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Abstract
Groundwater demands are growing in many arid regions, and the use of non-traditional water resources, especially during extreme droughts, is increasingly common. One non-traditional resource is deep groundwater, which we define from ~150 m to several kilometers or more deep. We analyze 41 081 data points from 17 basins in the southwestern United States (US) to estimate the distribution of fresh and usable deep groundwater for potential human consumption and irrigation. We find the Great Basin to have the largest percentages of fresh and usable deep groundwater with 88%, 96%, and 98% of the total dissolved solids (TDS) concentrations less than 1000 ppm, 3000 ppm and 10 000 ppm respectively. Seven out of the 17 southwestern basins indicate the presence of substantial quantities of usable deep groundwater (<10 000 ppm TDS). We also find that the Great Basin and the Central Valley of California have 64% and 36%, respectively, of deep groundwater with sufficiently low toxic (Na, Cl, and B) and trace element concentrations for irrigation use without treatment, with greater percentages available for more tolerant crops. Given the potentially large deep fresh and usable groundwater volumes across the southwestern US, it is important to characterize the resource and protect it for potential use in decades and centuries to come.

1. Introduction
Deep groundwater aquifers may be an increasingly valuable resource in the future, especially in arid areas and during droughts. However, even in water-stressed regions such as the Central Valley of California [1, 2], studies of this resource are limited [3–5] and are more often the secondary focus of papers on oil and gas drilling or carbon capture and storage [6]. Recently, brackish groundwater aquifers across the United States (US) have been evaluated in the context of potential use with a focus on the top 1000 m [7]. Global-scale groundwater volume studies have included depths of up to 2000 m [8] but do not consider total dissolved solids (TDS) and other water quality parameters. Geochemistry studies on the origin of groundwater [9–11] focus on water–rock interactions and other geochemical processes and rarely consider the potential of the groundwater for irrigation and other uses [12]. Therefore, it is important to evaluate deep groundwater quality and quantity more broadly and from the perspectives of protection and potential use.

The definition of deep groundwater varies. Here, we define deep groundwater as below 150 m (~500 ft) with depths of up to 7000 m, though most of the data we discuss are far shallower than such extremes. Recorded groundwater well depths, including those for domestic, agricultural, and industrial uses, in the western US average 72 m with approximately 4% of the wells deeper than 200 m [13]. Therefore, most groundwater wells today are shallower than our definition of 150 m, which is also a depth limit used in the US Geological Survey National Brackish Groundwater Assessment [7]. One in 30 groundwater wells across the western US drilled from 1950 to 2015 are estimated to have gone dry in 2013–2015 [13]. To combat drought and respond to increasing water demands,
groundwater wells are currently being drilled deeper than previously considered necessary [14].

A common assumption is that deep groundwater is of poor quality and is unlikely to serve as a water resource currently or in the future. Accordingly, any impacts to deep aquifers are often ignored. However, large volumes of fresh (<1000 ppm and <3000 ppm TDS) and usable (<10 000 ppm TDS) deep groundwater have been found to exist in an important aquifer, the Central Valley of California [4]. Furthermore, treatment options are improving [15–17] and brackish water (and seawater) is routinely desalinated for human consumption and irrigation [15, 18]. Therefore, analysis of deep groundwater in terms of water quality parameters, including and in addition to TDS, is needed. For irrigation purposes, the Food and Agriculture Organization (FAO) of the United Nations outlines irrigation water criteria and guidelines for elements toxic to crops, primarily sodium (Na), chloride (Cl), boron (B), and other trace elements of concern [19]. These irrigation water quality requirements depend on many factors including irrigation method (with surface irrigation being less stringent than sprinkler irrigation), crop types, soil conditions, and precipitation [20–23]. Therefore, an alternative to setting criteria based on the most sensitive crops and salt-affected soils is to match water quality with the crop and soil conditions.

Groundwater studies at large regional and global scales frequently suffer from data scarcity [13]. Wells are expensive to drill, especially deeper ones, and often water management organizations lack the funding and motivation to collect the necessary data. Deep geologic formations have been explored for other purposes such as oil and gas production, geothermal energy, carbon capture and storage, and hazardous waste disposal [24]. The consequence is a set of databases with hydrogeological parameters such as porosity and permeability and limited water quality information (primarily salinity) for deeper depths [25–27]. In this paper, we analyze multiple sources of deep groundwater data to identify the locations, extent, and quality of deep groundwater resources.

We focus on basins in the southwestern US states of California (CA), Arizona (AZ), Nevada (NV), Utah (UT), Colorado (CO), and New Mexico (NM) that are increasingly turning to groundwater to meet their growing water demands [2, 28, 29]. We analyze deep groundwater data from 17 basins covering ~2 000 000 km² (figure 1). We estimate the distribution of the TDS concentrations with depth for each basin to quantify fresh and usable groundwater resources. For basins with large percentages (>50%) of usable deep groundwater, we evaluate water quality in terms of toxic (Na, Cl, and B) and trace (aluminum (Al), arsenic (As), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), fluoride (F), iron (Fe), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), vanadium (V), and zinc (Zn)) element concentration limits for irrigation use.

2. Methods

2.1. Databases

We analyze 41 081 deep groundwater data points for 17 basins using the US Geological Survey (USGS) Produced Waters Database (PWD) [30], the USGS National Brackish Groundwater Assessment (BGA) (major ions database) [7], the Water Quality Portal (WQP) [31], and the California Department of Oil, Gas, and Geothermal Resources (DOGGR) [25–27]. For 14 basins, we use the USGS PWD only. For two basins (Los Angeles and Ventura), we combine the USGS PWD and the California DOGGR data sheets. Data points are attributed to the basin specified in the data source, even though boundaries for basins may differ depending on the data source (figure 1 and section 1.3.3 in the Supplementary Material (SM) is available online at stacks.iop.org/ERL/14/034004/mmedia). For the Central Valley, data from all four sources are compiled and compared based on TDS values (figure 2). All basins in California with data are selected for analysis, along with basins with more than 10 data points in Nevada, Utah, Arizona, New Mexico, and Colorado in the USGS PWD. Data from all 17 basins have data from 12 or more unique well locations, as identified by the American Petroleum Institute well numbers. Additional details on data processing approach are described in the SM.

Oil- and gas-based data sources (USGS PWD and CA DOGGR) provide information for depths not covered in groundwater-based data sources (USGS BGA and WQP) and appear to be different from groundwater-based data sources (figure 2). Focusing just on the top 1000 m of the Central Valley data, where there is extensive overlap in depths across data sources, the mean TDS value for the USGS BGA (1380 mg l⁻¹) is an order of magnitude less than the mean TDS value of the two oil- and gas-based datasets, the USGS PWD (18 177 mg l⁻¹) and the CA DOGGR data sheets (12 965 mg l⁻¹), combined (P = 1.6 × 10⁻⁹⁷; t-test). In contrast, a comparison of the PWD and the DOGGR data sheets show that they are statistically indistinguishable in their populations of TDS values (P = 0.11; t-test). Therefore, conclusions about groundwater quality based solely on oil- and gas-based sources are likely to underestimate the amount of better quality groundwater, whereas conclusions based solely on groundwater-based sources are likely to overestimate such quality (see SI figure S4). Because we primarily use the PWD, an oil- and gas-based data source, the deep groundwater quantities estimated here may be under-estimates.
2.2. Fresh and usable deep groundwater quantification

We determine the percentages of deep groundwater data indicating freshest (<1000 ppm TDS), fresh (<3000 ppm TDS), and usable (<10 000 ppm TDS) water for each of the 17 basins. The 1000 ppm TDS limit, chosen to define ‘freshest’ water, is a common definition for fresh water [7, 32]. The 3000 ppm TDS limit is another definition for fresh groundwater (e.g., California [33]) and is also used to describe fresh or ‘potable’ water for the purpose of controlling waste disposal by the US Environmental Protection Agency (USEPA) [7]. This 3000 ppm TDS limit also has several practical applications including the use of groundwater with up to 3000 ppm TDS in some rural domestic wells and <3000 ppm TDS requirement of many treatment facilities [7]. Some regions (e.g., the provinces of Alberta, Saskatchewan, and British Columbia in Canada) define fresh or usable water by a 4000 ppm TDS limit, which is not evaluated in this paper. The 10 000 ppm TDS limit is used because it corresponds to the USEPA’s definition for ‘Underground Sources of Drinking Water’ [34] and frequently used to define usable water by numerous government agencies (e.g., US Department of the Interior). This 10 000 ppm TDS limit is also commonly used to differentiate moderately and highly saline water [7]. We also evaluate deep groundwater quality of the basins with reference to seawater (<35 000 ppm TDS).

2.3. Depth intervals

Depth intervals of <150 m, 150–305 m, 305–1000 m, 1000–2000 m, and >2000 m are chosen based on our...
definition of deep groundwater, to facilitate comparison with previous studies, and to accommodate the decrease in data points with depth. As described above, most groundwater wells today are drilled within the top 150 m [13], which we consider to be ‘shallow’ groundwater. The next depth interval, 150–305 m, is chosen because 305 m \( \approx 1000 \) ft, which is the boundary that has been used to estimate groundwater volumes and study important aquifers such as the Central Valley [35]. The 1000 m depth interval limit is chosen as it represents the data boundary used in previous studies [4, 7]. The remaining depth intervals, 1000–2000 m and >2000 m, are chosen primarily based on data density (which decreases with depth), and previous studies [4, 8, 36].

2.4. Water quality parameters for irrigation water supply
In addition to TDS concentrations, we evaluate deep groundwater data using the toxic and trace element concentration limits for irrigation (see the SM) for basins with more than half of their deep groundwater data in the usable TDS range (<10 000 ppm). We first focus on the three toxic elements most often assessed for irrigation water quality: sodium (Na), chloride (Cl), and boron (B). The thresholds for irrigation are dependent on a variety of factors including climate, crop, and soil type. We first use the lowest threshold concentrations (3 SAR and 3 me/l for Na, 3–4 me/l for Cl, and 0.7 mg l\(^{-1}\) for B, table S1), which are lower than required in many regions and for many crops. In addition, we evaluate 17 trace element concentrations (Al, As, Be, Cd, Co, Cr, Cu, F, Fe, Li, Mn, Mo, Ni, Pb, Se, V, and Zn) with recommended maximum concentrations for irrigation purposes (table S2).

3. Results

3.1. Fresh and usable water distribution with depth
Of the basins evaluated (figures 3(a), 2(b), and S1 and table S1), the TDS data for the Great Basin and the Central Valley of California indicate the presence of substantial volumes of freshest (<1000 ppm TDS) and fresh (<3000 ppm TDS) deep groundwater in these basins. In the Great Basin, 88% of deep groundwater has TDS concentrations less than 1000 ppm; whereas in the Central Valley, 32% of deep groundwater has TDS concentrations less than 1000 ppm. Only two other basins have data indicating the presence of deep groundwater with <1000 ppm TDS, but the percentages are low at 1% and 2% for the San Juan and Green River basins, respectively. In contrast, fifteen out of the seventeen basins evaluated contain fresh (<3000 ppm TDS) deep groundwater. However, the Central Valley is the only basin with data from both oil- and gas-based and groundwater-based data sources. In other words, due to the bias in the oil- and gas-based USGS PWD (figure S4), basins other than the Central Valley may actually have larger percentages of freshest and fresh deep groundwater than presented in this paper. The Great Basin has the largest percentages of fresh water at all depths and at every depth range examined (98%, 99%, 76%, and 38% at 150–305 m, 305–1000 m, 1000–2000 m, and >2000 m respectively) (figure 2). Large quantities of fresh deep groundwater are also found in the Central Valley and in basins in Colorado and Utah (see SM).

More than half of the deep groundwater sampled across all depths in seven basins is usable (TDS <10 000 ppm) (table S4). Substantial quantities of deep groundwater are usable, even when found deep underground (i.e. >2000 m). The average percentages of usable water across basins are 71%, 55%, 32%, and 32% for 150–305 m, 305–1000 m, 1000–2000 m, and >2000 m, respectively. As with freshest and fresh deep groundwater, the Great Basin has the highest percentage of usable deep groundwater in the dataset (98%).

Nevada has the highest percentages of deep freshest, fresh, and usable groundwater (88%, 94%, and 97% respectively) due to the presence of the Great Basin across the whole state. For the other states and excluding the Great Basin and the Central Valley.
basins in Utah and Colorado appear to have the highest percentages of fresh and usable water (e.g. the Wasatch Uplift and Las Vegas-Raton basins), whereas basins in New Mexico and Arizona (e.g. the Permian and Black Mesa basins) that do not overlap with Utah and Colorado appear to have the lowest (figure 3 and table S4). In California, the percentages of fresh and usable water are relatively small in the coastal basins (0%–18% fresh and 5%–41% usable) and relatively large in the Central Valley (48% fresh and 58% usable) and the Great Basin (96% fresh and 98% usable) (table S4).

Most basins (15 out of 17) have substantial percentages of deep groundwater with TDS concentrations less than that of seawater (35 000 ppm) (figures 3d and S1). Fourteen basins have 65% or more of deep groundwater with < 35 000 ppm TDS. Only three basins, Paradox (UT, CO), Permian (NM, TX), and Black Mesa (AZ), have deep groundwater quality that is generally worse than seawater (39%, 19%, and 21%, respectively). Other than basins in NM, TX, and AZ, the percentages of deep groundwater with < 35 000 ppm TDS do not appear to decrease substantially with depth, in comparison to when the cutoffs for freshest, fresh, and usable water are used (figure 3).

3.2. Great Basin, the basin with the largest quantities of fresh and usable water

The Great Basin is large, extending from California in the west to Nevada, Utah, and Arizona to the east and south (figure 1) and has particularly large percentages of freshest, fresh, and usable deep groundwater (figure 3). Volumes of fresh and usable deep groundwater in the Great Basin appear to be extensive and there are no apparent differences for trends in TDS concentrations across states within the basin (figure 3 and S2). However, there are important data gaps. For example, the portion of the Great Basin in California has no data points at depths of 1000–2000 m in the basin and only four data points at depths deeper than 2000 m. Across the entire Great Basin, 78% of the data are found in the top 150 m, with only 19% of the data at 150–305 m depths. Even less data is available deeper, with only 3%, 1%, and 0.3% of the data across the basin available for depths of 305–1000 m, 1000–2000 m, and >2000 m, respectively. Nevertheless, the Great Basin has 10 750 data points with depth and TDS information, which is the largest number of the 17 basins studied (see table S3).

Surprisingly, a large portion (70%) of the deep groundwater in the Great Basin is not only less than 1000 ppm (freshest) but is also less than 500 ppm (figure 4). TDS concentrations < 500 ppm exist at all depths across the basin with percentages ranging from 72% at 150–305 m to 7% at > 2000 m depths. At shallow depths (< 150 m), TDS concentrations span from 11 to 523 977 ppm. However, the range becomes narrower with increasing depth and all data at 400–500 m depths have < 1000 ppm TDS. At deeper depths (> 500 m), TDS concentrations appear to linearly increase with depth, although substantial proportions of the water remain fresh and usable. Such trends of fresh deep groundwater have been found in other regions devoid of evaporites such as the Central Valley of California [9]. However, there are many factors contributing to the TDS distributions, including mineral dissolution, mixing, and contamination.
3.3. Toxic elements and trace elements of concern for irrigation use

Concentrations of toxic (Na, Cl, and B) and trace (Al, As, Be, Cd, Co, Cr, Cu, F, Fe, Li, Mn, Mo, Ni, Pb, Se, V, and Zn) elements of concern for irrigation provide additional constraints on the use of deep groundwater. The Great Basin has the largest percentages of deep groundwater that can be used for irrigation without treatment (table S1), even when considering the most sensitive crops and salt-affected soils (figures 5, S5, and S6). Larger percentages of water are potentially usable for irrigation when surface, rather than sprinkler, irrigation is used (figure 5). This disparity is greater for Na, for which a 50% increase in percentages of deep groundwater suitable for irrigation is possible (e.g. Central Valley), than for Cl. At depths where data is available (<1000 m), B concentrations appear to be sufficiently low in all cases in the Great Basin and in most cases in the Central Valley (77%, 61%, and 21% at depths of <150 m, 150–305 m, and 305–1000 m, respectively). Across the dataset of the twenty toxic and trace elements of concern evaluated for irrigation, Na or B appear to be the limiting toxic element (figure S5). In the Great Basin, the limiting toxic element is Na, whereas in the Central Valley, the limiting toxic element is B. Trace elements of concern with a significant percentage below recommended levels are F, Mo, and As in the Great Basin and Al, F, Fe, Li, and Mn in the Central Valley (figure S6). The trace elements of greatest concern depend on the depth range in consideration. For example, F is the main concern at 1000–2000 m depths in the Great Basin, whereas at deeper depths (>2000 m), As and Mo are of greater concern. Overall, the Great Basin and the Central Valley have 64% and 36%, respectively, of deep groundwater with sufficiently low toxic and trace element concentrations for irrigation use without treatment, with greater percentages available for more tolerant crops.

Crops tolerances to B vary widely, ranging from <0.5 mg l⁻¹ for very sensitive crops (e.g. lemons, blackberries) to 6–15 mg l⁻¹ for very tolerant crops (e.g. cotton, asparagus) (figure 6). In the Central Valley, B is the most limiting toxic element. However, considering the wide range of crop tolerances, 83% and 31% of water at depths of 305–1000 m and >1000 m respectively in the Central Valley can be used for irrigation without boron-specific removal, often required in addition to desalination [17].

4. Discussion

Our analysis based primarily on oil- and gas-based data sources indicates that there are substantial quantities of fresh and usable water for human consumption and irrigation in deep groundwater basins across the southwestern US. Oil- and gas-based data sources provide critical information on deeper...
groundwater aquifers. However, we find that oil- and gas-based data sources tend to over-represent lower water quality. In other words, our analysis of groundwater quantities and qualities presented here is likely to be conservative, with more fresh and usable deep groundwater likely than estimated. At the same time, studies relying primarily on groundwater-based data sources (e.g. USGS BGA and the Water Quality Portal) may be overly optimistic in terms of water quality. Based on our detailed analysis of the Central Valley data sources, combining the USGS BGA data (a groundwater-based data source) with the USGS PWD (an oil- and gas-based data source) will indicate higher water quality at depths where the BGA is dominant.

Estimated quantities of fresh and usable water quantity at different depths depend highly on the cut-off concentrations used to define them. Common definitions for fresh water include 1000 and 3000 ppm TDS [32, 33, 37]. However, the US Environmental Protection Agency’s Secondary Maximum Contaminant Level (SMCL), which is a guide for public water systems to consider aesthetic effects, such as taste, odor, and color, for TDS is 500 mg l⁻¹ or ppm [38]. Therefore, much of even fresh groundwater requires treatment for drinking water purposes.

In terms of usable water, we question the sole use of 10 000 ppm TDS as a cutoff for usable groundwater. In cases where treatment is already being performed, it is difficult to justify that 11 000 ppm TDS water, for example, is not usable, as the incremental cost to remove the extra TDS is likely to be small relative to the overall costs. Furthermore, seawater with 35 000 ppm TDS is routinely desalinated for human consumption and other uses [18, 39, 40]. Most southwestern basins contain substantial quantities of usable groundwater and groundwater with less than 35 000 ppm TDS at all depths, including shallow depths (<150 m) (figures 3 and S1). A broader definition of fresh and usable water that encompasses factors other than TDS alone, such as hydrogeological and geochemical conditions, water demands and uses, and economics, may be more appropriate.

Water quality requirements and treatment depend on the intended use. For irrigation purposes, we find that much of the limitation on deep groundwater is due to the toxic element concentrations, particularly Na and B. An alternative to treatment is crop selection, as there are many salt- and B-tolerant crops [19]. For Na, we find that irrigation type, specifically surface, rather than sprinkler, irrigation, may potentially increase the quantity of water for irrigation, because of the higher concentration thresholds for surface irrigation. However, additional criteria, beyond those identified by the FAO, such as the presence of uranium [7], may need to be considered before deep groundwater is used for irrigation. For industrial purposes, we expect a large range of water quality requirements with some being less stringent than those for irrigation and drinking purposes. In terms of drinking water, our study focuses on TDS and not the full suite of drinking water quality parameters. Our aim here is to identify the potential for deep groundwater for drinking and motivate future detailed studies on the suitability of deep groundwater for drinking. As societies consider groundwater management strategies [2] and new regulations, it is important to consider the potential water uses along with other water quality parameters, such as Na. At the same time, this would mean more data collection and research to identify key water quality parameters.

We identify the need for additional groundwater sampling programs that target deep groundwater aquifers beginning in basins with relatively high proportions of usable water identified in this paper. Additional data is needed to estimate fresh and usable deep groundwater volumes and availability and to evaluate their suitability for irrigation and other uses. Geographically, there are regions within basins with

Figure 6. Distribution of boron concentrations by five depth ranges and crop tolerances in the Central Valley of California.
relatively few data points, even if there are many data points for the basin as a whole. For example, more TDS data is needed in the San Joaquin sub-basin of the Central Valley and in the California portion of the Great Basin. Furthermore, even if TDS and depth data exists, there may be limited information on toxic and trace elements of concern for irrigation. In addition, the complex hydrogeological and hydrogeochemical processes that can affect deep groundwater quality, quantity, availability, and protection need further study.

One of the motivations for determining the potential to use deep groundwater is to protect it [34]. We recognize that the exploitation of deep groundwater resources may not be sustainable. Nevertheless, it is important to protect deep groundwater for potential temporary use in worst case scenarios (e.g. extreme droughts). Understanding potential contamination pathways and sources is essential for protecting groundwater resources. Baseline data are essential for attributing groundwater contamination to specific anthropogenic activities such as oil and gas production [41] and waste disposal but is often lacking [42]. Deep groundwater is already used in the US, and, more commonly, in Mexico and other arid regions around the world. Therefore, deep groundwater must be characterized through better data collection and monitoring.

5. Conclusions

We find that substantial quantities of fresh and usable deep groundwater (depths >150 m) exist in basins across the southwestern US. These deep groundwater resources are potentially valuable for domestic, agricultural, and industrial uses. The intended use, hydrogeological and geochemical characteristics, and economics should be considered in addition to TDS concentrations when defining usable water. Efforts are needed to fill existing data gaps in geographic coverage, water quality parameters, and vertical distribution, beginning with the basins with high proportions of usable water identified in this paper. Given the potentially large deep groundwater volumes, it is important to characterize the resource and protect it for use in decades and centuries to come.

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