Competition for shrinking window of low salinity groundwater

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Abstract
Groundwater resources are being stressed from the top down and bottom up. Declining water tables and near-surface contamination are driving groundwater users to construct deeper wells in many US aquifer systems. This has been a successful short-term mitigation measure where deep groundwater is fresh and free of contaminants. Nevertheless, vertical salinity profiles are not well-constrained at continental-scales. In many regions, oil and gas activities use pore spaces for energy production and waste disposal. Here we quantify depths that aquifer systems transition from fresh-to-brackish and where oil and gas activities are widespread in sedimentary basins across the United States. Fresh-brackish transitions occur at relatively shallow depths of just a few hundred meters, particularly in eastern US basins. We conclude that fresh groundwater is less abundant in several key US basins than previously thought; therefore drilling deeper wells to access fresh groundwater resources is not feasible extensively across the continent. Our findings illustrate that groundwater stores are being depleted not only by excessive withdrawals, but due to injection, and potentially contamination, from the oil and gas industry in areas of deep fresh and brackish groundwater.

Introduction
Groundwater is an increasingly important resource as competition for water rises. Shallow groundwater is subject to contamination from a variety of sources (e.g. agricultural nitrate contamination) that potentially limits their use as potable water supplies [1]. Deep aquifers sometimes contain fresh (salinity <3000 mg l\(^{-1}\)) and brackish groundwaters (salinity 3000–10 000 mg l\(^{-1}\)), and competition for these deep waters is increasing as deep well technologies improve [2]. When desalination technologies are available, deep brackish groundwater provides another opportunity to meet growing water demands, if managed adequately [3]. Our current understanding of fresh-saline water transitions is limited, so it is unclear how these transitions may compare to the depths of groundwater wells. Although previous works have characterized brackish groundwater at the national scale [4], it is unclear how widespread competition for subsurface space is across the USA because of the lack of a 3D, continental-scale assessment of groundwater salinity from both supply and demand perspectives.

Moreover, pore space containing deep brackish groundwater can be used for waste disposal at similar depths to areas where the oil and gas industry perform hydraulic fracturing or enhanced oil recovery figure 1 [5, 6]. Recent work in the California Central Valley shows that oil and gas activities, such as fluid injection, are taking place in or in close proximity to deep freshwater zones [7]. Other studies suggest that the Central Valley is not unique [8]. Current regulations to protect groundwater from deep subsurface development vary widely and may not be sufficient to protect fresh and shallow groundwater resources [9]. Aquifer exemptions have been granted to over 3300 injection wells in the USA [10]; approximately 95% of these exempt wells are used for enhanced oil recovery (EOR) or disposal of produced waters associated with oil and gas production (EPA Class 2) [11]. Injection wells are often exempt because they are at depths not used
currently for drinking water supplies and expected to remain undeveloped for such purposes [11]. Exempt aquifers historically include those with salinities exceeding 10 000 mg l\(^{-1}\), although there are cases where aquifers with lower salinities have been exempted [12]. In cases where aquifers are exempted for EOR wells, they contain hydrocarbons that are economically viable to produce. However, the increase in pressure associated with injection may drive these waters into adjacent strata that contain potable water. Although proximity alone does not necessitate contamination [13], proximity can be a proxy for the competition for deep groundwater. Currently, it is unclear how depths of hydraulic fracturing, EOR, and exempt injection wells compare to depths of fresh, brackish, and saline groundwaters and depths of groundwater wells across the United States’ major sedimentary basins. Without this information, it is difficult to assess where our limits to fresh groundwater availability exists from the bottom up. Pairing such information with the vast and important literature focusing on surficial contamination sources, that is, from the top down (e.g. nitrates, [14]), could provide a continental-scale picture of the window of fresh groundwater.

The objective of this paper is to improve our continental-scale understanding of water quality from the bottom up, especially in contrast to the depths at which groundwater is currently being accessed via constructed wells; this work specifically focuses on the competition for low salinity groundwater.

Here, we (1) calculate the degree of separation between fresh and brackish groundwaters at the continental-scale using 28 key sedimentary basins in the USA. We then overlay regional well data to (2) determine depths that groundwater is accessed for domestic, agricultural and industrial uses. Our findings provide the first estimates of underground fresh and brackish water depths in the some of the most prominent sedimentary basins across the contiguous USA. Additionally, for a subset of these basins we highlight considerable competition for deep fresh and brackish water and the pore spaces they occupy by comparing windows of fresh-brackish groundwater to (3) depths of oil and gas production and (4) depths that various fluids (e.g. CO\(_2\) for EOR; produced waters associated with oil and gas production) are injected. Our results suggest that the window of fresh and undeveloped groundwater is shrinking in some basins. Thus, we suggest improved characterization of deep groundwaters is critical to protect our groundwater resources.

**Methods**

Water chemistry data from the United States Geological Survey (USGS) brackish water [15] and produced water [16] databases were used in this study. Data from the brackish water database was assigned to 28 sedimentary basins based on the USGS classification [17], which were used as the primary hydrologic unit for this study (figure S1 is available online at stacks.iop.org/ERL/13/114013/mmedia). These sedimentary basins were selected on the basis of data availability. In each of these basins, total dissolved solids (TDS) values were present for each 100 m depth interval from the ground surface to a depth where TDS exceeded 10 000 mg l\(^{-1}\). TDS data was binned into these 100 m intervals to determine the depth where median TDS values were <3000 mg l\(^{-1}\) and <10 000 mg l\(^{-1}\).
(table S1), which we define as fresh and brackish waters, respectively following Robinove, Langford and Brookhart [18] and Hem [19]. We note that our approach does not address variation in TDS within individual basins due to factors such as the evolution of groundwater chemistry with regional flow [20], the effect of dipping formations [21] and interfering of fresh and saline groundwater [22].

We analyzed statistics of the depths of groundwater wells designed to produce groundwater for domestic, agricultural or industrial purposes. Data and quality control methods used are presented by Perrone and Jasechko [2] and Jasechko and Perrone [13]. Previous work finds that median agricultural wells can, in some places, be tens-of-meters deeper than median domestic or municipal wells [2]; this pattern does not hold true across the entirety of our study area. Some locations have deeper domestic wells and some locations have little difference between depths of domestic and agricultural wells (figure 5 in [2]). Most constructed wells in our dataset are domestic wells, suggesting that our analysis of well depths is weighted towards domestic well depths rather than agricultural or industrial well depths. Well depth percentiles were produced for each USGS sedimentary basin smaller than 250 000 km² and for the regions of Ohio, New York and Pennsylvania overlying the Marcellus Shale shapefile [23]. Similarly, statistics for exempt wells for the 28 sedimentary basins examined here were produced using the EPA’s aquifer exemption database [10]. This database does not contain comprehensive data for all states, notably Texas and California [11].

Results

Degree of separation between fresh and brackish groundwaters

The distribution of salinity with depth within the basins examined is highly variable (figure 2), both within individual basins and between basins. The mean transition between fresh groundwater (TDS of less than 3000 mg l⁻¹) and brackish groundwater (TDS between 3000 and 10 000 mg l⁻¹) for the 28 sedimentary basins in the USA occurs at a depth of 550 meters below the ground surface (mbgs). This transition occurs at a range of depths, with the shallowest transition at 50 mbgs in the Sedgwick Basin, and the deepest transition at 1350 mbgs in the Antler Foreland Basin (figure 3). In western basins (defined here as the Denver Basin and other basins west of 104° W), the mean transition between fresh and brackish groundwater occurs at a depth of 650 mbgs, while this transition occurs at a depth of 450 mbgs in eastern basins, although the difference in mean depths is not significant (p = 0.10).

The mean transition between brackish and saline (TDS exceeding 10 000 mg l⁻¹) groundwaters occurs at 950 mbgs. The shallowest transition occurs in the Sedgwick Basin at 50 mbgs, while brackish water is present to a depth of 2250 mbgs in the Big Horn Basin (figure 3(b)). The mean depth of the brackish to saline groundwater transition in eastern basins is 550 mbgs, which differs significantly from the mean depth of 1150 mbgs observed in western basins (p = 0.01). In the east, only the Fort Worth Basin and Mississippi Embayment have abundant brackish groundwater present at depths deeper than 1000 mbgs; in the west, brackish groundwater is present at depths deeper than 1000 mbgs in 8 of the 15 western basins. Eastern basins tend to have abrupt transitions from fresh to saline groundwater, while western basins with deep brackish waters tend to have more gradual increases in salinity and generally have lower maximum TDS values (figure 3(b)).

Water well depths compared to salinity transition zones

Among the studied basins, the 50th percentile of water well depths ranges from 17 to 89 mbgs and the 95th percentile of water well depths ranges from 40 to 291 mbgs (figure 2). Water wells in western basins have a mean 50th percentile depth of 50 mbgs and a mean 95th percentile depth of 183 mbgs. Eastern basins have slightly shallow water wells with a mean 50th percentile depth of 43 mbgs and a mean 95th percentile depth of 148 mbgs. Although data are not available for the Appalachian Basin in entirety, data are available for water wells in the northern Appalachian Basin. Water wells in New York, Ohio and Pennsylvania, in the region overlying the Marcellus Shale gas play, are typically shallow, with 95% of water wells completed at depths of less than 127 m.

For all basins examined, the transition depth between fresh and brackish groundwater has an R² correlation coefficient of 0.35 with the median water well depth, and 0.48 with the 95th percentile water well depth. That is, the median water well depth tends to be deeper in basins that have a deeper transition from fresh to brackish water. Both of these values are significant (p = 0.0002). There is no statistically significant relationship between water well depth and the position of the transition between brackish and saline groundwater at the p = 0.05 level.

Oil and gas well depths compared to salinity transition zones

Fresh groundwater is only present in the upper few hundred meters in most sedimentary basins in the eastern and midcontinent USA, creating a large amount of vertical separation between unconventional gas production and water wells (figures 2 and 4). Hydraulic fracturing of the Marcellus Shale typically occurs at depths of 1600–2600 m [24]. Most (95%) water wells in this region are less than 127 m deep and saline water exists at depths of only 350 m, allowing for
over 1000 m of separation between hydraulic fracturing and current groundwater extraction (figure 4(a)). Similar separation between hydraulic fracturing and groundwater wells is apparent in the Anadarko Basin (Woodford Shale; figure 4(b)) and to a lesser extent in the Fort Worth Basin (Barnett Shale; figure 4(c)) [24]. Separation between hydraulic fracturing and groundwater production is markedly less in the Michigan Basin, where gas wells are installed at depths as shallow as 270 m (Antrim Shale; figure 4(d)) [25].

In contrast, oil and gas production in some western basins is common over the same range of depths that brackish waters occur. In the Wind River Basin, hydraulic fracturing is occurring at depths of as little as 372 m (4(e)) [26]. Similarly, coalbed methane wells have been completed to depths as shallow as 91 m in the Powder River Basin [27], which contains freshwater to depths of 750 m (figure 4(f)). Coal bed methane wells also occur within the brackish water zones in the San Juan Basin [27].

Figure 2. Distribution of total dissolved solids (TDS) with depth is highly variable in the 28 sedimentary basins examined here. Drilling deeper water wells to access additional fresh and brackish water supplies is not possible in all basins.
Figure 3. Depth to water with TDS (a) <3000 and (b) <10000 mg L$^{-1}$ based on median values in 100 m bins. (c) TDS distribution relative to the 50th and 95th percentile of water well depths.
Injection well depths compared to regional transition zones

Aquifer exemptions have been granted to 1522 injection wells in the sedimentary basins examined here [10] (Table S1). Most of these wells are used to dispose of produced water from oil and gas production, but others are associated with injection for EOR or in situ uranium mining. Installation of these wells with aquifer exemptions has occurred at a steady rate since the 1980s. These injection wells are present in 22 of 28 basins examined in this study. The Big Horn, Denver, Gulf of Mexico, Green River, Illinois, Powder River, San Juan, Uinta, Williston and San Juan basins each contain over 40 injection wells with aquifer exemptions. In many basins, injection wells are installed at depths shallower than the overall transition from fresh to brackish water. Brines have been injected at depths of less than 100 m in the Illinois Basin and at depths of less than 300 m in both the Williston and Wind River basins (table S1).

Discussion

Less fresh groundwater than previously estimated

Our continental-scale findings suggest that the amount of fresh groundwater that is available globally may be less than thought previously. Gleeson et al [28] estimated that only 6% of water in the upper 2 km of the crust is young (i.e. less than 50 years old), and the rest is old water. Based on the average depth to the transition between fresh and brackish groundwater of 550 m found here, compared to the greater depths of 1000–2000 m used in previous global groundwater assessments [28–30], there is substantially less fresh groundwater than previously estimated. Further, because shallow (<100–200 m) groundwaters tend to be comprised disproportionately of recently recharged waters, a fraction of these shallow fresh groundwaters contain contaminants derived from the intensive use of land over the past ~100 years [31]. Our estimates are based on sedimentary basins, but depths where saline waters have been encountered in crystalline rock are not substantially different. Water samples from Precambrian shield environments have commonly found saline water at depths less than 1000 m [32–35].

Salinity constraints on depth of water wells

Understanding groundwater salinity variability with depth is increasingly important to water management; it is estimated currently that over 5 billion people live in water scarce areas [36], many of which rely on
groundwater and some of which are in overdrafted basins [37]. Drilling deeper wells is often an approach used to combat groundwater depletion or contamination problems [2, 38], but it is only economic for some uses to drill deeper wells before aquifer systems transition from fresh to brackish to saline water.

The correlation between water well depths and the depth to the transition between fresh and brackish water signifies that salinity-depth relations have influenced well drilling depths at the scale of individual sedimentary basins. Moreover, areas of groundwater depletion in the western USA [39] coincide with areas where fresh and brackish water are present at greater depths than they are in the east. For example, our findings corroborate large volumes of low TDS groundwater in California’s Central Valley [7], part of which coincides with the San Joaquin Basin.

The ability to drill deeper wells in some aquifer systems experiencing depletion appears to be limited. Based on data at the basin-scale, drilling deeper wells in the region of the High Plains aquifer, which coincides with parts of the Anadarko and Sedgwick basins, is not a viable solution to dropping water levels. Saline water is present at depths as shallow as 50 m in some areas of these basins. Some deeper wells are already completed near this depth in the Sedgwick Basin. Similar limitations are present in other basins, including the Michigan, North Park, Paradox, Wind River and Permian basins, where deep wells are already completed within 100 m of the basin-scale boundary between fresh and brackish water. With the exception of depletion in the Pecos River Basin, which coincides with part of the Permian Basin, large-scale depletion problems have not been documented in these other basins [39].

Vertical separation of water wells and hydrocarbon production

The amount of separation between potable groundwater resources and drilling, stimulation and operation of wells associated with oil and gas activities is a critical consideration in oil and gas producing regions [13, 40]. The required separation between unconventional oil and gas production and water wells in the USA is likely on the order of several hundred meters [41]. Analysis of several unconventional oil and gas plays indicated that only 1% of fractures propagate to distances of 350 m or more [42]. Factors, such as the permeability of the ‘intermediate zone’ between the oil/gas reservoir being produced and shallow aquifers [43] and the presence of conduits (e.g. poorly completed or abandoned oil and gas wells) to near-surface environments [44], are important considerations that have yet to be characterized comprehensively.

Existing oil and gas regulations in the USA vary by state and are primarily based on TDS rather than separation of activities to potable water supplies [9]. The implications of these regulations will vary in parts of the USA due to regional differences in the distribution of TDS, and as well as the depth of oil and gas resources, which can also vary substantially. In the case of natural gas extraction, thermogenic gas plays are typically quite deep and near basin centers, while biogenic gas plays are shallow and near basin edges [45].

Our data suggests that a large vertical separation exists between unconventional gas production and water wells where thermogenic gas is the target of hydraulic fracturing (e.g. Marcellus Shale; Appalachian Basin) [46–49]. The situation is markedly different in the Michigan Basin, where biogenic gas is present in the Antrim Shale along the basin margins [50]. Antrim Shale biogenic gas wells are installed at depths as shallow as 270 m, allowing for only 200 m of vertical separation from the deeper water wells in the basin (figure 4(d)). A similar situation exists in Pavilion, Wyoming, which is situated in the Wind River Basin, where hydraulic fracturing occurred at depths of less than 500 m in several instances. This has been linked to contamination of several domestic water wells at depths of approximately 300 m [51].

Contamination of transition zones by deep waste disposal

There are many instances where disposal (injection) wells, related to oil and gas production, have been installed in aquifers containing low TDS waters [10]. In contrast to hydraulic fracturing, where few cases of groundwater impacts to overlying strata have been documented [52, 53], the impacts of injection are more certain where displaced fresh and brackish groundwater are replaced by wastewater. Such injection has occurred in many exempt aquifers [10] but there are no comprehensive studies of the fate of these injected fluids. Injected flowback and produced waters typically have high TDS and frequently contain hydrocarbons and other contaminants [10, 54–56]. The EPA has exempted areas ranging from a few hectares up to several hundred km² from aquifers to allow for installation of disposal wells, effectively removing the possibility of future use of fresh, potable groundwater from these zones. Installation of injection wells in exempt aquifers has occurred at a steady rate for the past few decades, and concomitant fluid injections are progressively decreasing available fresh and brackish groundwater resources.

Conclusions

The extent of fresh and brackish groundwater varies across USA sedimentary basins. Deep fresh groundwater stores are present in the western USA, and exploitation of these aquifers continues [2]. Saline groundwater is present at shallower depths in the eastern and midcontinent USA. Drilling deeper water wells to address groundwater depletion issues represents no more than a stopgap measure in these areas.
Furthermore, in many regions, particularly the western USA, deep groundwater resources are threatened by pore space competition from the oil and gas industry. This pore space competition includes injection of waste fluids directly into deep fresh and brackish aquifers as well potential impacts from injection and hydraulic fracturing in underlying units with little vertical separation. Areas where potable groundwater resources have little to no vertical separation from oil and gas production or disposal wells may be particularly vulnerable to contamination and warrant additional attention. Even where not currently exploited, these deeper fresh and brackish groundwater resources constitute an important and strategic water reserve for mitigating future water scarcity.

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