



Columbia Water Center White Paper

Assessment of trends in groundwater levels across the United States

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Key Points

1. Groundwater levels have declined across much of the United States
2. An increase in pumping rates corresponds with declining groundwater levels in most counties
3. On average, long-term climate trends appear to correspond to groundwater level changes, and there is not as much sensitivity to annual precipitation variability

1. Introduction

The objective of this study is to address the following questions:

- (1) How have groundwater levels changed across the US between 1949 and 2009?
- (2) How do groundwater level trends correlate with extraction rates?
- (3) How do groundwater level trends correlate with precipitation and climate trends?

This study addresses these questions by analyzing historical groundwater records across the continental USA, and comparing observed trends to climate and groundwater use records.

Groundwater constitutes a critical component of our water resources. In the United States, groundwater accounts for 60% of irrigation and provides drinking water for more than 40% of the population. It serves as a valuable resource in regions lacking access to surface water and, in most areas, provides an essential buffer during dry periods. If human use upsets the balance between recharge, capture, and natural outflows, aquifer equilibrium is lost until a new balance is reached (Alley and Leake 2004).

As a critical national resource, it is important that water users and managers are aware of groundwater level trends and the dominant controls on availability. Understanding aquifer response to extraction and climate should serve as the basis for water use policies to avoid irreversible negative consequences. Sustainable planning and proper management of groundwater extraction must also account for climate change and climate variability. As precipitation patterns change across the US (e.g. Karl & Knight, 1998), so will recharge rates, potentially exacerbating water stressed regions (Döll 2009).

In arid and semi-arid areas where low precipitation results in low or zero natural recharge, mining of fossil groundwater from aquifers depletes a non-renewable resource. With less water to support the aquifer structure, compaction can cause land subsidence and permanent reduction in storage capacity. Groundwater extraction rates have shown to be more influential than climate change in the Edwards Aquifer in Texas (Loáiciga 2003). In the High Plains Aquifer system, including the Ogallala, fossil water is extracted at nearly 10 times the rate of recharge, resulting in the largest groundwater depletion in the country (Scanlon et al. 2012; Konikow 2013).

Correlations between groundwater levels and precipitation can help assess aquifer vulnerability to climate change (Ng et al. 2010). Deep groundwater production wells can show high water level variability over time, sometimes with a variable lag in response times to climate ranging from a few seconds to millions of years (Sophocleous 2012). Several studies have investigated groundwater

levels and climate correlations in US aquifers. Long term climate cycles have the most observable effects on groundwater levels, generally due to the relatively long recharge and aquifer response time. In Southern California, the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) have been shown to cause the largest variations of groundwater levels (Hanson and Dettinger 2005). In the High Plains Aquifer system, groundwater levels were most highly correlated with PDO (Gurdak et al. 2007). Groundwater response to climate also depends on local geology (Chen, Grasby, and Osadetz 2004), land use and land cover (Scanlon et al. 2005), and other factors affecting infiltration and recharge rates.

2. Data source and description

Groundwater level and usage data for this study were obtained from the US Geological Survey (USGS-NWIS). Depth to groundwater values were downloaded for 24,532 wells having >30 records from 1949 to 2009 and a screen depth > 30 m (100 ft) (**Figure 1**). To preclude wells with short records unlikely to span multiple years, we set a minimum threshold of 30 observations. Groundwater level measurements were rarely recorded at regular intervals; the number and frequency of measurements taken each year varies by site.

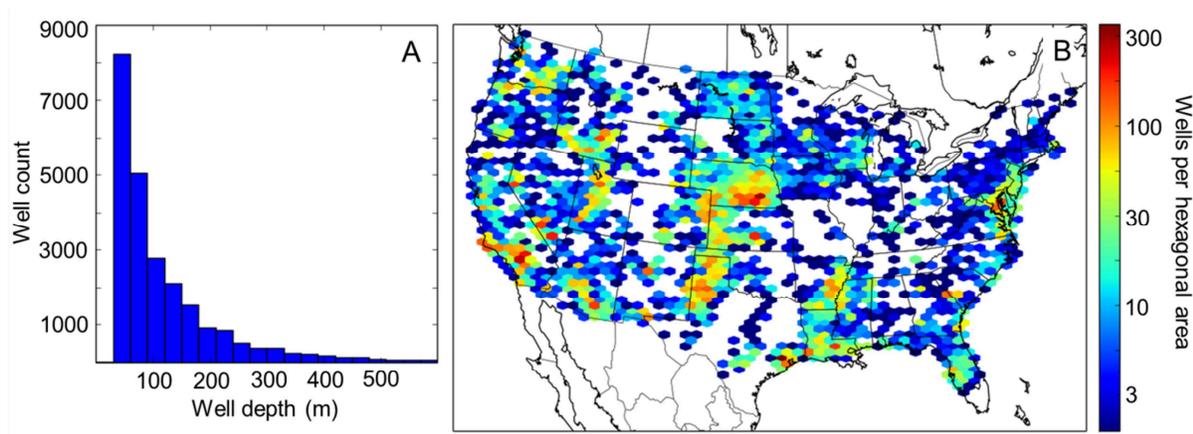


Figure 1 Groundwater well data retrieved from the US Geological Survey, (A) Histogram of well depths, and (B) Density of monitoring wells deeper than 30 m (100 ft).

We obtained water use data from the USGS Estimated Use of Water reports (USGS-NWIS). State-scale water use data including surface and groundwater use is available every 5 years from 1960 to 2005 (2010 will be released later this year, 2014). Higher resolution data is available at the county-scale from 1985 to 2005 (e.g. **Figure 2**). This study used only the more recent county-scale data.

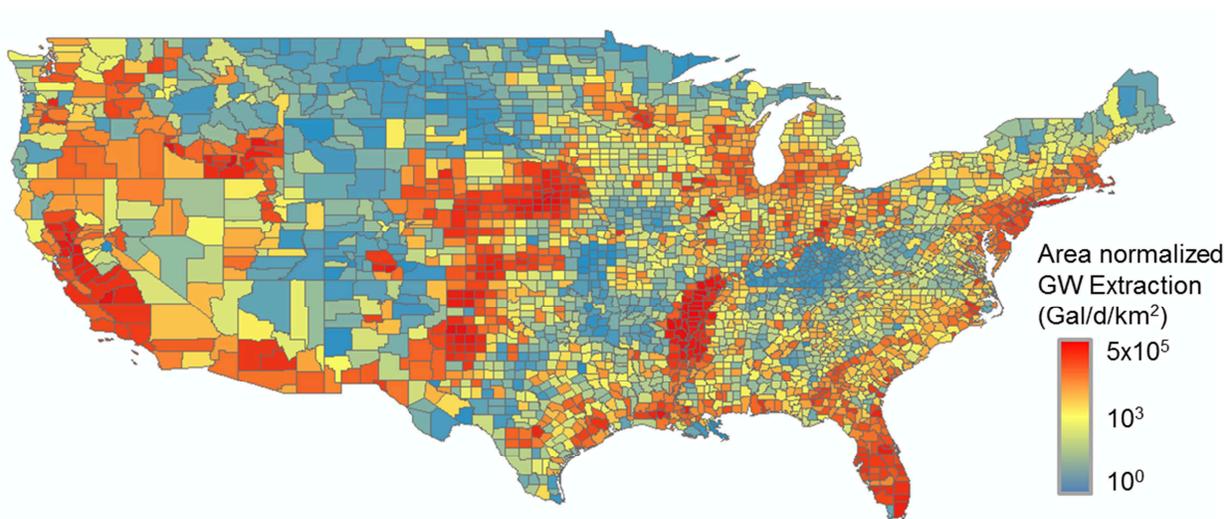


Figure 2. Area normalized fresh groundwater extraction in 2005.

Annual average precipitation for each county from 1949 to 2009 was obtained from Maurer et al. (2002). Data for the long term climate cycle analysis, including the PDO indices and the North Atlantic Oscillation (NAO) indices were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service group.

3. Methods

3.1. Analysis of Groundwater Elevation Trends over Time

Groundwater level depths were analyzed for each well over the study time period, 1949 to 2009. The analyses in this paper use annual averages based on the calendar year. For every well record, the presence and statistical significance of groundwater elevation trends over the 61 year period were evaluated using the Kendall's tau-b tests. We consider groundwater records with a p-value < 0.1 in support of the null hypothesis of no trend to be significant. There are 16,410 wells with significant ($p < 0.1$) trends in groundwater level. For these wells, the slope of the time trend of groundwater level was calculated using the Theil-Sen method. This is a robust trend estimator that is not affected as much by a few outliers in the data. The average of the slopes for a given grid area are presented in the results.

We used a similar method for calculating the 5-year slopes with data centered at 1950, 1955, ..., 2005. This produced twelve 5-yr slope values per well with a 61 year record, and several 5-year slope values for shorter total records. The trend anomaly of each 5-year slope is presented as a ratio with the long term trend ($S_{5-year}/S_{long-term}$), so that the short term departure that may be due to climate or other factors can be easily identified. For example, a well that shows an overall declining 61-year trend may experience a groundwater level increase at some point, resulting in a positive 5-year trend anomaly for this period. The 5-year analysis period data were also compared to the 5-yr water use data, described in the next section.

To identify groups of wells whose behavior in time is similar, we performed a k-means cluster analysis on a subset of the wells that have continuous records for annual average depth to groundwater. The groundwater depth time series values were first normalized by dividing by average depth over the period of record. This analysis was done for wells with continuous records between 1965 and 2005, a shorter period than the full study time period. This allowed us to analyze a larger number of locations.

3.2. Correlation between Groundwater Elevation and Groundwater Extraction

County-level water use data are available every 5 years from 1985 to 2005, and they include both groundwater and surface water consumption. The trend of groundwater extraction was calculated for each county over the period of record, 1985 to 2005, using the Theil-Sen slope. Positive slopes indicate increases in groundwater extraction, while negative slopes indicate declines. The anomaly at each year of record (1985, 1990, ..., 2005) was calculated to illustrate the variation from the long-term trend of extraction over time.

3.3. Correlation between Groundwater Elevation and Climate

Preliminary studies showed that groundwater level and annual precipitation were weakly correlated for medium and deep wells (>100 ft, 30 m). For shallower wells, rainfall and groundwater levels appeared to correlate at diurnal to seasonal time scales. In this report, we focus on the deeper wells and the longer time scales.

The time variations in groundwater level records and annual precipitation in the county where the well is located were compared using a cross wavelet analysis (Torrence and Compo 1998; Grinsted, Moore, and Jevrejeva 2004). A Morlet wavelet was used for the wavelet analysis. Wells with continuous annual average records between 1949 and 2009 were selected for analysis. The cross wavelet analysis allows one to identify periods where there may be synchronous variations in two time series that correspond to a “signal” in one of them. Here, a signal is something that recurs with a certain period. For example, precipitation might have a signal corresponding to climate patterns including ENSO, PDO and NAO.

Five-year mean values of the NAO and PDO indices were compared to groundwater elevation trends using the 5-yr periods described in Section 3.1. Annual precipitation at the county level was combined with county area to calculate the area-averaged precipitation over the US. The corresponding precipitation anomaly throughout the study time period is the difference of the 5-yr trend and the long-term trend (**Figure 3**). We also illustrate the relationship between climate patterns (NAO and PDO), precipitation anomaly, and groundwater trend anomaly.

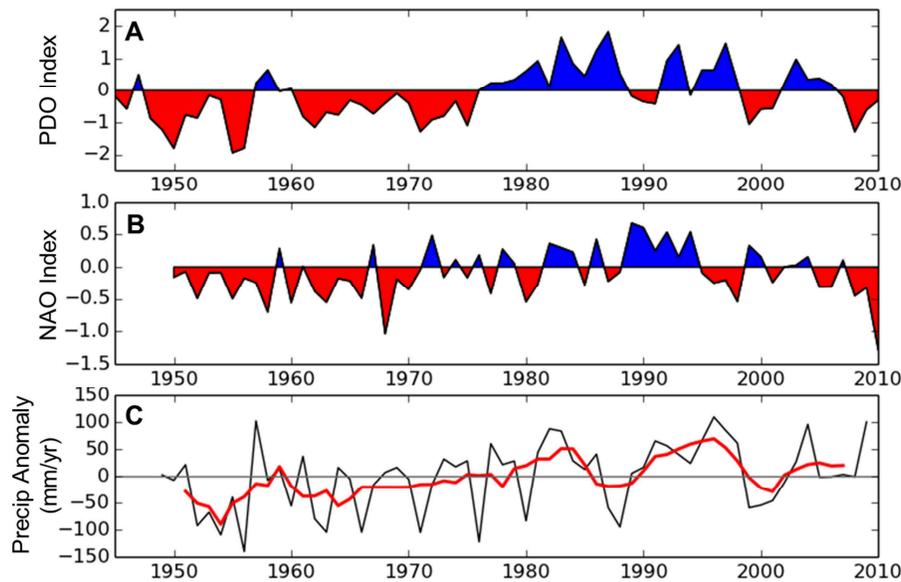


Figure 3 Average climate and precipitation trends: (A) Annual average PDO index (B) Annual average NAO index, and (C) Area averaged precipitation anomaly over the continental US (annual anomaly in black, 5-yr running mean in red). Note the overall increasing trend that is punctuated by two continental scale droughts in the mid-1980s, and late-1990s.

4. Results and Discussion

A majority of deep wells in the USGS dataset with trends show declines in groundwater over the study period. The relationship between groundwater pumping, climate, and groundwater level is complicated and spatially variable. In this report, we illustrate some of the dominant patterns observed, and potential correlations between resource use and availability. On average, we see that dry periods in the climate record correlate with increased groundwater decline, while wet periods correlate with groundwater recovery. During a wet period, groundwater pumping may decrease while aquifer recharge increases, both reducing stress on groundwater resources. The opposite conditions and results occur during a dry period. This relationship is captured in the 5-year average groundwater trends, when compared to the average precipitation over the US (**Figure 4**). Further relationships between groundwater and climate are discussed in *Section 4.3*.

Though the median trend for every 5-yr period is negative, the distributions of slope anomalies are relatively large, spanning both negative and positive values (**Figure 4B**). Almost all regions of the country have both rising and declining groundwater levels in different wells. There are 11,483 wells with significant ($p < 0.1$) long-term declining trends, and 4,839 wells with significant long-term rising trends. Wells with differing trends can be located close together in space because wells may be drilled within a large depth range (**Figure 1A**), potentially reaching different aquifers. These layered aquifers can have different head level trends based on their own physical parameters, extraction rates, and recharge rates.

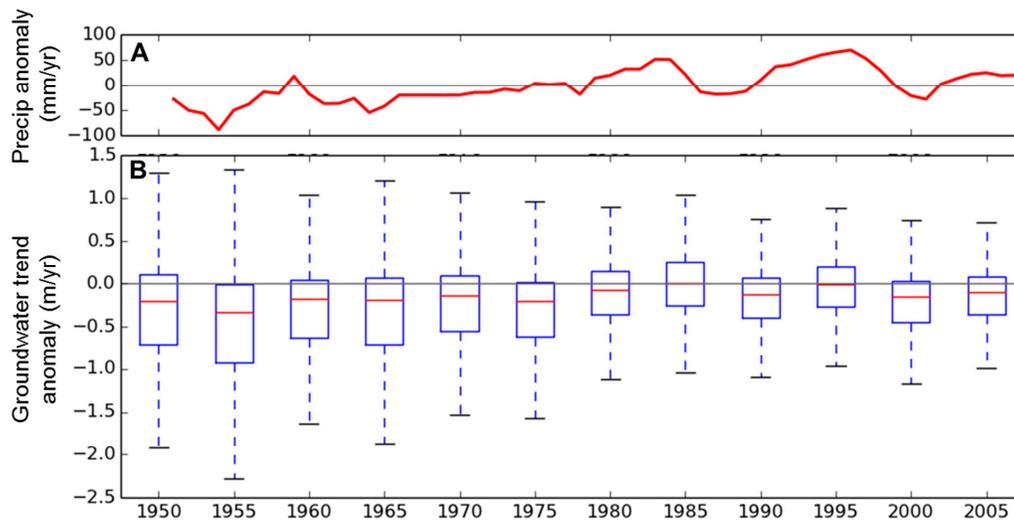


Figure 4 (A) Area average precipitation anomaly 5-year running mean (from **Figure 3**). **(B)** Calculated 5-yr trend anomalies of groundwater level change for continental US, negative indicates greater decline than average.

4.1. Groundwater Level Trends

Long term groundwater level trends vary in magnitude and direction across the country during the study period, 1949 – 2009 (**Figure 5**). Large regions with generally contiguous groundwater declines include the central and southern Ogallala aquifer (western Nebraska, Kansas, Oklahoma, and northwest Texas), the lower Mississippi (Arkansas, Mississippi, and Louisiana), the Southwest and central western United States (Southern California, Nevada, Arizona, Utah, and southern Idaho), and the central Atlantic Coastal Plain (Maryland, eastern Virginia, North Carolina).

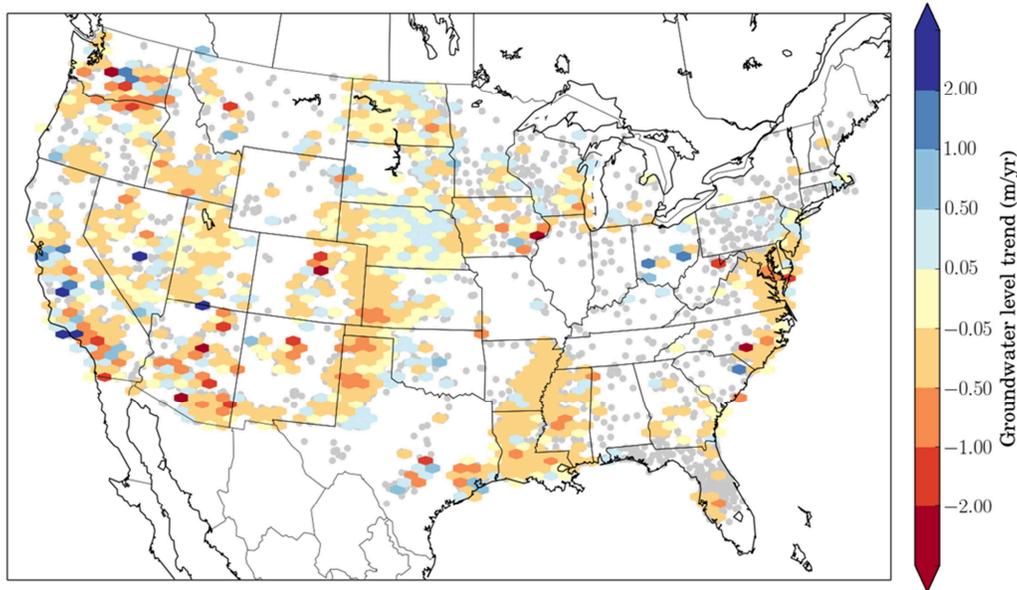


Figure 5 Average slope from wells with statistically significant trends at the 10% level observed between 1949 and 2009. Negative (red/orange) indicates decline in groundwater level, while positive (blue) indicates a rise in groundwater level. Wells with insignificant trends shown in gray.

Despite extensive negative trends across the US, groundwater trend anomalies vary significantly by region during the study period (**Figure 6** and **Figure 7**). In the 1970s, central and coastal California experienced their highest rates of decline during the study period. Similarly at this time, the entire Ogallala Aquifer saw groundwater declines, as did much of the mid-west including North Dakota, South Dakota, Wisconsin, Iowa, and Michigan. The lower Mississippi and regions of the Atlantic Coastal Plain were also experiencing relatively high groundwater declines during this period.

The 1990s brought a period of groundwater recovery for several regions in the western US, including central California, southern Idaho, and northern Utah. Widespread groundwater rise was seen in North Dakota and the northern Ogallala (central Nebraska). There were still groundwater declines in the south, and southwestern US, though smaller than average in many areas. In the 2000s, trend anomalies indicate groundwater declines in the northern Midwest and northern Ogallala. Groundwater declines in the central and southern Ogallala, the lower Mississippi, the southeast, and the Atlantic Coastal Plain all generally had negative anomalies from the 1970s through 2000s, indicating continuous declines through this period.

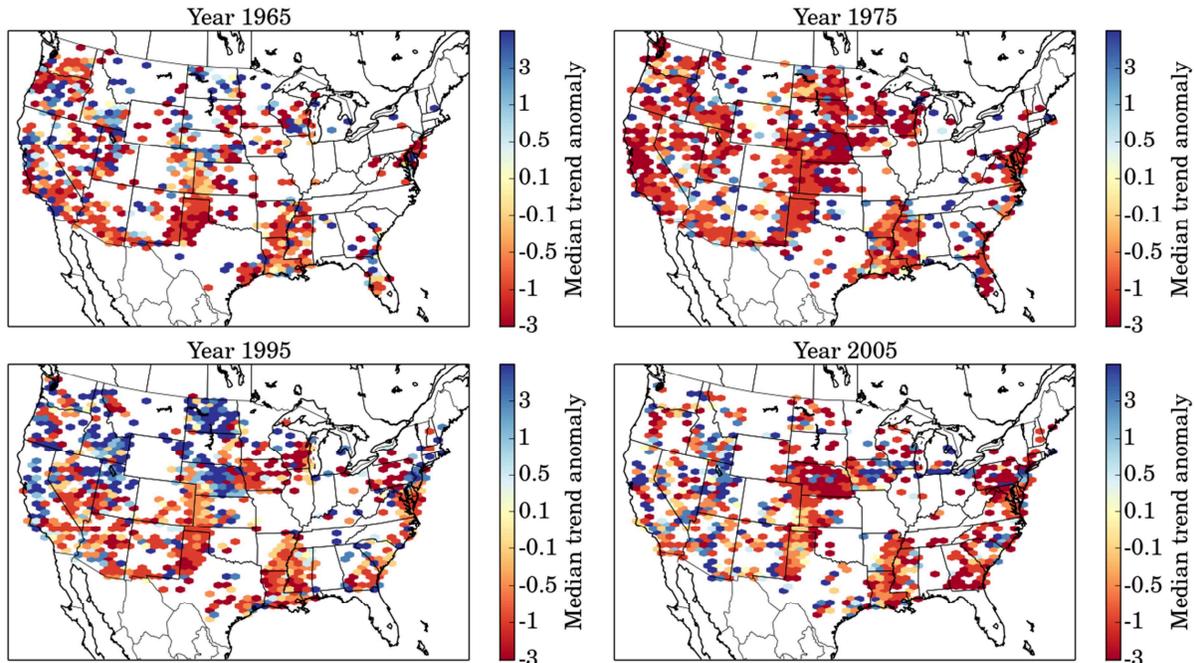


Figure 6 Five-year trends anomalies (1965, 1975, 1995 and 2005) for wells with long-term declining records. The median trend anomaly is shown at each point. Positive (blue) indicates groundwater level increases, while negative (orange to red) indicates groundwater level declines.

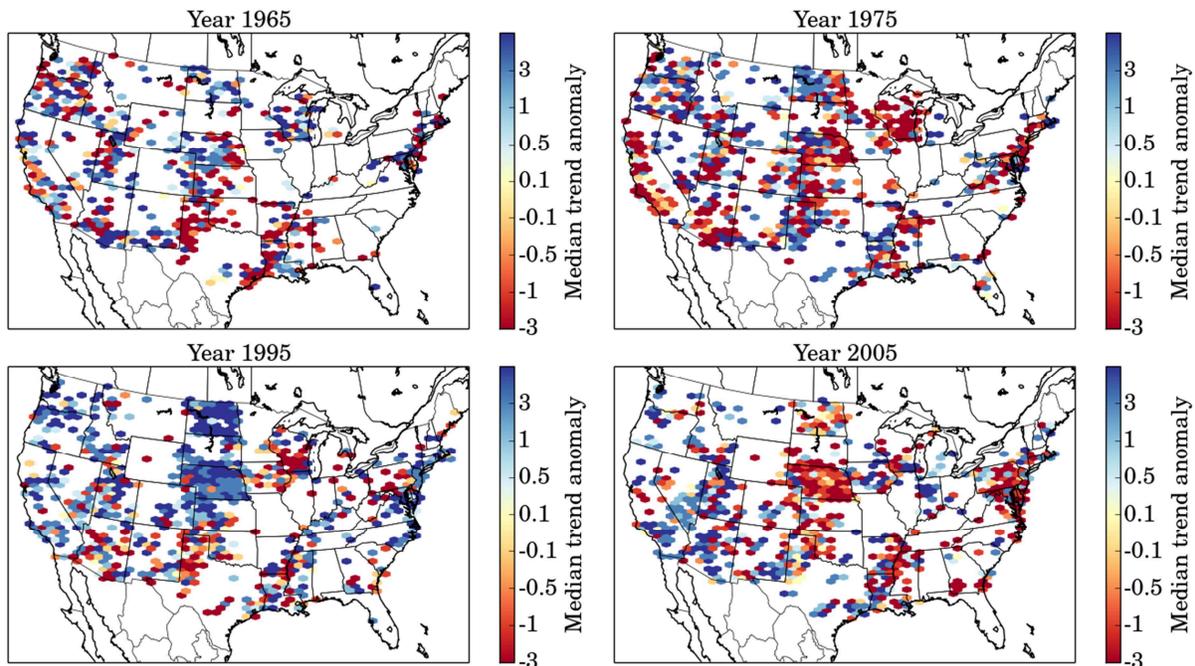


Figure 7 Five-year trends anomalies (1965, 1975, 1995 and 2005) for wells with long-term rising records. The median trend anomaly is shown at each point. Positive (blue) indicates groundwater level increases, while negative (orange to red) indicates groundwater level declines.

The wells with long-term rising trends (**Figure 7**) provide additional information about groundwater behavior, and combined with **Figure 6** illustrate the spatial proximity of declining and rising wells across the country. The anomalies are often the same sign for both long-term declining and rising wells, during the most extreme periods of decline or recovery. For example, the wells in the California Central Valley which experienced long-term rises, have short periods of groundwater level decline during the 1970s (**Figure 7**), the period of time when long-term declining wells experienced their largest declines (**Figure 6**). Wells with rising trends in the northern Ogallala experienced their greatest increases during the 1990s, when long-term declining wells also experienced increases. The rises observed in the 1990s in the northern Ogallala were followed by declines in the 2000s, again for both wells with long-term rising and declining trends. The results discussed here do not account for groundwater well depth and aquifer properties, which would provide further insight and possibly explain the observed spatial variability.

The similarity of trends between wells across the country can be illustrated using a cluster analysis. Continuous groundwater level records between 1965 and 2005 can be grouped into four clusters (**Figure 8**). Each cluster includes wells located across the US, with relatively low regional grouping, indicating groundwater levels are changing by similar amounts in many regions of the country (**Figure 8B**). The distribution of well depth varies across clusters (**Figure 8C**), suggesting there may be a relationship between aquifer depth and groundwater trend in multiple US aquifers.

Cluster 1 wells have a small rising trend in groundwater levels overall (**Figure 8A**) and include the shallowest wells ranging from 30 to 100m (**Figure 8C**). Overall, the clusters with declining trends (2 and 3) have the deepest wells and the largest spread in well depth. Of these the shallower wells have a smaller decline. Cluster 2 wells show large, consistent declines in groundwater level. Cluster 3 wells show declines as well, though approximately 1/3 smaller than in Cluster 2. Clusters 2 and 3 have the deepest well distributions. Deep aquifers and wells are often used for water supply, however they may take the longest to recharge. The middle and southern Ogallala contains wells with groundwater level declines seen in Clusters 2 and 3. Cluster 4 well depths vary around the mean, but do not have a consistent rising or declining trend. The depth distribution is similar to Cluster 3, though with fewer deep wells. The northern Ogallala contains wells in Clusters 1 and 4, indicating small to no change, and slight rising groundwater levels over time (**Figure 8B**). Other regions, including the Atlantic Coastal Plain, the lower Mississippi, and southern Idaho/eastern Utah, contain wells from all four clusters, suggesting that there is considerable heterogeneity in the wells in that region and local extraction patterns vary.

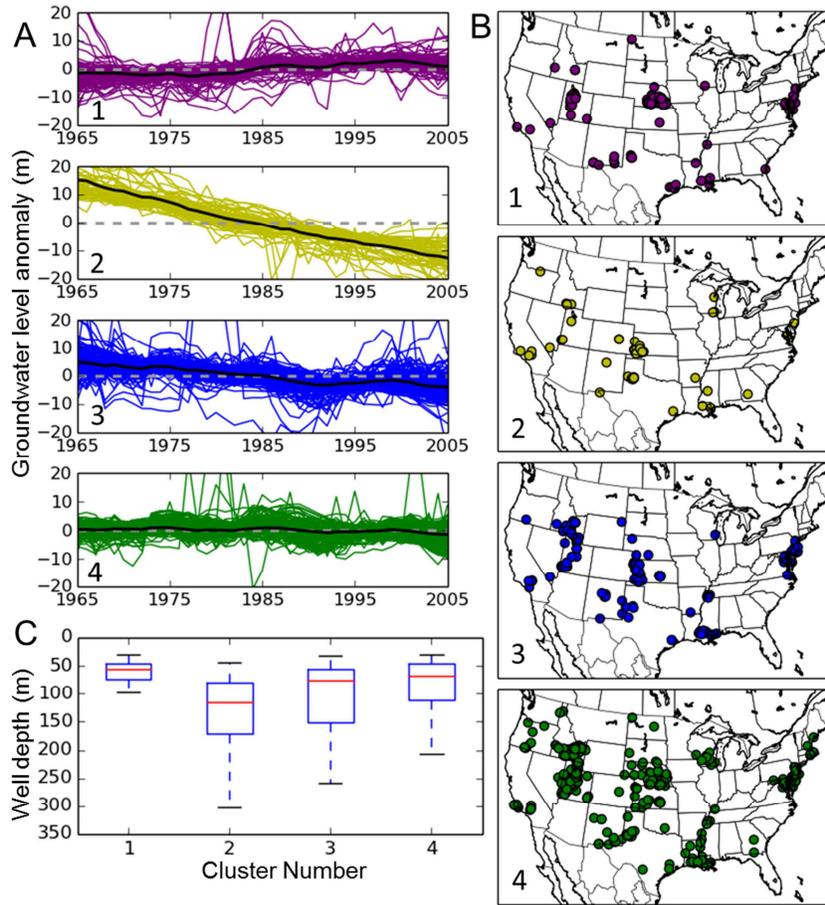


Figure 8 Cluster analysis of wells with continuous records from 1965 to 2005. **(A)** GW elevation normalized by the long-term mean for each of the four k-means clusters. Individual well records shown in color, mean shown in black. Negative slopes represent declining water levels. **(B)** Location of wells identified by color for each cluster. **(C)** Distribution of well depths for each cluster.

4.2. Relationship between Groundwater Elevation and Pumping

The median normalized groundwater extraction rates show a linear increase between 1985 and 2005, with the exception of a notably larger increase in pumping in 2000 (**Figure 9A and 9B**).

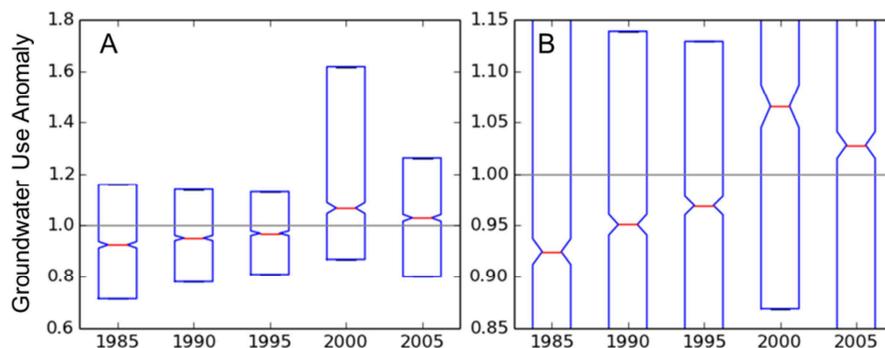


Figure 9 **(A)** Boxplot of groundwater use anomalies for all counties in each of the 5 years with water use data, **(B)** Detail of Figure 9A close to the mean.

We do not see a strong direct correlation between the area normalized groundwater extraction trend and the groundwater level trend for the period 1985 to 2005. A majority of counties do agree on the sign of the trends; groundwater extraction increases correspond with groundwater level declines. However, in some counties the relationship between pumping trend and groundwater trend is an inverse relationship. This indicates groundwater elevation changes cannot be explained exclusively by changes in pumping. To illustrate the spatial variability of the relationship between groundwater extraction trend and groundwater elevation trend, we overlay the two plots in map-view (**Figure 10**).

A majority of the counties with data have declining groundwater levels and increasing extraction rates, signified by yellow to red fill and horizontal hatching, respectively. These trends are most notable along the Mississippi River in Arkansas, Mississippi, and Louisiana, the southwest US, and the coasts of Virginia and North Carolina.

The groundwater extraction rate does not always correlate with groundwater level trends. Some counties with declining groundwater extraction still see declining groundwater levels. This combination of pumping and groundwater behavior is most notable in southern California, northern Nevada, southern Idaho, and some counties in northern Texas. Though the extraction rate is declining, its magnitude may still be high relative to the safe yield or sustainable extraction rate of the aquifer. Conversely, counties experiencing groundwater level rise in light of increasing groundwater extraction rates may be experiencing the opposite, where the relative magnitude of extraction rates are still within the sustainable limits, despite increases. This combination is most notable in the northern and southern regions of the Atlantic Coastal Plain. These counties should evaluate their groundwater balance and rates of use in more detail to determine where aquifer recharge or capture is coming from, and how long extraction can increase before it is no longer sustainable.

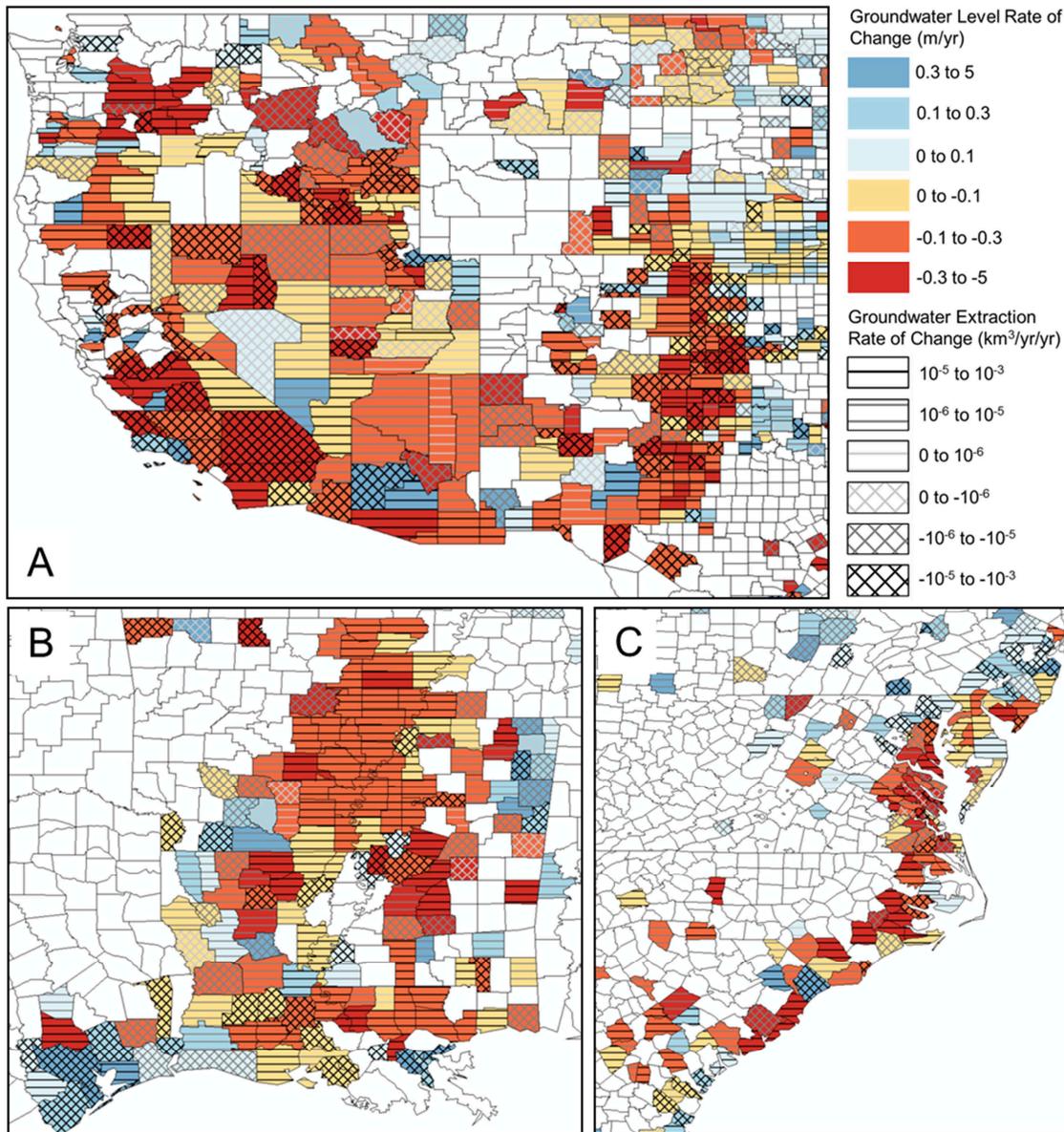


Figure 10 Groundwater extraction rate of change plotted on top of groundwater elevation rate of decline (1985 to 2005). Decreasing extraction rates shown with crosshatch, increasing extraction rates shown with horizontal hatch, increasing in grayscale. Rising groundwater elevations shown in blues, and declining groundwater elevations shown in yellow to red. White is no data. Areas shown: (A) Western United States, (B) Lower Mississippi River, and (C) Central Atlantic Coastal Plain.

4.3. Correlation between Groundwater Elevation and Climate

There are two common relationships between deep groundwater wells and local precipitation. Some wells have constant trends with minimal to no correlation with either local precipitation or long term climate (e.g. **Figure 11A,B,C**). Other deep wells wavelet spectra show an increase in power between the 8 to 16 year period band (e.g. **Figure 11D**) which often corresponds to oscillations seen in the precipitation spectrum (**Figure 11E,F**). This supports the general conclusion

that these deeper wells are either not affected by precipitation patterns, or respond to longer term climate cycles, rather than inter-annual rainfall variability.

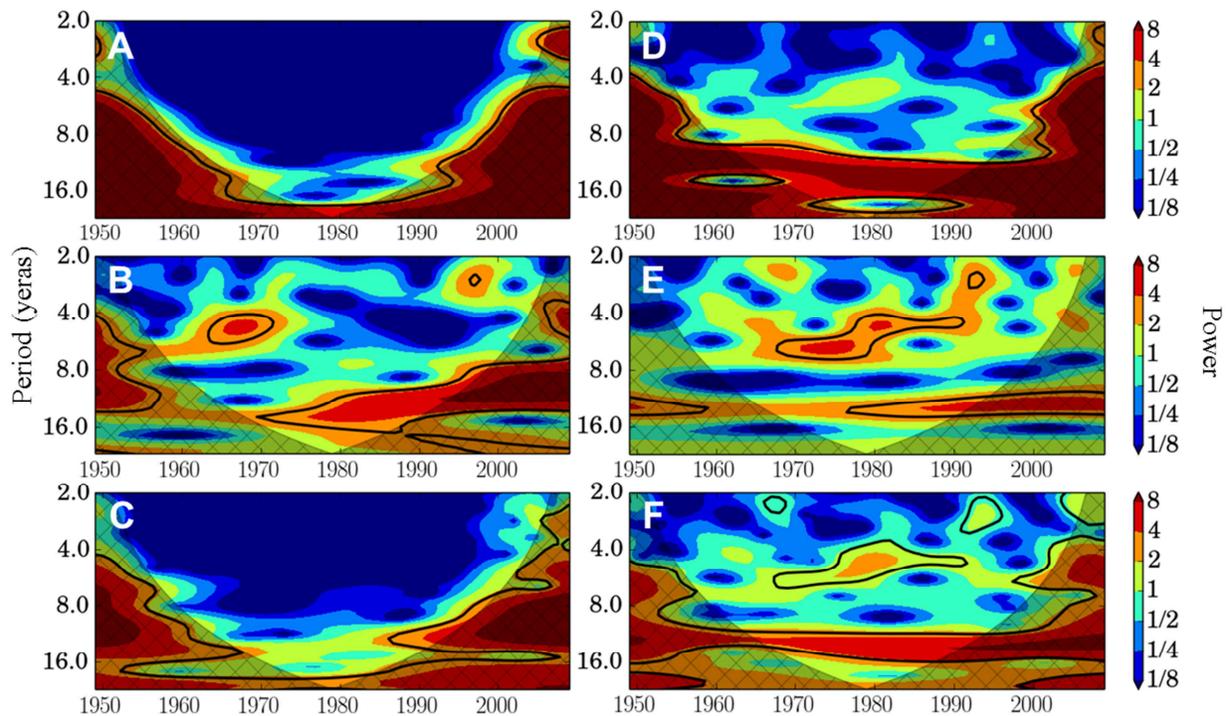


Figure 11. Wavelet and cross wavelet power spectra results for two groundwater level records with the local county precipitation records. (A) A 87 m deep well in eastern LA County, (B) spectrum for precipitation for LA County suggesting some power in the 8 to 16 year band post 1970, (C) cross wavelet power spectrum for groundwater level and precipitation indicating some commonality in the 8 to 16 year band post 1985, but this cannot be assessed reliably due to edge effects. (D) A 70 m deep well in southern Idaho (Minidoka County), near the Snake River showing strong periodic oscillations between 8 and 16 years, (E) spectrum for precipitation with a 4 to 8 year signal in the 1970 to 1990 period and a 12 to 16 year band active over the period of record, (F) cross wavelet power spectrum for groundwater level and precipitation in Minidoka County, indicating agreement both frequency bands identified for precipitation.

Further assessment is required to determine whether the dominant relationships between groundwater and climate can be broadly categorized across the country based on aquifer properties, well depth, pumping, and other parameters.

We find that the 5-yr groundwater trend anomaly correlates positively with the average PDO and NAO indices (Figure 12). Positive PDO and NAO generally result in more precipitation in the western and eastern US, respectively. Average precipitation over each 5-yr record suggests that nationally wetter years (positive precipitation anomaly), generally associated with a positive PDO index, result in smaller magnitude groundwater declines (Figure 12). The relationship between average precipitation anomaly and NAO is not as clear as for PDO. We see a stronger correlation between PDO and groundwater elevation trends, where five out of six wet periods correspond to positive indices, and the smallest groundwater declines of the study period.

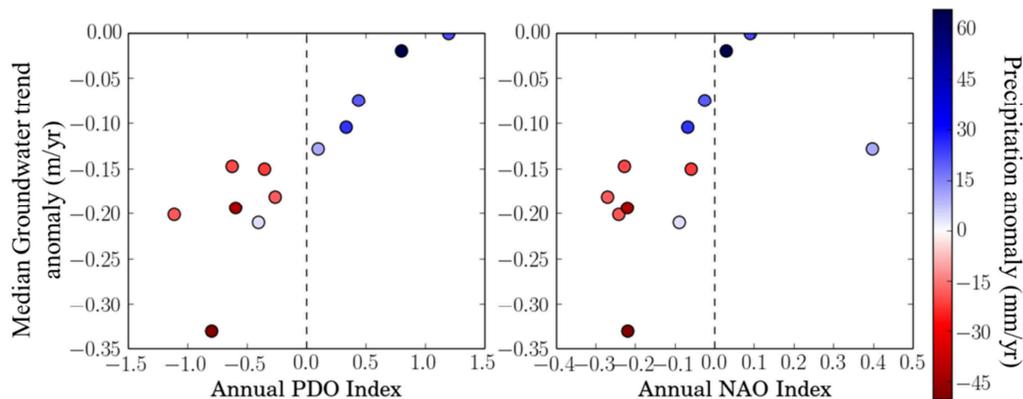


Figure 12 Five year average (A) PDO and (B) NAO Index values plotted against the 5-yr average groundwater elevation trend anomaly (the long-term average is removed). Point color indicates 5-yr precipitation anomaly averaged over US (red = lower precip, blue = higher precip).

The average NAO indices are negative for a majority of the study period, with positive values occurring in the 1980s and 1990s (**Figure 3**). The PDO cycling is similar, with negative indices on average until 1980, followed by positive indices for the remainder of the study time period except for the early 2000s. The positive PDO indices in the 1980s and 1990s may explain the groundwater elevation recovery through much of the west during wet conditions (**Figure 6**). Wet conditions appear to correspond to smaller groundwater declines, possibly due to increased groundwater recharge and/or less pumping for irrigation and other uses. Similarly, positive NAO indices and wet conditions in the eastern US may contribute to the groundwater elevation recovery along the northern Atlantic Coast, and the increase in rate of groundwater rise for wells with long-term rising trends (**Figure 7**).

5. Comparison to other US Groundwater Studies

We compare our results to previous studies of groundwater depletion and groundwater stress. Groundwater depletion calculated by Wada et al. (2010) for the year 2000 only exceeds 2mm (0.08 in) west of 95°W, including the Ogallala, select regions in the southwest and northwest, and California (**Figure 13A**). Our study of the historic groundwater levels suggests groundwater depletion covers a much greater area of the United States, including much of the southeastern US and Atlantic Coastal Plains (**Figure 13B**). Further analysis of aquifer storativity and thickness is needed to determine whether depletion volume in these regions is comparable to the areas in the western US.

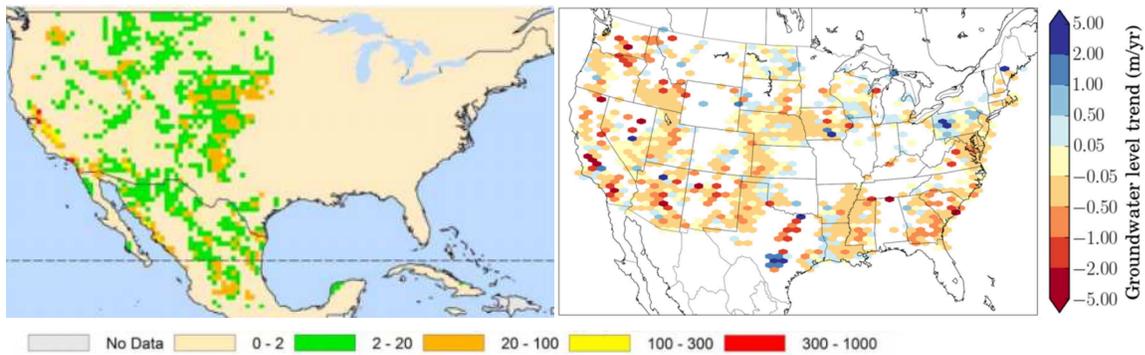


Figure 13. (A) Groundwater depletion for the year 2000 in mm/yr (modified from Wada et al. (2010)), (B) Average groundwater elevation declines between 1998 and 2002. N.b. groundwater depletion rate is not directly comparable to changes in groundwater level trend without accounting for aquifer storativity, which is not included in this study.

Groundwater depletion estimates were assembled by Konikow (2013), using a synthesis of studies for the major US aquifers spanning between 1900 and 2008 (**Figure 14**). The results highlight the depletion in the California central valley and the Ogallala aquifers. This paper also captures the depletion along the lower Mississippi, though suggests relatively minimal depletion along the Atlantic Coastal Plain. The results contrast the present study primarily in the amount of recharge occurring in the Northwest volcanic systems (Columbia River, WA and Snake River, ID), and possibly the Atlantic Coastal Plain. The latter areas show high groundwater trend variability in both space and time, with no clear indication of significant recharge (**Figure 6, Figure 13B**). The storativity of the aquifers is needed to quantitatively compare the rates of groundwater level change to the depletion volumes.

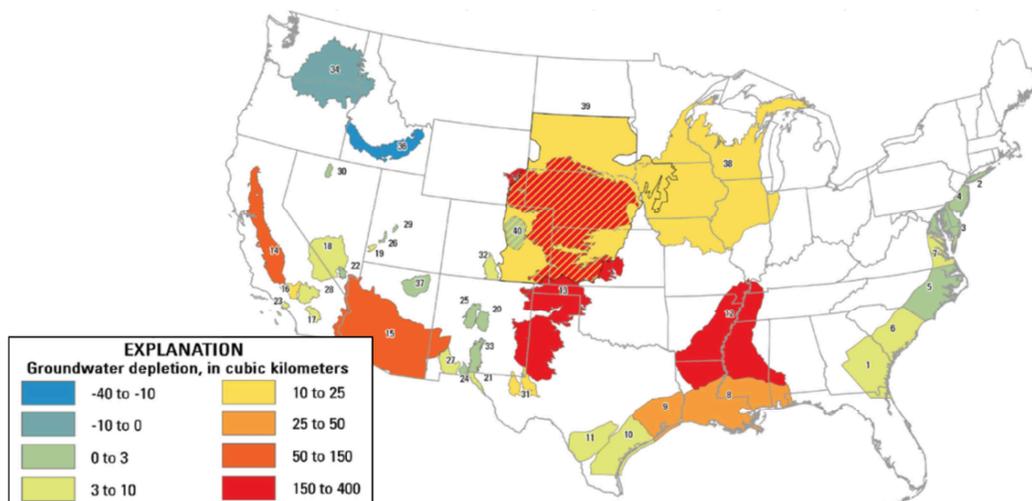


Figure 14. Groundwater depletion estimates, modified from Konikow (2013).

6. Summary

Analysis of historical groundwater level records indicates groundwater levels declined between 1949 and 2009 throughout much of the continental US. Most notably, groundwater level declines in the southern and eastern US are comparable to declines in areas of the often-discussed water stressed areas of the Ogallala and southwest US. Results suggest significant downward trends in water storage over several decades, however rates of groundwater depletion cannot be inferred from groundwater level changes without knowing aquifer storativity. As the groundwater levels decline, impacts may include increased energy consumption for pumping, requirement of deeper wells, and irreversible consequences including permanent aquifer compaction and land subsidence.

The causes of groundwater level change are multifaceted, varying in time and space across the US. In this study we found correlations between pumping rate and groundwater level in a majority of counties. However, there are a number of counties with contrasting changes in pumping rates and groundwater trends, for example increasing pumping rates and rising groundwater levels in the northern and southern extents of the Atlantic Coastal Plain. Climate is a clear controlling factor on groundwater levels. Due to the focus on deep wells, we found minimal correlation with inter-annual precipitation patterns, though on average the wells correlated with the long-term climate patterns, and specifically with the PDO.

Groundwater is increasingly relied on as a critical resource for meeting everyday water demands and buffering variability in surface water supply. Overall, the US is extracting groundwater at unsustainable rates, causing long-term groundwater level declines and loss of groundwater storage. The dynamics of extraction, recharge, and changes in the surface water – groundwater balance are complicated and variable across the US. A national scale study or model of these dynamics would be time and computationally prohibitive. Results from this study can be used to identify regions within the US where a more detailed aquifer or sub-aquifer scale analysis is required to improve groundwater management.

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