Base of fresh water, groundwater salinity, and well distribution across California

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The depth at which groundwaters transition from fresh to more saline—the "base of fresh water"—is frequently used to determine the stringency and types of measures put in place to manage groundwater and protect it from contamination. Therefore, it is important to understand salinity distributions and compare defined bases of fresh water with salinity distributions and groundwater well depths. Here we analyze two distinct datasets: 1) a large set of total dissolved solids concentration (TDS) measurements (n = 216,754) and 2) groundwater well locations and depths (n = 399,454) across California. We find that 19 to 56% of the groundwater TDS measurements made at depths deeper than defined bases of fresh water pump fresh groundwater (TDS $<$ 2,000 mg/L). Because fresh groundwater is found at depths deeper than the base of fresh water, current policies informed by base of fresh water assessments may not be managing and protecting large volumes of deep fresh groundwater. Furthermore, we find that nearly 4% of existing groundwater wells penetrate defined bases of fresh water, and nearly 16% of wells overlie it by no more than 100 m, evidencing widespread encroachment on the base of fresh water by groundwater users. Consequently, our analysis suggests that groundwater sustainability in California may be poorly safeguarded in some places and that the base-of-fresh-water concept needs to be reconsidered as a means to define and manage groundwater.

groundwater | base of fresh water | wells | salinity | California

Groundwater in California is a critical resource that supplies water to communities, farmlands, industries, and ecosystems (1–4). To manage this important water supply, administrative definitions of groundwater in California rely upon the "base of fresh water," a term defined as "the depth in a well where the water in overlying aquifers has less than or equal to 3,000 mg per liter (mg/L or parts per million) of total dissolved solids" (quoting ref. 5). The term has been used to delineate the range of depths subject to sustainable groundwater management laws and to determine depths at which subsurface activities, such as oil and gas operations, can occur (5–8). Implicit assumptions embedded into the application of the base of fresh water in management decisions are that salinity increases monotonically with depth and that groundwater users are not likely to use brackish or saline water (e.g., total dissolved solids [TDS] concentration $>$ 1,000 mg/L, TDS $>$ 3,000 mg/L) (*SI Appendix*, Fig. S1).

Nevertheless, fresh, brackish, and saline water, which are categorized differently across disciplines and regulatory agencies (8–11), may be usable for various purposes, from domestic to agricultural to industrial uses (2) (*SI Appendix*, Fig. S1). When water scarcity constrains users, municipalities and irrigators have shown a willingness to use deeper and often brackish groundwaters (12–14). Investments to treat or blend brackish water can be more cost effective than importing surface water or dealing with the socioeconomic consequences of losing access to water. For example, brackish water has been used to meet water demands such as thermoelectric power generation (2) and livestock drinking water supply (15). There is also a wide range of saline water management options, including crop selection, irrigation and drainage solutions, and fresh water blending (14, 16–19).

California's Central Valley hosts immense stores of fresh water, especially at depth (20, 21), and managing deep groundwaters in the Central Valley and throughout California may prove strategic. A previous study considered depths up to 3,000 m and concluded that there is 3 to 4 times more fresh water in the Central Valley than previously estimated (20). This and other previous studies (20, 21) analyzed groundwater TDS data, which are determined from sampling groundwater or oil and gas wells, or applying geophysical methods. Importantly, the previous studies did not perform spatially distributed analysis and did not account for depths of groundwater wells being pumped to meet domestic, agricultural, or industrial water demands. Across California's Central Valley, such groundwater wells are being constructed deeper over time (22, 23), suggesting that some wells are encroaching upon deeper aquifers bearing more saline waters. Despite the importance of understanding the base of fresh water to groundwater management from both quantity and quality perspectives, there has yet to be a statewide estimate of salinity variations with depth nor a direct comparison of the base of fresh water to salinity distributions and groundwater well depths. The objectives of our study are to characterize TDS in groundwater and to evaluate current bases of fresh water against TDS and groundwater well depth data.

Here, we couple densely distributed measurements of groundwater salinity (n = 216,754 groundwater TDS measurements), two previous estimates of the base of fresh water, and groundwater wells (n = 399,454 well locations and depths) across California. The high density of our compiled TDS measurements enables us to map salinities across California, test how realistic

Significance

To sustainably manage groundwater, water managers and regulators currently rely upon understanding the depths at which groundwater transitions from fresh (shallower) to more saline (deeper). This base of fresh water, while important, remains poorly understood. Here we show that, in California, 1) available base-of-fresh-water data do not represent actual base of fresh water, as exemplified by the widespread occurrence of fresh water deeper than the defined bases of fresh water, and 2) wells are already penetrating or encroaching on the defined bases of fresh water. We conclude that using current base-of-fresh-water data may limit efforts to manage deep groundwater effectively.

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previous estimates of the base of fresh water are, and assess how frequently groundwater wells encroach upon base-of-fresh-water delineations that are used administratively. We show that 1) available base-of-fresh-water data poorly represent actual salinity profiles, as exemplified by the widespread occurrence of fresh water deeper than the defined bases of fresh water, and 2) some wells are already encroaching on or penetrating the defined bases of fresh water. We conclude that using current base-of-fresh-water boundaries could limit management and sustainability of deep groundwater.

Approach

Data Compilation. We compiled and analyzed three types of data: bases of fresh water, TDS measurements, and locations and depths of groundwater production wells (*SI Appendix*, Fig. S2).

We digitized and analyzed base-of-fresh-water data from two sources: the United States Geological Survey (USGS) (24, 25) and California Geologic Energy Management Division [CalGEM; formerly the Division of Oil, Gas, and Geothermal Resources (DOGGR) (26–28)] (Fig. 1). The USGS-estimated base of fresh water (TDS = 2,000 mg/L) exists solely for the Central Valley. The base-of-fresh-water data from the oil-and-gas-based source (i.e., CalGEM/DOGGR), hereafter referred to as the DOGGR-reported base of fresh water (TDS = 3,000 mg/L), are provided for oil and gas fields or field areas. A comparison of the two base-of-fresh-water datasets is provided in *SI Appendix*, Fig. S7.

To independently evaluate the USGS-estimated and DOGGR-reported bases of fresh water, we compiled and quality controlled an updated database of five different sources of TDS measurements across California: 1) USGS Brackish Groundwater Assessment (9), 2) USGS Produced Waters Database Version 2.3 (29), 3) Water Quality Portal (30), 4) DOGGR data sheets (26–28), and 5) Groundwater Ambient Monitoring and Assessment Program (31) (*SI Appendix*, Table S1).

To evaluate where groundwater production wells are located in relation to the defined USGS-estimated and DOGGR-reported bases of fresh water, we compiled and quality controlled over 900,000 groundwater well construction records to obtain a dataset of 399,454 reported domestic, agricultural, and industrial groundwater wells (32); data processing and analysis details are presented in *SI Appendix*. In addition, we compiled groundwater sustainability plans submitted in 2020 to determine the bases of fresh water that groundwater sustainability agencies consider in their plans (*SI Appendix*, Table S3).

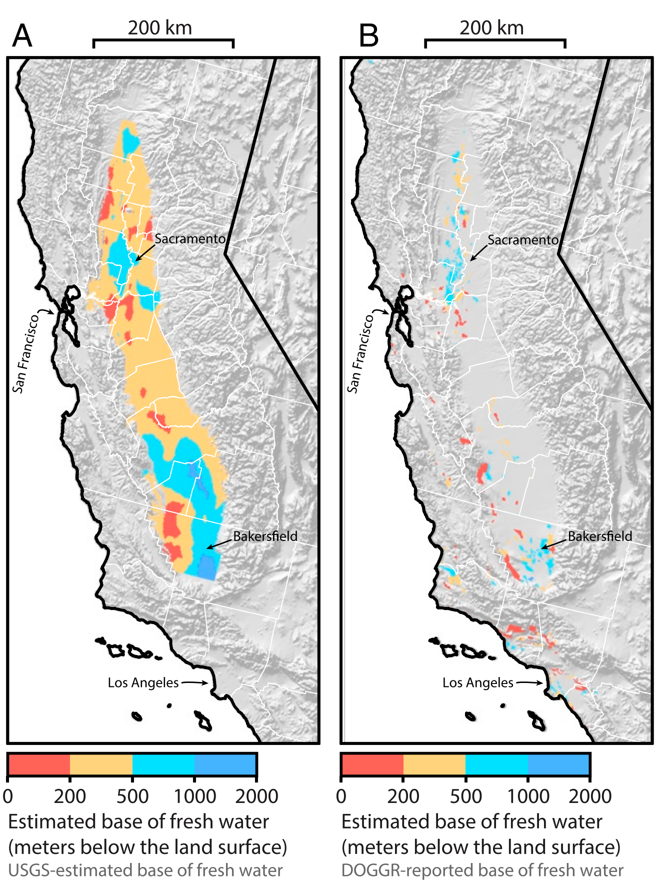

Fig. 1. Base of fresh water from two sources: (*A*) the USGS reports (24, 25) and (*B*) the DOGGR data sheets (26–28). The USGS-estimated contours are available for the Central Valley, and the DOGGR-reported base of fresh water are available for oil and gas fields and field areas. County boundaries are shown in white.

Analysis of Water Quality and Groundwater Well Data

TDS Data Analysis. We analyzed 216,754 groundwater TDS measurements to characterize three-dimensional TDS distributions in California. The depth associated with the TDS measurements generally represents the total well depth or the average depth of the water-producing formation. The total well depths were used as the preferred well depth (*SI Appendix*, Fig. S3), because other depths (e.g., screening intervals) are less readily available. We grouped our TDS measurements by the associated depths: 0 m to 75 m, 75 m to 150 m, 150 m to 305 m, 305 m to 1,000 m, 1,000 m to 2,000 m, and >2,000 m (*SI Appendix*, Fig. S2). The first depth limit (75 m) was chosen because it is close to the average groundwater well depth in the western United States [72 m (22)]. The remaining depth intervals we studied use boundaries at commonly used depths (e.g., 305 m (or 1,000 ft) in ref. 33) and aim to maintain sufficient data in deeper depth intervals. For each depth range, we used inverse distance weighting where we have at least one TDS measurement within a 30 km by 30 km search neighborhood (*SI Appendix*, Fig. S5).

Using the interpolations, we evaluated the distribution and volumes of fresh (TDS > 3,000 mg/L) and brackish (TDS of 3,000 mg/L to 10,000 mg/L) water. We use a TDS threshold of 3,000 mg/L to be consistent with previous studies (20, 21) for the volume estimates. We analyzed the TDS distributions to gain insights on data density and range of TDS values, which are important to consider when comparing the base-of-fresh-water data to TDS measurements and groundwater production well depths. The interpolated TDS distributions are not used in comparisons to bases of fresh water.

Comparison of Base of Fresh Water to TDS Data. We analyzed two base-of-fresh-water databases: 1) the USGS-estimated base of fresh water and 2) the DOGGR-reported base of fresh water. There are many regions without any defined bases of fresh water (Fig. 1), and, thus, comparisons are limited to regions where a defined base of fresh water is available. We compared the USGS-estimated base-of-fresh-water contours (24, 25) with TDS data across the Central Valley (Fig. 2 *A* and *B* and *SI Appendix*, Fig. S9 *A* and *C*). We analyzed the DOGGR-reported base of fresh water (26–28) in oil and gas fields/field areas for which the base of fresh water has been reported (Fig. 2 *C* and *D* and *SI Appendix*, Fig. S9 *B* and *D*).

We compared the estimated depth at which each TDS measurement was made (*SI Appendix*, Fig. S3 and Table S1) to the defined base-of-fresh-water data at that location. That is, we compared TDS measurements, not TDS interpolations, to the defined bases of fresh water. We then analyzed the TDS measurements made at depths deeper than the defined base of fresh water. We applied the 2,000 mg/L TDS threshold for comparisons with bases of fresh water. Although this TDS threshold is consistent with the USGS-estimated base of fresh water definition, it is likely lower than the threshold corresponding to DOGGR-reported base of fresh water, which is likely to be

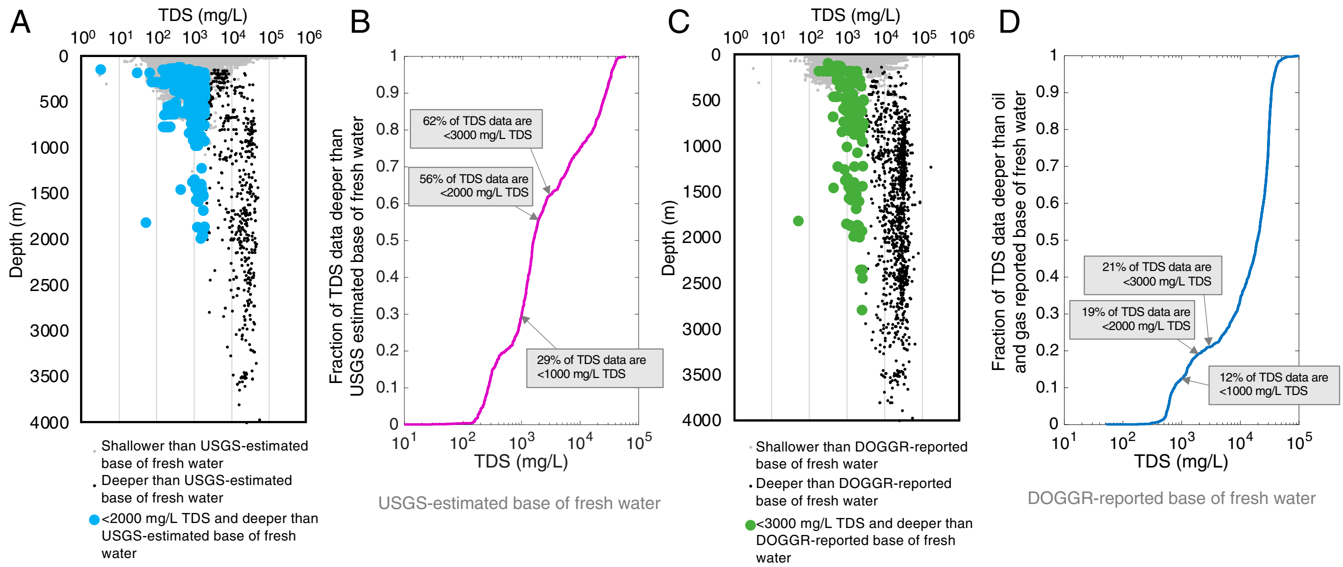

Fig. 2. Comparison of TDS measurements with (*A* and *B*) the USGS-estimated base of fresh water contours for the Central Valley and (*C* and *D*) the DOGGR-reported base of fresh water for oil and gas fields and field areas. *A* and *C* show TDS measurements indicating fresh water that are located deeper than the base of fresh water in blue and green points, respectively. TDS measurements at depths shallower than the base of fresh water are presented in gray, and the nonfresh TDS measurements deeper than the base of fresh water are presented in black. *B* and *D* show the cumulative fractions of TDS measurements deeper than bases of fresh water, highlighting TDS thresholds of 1,000 mg/L, 2,000 mg/L, and 3,000 mg/L. Spatial distribution of the TDS measurements found deeper than the bases of fresh water and the vertical separation of the TDS measurements and the bases of fresh water are presented in *SI Appendix*, Fig. S9.

3,000 mg/L TDS. Therefore, and because definitions for fresh water vary among agencies, jurisdictions, and uses (5, 7–10, 34, 35) (*SI Appendix*, Fig. S1), we also note the 3,000 mg/L TDS thresholds for fresh water, as well as another common and more stringent threshold, 1,000 mg/L TDS (Fig. 2).

Comparison of Base of Fresh Water to Groundwater Production Well Depths. We compared spatial distributions of groundwater production well depths against our two base-of-fresh-water datasets (Fig. 1). Groundwater production well depths are taken to be the total well depth. We determined the number of wells constructed deeper than defined bases of fresh water, and also the number of wells that are close to the defined bases of fresh water (i.e., well bottom overlies the base of fresh water, but by no more than 100 m or 200 m).

Results

TDS Distributions Highlight Spatial Variation with Depth across California. We analyzed spatial distributions of groundwater TDS concentrations via inverse distance weighting and report these interpolated results for 30-km by 30-km areas with at least one TDS measurement. Among these analyzed areas, we find that groundwater with TDS less than 3,000 mg/L, indicative of fresh water, can be found at depths of up to 1,000 m across many analyzed areas (Fig. 3). Groundwater with TDS less than 3,000 mg/L is most common in the second and third shallowest depth zones (75 m to 150 m and 150 m to 305 m), rather than the shallowest depth zone (0 m to 75 m). Deeper than 1,000 m, groundwaters with TDS less than 3,000 mg/L are found in less than 2% of analyzed areas.

Groundwater with TDS greater than or equal to 3,000 mg/L but less than 10,000 mg/L can be found across California at all depth ranges analyzed. At depths shallower than 1,000 m, between 16% and 21% of analyzed areas indicate the presence of brackish water representing TDS values between 3,000 and 10,000 mg/L. Similarly, 8 to 15% of analyzed areas in the 1,000- to 2,000-m-depth zone suggest the presence of brackish water.

Assuming a porosity range of 0.05 to 0.25 and considering depths of up to 3,000 m, the volume of groundwater with TDS

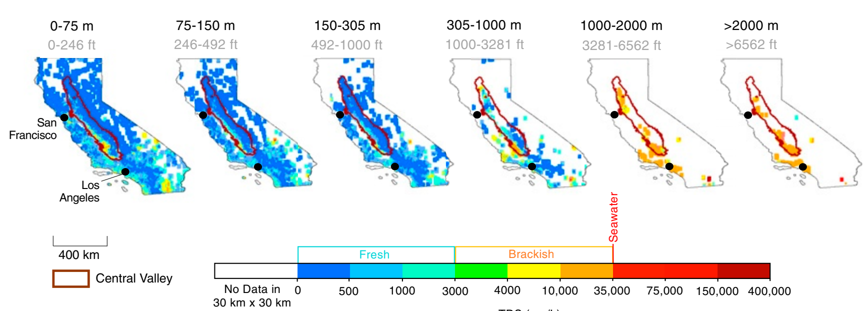

Fig. 3. Distribution of TDS concentrations across California for depth ranges of 0 m to 75 m, 75 m to 150 m, 150 m to 305 m, 305 m to 1,000 m, 1,000 m to 2,000 m, and >2,000 m. Note that the average groundwater depth in the United States is 72 m (22). For each depth range, the TDS distribution is obtained using inverse distance weighting with a power parameter of two and variable search radius using 12 points (*SI Appendix*). The TDS distribution is provided in areas where the point density indicates at least one data point in a 30 km by 30 km square area. The two major cities, San Francisco and Los Angeles, are shown with black closed circles.

less than 3,000 mg/L is estimated to be 8,000 km^3 to 40,000 km^3 (*SI Appendix*, *Supplementary Text* and Fig. S6). Also, assuming a porosity of 0.05 to 0.25 and depths of up to 3,000 m, the volume of groundwater with TDS less than 10,000 mg/L is estimated to be 10,000 km^3 to 50,000 km^3 (*SI Appendix*, Fig. S6).

Fresh Groundwater Exists below Defined Bases of Fresh Water. The base of fresh water (Fig. 1) is interpreted administratively as the depth at which water transitions from fresh to brackish (*SI Appendix*, Fig. S1). Our compilation of groundwater sustainability plans (*SI Appendix*, Table S3) shows that most plans 1) use a TDS threshold of 2,000 mg/L to determine groundwaters to be managed and 2) rely on the USGS-estimated base of fresh water analyzed in this paper. Using the 2,000 mg/L threshold, we find that 56% of TDS measurements made at depths deeper than the USGS-estimated base of fresh water are fresh (Fig. 2 *A* and *B*). Using the same 2,000 mg/L threshold with the DOGGR-reported base of fresh water, we find that 19% of TDS measurements made at depths deeper than the base of fresh water are fresh (Fig. 2*D*).

If, instead, we use the 3,000 mg/L threshold used for oil and gas development and the DOGGR-reported base of fresh water (5), we find that 21% of TDS measurements made at depths deeper than the DOGGR-reported base of fresh water are fresh (Fig. 2 *C* and *D*).

Another common threshold for fresh water is 1,000 mg/L. Using 1,000 mg/L, we find that 29% and 12% of TDS measurements made at depths deeper than the USGS-estimated and the DOGGR-reported bases of fresh water, respectively, are fresher than 1,000 mg/L TDS (Fig. 2 *B* and *D*).

Fresh water is found at depths of more than 100 m below both estimates of base of fresh water (*SI Appendix*, Fig. S9). Available screened intervals of wells from which TDS measurements were made average at 19 m. For total well depths, discrepancies in depths estimated using different approaches average at 6 m (*SI Appendix*). The difference between the two defined bases of fresh water is generally ±100 m (*SI Appendix*, Fig. S7). Therefore, the prevalence of fresh water much deeper than the defined bases of fresh water cannot be explained by uncertainties in the base-of-fresh-water or the depths of the TDS concentration measurements.

In the Central Valley, fresh water is found deeper than the defined bases of fresh water in five groundwater subbasins defined by the California Department of Water Resources: Colusa, Solano, Delta, Kern County, and Westside (36) (*SI Appendix*, Fig. S8). Colusa and Solano Counties are found in northern Central Valley (Sacramento Valley), while Delta, Kern, and Westside Counties are found in southern Central Valley (San Joaquin Valley). We find similar results using the more stringent threshold of 1,000 mg/L TDS (*SI Appendix*, Fig. S8).

Groundwater Production Wells Encroaching on the Base of Fresh Water. Groundwater production wells with bottoms deeper than the USGS-estimated and DOGGR-reported bases of fresh water represent 0.4% and 4.6% of groundwater wells, respectively, and are common to the western Central Valley and the southern coastal basins (Fig. 4). The western Central Valley and the southern coastal basins also have high densities of groundwater wells that are encroaching on the base of fresh water. Across the Central Valley, 3.8% and 15% of groundwater well bottoms are within 100 and 200 m, respectively, of the USGS-estimated base of fresh water. In oil and gas areas, 14% and 22% of groundwater wells have bottoms within 100 and 200 m, respectively, of the DOGGR-reported base of fresh water.

Groundwater wells are more likely to be found deeper than defined bases of fresh water in oil-and-gas-producing areas, as represented by the DOGGR-reported base of fresh water, than throughout the Central Valley, as depicted by the USGS-estimated base of fresh water. Groundwater wells in oil-and-gas-producing areas are 11 times more likely to penetrate through DOGGR-reported base of fresh water (4.6%) than groundwater wells across the Central Valley penetrating through USGS-estimated base of fresh water (0.4%). Similarly, groundwater wells in oil-and-gas-producing areas are 3.5 times more likely to encroach on DOGGR-reported base of fresh water (13.5% have bottoms that overlie bases of fresh water by no more than 100 m) than groundwater wells encroaching on USGS-estimated base of fresh water (3.8% have bottoms that overlie bases of fresh water by no more than 100 m).

All three well types—domestic, agricultural, and industrial—are represented in wells with bottoms below or encroaching on the defined bases of fresh water. However, groundwater wells with depths that are below or encroach on the defined bases of fresh water are more likely to be agricultural and industrial water supply wells. Groundwater wells with bottoms that overlie the USGS-estimated base of fresh water by no more than 200 m represent 11% of domestic wells, 24% of agricultural wells, and 23% of industrial water supply wells in the Central Valley. In oil-and-gas-producing areas, 21%, 23%, and 23% of domestic, agricultural, and industrial groundwater wells, respectively, have bottoms that overlie the DOGGR-reported base of fresh water by no more than 200 m.

Discussion

Defined Base of Fresh Water Informing Sustainable Management Inconsistent with TDS Distribution. In 2014, California passed the Sustainable Groundwater Management Act (SGMA) to regulate groundwater use. Under SGMA, each groundwater basin is managed locally by groundwater sustainability agencies to bring groundwater basins into balance and achieve groundwater sustainability by 2040. While the state has taken the lead in delineating the horizontal extent of basin boundaries, groundwater sustainability agencies are tasked with delineating the vertical extent of their basins with discretion, which corresponds to California's focus on local management, resulting in limited guidance from the state. The vertical extent can be delineated using physical (e.g., depth to bedrock) or geochemical properties (e.g., base of fresh water). Defining the basin bottom is crucial for establishing an accurate hydrogeologic conceptual model, water budget, and extent of numerical groundwater modeling domains.

A review of the 2020 groundwater sustainability plans reveals that most groundwater sustainability agencies rely on the base of fresh water approach (*SI Appendix*, Table S3). The widely used base of fresh water estimates by the USGS and DOGGR were established decades ago and were not necessarily developed for sustainable management of groundwater (i.e., SGMA). The USGS estimates were established using water salinity information obtained largely from oil and gas sources (24, 25) collected during exploration and production. The USGS contours of bases of fresh water (24, 37) were developed based on a specific conductance of generally less than 3,000 micromhos per centimeter, which is approximately 2,000 mg/L TDS. This definition does not align with recent literature values of 1,000 mg/L or 3,000 mg/L for TDS thresholds for fresh water (5, 9). The methods used to determine the bases of fresh water in oil and gas reports (26–28) are not apparent in most cases (5, 20). The DOGGR base-of-fresh-water data are likely based on groundwater salinities estimated using geophysical logs and water samples (38), but could also be based on other factors, such as boron concentrations or the base of aquifers (26–28).

Defining the vertical extent of aquifers using DOGGR-reported or USGS-estimated base of fresh water may be problematic for four key reasons. First, salinity profiles do not always change monotonically with depth; for example, saline groundwaters overlie fresh groundwaters in the southwestern Central Valley (Fig. 3) (39). Second, defining the base of fresh water by the depth below which only unsuitable brackish or saline groundwater can be found (6) requires a specific definition for fresh

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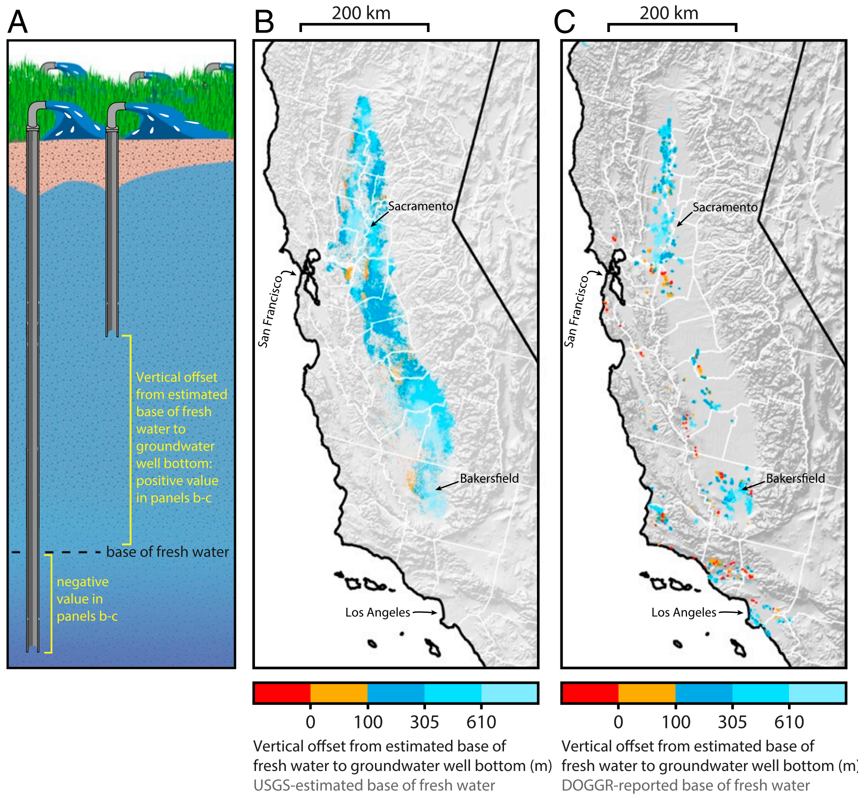

Fig. 4. Comparison of groundwater wells with (*B*) the USGS-estimated base of fresh water contours for the Central Valley and (*C*) the DOGGR-reported base of fresh water for oil and gas fields and field areas. A schematic showing the difference between positive and negative vertical offsets from estimated base of fresh water to groundwater well bottom is presented in *A*. In cases where groundwater well bottom is deeper than the base of fresh water (negative values as shown schematically in *A*), the vertical offset from estimated base of fresh water to groundwater well bottom is negative (red). Positive vertical offsets indicate groundwater well bottoms located above bases of fresh water (yellow and blues). County boundaries are shown in white. Cumulative histogram of vertical offset from estimated base of fresh water to groundwater well bottoms (m) for the USGS-estimated base of fresh water and the DOGGR-reported base of fresh water are presented in *SI Appendix*, Fig. S10.

water, which can vary from less than 500 mg/L to 3,000 mg/L TDS (*SI Appendix*, Fig. S1) depending on the jurisdiction or agency. Third, salinity distributions can change with time: for example, due to pumping/injection activities. Fourth, using base-of-fresh-water data without taking into account groundwater well depths can provide a loophole for groundwater pumpers possibly seeking to evade pumping restrictions by pumping from below bases of fresh water.

Deep Groundwater Increasingly Accessed. As technology evolves, it is possible that water with TDS values as high as 10,000 mg/L may be routinely used for a range of beneficial uses. For management and protection, deep groundwater should be characterized and continually monitored in California and elsewhere. Following concerns with aquifer exemptions, produced water injections, and renewed attention to protect groundwater from oil and gas development across the United States and internationally (40–47), there is a move toward increasing the TDS threshold for groundwater protection from 3,000 mg/L to 10,000 mg/L (38, 48). Because this move has just begun, studies of the depth to which groundwaters have TDS $<$ 10,000 mg/L are limited to a few localized studies (38), and previous regional characterizations (20) remain at too coarse of a scale to be useful for regulators.

Characterization is possible using a combination of historic groundwater quality data (20, 21, 38), new groundwater monitoring (7, 46), and oil and gas data, including geophysical logs and production activities (such as injections for enhanced recovery and wastewater disposal) (38). There are challenges to relying solely on oil and gas data, particularly because they are limited to oil-and-gas-producing regions. Existing groundwater monitoring wells are generally too shallow to monitor deep groundwater quality. New groundwater monitoring can fill these critical gaps, but deploying a widespread deep groundwater monitoring network would be expensive: Even one deep groundwater monitoring well is likely orders of magnitude more expensive than the ∼$10,000 USD required to install a typical groundwater monitoring well (49). SGMA provides the opportunity for local groundwater sustainability agencies to monitor important temporal variations in TDS; in places where groundwater wells are already accessing deep groundwater, there may be an opportunity to work with existing well owners to sample and provide temporal trends. Moreover, there may be new opportunities under SGMA to increase data sharing between groundwater sustainability agencies and the oil and gas industry to facilitate the conjunctive management of shallow and deep groundwater.

Conclusion

We show that fresh groundwater can be found at depths deeper than defined bases of fresh water (Fig. 2) and that groundwater wells are encroaching upon the defined bases of fresh water (Fig. 4). Our finding indicates that bases of fresh water may be inappropriate indicators to inform the management and protection of groundwater. Nevertheless, these bases of fresh water are still informing how California manages groundwater (e.g., *SI Appendix*, Table. S3).

Groundwater is vital to California's economy and the provision of perennial drinking and irrigation water supplies.

Threats to the long-term security of groundwater have implications well beyond California's state borders: Food produced via groundwater-fed irrigation is critical to food supplies both across the United States (50) and internationally (51). We stress the importance of managing deep groundwater and eliminating potential loopholes and contamination threats: where groundwater wells can drill deep and beyond the reach of current sustainable groundwater management regulations. Groundwater quantity and quality management can continue to be based on static definitions, like the base of fresh water, or can evolve with the water demands, technologies, and economics of the time.

Data Availability. Data have been deposited in Open Science Framework (https://osf.io/g42s7) (52). The page provides csv of the TDS-depth data and the shapefiles for the Base of Fresh Water.

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