5,325 of n_{sig} = 6,745 (79%)
2000–2015	n_{deep} = 20,934 of n_{all} = 35,494 (59%)	$n_{deep\text{-}sig}$ = 3,843 of n_{sig} = 5,319 (72%)
1950–2015	n_{deep} = 7,138 of n_{all} = 9,025 (79%)	$n_{deep\text{-}sig}$ = 4,495 of n_{sig} = 4,984 (90%)
1975–2015	n_{deep} = 16,698 of n_{all} = 23,954 (70%)	$n_{deep\text{-}sig}$ = 7,547 of n_{sig} = 8,839 (85%)

co-occurrence of groundwater level declines and well deepening is clearest from 2000 to 2015 (Fig. 2) relative to earlier time intervals (1950–1975 and 1975–2000; Supplementary Figs. 24 and 25).

In the High Plains aquifer, relations between groundwater-level trends and well construction depth trends are less clear. In the northern part of the High Plains aquifer (Fig. 3d), groundwater levels do not demonstrate systematic declines; even where levels are declining, no clear relation is apparent between groundwater-level trends and well depth trends. In the central part of the High Plains aquifer (Fig. 3e), most (80%) analysed monitoring-well records demonstrate groundwater-level declines, yet both well-deepening and well-shallowing trends occur. Similarly, although 89% of the analysed monitoring-well water levels in the southern part of the High Plains aquifer demonstrate declines from 2000 to 2015 (Fig. 3f), well deepening is not ubiquitous; well deepening occurs in 56% of the locations where groundwater levels are declining in the southern part of the High Plains aquifer.

In the Northern Atlantic Coastal Plain and Floridan aquifer systems (Fig. 3g,i), no clear relation emerges between the well construction depth trends and groundwater-level trends. Both systems include confining units (Supplementary Sections 39.3 and 39.4) and their stratigraphy is more complex than much of the Central Valley and High Plains aquifers.

In the Mississippi embayment aquifer system (Fig. 3h), another aquifer characterized by complex stratigraphy, groundwater levels are declining in 73% of the studied monitoring wells. The well-deepening trends are nearly twice as common as the well-shallowing trends.

We completed a sensitivity analysis to test the potential that monitoring wells may be capturing conditions in a deeper, confined formation that may be of little relevance to well construction in shallower formations (Supplementary Section 38.8). Our findings were largely insensitive to the monitoring-well depth (Supplementary Figs. 27–35).

Agricultural wells deeper than domestic wells. Well deepening is not occurring in all places where groundwater levels are declining, implying that shallow wells may be vulnerable to drying up if depletion continues. To quantify which types of wells are most vulnerable to declining water levels, we compared county-scale domestic-versus-agricultural well depths against domestic-versus-agricultural groundwater withdrawals (Fig. 4 and Supplementary Figs. 16–23).

In the Central Valley aquifer system (Fig. 4a), in much of the High Plains aquifer (Fig. 4b) and in the Mississippi embayment aquifer system (Fig. 4d), agricultural groundwater withdrawals exceed domestic withdrawals. In the Central Valley aquifer system and the High Plains aquifer, typical agricultural wells are deeper than typical domestic water wells. In the Mississippi embayment aquifer system (Fig. 4d), agricultural wells pump groundwater from an aquifer tens to hundreds of metres shallower than the deeper confined formations tapped by domestic water wells (Supplementary Fig. 39).

In the Northern Atlantic Coastal Plain and the Floridan aquifer systems (Fig. 4c,e), domestic groundwater withdrawals exceed agricultural withdrawals for most counties, with no clear difference between agricultural and domestic well depths.

Discussion

Drilling deeper: unsustainable stopgap to groundwater declines. Collated and quality-controlled groundwater-well data (Fig. 1) represent a nationwide analysis of well locations, purposes and depths. Our analysis of well construction records reveals that wells are often being constructed deeper with time (Fig. 2). Many factors may lead groundwater users to construct deeper wells over time, including (1) improved well construction and pump technologies[11,19], (2) 'discoveries' of deep formations or aquifers bearing fresh groundwater[20], (3) differing groundwater permitting requirements for wells of varying depths (for example, South Dakota Codified Laws § 46-6-3.1), (4) inadequate water yields or declining water levels[21] and (5) attempts by groundwater users to drill deeper to avoid pumping shallow groundwater polluted by bacteria or contaminants derived from near-surface activities[11,21]. Regardless of driving factors, we suggest that drilling deeper is an unsustainable stopgap to groundwater depletion for four reasons.

First, deep wells are often costlier than shallow wells to construct, suggesting that economically disadvantaged groundwater users may be unable to construct deeper wells[14,22]. Little data are available to determine groundwater-well construction costs, but news reports suggest that new domestic groundwater wells cost tens of thousands of dollars in California (Supplementary Table 56). In areas where water levels are declining, rural private-well owners are likely to be at the greatest risk of fresh water insecurity[22,23]. Rural communities often face limited opportunities to diversify economies and may also have higher poverty rates than urban or suburban counterparts[24]. Constructing deeper wells, even if hydrogeologically feasible, may not be economically feasible. Additionally, access to centralized or urban water-supply infrastructure may be lacking due to the geographic isolation of households[24]. Even municipalities may be vulnerable to water insecurity if they have long relied solely on groundwater. Attempts to diversify water-supply portfolios may be hampered by fully allocated surface water[25] and a limited capacity to invest capital in technologies or infrastructure for desalination, water treatment or water recycling. Thus, drilling deeper wells may not be feasible for some well owners, even if fresh groundwater is available at depth.

Second, on average, deeper wells also tend to have deeper water levels than shallower wells (Supplementary Fig. 13), implying that well deepening is increasing the energy intensity of groundwater pumping (that is, increasing the energy required to lift each unit of pumped groundwater to the land surface). In areas where pumps are powered by high-carbon energy sources (oil or natural gas), well deepening is also increasing the carbon intensity of groundwater withdrawals (that is, increasing CO_2 emissions per unit of pumped groundwater). Improving pump efficiencies may mitigate the cost increases associated with higher energy requirements. Adopting low-carbon energy technologies may moderate the increases in energy and CO_2 emission intensities associated with pumping deep well water.

Third, drilling deeper wells is impractical where the underlying rock formations lack the requisite permeability and storativity for wells to pump water at the rate needed to meet local demands. For example, the presence of low-permeability rock formations underlying parts of the High Plains aquifer means that wells completed in these formations produce little groundwater relative to wells completed in more permeable formations (for example, the Brule and Arikaree Formations underlying the northern High Plains aquifer[26]). Permeability does not always decrease predictably with depth[27], highlighting the importance of considering (1) local stratigraphy, (2) fracture networks and (3) the presence, continuity and thickness of confining layers when determining how deep a useful well may be constructed.

Fourth, because deep groundwater is often brackish or saline, indefinitely deepening wells without concomitant desalination will prove to be an unsustainable way to meet fresh water demands. The majority of groundwater sampled from wells in the United States at depths exceeding about 660 m are brackish or saline (Supplementary Figs. 14 and 15 and Supplementary Section 38.3). Recent analyses of major sedimentary basins in the United States demonstrated that fresh to brackish transition zones can occur within a few hundred metres of the land surface[28]. Another recent analysis highlighted the presence of high sodium and boron concentrations, which make water from many deep wells unsuitable for irrigation[29]. Considering the high capital investments for water purification and desalination, treating increasingly saline, boron-rich or sodium-rich groundwater is unlikely to be feasible for many domestic and small-operation agricultural well owners.

Implications for groundwater use. Three-dimensional lithology data (Supplementary Sections 39.1–39.5, Supplementary Figs. 38–43 and Supplementary Table 55) and well data may identify areas where well deepening trends may be approaching a 'hydrogeologic floor', defined here as the depth below which wells cannot reliably produce fresh groundwater at high rates. Combined with lithology data, our well depth maps can be used to identify the shallow wells most at risk of running dry should water tables decline in the uppermost unconfined aquifers. Our maps of well depths can be used to identify places where wells are being encroached upon by naturally occurring brackish or saline groundwater that dominates groundwater stores deeper than about 500 to 1,000 m below the land surface (Supplementary Fig. 14). Additionally, when combined with lithology data, our maps can be used to identify wells with bottoms within confined versus unconfined aquifers (Supplementary Section 39).

We note that well deepening is common to some of the places where groundwater levels are declining, such as in the central and southern parts of the Central Valley aquifer system (Fig. 2). We also note that groundwater wells are not being constructed deeper in some areas where groundwater levels are declining, such as parts of the central and southern High Plains aquifer. Therefore, we emphasize a clear, novel distinction between parts of two major aquifers undergoing chronic groundwater level declines: the Central Valley and High Plains. Groundwater-well deepening occurs in only about half of the locations where groundwater levels are declining in the southern part of the High Plains aquifer compared to 91% in the southern part of the Central Valley aquifer system (the Tulare Lake hydrologic region).

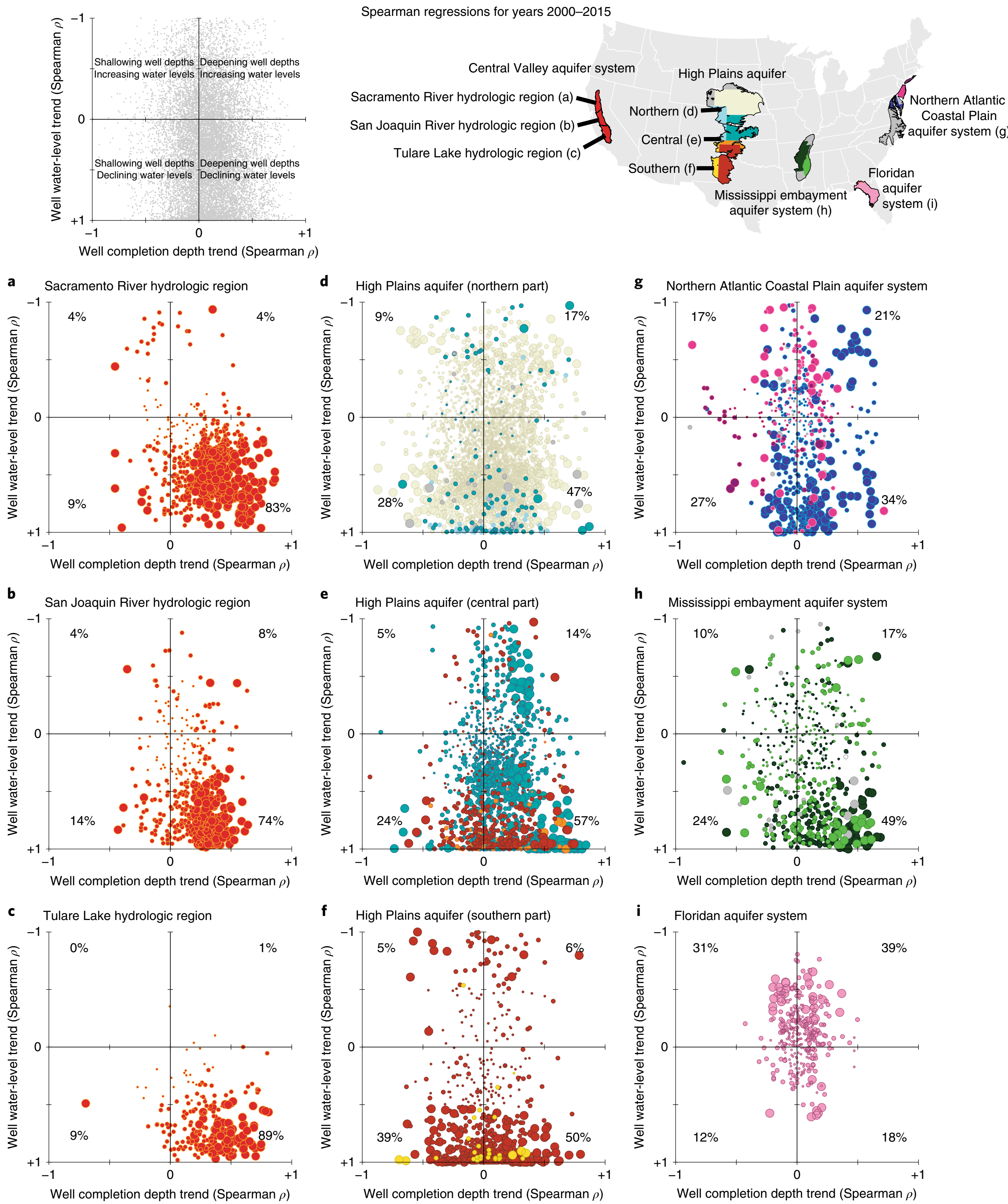
This distinction has key implications for the continuous availability and reliability of high-quality groundwater resources. Because groundwater levels in the central and southern parts of the High Plains aquifer are declining—yet wells are not being constructed deeper—some existing wells have run dry[14]. If groundwater levels continue to decline, more wells will run dry[14]. The peripheries of the central and southern parts of the High Plains aquifer are characterized by a thin 'saturated thickness'—defined by the vertical offset "between the bedrock surface and the water table"[30]. In some parts of the High Plains, underlying bedrock aquifers are brackish or saline, which indicates that well deepening can no longer stave off the loss of access to fresh groundwater that has resulted from declining water tables (as in, for example, Portales, New Mexico[31]). Recent work indicates that the depths at which groundwater transitions from fresh to brackish are shallower than previously estimated[28], suggesting that the marginal areas of the High Plains aquifer may not be the only areas where the strategy to drill deeper for fresh water is hindered by hydrogeology. Existing wells often have bottoms that are close to the base of the High Plains aquifer (Supplementary Section 39.5), implying that drilling deeper wells is impractical in these areas.

Many well bottoms in the Floridan aquifer system are at a similar depth to saline groundwater (Supplementary Fig. 41). Constructing deeper wells may result in the withdrawal of brackish or saline water, requiring treatment for domestic purposes and many agricultural uses. In some cases, groundwater wells affected by salinity may be abandoned; records of well abandonment may provide a proxy for places where access to fresh groundwater is compromised by diminishing quantity or quality. Unfortunately, well abandonment records are missing or incomplete among many of the analysed databases (Supplementary Section 38.9). Coupling groundwater-well data to lithological data may provide information about groundwater quantity and quality while promoting a better understanding of local hydrogeology.

In locations where deep, fresh and high-quality groundwater exists, there may be a need to prioritize water management and

Fig. 3 | Spearman regressions for years 2000–2015. Comparison of monitoring-well water-level trends versus well completion depth trends over the time interval 2000–2015. Trends are described by Spearman rank correlation coefficients 'ρ' describing changes over time in water levels observed in a monitoring well (y axes) and changes over time in groundwater-well depths near each monitoring well (x axes). Monitoring-well water-level ρ values greater than zero (that is, point plots on bottom half of plot) imply that groundwater levels are declining, whereas ρ values less than zero signify that well water levels are increasing (that is, point plots on top half of plot). Recorded groundwater-well construction trends with ρ values exceeding zero imply that wells are being constructed deeper over time near (<5 km) the monitoring well (that is, point plots in right half of plot), whereas ρ values of less than zero imply that a shallowing of wells constructed near (<5 km) the monitoring well (that is, point plots in left half of plot). The uppermost left plot qualitatively describes the meaning for each quadrant; the light-grey points show all monitoring wells, including those that exist both within and outside of the key aquifers. Each of the nine subplots represents monitoring-well and groundwater-well depth comparisons for a single aquifer system (for example, panel **a** presents data for the Sacramento River hydrologic region of the Central Valley aquifer system; see map in upper right). Colours convey the state that the monitoring well is located within; refer to the inset map for colours applied to specific states. The data-point sizes represent three scenarios: (1) the smallest point indicates that well construction depth and well water-level trends are both non-significant (that is, both rank regressions yield Spearman P value > 0.05); (2) the medium-sized point indicates that one of the two trends is significant (Spearman P value < 0.05) but the other is not (Spearman P value > 0.05); and (3) the largest point indicates that both trends are significant (Spearman P value < 0.05). Percentages displayed in each of the four corners of each plot express the proportion of all points that fall within a given quadrant in the plot. Aquifer boundary credit: US Geological Survey.

water-quality protection[32]. Historically, many deep formations have been viewed as strategic reservoirs for wastewater disposal by use of injection wells[28]. Over the long term, groundwater recharge is projected to decline in much of the southwestern part of the United States due to climate change[33,34]; in areas where withdrawals are high and recharge rates are low, it is likely that deep, fresh groundwater will become a strategic resource. As climates change, groundwater resources may become increasingly valuable because they are generally more resilient to short-term climate variations than surface waters[35]. We show that wells are tapping increasingly deep groundwater



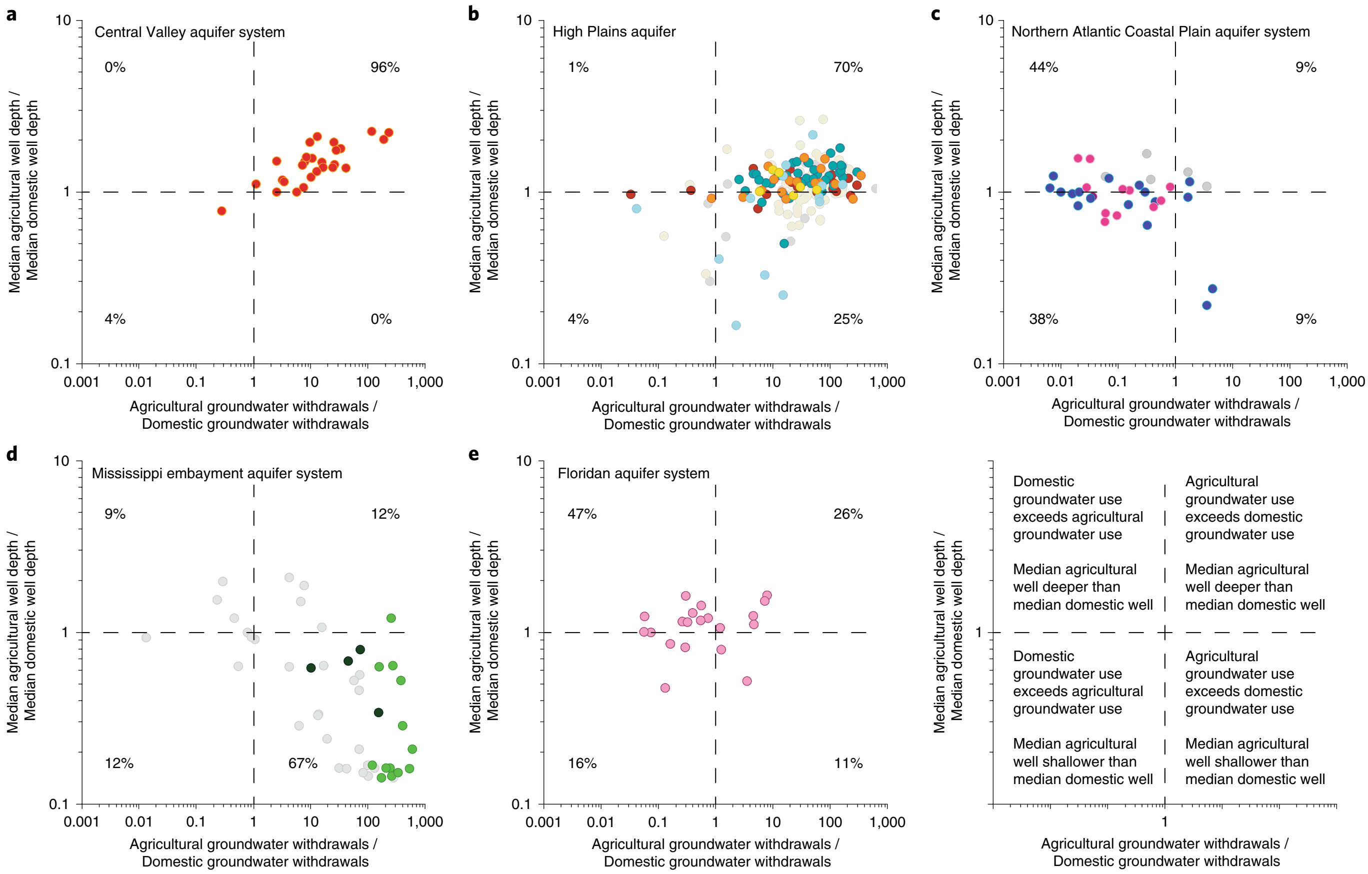


Fig. 4 | Comparison of agricultural and domestic groundwater uses versus well depths. We identified counties that overlay each of the five key aquifers and that have (1) non-zero agricultural and non-zero domestic groundwater withdrawal estimates and (2) at least $n=100$ agricultural groundwater wells and at least $n=100$ domestic groundwater wells. We calculated the ratio between the median agricultural groundwater-well depths in a county and median domestic groundwater-well depths in the same county (y axis). We calculated the ratio between agricultural and domestic groundwater withdrawals estimated by the US Geological Survey (x axis): (agricultural groundwater withdrawals)/(domestic groundwater withdrawals). Points in each plot are coloured by their state (see Fig. 3 for colours for each state) and each point represents one county. Percentages displayed in each of the four corners of each plot express the proportion of all points (that is, counties) that fall within a given quadrant in the plot (quadrants delimited by dashed black lines). The inset in the lower-right qualitatively describes the meaning for each quadrant.

(Fig. 2), suggesting that protecting deep groundwater quality is becoming increasingly important for future groundwater uses.

Domestic-versus agricultural groundwater use and well depths. Aggregated well data for the United States provide the highest resolution map of locations where groundwater can be withdrawn and help identify the most common purposes for groundwater use. Well data provide locally pertinent information that can be used to develop more targeted water policies specific to the largest water users in an area. Compiled data demonstrate that most groundwater wells have been constructed for domestic uses (Fig. 1a), even though the agricultural sector withdraws more groundwater by volume than the domestic sector (Supplementary Figs. 16 and 17; Supplementary Section 38.4).

Our five study aquifers (Figs. 2 and 3) encompass a variety of groundwater withdrawal purposes and associated well depths. For unconfined aquifer systems, the shallowest wells are the most vulnerable to going dry should the water table decline. In the Central Valley aquifer system and the central and southern parts of the High Plains aquifer, typical agricultural wells are often tens of metres deeper than typical domestic wells (Fig. 4 and Supplementary Fig. 22). In these aquifers, typical domestic wells are more vulnerable to running dry than deeper agricultural wells, even though total agricultural withdrawals often far exceed domestic withdrawals. In addition to their disproportionate vulnerability to going dry, the shallow depths of domestic wells make them more vulnerable to pumping groundwater contaminated by nitrate derived from near-surface sources (for example, urban waste, manure and fertilizers spread over land surfaces[36,37]).

A well's vulnerability to drying is more complex in aquifer systems where shallow unconfined aquifers overlay deeper confined formations, such as in the Mississippi embayment, Northern Atlantic Coastal Plain and Floridan aquifer systems. In the Northern Atlantic Coastal Plain and Floridan aquifer systems, domestic groundwater use exceeds agricultural withdrawals for most counties, and no clear difference exists between agricultural-versus domestic well depths. The Mississippi embayment aquifer system appears to be unique among the aquifers we studied; here, agricultural groundwater withdrawals far exceed domestic withdrawals, but typical agricultural wells are often about 10 to 200 m shallower than typical domestic wells (Supplementary Fig. 22). Constructing deep wells for domestic purposes gained popularity in the early 1900s, when shallow well water was associated with typhoid[11,38]. Agricultural pumping is depleting groundwater in parts of the shallow alluvial aquifer[11]. About two-thirds of agricultural wells are perforated in the shallow alluvial aquifer of the Mississippi embayment system (Supplementary Section 39.2 and Supplementary Table 55), but the effects on domestic wells are likely to be small relative to those in the Central Valley aquifer system because most domestic wells in the Mississippi embayment aquifer system derive water from deeper confined aquifers (namely, the Claiborne aquifer[11]).

In summary, our assessment of groundwater-well construction in the Central Valley, Floridan, Northern Atlantic Coastal Plain and Mississippi embayment aquifer systems and High Plains aquifer quantitatively evaluates groundwater from a demand-side perspective and identifies where groundwater wells are constructed, how deep the wells are drilled and why the wells are constructed. By exploring trends in groundwater-well construction depths and trends in monitoring-well water levels, our analysis identifies regions where groundwater wells are vulnerable to declining groundwater levels.

Global implications and opportunities. The United States is one of the world's largest food exporters; growing some of this exported food relies on groundwater-fed irrigation that is driving groundwater depletion in some aquifers[39,40]. Projections for the central part of the High Plains aquifer suggest that groundwater depletion will reduce irrigated agriculture and agricultural yields[41], possibly reducing food exports and affecting global access to nutritious food[42]. Should such dire food-production projections be realized, these food-production declines could have global implications.

Our US-based analysis has implications for parts of other nations where aquifers are currently undergoing depletion (for example, the North China Plain[43], Upper Ganges[44] and North Arabian[44] aquifers). Publicly available groundwater-well data are accessible for at least 20 other nations around the globe (Supplementary Section 41 and Supplementary Table 57). In some regions, declining water tables have encouraged deeper well drilling that has increased the salinity of abstracted groundwater, thus degrading its quality (for example, in Jordan[45]). Using well data to better understand and quantify hydrogeochemical and socioeconomic limitations to global groundwater use can improve projections of drinking-water access and food production that is reliant on groundwater-fed irrigation.

Our findings suggest that data about groundwater-well location, depth and purpose may help connect groundwater quantity and quality research to water policy, demand and management sciences. Our work builds upon a 1966 US Geological Survey report[46] that identified regional trends in groundwater-well construction depths during the early 1960s, suggesting well drilling to be a proxy for the "importance of ground water to our national economy"[46]. Indeed, understanding where wells are located and why they were constructed presents an opportunity to understand drivers of land-use changes, such as rural and suburban transitions, rain-fed to irrigated land areas and industrial growth[46]. Quantifying well depths presents an opportunity to identify (1) shallow wells imperilled by surface-borne contaminants or declining water tables and (2) deeper wells that are encroaching on depths dominated by saline waters and geogenic contaminants. We show that groundwater wells are being constructed deeper over time in the United States; we suggest that deeper drilling is limited by socioeconomic conditions, hydrogeology and groundwater quality, thus implying that it is an unsustainable stopgap to groundwater depletion.

Methods

Groundwater-well data synthesis. We collated groundwater-well construction records from state-, regional- and county-scale groundwater-well construction databases curated by engineering offices, water management districts, geological surveys and well construction companies. Groundwater quantity is mostly a matter of state regulation[47,48], so we controlled the compiled datasets for quality, as each state or sub-state entity that provided data has unique guidelines in historical data collection and digitization efforts (Supplementary Section 1 and Supplementary Table 1). In total, we compiled and performed quality-control measures on $n=43$ unique state-, regional- or county-scale well construction databases (Supplementary Sections 2–34), adding to (and more than doubling) recently presented well completion datasets ($n=21$ state-level databases[14,49]; Supplementary Fig. 2). In total, we analysed $n=64$ well construction databases.

We carefully evaluated each groundwater-well construction database by (1) excluding records with unclear construction dates, (2) removing duplicate records, (3) removing records that did not correspond to well construction or well deepening (for example, well repair), (4) removing records lacking well depth information, (5) removing records with unrealistic locations (for example, a well construction record in California's database that had a recorded location outside of California's state boundaries) and (6) removing records of wells constructed for a purpose other than domestic, agricultural or industrial use (Supplementary Sections 2–34).

We describe the dataset availability and quality-assurance steps specific to each state or sub-state database in the Supplementary Information (Supplementary Sections 2–34). It is important to note that each state or sub-state database has been curated differently; the amalgamation of these databases introduces uncertainties[14], most of which can be described only qualitatively. We surveyed the data managers responsible for creating the groundwater-well construction datasets to ensure that any dataset limitations could be communicated clearly (Supplementary Table 1). We took particular care to evaluate the purpose of the constructed well so that the well could be categorized as domestic (for example, self-supply or public-supply wells), agricultural (for example, irrigation or livestock uses) or industrial (for example, groundwater to support energy production or commercial activities; Supplementary Sections 2–34). We detail the groundwater-well construction database limitations in the Supplementary Information. Specifically, we refer readers to Supplementary Table 1 and Supplementary Section 35 where many known biases in the well completion data collection are described. We mapped the collated data to identify spatial patterns in constructed well depths and purposes (Fig. 1). Results for Hawaii and Alaska are not shown in the figures in the main text but are included in results presented in the text and in Table 1.

Well construction depth trend analysis. We analysed recorded groundwater wells within 10 km × 10 km grids. We categorized the well construction depth trends into three time intervals: (1) 1950 to 1975 (Fig. 2a), (2) 1975 to 2000 (Fig. 2b) and (3) 2000 to 2015 (Fig. 2c; see Supplementary Figs. 24 and 25 for results for 1950–2015 and 1975–2015). We strategically selected these time intervals to account for differences in state groundwater-well record collection; for example, Kansas' database contains mostly records postdating 1975 and Texas' database contains records mostly postdating 2000 (ref. [14]). We analysed all records that met our quality-control benchmarks, which included (1) recorded completion of a newly constructed well or (2) recorded deepening of an existing well (Supplementary Section 1). To evaluate changes in well depths over time, we used Spearman rank correlations. Spearman rank correlations are more resistant than Pearson correlations to atypical values and non-linearities likely to arise because of heterogeneities inherent to the subsurface that influence well completion depths (for example, confined versus unconfined aquifers). We calculated the Spearman rank correlation coefficients using 10 km × 10 km areas that contained at least ten groundwater wells (domestic, agricultural or industrial) constructed within each studied time interval. We only analysed grids with at least one sample in the first 5 years and one sample in the last 5 years of the specified time interval. Each correlation coefficient characterized how the groundwater-well completion depths varied over each analysed time interval within each 10 km × 10 km area.

We completed an additional geospatial sampling analysis to assess if our main conclusions are susceptible to the way we grouped wells in space by using the 10 km × 10 km grids. We used ArcGIS Pro to generate polygons based on a minimum sample size (that is, the number of constructed groundwater wells within each polygon) using the same time intervals used for the 10 km × 10 km gridded analysis: (1) 1950–1975 (Supplementary Fig. 6), (2) 1975–2000 (Supplementary Fig. 7), (3) 2000–2015 (Supplementary Fig. 8), (4) 1950–2015 (Supplementary Fig. 9) and (5) 1975–2015 (Supplementary Fig. 10). We set the target sample size per polygon to $n=100$; we analysed the trends for polygons with at least $n=90$ samples (Supplementary Section 37). As with the gridded analysis, we only computed the Spearman rank correlation coefficient for a polygon with at least one sample in the first 5 years and one sample in the last 5 years of the specified time interval.

Comparing groundwater level versus well depth trends. We assessed how groundwater-well construction depths have varied over time near monitoring wells with long-term groundwater-level records. First, we downloaded US Geological Survey groundwater-well water-level measurements (Supplementary Section 36.2). Second, we calculated the Spearman rank correlation coefficients describing how the observed groundwater levels vary within three time intervals: (1) 1950–1975 (Supplementary Fig. 24), (2) 1975–2000 (Supplementary Fig. 25) and (3) 2000–2015 (Fig. 3). We only analysed monitoring-well water-level records that met all of the following criteria: (1) reported one water-level measurement within the first 5 years of the analysed time interval, (2) reported one water-level measurement within the final 5 years of the analysed time interval, (3) reported at least one constructed well within the first 5 years of the analysed time interval and within 5 km of the monitoring well, (4) reported at least one constructed well within the final 5 years of the analysed time interval and within 5 km of the monitoring well, (5) reported at least $n=10$ wells constructed within the time interval and within 5 km of the monitoring well and (6) reported at least $n=10$ water-level measurements within the time interval. Third, we identified all recorded constructed wells located within 5 km of each monitoring well. A 5-km buffer was chosen strategically to allow for a large enough sample size of nearby groundwater wells to perform a statistical analysis, while remaining small enough to retain local relevance. We then calculated Spearman rank correlation coefficients to quantify variations in the constructed-groundwater-well depths within each analysed time interval (that is, 1950–1975, 1975–2000 or 2000–2015). Next, we compared variations in observed groundwater levels over time to temporal variations in the depths at which wells located near each monitoring well have been constructed (see schematic diagram depicting analysis approach in Supplementary Fig. 26).

We constrained the results of our analysis to the monitoring wells located within the boundaries of the five principal aquifers chosen for their importance in supplying groundwater and for their geographic distribution across the continent: (1) California's Central Valley aquifer system, (2) the High Plains aquifer, (3) the Mississippi embayment aquifer system, (4) the Northern Atlantic Coastal Plain aquifer system and (5) the Floridan aquifer system. Because of the extent of the Central Valley and the High Plains aquifers, we separated each into three subregions as follows: (1) for the Central Valley aquifer system, the subregions are the Sacramento River hydrologic region, the San Joaquin hydrologic region, and the Tulare Lake hydrologic region; (2) for the High Plains aquifer, they are simply the northern, central and southern subregions.

Some portions of the studied aquifer systems are confined or semiconfined, best described by interfingered layers of permeable and less-permeable formations; this is the case for portions of the High Plains aquifer and the Floridan, Mississippi embayment and Northern Atlantic Coastal Plain aquifer systems. Unfortunately, three-dimensional, continental-scale, disaggregated geological data are not yet available (see Supplementary Section 39 for regional analyses). Because monitoring wells represent conditions specific to a given formation (for example, a monitoring well perforated in a deep confined aquifer), it is possible that monitoring-well water-level trends do not represent groundwater-level trends in other formations (for example, a shallow unconfined aquifer). We excluded increasingly deep monitoring wells, repeating our analyses to evaluate how sensitive our findings were to transitions from unconfined to confined conditions (Supplementary Section 38.8). We determined that our main findings were largely unaffected by the depth of the monitoring wells that we analysed (Supplementary Figs. 27–35). It is also important to note that few states provided depths to perforations; to maintain consistency across all the states we analysed, we considered the total well depth rather than the depth to perforations.

Agricultural-versus domestic well depths and groundwater use. We analysed the median agricultural and domestic well depths across the United States by 10 km × 10 km areas (Supplementary Figs. 18 and 19) and by county (Fig. 4 and Supplementary Figs. 20–23). We compared the county-scale median agricultural-versus-domestic well depth differences to county-scale differences in agricultural-versus-domestic groundwater withdrawals. 'Domestic' withdrawals are calculated to be the sum of the public-supply groundwater withdrawals and self-supplied groundwater withdrawals; 'agricultural' withdrawals are calculated as the sum of fresh groundwater for irrigation and fresh groundwater withdrawals for aquaculture (Supplementary Section 38.4). Although well construction data are available in disaggregated form, water-use estimates from the US Geological Survey are available at the county and state scale only for recent years; as a result, we aggregated well data to the county scale. We identified all counties that coincided with our study aquifer boundaries and do not attempt to disaggregate water-use information within aquifer boundaries due to uncertainties with the water-use estimates[50].

Data availability

The groundwater-well datasets that support the analyses are available from state and sub-state agencies; some states require consent to share groundwater-well data, some states prefer that requests go through their agency for various reasons and other states require public records requests. Supplementary Table 1 includes websites for direct download and contact information for requesting access to data. Groundwater-level data are available from the US Geological Survey (waterdata.usgs.gov/nwis/inventory) and California's GAMA Program (gamagroundwater.waterboards.ca.gov/gama/gamamap/public).

Code availability

MATLAB codes that support the analyses are available from D.P. upon request.

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D.P. and S.J. contributed equally to compiling and analysing the well completion data, and to writing the paper.

Competing interests
The authors declare no competing interests.

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