Manuscript entitled: Undrainable pore spaces comprise half of US groundwater storage

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Authors: Merhawi GebreEgziabher [1,*], Debra Perrone [2], Scott Jasechko [1,*]

Affiliations:
[1] Bren School of Environmental Science & Management, University of California, Santa Barbara, California, 93106, USA
[2] Environmental Studies Program, University of California, Santa Barbara, California, 93106, USA
[*] these authors contributed equally

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Corresponding author:
Merhawi GebreEgziabher GebreMichael
Incoming Assistant Professor at Auburn University (starting January 2026)
University of California at Santa Barbara
2400 Bren Hall, Santa Barbara, California, 93106
Email: gebremichael@ucsb.edu

Groundwater is vital to global freshwater access, streamflow generation, and biogeochemical cycling, but not all groundwater can be drained due to adhesive and capillary forces. Quantifying the proportion of groundwater that can be drained—and is, thus, theoretically recoverable—is critical for characterising groundwater's role in earth system processes. Unfortunately, estimates of theoretically recoverable groundwater are poorly constrained due to a lack of three-dimensional lithologic observations. Here we analyse ~19.2 million 3D lithologic observations recorded in ~3.7 million drilling reports across the United States. We show that only half of US groundwater is theoretically recoverable by wells due to the abundance of aquitards, which retain most of their water when drained. The abundance of aquitards emphasizes that the great majority of groundwater is stored in confined aquifers, which are often more sensitive to rapid groundwater-level declines than shallower unconfined aquifers. The widespread prevalence of aquitards and confined conditions suggests that even modest groundwater pumping can lead to substantial drawdown in many aquifers, inducing land subsidence and creating potential water quality risks.

Main

Groundwater comprises ~99% of all unfrozen freshwater[1] and supplies perennial water for food production and drinking. Groundwater is stored in pores, which include fractures in rock and spaces in between grains of sediment[2]. Some groundwater cannot be drained because it is stored within pores that are disconnected from other pore spaces or because the water is bound to the surrounding rock and sediment by adhesive and capillary forces[2,3]. Other groundwater is 'theoretically recoverable groundwater'—defined here as groundwater that can drain from rock or sediment by gravity—and can be accessed by a well or borehole[4].

Theoretically recoverable groundwater often comprises the majority of all of the groundwater that is stored within permeable lithologic units known as aquifers (e.g., sand and sandstone, which have coarse grains and weak matric forces that allow water to drain readily from pores; ref.[2]), but comprises a minority of all groundwater stored within low-permeability lithologic units known as aquitards (e.g., clay and shale, which have fine grains and strong matric forces that retain water even when drained by gravity; refs.[5,6]). Characterising theoretically recoverable groundwater storage requires 3D observations of aquifers and aquitards. Understanding theoretically recoverable groundwater is important for managing groundwater quantity and quality, and can help define (a) the potential yield of wells[7], which is important for managing domestic well supplies and groundwater-fed irrigated agriculture[8], (b) land areas that are vulnerable to subsidence[9], which is important for protecting infrastructure and evaluating flood risk, (c) the water table depth[10], which is vital for understanding how groundwater generates streamflow and sustains riparian ecosystems[11], (d) how groundwater withdrawals from various depths may disturb and reorganise flow pathways[12], which is important for contaminant fate and transport, and (e) subsurface geochemical reactions, which is important for predicting risks to water quality from geogenic and anthropogenic contaminants.

Many studies have estimated the total volume of stored groundwater (e.g., refs.[1,13,14]), but the proportion of total stored groundwater that is 'theoretically recoverable' is poorly constrained. For example, despite being acknowledged as a more relevant metric than total groundwater storage[4], theoretically recoverable groundwater storage estimates and 3D maps of aquifers and aquitards are not readily available across the contiguous US. Theoretically recoverable groundwater storage estimates require lithologic and hydrogeologic property data, but this information has not been available at the scale needed to complete national-scale assessments. This study addresses a crucial gap by compiling and categorizing lithologic log data into representative hydrolithologic categories from over 19 million well log records to directly quantify recoverable groundwater at the national level.

In this study, we compile and analyse lithologic logs recorded during the drilling of 3.7 million wells, providing 3D lithologic information across much of the contiguous US (Fig. 1). We create a database of ~19.2 million lithologic descriptions sorted into 15 broad categories, each capturing materials encountered during the drilling of a well (Methods: 'Definitions'). The inherent three-dimensional nature of the lithologic observations enables us to analyse lithologic conditions along continua spanning from shallow to deep depths. The lithologic observations provide new constraints on theoretically recoverable groundwater storage (Fig. 2). Because the lithologic observations provide information on low-permeability lithologic units (aquitards), they also enable us to evaluate the 3D distributions of unconfined versus confined aquifer conditions (Fig. 3). Understanding confined and unconfined conditions is critical for (a) assessing land subsidence[15], (b) quantifying streamflow depletion[16], (c) characterising subterranean ecosystems[17], (d) estimating pumping-induced groundwater declines at seasonal[18] and interannual[19] timescales, (e) enforcing groundwater policies that distinguish between unconfined versus confined aquifers (e.g., in Colorado's San Luis Valley[20]), and (f) predicting groundwater quality risks[21].

Results

3D lithologic observations

To evaluate 3D lithologic conditions across the US, we compiled or manually transcribed ~19.2 million lithologic intervals detailing the rocks and sediments encountered during well drilling; these data derive from lithologic logs within ~3.7 million well drilling reports. We categorised 1.4 million unique lithologic descriptions into 15 lithologic categories; these categories are informed by refs.[22–24] (Methods: 'Compiling lithologic log data', 'Categorising lithologic descriptions', 'Definitions'; Supplementary Notes 1 and 2).

The great majority (~93%) of the lithologic intervals are at depths shallower than 100 m; the lithologic intervals are densely distributed at the near-surface and are sparser at deeper depths (Fig. 1 a-f). The five most common groups of categorised lithologies are unconsolidated materials (e.g., sand, clay; accounts for 72.9% of all 19.2 million lithologic intervals), clastic sedimentary materials (e.g., sandstone, shale; 17.6% of intervals), carbonate rocks (e.g., limestone; 7.1% of intervals), glacial tills (1.1% of intervals), endogenous rocks (e.g., granite; 0.9% of intervals), and volcanic rocks (e.g., basalt, rhyolite; 0.4% of intervals).

Lithology varies with depth. Unconsolidated materials comprise most of the lithologic intervals within the first few metres below the land surface (i.e., 95% of the lithologic observations at a depth of 1 m), but become less common at deeper depths (i.e., only 59% of the lithologic observations at a depth of 100 m; Fig. 1g-h). Sedimentary rocks—including clastic and carbonate sedimentary rocks such as sandstone, shale, and limestone—become more common with depth, surpassing unconsolidated materials as the most common lithologic group at depths exceeding 150 metres (Fig. 1g-h). Although relatively rare among the lithologic observations, volcanic and endogenous rocks are observed at the near surface in some areas. For example, endogenous rock exists at shallow depths in the Sierra Nevada mountains of California, and volcanic rock exists at shallow depths in south-eastern Idaho (Fig. 1b). We stress that the lithologic logs disproportionately represent locations where groundwater wells have been drilled; the 3D variations in lithology presented in Fig. 1a-f do not derive from a randomly distributed sampling array. Nevertheless, the compiled observations constrain vertical variability in national-scale lithology, enabling us to evaluate 3D groundwater conditions such as theoretically recoverable groundwater storage.

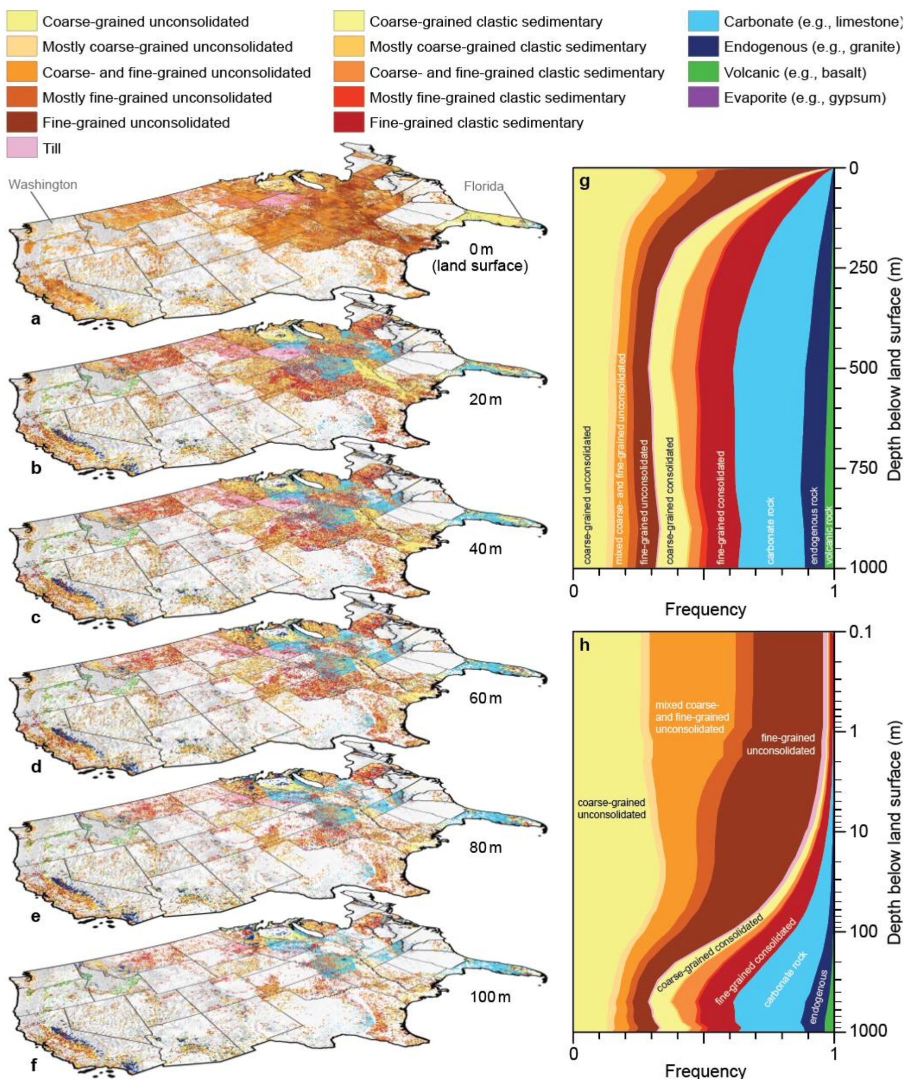

Fig. 1. Observed lithologies at various depths during well drilling across the United States. **a-f)** Locations of well drilling events with lithologic information at 20m increments from the land surface to 100m below land surface. Points represent well drilling events, and the colour of each point is coded to the lithology at a given depth. **g-h)** Frequency with which each lithologic category (represented by different colours) occurs between land surface and 1,000 m below ground surface. Well depths (y-axis values) are presented with a linear scale for panel g, and a log-scale in panel h.

Only half of groundwater is theoretically recoverable

To analyse theoretically recoverable groundwater storage, we compiled hydrogeologic data for each of the 15 lithologic categories presented in Fig. 1 (Methods: 'Compiling hydrogeologic property data'; Supplementary Note 3). We analysed 3D distributions of lithologies and hydrogeologic properties from the land surface to 100 m below the land. This 100 m threshold was selected because (a) it encompasses the great majority of US groundwater wells (i.e., ~80% of US wells are shallower than 100 m; ref.[25]), and (b) shallower groundwater tends to circulate faster than deeper groundwater, making our analysis more relevant to global water and biogeochemical cycling. We calculated the proportion of pores that are drainable—defined as [specific yield] divided by [specific yield plus specific retention] (Fig. 2).

Where groundwater is present, drainable porosity describes how much stored groundwater is theoretically recoverable[4]. The proportion of pore space in the uppermost 100 m of the crust that is drainable ranges has a median of 46%, a lower-upper quartile range of 37-59%, and a 10th-90th percentile range of 32-68% (Fig. 2). This finding remains largely unchanged across a suite of sensitivity analyses where we vary the hydrogeologic parameters ascribed to each lithologic category (Supplementary Notes 4 and 5).

The proportion of pore space that is drainable tends to be low (<40 %) in flat plains underlain by thick sequences of clay (e.g., the northern portion of California's Central Valley) or shale (e.g., the Judith Basin in central Montana). The lack of drainable pore space poses a challenge for water access, and some wells yield limited amounts of water when pumped (e.g., Colorado shales in the Judith Basin[26]). In contrast, the proportion of pore space that is drainable tends to be relatively high (>60 %) where well-drained sandy deposits are common (e.g., the 'Surficial Aquifer' within the Floridan Aquifer System).

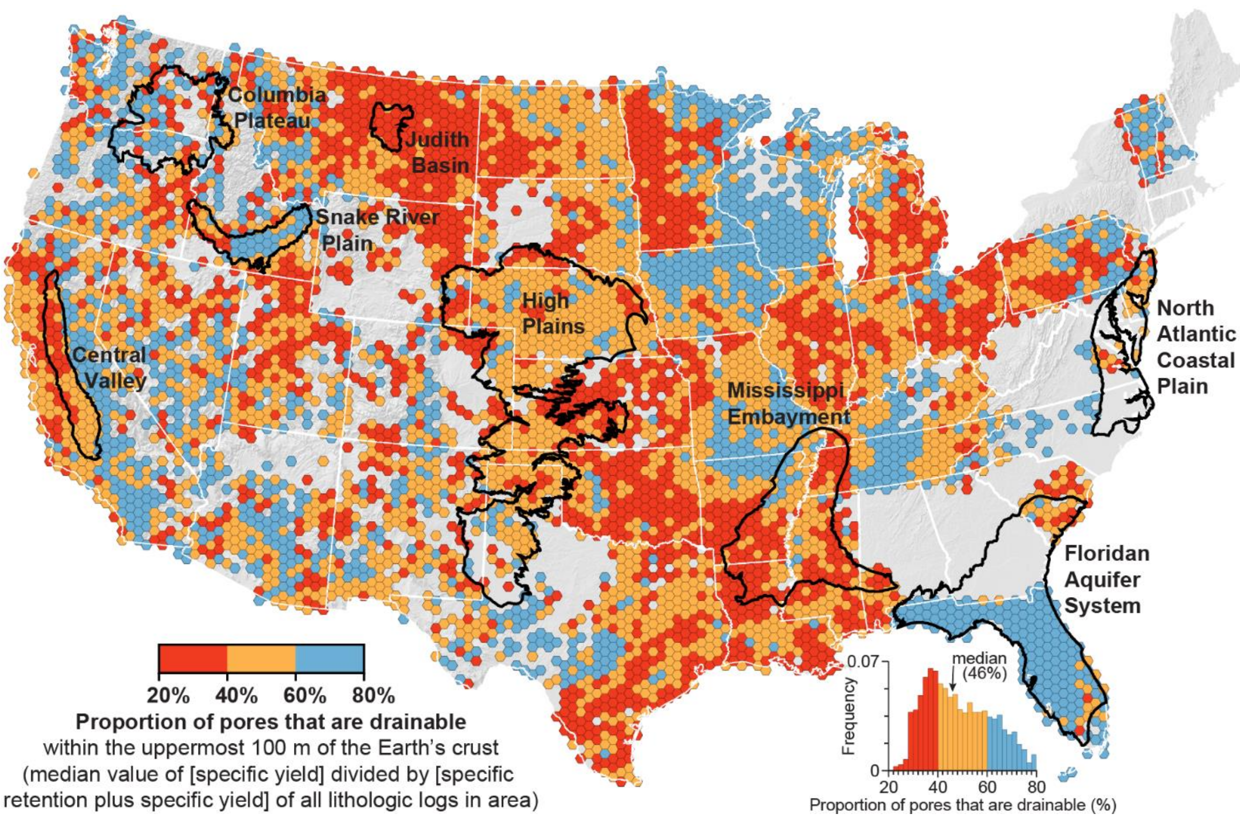

Fig. 2. The proportion of pore space that can be drained by gravity. The map presents tessellated 1,000 km^2 areas, each representing the uppermost 100 m of the Earth's crust. The colours correspond to ranges of values for the proportion of total porosity that could be drained by gravity. Red colours represent areas where a small proportion of pores can be drained by gravity (i.e., if filled with groundwater, the majority of the stored groundwater is undrainable), whereas blue areas represent areas where most pores can be drained by gravity. Estimates are based on the median value for all lithologic logs within each hexagonal area. That is, for each lithologic log extending to 100 m depth, we calculated the value for [specific yield] divided by [specific retention plus specific yield]; the value presented for each hexagon is the median of all well drilling events within the boundary of the hexagonal area. The outer boundaries of several major aquifer

systems are delineated by black lines (e.g., the Central Valley in California and the Snake River Plain in Idaho; aquifer system boundaries are from the US Aquifer Database[45]).

Confined aquifers underlie low-permeability sediments

Aquifers can be classified as confined or unconfined. Confined aquifers are overlain by one or more low-permeability layers, whereas the top of an unconfined aquifer is the water table[2]. Many local- and regional-scale studies have mapped confined and unconfined aquifers in 3D, but observationally constrained estimates of the depth to confined conditions are rare at the continental-scale. To better understand the 3D distribution of confined aquifer conditions, we examined how the prevalence of wells tapping confined versus unconfined conditions varies with total well depth and with the thickness of low-permeability clastic sedimentary material overlying the bottom of the well (Supplementary Note 6).

We analysed lithologic logs from the US Geological Survey that include lithologic observations for wells and, critically, also specify whether the well taps confined or unconfined conditions. We show that the proportion of wells that tap confined conditions tends to be higher where well bottoms are overlain by thick low-permeability clastic sedimentary materials, such as clay and shale (red in Fig. 3a-b). Thick low-permeable clastic formations can act as confining layers, limiting water movement through pores and creating confined conditions. Conversely, deeper wells that are not overlain by thick layers of low-permeability clastic sedimentary material rarely tap confined conditions (blue in Fig. 3a-b). We find that half of all wells that are overlain by at least 60 m of low-permeability clastic sedimentary material tap confined aquifer conditions (Fig. 3c), demonstrating the value of lithologic observations for constraining the depths of confined aquifers.

Using our finding from the US Geological Survey dataset—that half of all wells that are overlain by at least 60 m of low-permeability clastic sedimentary material tap confined aquifer conditions—we estimate the plausible depth to confined conditions for our lithologic logs. Specifically, we calculated the shallowest possible depth below the land surface that is overlain by at least 60 m of low-permeability clastic sedimentary material, and use this as a proxy for the depth to confined conditions (Figure 3d-g). These proxy depths-to-confined-conditions have a median of 73 m, a lower-upper quartile range of 64-93 m, and a 10^{th}-90^{th} percentile range of 63-120 m. Previous work[11] has estimated the depth of unconfined aquifers to be 100 m below the land surface; our analyses of the depth to confined conditions based on lithologic observations suggests this previous estimate was an appropriate approximation for many aquifers. Considering the total groundwater storage in the uppermost few kilometres of the crust[14], we conclude that the overwhelming majority of groundwater exists under confined conditions.

Unsurprisingly, the depth below the land surface that is overlain by 60 m of low-permeability clastic sedimentary material varies spatially (Figs. 3d-g). In some areas, low-permeability clastic sediments comprise nearly all of the lithologic observations made in the uppermost 60 m of the crust (e.g., the western part of the Garber-Wellington aquifer system in central Oklahoma, where a thick confining unit, the 'Hennessey Group', subcrops[27]). In other areas, the depth below the land surface that is overlain by 60 m of low-permeability clastic sedimentary material can be deeper than 150 m, such as the southern portion of California's Central Valley aquifer system and the central High Plains aquifer system in southwestern Kansas (Fig. 3e-f). These two areas are widely acknowledged as major hubs of groundwater-fed irrigated agriculture. Continent-wide lithologic data—such as those compiled here—may be key for prospecting for areas with thick unconfined aquifers that may be able to support irrigated agriculture. Because the effects of groundwater pumping differ among confined and unconfined aquifers, the spatial patterns of depths to confined conditions estimated here can help understand the impacts of historic groundwater use and improve predictions of future impacts.

Our results have considerable uncertainty that arises from multiple sources, including poorly constrained measurements of local hydrogeologic properties and unthorough lithologic descriptions (Methods: 'Limitations'). Nevertheless, the compiled lithologic observations enable us to provide first-estimates of the plausible depth below the land surface to confined aquifer conditions, based on observed thicknesses of low-permeability sedimentary materials (Fig. 3).

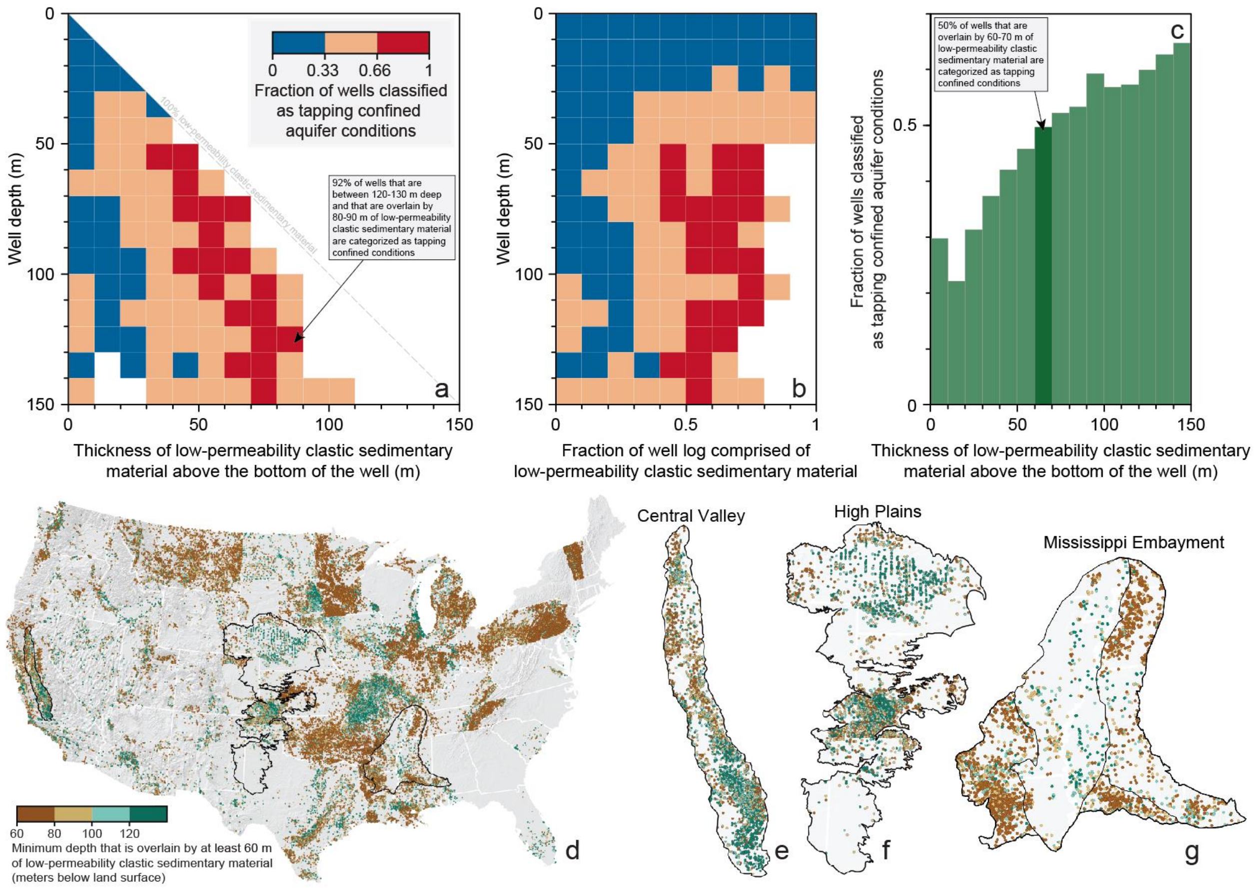

Fig. 3. Statistical relationships between low-permeability clastic material and confined conditions. a-b) Prevalence of wells that have been classified as tapping confined conditions among US Geological Survey wells. The colour of each square represents the fraction of wells classified by the US Geological Survey as tapping confined aquifer conditions. Red squares correspond to a large fraction of wells that the US Geological Survey has classified as tapping confined aquifer conditions (i.e., at least two-thirds of wells are classified as tapping confined aquifer conditions); blue squares represent small fractions (i.e., fewer than one-third of wells are classified as tapping confined aquifer conditions). Panel **a** presents the

prevalence of wells tapping confined conditions in the context of a range of well depths (y-axis values, each square represents all wells within a given 10 m depth range, such as from 0-10 m) and thicknesses of overlying low-permeability clastic sedimentary material (x-axis values). Panel **b** presents the identical data as displayed in panel a, except x-axis values are now presented in units of the fraction of the lithologic log comprised of low-permeability clastic sedimentary material (instead of the cumulative thickness). **c)** The fraction of wells classified as tapping confined aquifer conditions (y-axis values) for 10 m binned intervals of the thickness of low-permeability clastic sedimentary material above the bottom of the well (x-axis values). Half of all wells overlain by at least 60-70 m of low-permeability clastic sedimentary material are classified as tapping confined aquifer conditions (see flyout text box and dark-green bar). We used this statistical relationship to map the minimum depth (i.e., below the land surface) to a point that is overlain by at least 60 m of low-permeability clastic sedimentary material; these maps are presented for **d)** the contiguous US, **e)** the California Central Valley, **f)** the High Plains, and **g)** the Mississippi Embayment (see black lines in panel d for the locations of these three aquifer systems).

Discussion

Groundwater quantity

From the perspective of groundwater quantity, the lithologic observations (Figs. 1-3) have implications for (a) evaluating groundwater declines, (b) characterising land subsidence, and (c) identifying optimal locations to artificially recharge depleted aquifers.

(a) The lithologic observations can constrain hydrogeologic properties and groundwater-level changes in 3D, enabling improved monitoring and management where groundwater levels are declining. We note that much groundwater withdrawals are sustained not by draining pore spaces but by the process of capture (e.g., increasing recharge, decreasing discharge). Declines in groundwater levels are widespread in cultivated drylands[28] and constitute a risk to the sustainability of irrigated agriculture[29]. Two critical datasets for characterizing groundwater-level changes are (i) in-situ monitoring wells (Fig. 4a), and (ii) the Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow-On (GRACE-FO) missions. Efforts to reconcile these two complementary datasets can benefit from observationally constrained groundwater storage properties, namely, drainable porosity[30]. We estimate drainable porosity across the US, providing observational constraints that may be used to reconcile in-situ monitoring and GRACE data (Supplementary Note 7).

(b) The lithologic observations can characterise the consequences of overpumping, such as land subsidence. Because pumping-induced land subsidence is driven primarily by the compaction of low-permeability layers, land-subsidence risk assessments can be improved by incorporating spatial variations in clay content (Fig. 4e). Furthermore, 3D lithologic data can help predict the response of subsidence to groundwater-level recoveries. Some areas may experience residual compaction where clay-rich layers continue to drain even after groundwater-levels recover (e.g., Las Vegas[31]). Other areas may experience land uplift after groundwater declines are reversed (e.g., New Orleans[32]). Coupling spatial variations in low-permeability sediment (Fig. 4e) with InSAR-based land subsidence data[9] and well construction data[25] could identify specific sectors driving pumping-induced land subsidence. Identifying specific sectors can help to address land subsidence through targeted policy interventions (e.g., Tokyo[33]).

(c) The lithologic observations can inform managed aquifer recharge siting. A common managed aquifer recharge scheme is water spreading, either by ‘infiltration basins’ or intentional inundation of land areas during periods of excess surface flows. The prevalence of fine-grained sediments (Fig. 4e) can be the largest source of uncertainty in models of managed aquifer recharge[34], emphasising the value of 3D lithologic observations. Critically, the lithologic observations enable us to identify areas with thick coarse-grained sedimentary deposits (Fig. 4c). Some areas with thick coarse-grained sedimentary deposits (Fig. 4c) and deep groundwater levels (Fig. 4a) may have suitable conditions for managed aquifer recharge (Supplementary Note 8).

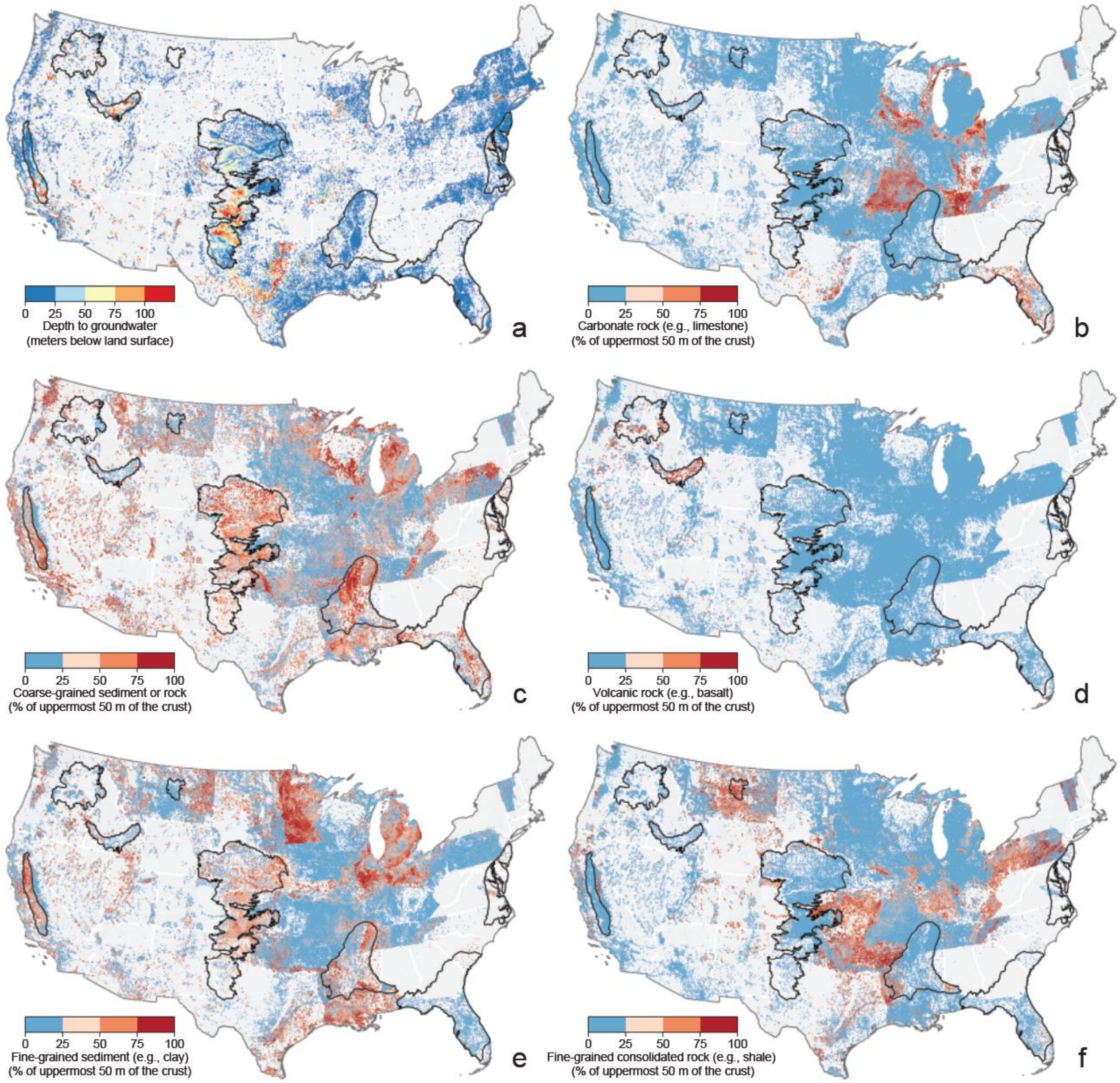

Fig. 4. Groundwater levels and prevalence of specific lithologies in the uppermost 50 m of the Earth's crust. a) Recent (since January 1, 2015) measurements of the depth to groundwater made in >200,000 wells across the US. Blue dots represent wells where groundwater is close to the land surface, whereas yellow, orange and red dots represent wells where groundwater is >50 m below the land surface. b-g) The proportion of the uppermost 50 m of the Earth's crust comprised of carbonate rock (e.g., limestone; panel b), coarse-grained material (e.g., sand, sandstone; panel c), volcanic rock (e.g., basalt; panel d), fine-grained unconsolidated sediment (e.g., silt, clay; panel e), or fine-grained consolidated rock (e.g., shale; panel f). In each of these five panels (b-f), blue dots represent wells where the specified lithology is rare, whereas red shades suggest that the majority of all material found in the uppermost 50 m of the Earth's crust is the material specified in the legend. Black lines represent notable aquifer systems or aquifer systems referenced within the text; each are labelled in Fig. 2.

Groundwater quality

From the perspective of groundwater quality, our results have implications for (a) estimating geogenic pollutant levels, (b) understanding where overpumping can lead to seawater intrusion, and (c) predicting the migration of surface-borne pollutants to wells.

(a) The lithologic observations can improve predictions of geogenic contaminant hazards, especially for arsenic and fluoride. For example, groundwater arsenic concentrations tend to be higher in wells drawing water from argillaceous deposits, and tend to be lower in wells tapping coarse-grained consolidated sedimentary rocks (e.g., sandstone[35]). In areas dominated by thick unconsolidated sediments, intensive groundwater withdrawal can compact clay layers, releasing arsenic or arsenic-mobilizing solutes into surrounding aquifers (e.g., California's Central Valley[36]). Beyond sedimentary formations, arsenic contamination of groundwaters has been exhibited in volcanic rocks (e.g., the East African Rift System in Ethiopia[37]), suggesting that the lithologic observations may be used to map arsenic risks arising from volcanic rocks (Fig. 4d). Similar to arsenic, fluoride contamination often derives from geogenic sources[38]; for example, groundwater can dissolve fluoride-bearing minerals in rocks and sediments[39], leading to high fluoride concentrations. Given that high fluoride concentrations are associated with specific lithologic conditions, the lithologic observations can improve statistical models of fluoride contamination risk.

(b) The lithologic observations can forecast seawater intrusion risk. Seawater intrusion rate and risk assessments are aided by reliable lithologic frameworks that identify high-permeability sediments and rocks (e.g., fractured limestone; Fig. 4b). These permeable layers can enable relatively rapid horizontal incursions of seawater into aquifers that are pumped excessively. Even where aquitards are common, high-permeability intercalations—identifiable by lithologic logs—can allow seawater to move vertically and contaminate underlying aquifers (e.g., downward movement of intruded seawater in the Salinas Valley[40]). The lithologic observations compiled here may help improve seawater intrusion risk assessments by providing 3D estimates of coastal aquifer system permeability.

(c) The lithologic observations can be used to evaluate the likelihood of surface-borne contaminants will migrate into zones where wells access groundwater. Increases in nitrogen-based fertiliser applications since the 1940s have elevated nitrate concentrations in shallow groundwater; lithologic conditions can impact how quickly nitrate or other surface-borne contaminants will flow to deeper depths within an aquifer system. For example, confining layers can impede surface-borne contaminant transport and provide some protection for deeper portions of the aquifer[41] (e.g., shale; Fig. 4f). This shows that clay layers can act as natural protective barriers by reducing the risk of contaminant movement to the underlying aquifer. The lithologic observations presented here have the potential to improve predictions of nitrate fate and transport model.

United States hydrogeology

Groundwater is stored in various lithologic materials, ranging from unconsolidated deposits to consolidated sedimentary rocks (Fig. 1). Our analyses of lithologic descriptions suggest that ~50% of pores in the uppermost crust are drainable by gravity, implying that only half of groundwater is theoretically recoverable (Fig. 2). Further, we show that confined conditions generally prevail at depths of ~100 m in most parts of the US (Fig. 3). Our two main findings (Figs. 2-3) have key implications for groundwater quantity and quality (Fig. 4). Integrating the lithologic observations with other national-scale groundwater datasets—such as contaminant concentrations[42], groundwater-level trends[28], total water storage variations[43], groundwater well locations[25], and groundwater withdrawals[44]—can improve groundwater management at local- to regional- to continental-scales.

Methods

Compiling lithologic log data

We accessed lithologic log data from 37 sources (Supplementary Note 1). Because some states lack a digital dataset of lithologic logs, we manually transcribed lithologic logs by typing information from scanned well drilling reports into spreadsheets. In total, ~90,000 lithologic intervals with descriptions from ~7,400 scanned drilling reports were transcribed manually (Supplementary Note 1). When selecting lithologic logs to transcribe manually, we focused on those located within the boundaries of the aquifer systems identified in the US Aquifer Database[45] and on wells with total depths of >100 m. Wells with depths >100 m were more likely to be relevant to our analysis of drainable porosity in the uppermost 100 m of the crust (Fig. 2).

We excluded lithologic logs that lack well location data or report an implausible location (e.g., far offshore). We excluded any lithologic interval where (a) the recorded bottom of the interval was shallower than the top depth, (b) the top depth was less than zero (i.e., above the land surface), or (c) the lithologic interval spanned more than 1,000 ft. (such records were deemed less likely to provide detailed lithologic descriptions). We then excluded any lithologic logs (not only one interval, but all lithologic intervals for the entire well drilling event) if there were any overlapping intervals; there were ~23,000 lithologic logs that recorded one or more overlapping lithologic intervals, which comprised <1% of all lithologic logs in the dataset.

Categorising lithologic descriptions (Fig. 1)

The compiled lithologic descriptions comprise 19.2 million distinct lithologic intervals (e.g., “fine sand” from 0 m to 6 m depth; “clay” from 6 m to 13 m). Among these 19.2 million lithologic descriptions, we found 1.4 million unique strings of text describing lithologic conditions (e.g., “clay”, “yellow clay”, “sand”, “limestone”, “gravel with some clay”); the number of unique lithologic descriptions (1.4 million) is less than the total number of lithologic descriptions (19.2 million), because some descriptions occur more than once.

We manually categorized n=107,804 unique lithologic descriptions (~6% of all unique lithologic descriptions; Supplementary Note 2) into one of 17 broad lithologic categories: (1) *Unconsolidated: Coarse-grained material (e.g., sand, gravel),* (2) *Unconsolidated: Mostly coarse-grained (e.g., sand, gravel) some fine-grained material,* (3) *Unconsolidated: Mixture of coarse and fine grained (e.g., undifferentiated soil),* (4) *Unconsolidated: Mostly fine-grained (e.g., silt, clay) some coarse-grained material,* (5) *Unconsolidated: Fine grained material (e.g., silt, clay),* (6) *Till/drift,* (7) *Consolidated: Coarse-grained material (e.g., sandstone, conglomerate),* (8) *Consolidated: Mostly coarse-grained (e.g., sandstone, conglomerate) some fine grained material,* (9) *Consolidated: Mixture of coarse and fine grained,* (10) *Consolidated: Mostly fine-grained low-permeability (e.g., siltstone, shale, chert) some coarse grained material,* (11) *Consolidated: Fine grained low-permeability (e.g., siltstone, shale, chert),* (12) *Mostly carbonate rock (e.g., limestone, dolomite),* (13) *Endogenous (metamorphic rocks, granite, etc.),* (14) *Volcanic (rhyolite, basalt),* (15) *Evaporites (e.g., gypsum),* (16) *Could not be categorised due to inadequate or absent lithologic description, and* (17) *Undifferentiated bedrock.* Importantly, our analyses, and figures, focus only on the first 15 categories; by their definitions, category 16 includes intervals that could not be categorized, and category 17 includes intervals with consolidated rock but where a more specific lithology was not possible to define.

These n=107,804 unique lithologic descriptions may only represent 6% of all 1.4 million unique descriptions, but they encompass the most common descriptions among the lithologic observations. For example, the single-word description “clay” represents >1 million of the 19.2 million lithologic intervals. Therefore, of the 19.2 million lithologic intervals with observations, 89% (n=17.1 million) were categorised manually via one of these n=107,804 unique lithologic descriptions. In short, categorising 6% of unique lithologic descriptions enabled us to append categories for 89% of the 19.2 million lithologic intervals.

For the remaining 11% (n=2.1 million) of the 19.2 million lithologic intervals, we developed an automated classification algorithm. Specifically, we used the n=107,804 manually categorised lithologic descriptions to create a text model for classification (i.e., “bag-of-words” model). Specifically, we randomly split the n=107,804 manually categorised lithologic descriptions into two groups: (a) 80% of the n=107,804 lithologic descriptions were used for model training (‘training dataset’), and (b) 20% of the n=107,804 lithologic descriptions were used for model testing (‘testing dataset’). When the classification model was applied to the ‘testing dataset’, it yielded the same lithologic classification as the manual lithologic classification in 91% of cases. Given the high percentage of matches, we applied the classification system to the remaining 2.1 million (11%) lithologic intervals that were not categorized manually. Our main results are unlikely to be sensitive to our reliance on an automated classification approach, given that just 11% of the 19.2 million lithologic descriptions were classified using an automated approach.

The total number of lithologic intervals with descriptions in the original compilation was 20.7 million. After excluding records based on suspect data (see preceding Methods section) and excluding records falling under category 16 or 17 (see above), the total number of lithologic intervals with descriptions was 19.2 million; these 19.2 million intervals were from ~3.7 million well drilling reports from across the contiguous US. The categorised lithologic descriptions for these 3.7 million lithologic logs are presented in Fig. 1.

Analysing hydrogeologic properties (Fig. 2)

We compiled hydrogeologic-property data for 15 lithologic categories (i.e., Fig. 1). Specifically, we compiled specific yield, specific retention, and total porosity estimates from the primary literature (Supplementary Note 3). For lithologic categories that are a mixture of materials and where we could not identify hydrogeologic property data for the category in the primary literature, we estimated the hydrogeologic properties by using values for multiple materials. For example, specific yield and specific retention for the '*Unconsolidated: Mostly coarse-grained'* category was estimated based on an average of literature-based values for '*Unconsolidated: Coarse-grained material*', and '*Mixture of coarse and fine-grained*' (Supplementary Note 3).

Of specific interest to this project were the compiled values of [specific yield] divided by [specific yield plus specific retention] (Supplementary Note 3). To prepare Fig. 2, we only examined lithologic data extending from the land surface (0 m) down to 100 m. To estimate [specific yield] divided by [specific yield plus specific retention] for the uppermost 100 m of the Earth's crust, we first excluded logs where they lack lithologic data for more than 20 m of the uppermost 100 m of the crust. Therefore, we excluded wells with total depths shallower than 80 m and wells where there was incomplete lithologic data for more than 20 m of the uppermost 100 m of the crust.

For each well meeting our criteria for analysis, we estimated [specific yield (S_Y)] divided by [specific yield (S_Y) plus specific retention (S_R)] for the uppermost 100 m of Earth's crust following:

$$\frac{S_Y}{(S_Y+S_R)} = \frac{\sum_{i=1}^{n}\left(\frac{S_Y}{(S_Y+S_R)}\right)_i(\theta_i b_i)}{\sum_{i=1}^{n}(\theta_i b_i)} \quad \text{Eqn. 1}$$

where $\frac{S_Y}{(S_Y+S_R)}$ is the proportion of pore space that can be drained under gravity (i.e., theoretically recoverable groundwater, if the pores are filled with groundwater) for a given lithologic interval '*i*', θ is the porosity for a given lithologic interval '*i*', and *b* is the vertical thickness of a given lithologic interval '*i*' (e.g., if the lithologic interval '*i*' extends from 22 m to 32 m, the thickness (i.e., b_i) is 10 m). This equation represents the weighted average $\frac{S_Y}{(S_Y+S_R)}$ for the uppermost 100 m of the crust, where the weighting terms include porosity and the thickness of the interval. More porous layers are, appropriately, provided greater statistical weight in this calculation of total drainable pore space. Thicker lithologic intervals are, appropriately, provided greater statistical weight; for example, an interval extending from 10 m to 20 m is provided with greater statistical weight than an interval that extends from only 9 m to 10 m. After calculating $\frac{S_Y}{(S_Y+S_R)}$ for individual lithologic logs, we then grouped nearby logs; groupings were developed based on all lithologic logs existing within the same 1,000 km^2 hexagonal area (Fig. 2). We then calculated the median value of $\frac{S_Y}{(S_Y+S_R)}$ for each hexagonal area (where the median was determined from a statistical sample of all lithologic logs within a given hexagon).

Analysing confined aquifer conditions (Fig. 3)

We examined how confined and unconfined conditions vary with total well depth and with the thickness of low-permeability clastic sedimentary material (Supplementary Note 6). To complete this analysis, we use the US Geological Survey's National Groundwater Monitoring dataset; specifically, we analysed wells where the US Geological Survey specified that the well taps either (a) unconfined aquifer conditions, or (b) confined aquifer conditions. We analysed lithologic logs with lithologic descriptions for at least 90% of the total depth of the well. That is, if the recorded well depth is 100 m, we required lithologic intervals to be available for at least 90 m of the lithologic log overlying the well bottom.

For each lithologic log meeting our basic criteria for analysis, we calculated the total thickness of low-permeability clastic sedimentary material overlying the bottom of each well. Our assessment of low-permeability clastic sedimentary material is based on our 15 lithologic categories. Some lithologic categories were assumed to contain more low-permeability clastic sedimentary material than others; for example, lithologic intervals of "clay" were ascribed values between 90-100% low-permeability clastic sedimentary material, whereas "sand and clay" were ascribed values between 40-60% low-permeability clastic sedimentary material (Supplementary Note 6). Next, we calculated the proportion of lithologic logs that were classified as tapping confined conditions based on variable total well depths (y-axis values in Fig. 3a-b) and variable thicknesses of low-permeability clastic sedimentary material (x-axis values in Fig. 3a-b).

We identified a statistical relationship between the frequency with which wells are classified as tapping confined aquifer conditions and the total thickness of low-permeability clastic sedimentary material overlying the bottom of the well (Fig. 3c). Specifically, we found that half of all wells with 60-70 m of low-permeability clastic sedimentary material overlying their bottom were classified as tapping confined aquifer conditions (Fig. 3c); the proportion of wells classified as tapping confined conditions tended to be greater where the total thicknesses of low-permeability clastic sedimentary material overlying well bottoms was higher (Fig. 3c).

We apply the statistical relationship found using the US Geological Survey data to the lithologic logs to understand broad spatial patterns. Specifically, we estimated the minimum depth below the land surface overlain by at least 60 m of low-permeability clastic sedimentary material for each of the lithologic logs (Fig. 3d-f).

Limitations

Our analyses have a number of limitations, as documented in each of the paragraphs below.

Potentially replicated lithologic logs—We cannot rule out the possibility that some records are replicated within the lithologic observations. Our compilation includes several repositories that span multiple states (e.g., a national-scale geothermal drilling database, a database for the Northern High Plains aquifer system). In some cases, we also compiled a separate database that spans one or more of the states within these more expansive (multi-state) datasets, introducing the potential for replicate records to enter into our final compilation. We cannot rule out the possibility that replicate records exist within the state-level datasets that we analysed.

Spatial bias in lithologic log locations—The lithologic observations represented here do not derive from a randomly distributed sample of lithologic logs. There is spatial bias in the locations of lithologic logs (Fig. 1). The lithologic observations are mostly from groundwater well drilling events, and the lithologic observations are densely distributed in valleys where groundwater use is most common. In ways, this sampling bias makes our results relevant to groundwater management, because the lithologic observations represent areas where groundwater is accessed more frequently. Nevertheless, we emphasise that the results presented here are subject to the inherent spatial bias in the databases we analyse.

Uncertainties introduced by aggregated lithologic categories—To classify individual drilling report lithologic descriptions, we aggregated lithologic descriptions into a finite set of categories (Supplementary Note 2). For example, in our classification, we combined the classes silt and clay into one category: fine-grained unconsolidated material. We note that the hydrogeologic properties of silt differ from clay, often by substantial margins. Our sensitivity analyses (Supplementary Note 4) test how our results change as we vary certain hydrogeologic conditions (i.e., specific yield, specific retention, and porosity) across different lithologies that fall within a single aggregated category. The sensitivity analyses rarely produce results that differ substantially from those presented in the main text, suggesting that our results may not be extremely sensitive to the way we aggregated lithologic descriptions.

Subjectivity in lithologic categorization process—Our analyses rely on the manual categorization of n=107,804 lithologic descriptions into one of 17 lithologic categories, 15 of which are presented in Fig. 1 (Methods: 'Categorising lithologic descriptions (Fig. 1)'). The manual categorization of lithologic descriptions embeds unavoidable subjectivity. Furthermore, our decision to create 17 categories (rather than fewer than 17, or more than 17) is also subjective; for example, ref.[46] uses 11, rather than 17, categories. We acknowledge that 17 categories cannot capture all of the information provided in some of the more-detailed lithologic descriptions. Some lithologic descriptions provide detailed information on the exact proportion of sand in the sample, and our categories are not designed to capture quantitative and highly detailed descriptions. For example, 'fine sand - 15% clay', and 'fine sand and 30% clay' are both categorized as 'Mostly coarse-grained (e.g., sand, gravel) some fine-grained material'.

Potential for minor inconsistencies in lithologic categorization process—We completed consistency checks during our categorization process. Specifically, we ran a bag-of-words categorization model to create an automated categorization for each of the descriptions; the categorization model was then rerun several times. In fewer than 15% of cases, the automated categorization produced a different outcome than the manual categorization; we then re-checked each of these cases to help us to identify potential inconsistencies in our manual categorization process. We highlight that (a) this inconsistency check may not capture all possible inconsistent categorization cases, and (b) this inconsistency check procedure does not address the issue of subjectivity in the categorization process. We document and provide our list of n=107,804 lithologic descriptions as a supplementary dataset, and acknowledge that other geoscience experts may categorise the original lithologic descriptions differently than we have in some cases.

Potential inaccurate lithologic descriptions within drilling reports—None of the co-authors of this article were on site during any of the ~3.7 million drilling events analysed in this study; therefore, we cannot validate the lithologic descriptions provided within the lithologic logs. There are inconsistencies in the level of detail among lithologic logs. For example, some drilling reports include one or two lithologic categories for the entire well drilling event, whereas others provide highly detailed lithologic descriptions for every vertical metre. To evaluate the sensitivity of our results to the inclusion of less-detailed lithologic logs, we followed the approach of ref.[23] and excluded all lithologic logs where the average depth interval—the vertical offset from the top to the bottom of an interval with a lithologic description—was greater than six metres. After excluding these less-detailed lithologic logs, we find that our main results remain largely unchanged (Supplementary Note 9).

Groundwater at depths of deeper than 100 m—Although groundwater that is within 100 m of the land surface is the most commonly accessed (given that ~80% of US wells at less than 100 m deep; ref.[25]) and tends to be better-connected to surface-waters, the great majority of groundwater stocks are deeper than 100 m (ref.[14]). To explore how sensitive our main findings are to our decision to explore just the uppermost 100 m of the crust, we reproduced our findings using different threshold depths (Supplementary Note 10).

Incomplete information on bedrock fracture prevalence—The lithologic observations are unlikely to provide a complete picture of bedrock fracture prevalence. Bedrock fractures can be critical determinants of the permeability of the subsurface (see discussion by Worthington[47]). Some lithologic descriptions provide qualitative information on fracture abundance (e.g., the lithologic description 'Limestone with fractures'), highlighting that the data compiled here could be analysed further to develop more refined local analyses of hydrogeologic conditions.

Lack of site-specific hydrogeologic property data—We categorised lithologic descriptions into one of 17 broad lithologic categories, 15 of which are used throughout the analysis; these broad categories were used to estimate hydrogeologic properties, such as specific yield as a proportion of the sum of specific yield plus specific retention (Fig. 2). Yet, we acknowledge that the hydrogeologic properties of lithologies differ from place to place, even when the same terminology is used to describe each category. For example, the term 'shale' is widely used in lithologic logs across many different states, but different shale formations can have substantially different hydrogeologic properties (including specific retention and specific yield, which are the primary properties analysed here). Differences in hydrogeologic properties among different shale formations can arise for multiple reasons, including the degree to which these formations have been fractured to create ‘secondary porosity’. The existence of secondary porosity also adds uncertainty to our estimates of carbonate rock hydrogeologic properties that vary widely depending on the degree to which dissolution has altered storage conditions. Our application of literature-based estimates of storage properties for specific lithologies means that our results are approximations and cannot capture specific features that may be key to local storage and flow (e.g., joints, faults, secondary porosity).

Field versus in-situ hydrogeologic properties—Our compilation of specific yield, porosity, and specific retention data contains a number of sources of uncertainty. Inherent uncertainties and even potential biases may exist in the techniques used to estimate these parameters in the original studies that we compiled data from. For example, some of the hydrogeologic storage property data that we analyse are from field samples assessed in laboratory settings rather than in-situ measurements. The laboratory-based nature of some hydrogeologic property measurements adds uncertainty to our analyses; it is possible that these laboratory-measured specific yields exceed field-based specific yields[48]. Therefore, some of the compiled specific yield estimates that we analyse (Supplementary Note 3) may be overestimates of actual specific yields. If our compilation indeed overestimates specific yield, our main finding that about half of US groundwater is drainable could be, if anything, an overestimate (rendering our main finding—that only half of US groundwater is drainable—to be, if anything, conservative).

Inconsistent hydrogeologic property definitions—We are aware that the compiled hydrogeologic property data may be impacted by inconsistencies among articles in their definitions of specific terms. For example, table 11 within ref.[22] equated specific yield and effective porosity, but, ref.[49] discouraged conflating effective porosity and specific yield, and ref.[50] demonstrated differences between effective porosity and specific yield. Thus, the compiled hydrogeologic property data contain uncertainties, some of which cannot be quantified straightforwardly. Scaling issues arise with respect to determinations of specific yield, both in terms of spatial and temporal scales (i.e., timespan of testing method; see section entitled “Trends in effective porosity and specific yield data” within ref.[47]).

Porosity data—The compiled porosity data are more-limited compared to other compilations[46]; in general, the average porosities in our compilation tend to exceed those reported in some other compilations (Supplementary Note 5). These differences may be due to the disturbed nature of some of the samples in our compilation of measured hydrogeologic properties. While the primary focus of our study is on the proportion of pore space that is drainable—rather than total porosity—the estimated porosity of each lithologic category is applied as a weighting term in our calculations of drainable porosity (Methods: ‘Hydrogeologic properties (Fig. 2)’). Therefore, we re-ran our calculations using a different porosity compilation[46]; the resulting estimate of the proportion of pore space that is drainable is similar to the estimated [specific yield] divided by [specific yield plus specific retention] reported in the main text. The proportion of pore space in the uppermost 100 m of the crust that is drainable—using porosity data presented in Table 1 within ref.[46]—has a median of 51%, a lower-upper quartile range of 42-61%, and a 10^{th}-90^{th} percentile range of 35-68%. The similarity of these values to those reported in the main text imply that our main finding is not extremely sensitive to uncertainties in porosity values.

Definitions

For clarity, we define the following terms:

- *lithologic log*: dataset of lithologic information obtained from a well drilling report;
- *lithologic interval*: range of depths that have a specific lithologic description;
- *lithologic description*: explanation of lithology from a lithologic log for a lithologic interval;
- *lithologic category*: one of 15 broad classes of lithologic descriptions; and,
- *lithologic observations*: our compiled and evaluated dataset, including lithologic intervals, their descriptions, and assigned categories.

Code Availability. Analyses presented here do not depend on specific code; the approach can be reproduced following the procedures described in the Methods section.

Data Availability. Our compiled lithologic observations are available via *[a link to a CUAHSI HydroShare website containing the full compilation of lithologic observations to be added here in the event this work is published]*. Additionally, detailed instructions and hyperlinks for downloading lithologic observations are presented in Supplementary Note 1.

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Author Information

Competing interests. The authors declare no competing interests.

Corresponding author. Correspondence to Merhawi GebreEgziabher GebreMichael (gebremichael@ucsb.edu)

Supplementary Information line

Supplementary information. Supplementary Notes 1-10, Tables 1-26, Figs. 1-39