Appendix 3-1: Well Impact Analysis

Vulnerable well impact analysis in the Sierra Valley Subbasin: well inventory, historical groundwater trends, and analysis to inform Sustainable Management Criteria

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1. Executive Summary

Groundwater planning under the Sustainable Groundwater Management Act (SGMA) aims to curb the chronic lowering of groundwater levels, which may impact shallow, vulnerable wells and cause dewatering or failure. Relatively shallow residential, agricultural, and public wells (henceforth “vulnerable wells”) in the Sierra Valley Subbasin (SV) are beneficial uses of groundwater identified by stakeholders in the SV groundwater sustainability plan (GSP) working group. Residents and water users in the SV that rely on drinking water obtained from private domestic wells are considered beneficial users of groundwater. The GSP aims to halt the chronic groundwater level decline that can lead to significant and unreasonable impacts to vulnerable wells that hamper access to water for drinking, irrigation, and municipal/industrial use.

Although shallow wells in the SV provide beneficial uses of groundwater, the SV lacks a comprehensive well census (i.e., inventory) for domestic wells and understanding of how sustainable management criteria (SMC) may impact vulnerable wells in the SV. These knowledge gaps motivate this memorandum, which aims to provide a well inventory based on best available data, and well protection analysis to inform critical decision-making in support of unstainable groundwater management in the SV.

No wells in the SV were reported dry during the past 2012-2016 drought. Herein, we assess potential impacts to vulnerable wells that may result during the SGMA planning and implementation period (2022-2042). First, we take inventory of wells in the SV using publicly available, digitized well completion reports to describe the location and depths of different types of wells (e.g., domestic, public, agricultural). Next, we analyze historical groundwater elevation trends in the SV from 2000-2020. Then, we combine well construction data and modeled groundwater levels to assess the count and location of impacted wells assuming different groundwater level scenarios (i.e., a return to the fall 2015 low, and established groundwater level minimum thresholds, or MTs). Finally, we advance recommended sustainable management criteria that mitigate impacts to vulnerable wells.

Results suggest that the most common well types with direct beneficial uses are domestic (n = 540), agricultural (n =105), public (n = 22) and industrial (n = 6) wells[1], although the actual number of “active” wells today is likely less due to ageing and well retirement. Assuming 31 to 40 year retirement ages (based on Pauloo et al, 2020), and that wells with pumps above initial groundwater level conditions are inactive, the number of assumed active wells in the SV is much lower: domestic (n = 325 - 450), agricultural (n = 57 - 61), public (n = 14 - 21), and industrial (n = 1). An ongoing well “census” would supersede these data, but in its absence, this approach provides a reasonable approximation of the count and location of active wells.

During fall of 2015, groundwater levels reach a [modern] historical low in the SV after four consecutive years of drought and excess pumping to augment lost surface water

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[1] At the time of writing (2021-09-12), these are the well counts provided by the online well completion report database. Note that “public” wells are municipal wells, and “domestic” wells are private residential wells.

supply. Data from the DWR and Cal OPR suggests that during this time, no wells in the SV were reported dry, in contrast to more than two thousand wells reported dry across California (Pauloo et al, 2020)[2]. Thus, a return to Fall 2015 groundwater level lows is unlikely to result in catastrophic and widespread well impacts, which we confirm via modeling described in this memorandum.

For the purposes of this study, we assume significant and undesirable results to occur when 5% or more of wells of any type (domestic, agricultural, public, industrial) are impacted. Thus, well impact analysis under projected groundwater level conditions was evaluated to assess impacts assuming a return to historic Fall 2015 lows, and projected groundwater level MTs. Results suggest that even assuming a worst-case scenario where all representative monitoring points (RMPs) reach MTs at the same time, only domestic wells are impacted on the order of 2% (n = 6 - 10). Thus, all well types are highly unlikely to impacted at the 5% undesirable result threshold.

Well protection analysis thus informed and validated minimum thresholds (MTs) which avoid significant and unreasonable impacts to wells in the basin. Possible well protection measures may include a combination of regional groundwater supply and demand management (e.g., managed aquifer recharge and pumping curtailments that increase or maintain groundwater levels); well protection funds to internalize well refurbishment and replacement costs; domestic supply management, (e.g., connecting rural households to more reliable municipal water systems); and proactive community-based monitoring that acts as an early warning systems to anticipate impacts at the level of individual wells.

[2] Outage data analyzed by Pauloo et al (2020) was provided via an agreement between Cal OPR and the authors, but has since been released by the DWR at MyDryWaterSupply: https://mydrywatersupply.water.ca.gov/report/publicpage.

2. Introduction

Around 1.5 million Californians depend on private domestic wells for drinking water, about one third of which live in the Central Valley (Johnson and Belitz 2016). Many fewer wells are found in the Sierra Valley Subbasin (SV), and these wells tend to be in mixed agricultural-residential land. Private domestic wells are more numerous than other types of wells (e.g., public or agricultural), and tend to be shallower and have smaller pumping capacities, which makes them more vulnerable to groundwater level decline (Theis 1935; Theis 1940; Sophocleous 2020; Greene 2020; Perrone and Jasechko 2019). During previous droughts in California, increased demand for water has led to well drilling and groundwater pumping to replace lost surface water supplies (Hanak et al 2011; Medellín-Azuara et al 2016). Increased pumping lowers groundwater levels and may partially dewater wells or cause them to go dry (fail) altogether. During the 2012–2016 drought, 2,027 private domestic drinking water wells in California's Central Valley were reported dry (Cal OPR 2018). Notably, zero dry wells were reported in the SV, which suggests a combination of relatively stable groundwater levels and more favorable well construction properties (e.g., deeper wells and pump locations). Moreover, this observation implies that a return to 2015 low groundwater levels would not cause widespread and catastrophic well failure in the SV.

Until recently, few solutions and data products existed that addressed the vulnerability of shallow wells to drought and unsustainable groundwater management (Mitchell et al. 2017; Feinstein et al. 2017). A lack of well failure research and modeling approaches can largely be attributed to the fact that well location and construction data (well completion reports, or WCRs) were only made public only in 2017. Released digitized WCRs span over one hundred years in California drilling history and informed the first estimates of domestic well spatial distribution and count in the state (Johnson and Belitz 2015; Johnson and Belitz 2017). Since then, these WCRs, provided in the California Online State Well Completion Report Database (CA-DWR 2018), have been used to estimate failing well locations and counts (Perrone and Jasechko 2017), and domestic well water supply interruptions during the 2012–2016 drought due to overpumping and the costs to replenish lost domestic water well supplies (Gailey et al 2019). A regional aquifer scale domestic well failure model for the Central Valley was developed by Pauloo et al (2020) that simulated the impact of drought and various groundwater management regimes on domestic well failure. More recently, Bostic and Pauloo et al (2020), EKI (2020), and Pauloo et al (2021), estimated the impact of reported groundwater level minimum thresholds in critical priority basins on domestic wells across California's Central Valley and found that thousands of domestic wells were potentially vulnerable.

California's snowpack is forecasted to decline by as much as 79.3% by the year 2100 (Rhoades et al 2018). Drought frequency in parts of California may increase by more than 100% (Swain et al 2018). A drier and warmer climate (Diffenbaugh 2015; Cook 2015) with more frequent heat waves and extended droughts (Tebaldi et al 2006; Lobell et al 2011) will coincide with urban development and population growth, land use change, conjunctive use projects, and implementation of the Sustainable Groundwater Management Act (SGMA 2014), in which groundwater sustainability plans (GSPs) will specify groundwater level minimum thresholds (MTs) that among other outcomes, protect vulnerable wells.

In this technical memorandum, we analyze how projected hydrologic conditions may impact vulnerable wells in the SV, and acknowledge that results are limited by the uncertainty on the actual number and/or construction information available for domestic wells in the SV. In Section 3, the methodology is explained, followed by the results in Section 4, and a discussion of the results in terms of how they impact sustainable groundwater management in Section 5. This memorandum closes with a discussion of future actions and SGMA management recommendations.

3. Methods

Key data that inform this analysis include seasonal groundwater level measurements taken by various state-level and local sources, and well completion reports (WCRs) from the California Department of Water Resources (CA-DWR 2018).

3.1 Groundwater level

Historic and present-day groundwater conditions were analyzed using all available data from the California Department of Water Resources (DWR) Periodic Groundwater Level Database. Most groundwater level data is collected biannually in spring and fall and intended to capture seasonal variation – notably due to winter recharge and pumping and recharge during the dry growing season.

Duplicate measurements between data sources were reconciled by comparing monitoring site identification codes and position (latitude and longitude).

Groundwater levels were assessed at biannual seasonal intervals during the period from spring 2000 to fall 2020 and encompass what can be considered “historic”[3] to approximately “present-day” seasonal conditions. This temporal range was selected because poor data density prior to spring 2000 and after fall 2020 prohibits meaningful analysis. “Spring” was defined as the months of March, April, and May and “fall” was defined as the months of August, September, and October.

At each monitoring location, the average groundwater level measured during spring and fall was computed by taking the grouped mean of observations in each spring and fall respectively. Next, to improve spatial data density and ascertain long-term regional trends, data were arranged in 4-year running seasonal means. For example, the 2000-2003 spring level is defined as the average spring groundwater elevation in 2000, 2001, 2002, and 2003. A four-year sliding window was applied to data from 2000 to 2020, resulting in 36 seasonally averaged groundwater elevation conditions (e.g., spring 2000-2003, fall 2000-2003, …, spring 2017-2020, fall 2017-2020). Windows of differing length (e.g., 1, 2, and 3-year long running means) were explored but resulted in larger groundwater level variance due to a lack of adequate spatial density, and hence, not used. By contrast, 4 year running means gave adequate regional spatial data density and were not so long in duration as to dampen the impact of significant dry periods such as the 2012-2016 drought.

After data were grouped into seasonal 4-year windows, ordinary kriging[4] (Journel A.G. and Huijbregts, 1978) was applied to groundwater elevation measurements to generate

[3] Importantly, this period contains the recent 2012-2016 drought.

[4] An exponential variogram model was used, and results did not appreciably differ from linear or spherical models. Stationarity across the unconfined to semiconfined aquifer is a reasonable assumption in the unconsolidated, alluvial aquifer-aquitard system that spans Sierra Valley. Data outliers were controlled by removing tails of the distribution above and below the 97.5th and 2.5th percentiles respectively. Groundwater elevations were approximately normal in distribution, thus log-transformation and exponentiation after kriging was not required.

groundwater level surfaces across the SV at a 500 meter (0.31 mile) resolution. Groundwater level measurements were screened to include data from wells shallower than 300 feet in total completed depth to reflect conditions in the unconfined to semiconfined production aquifer.

3.2 Well Completion Reports (WCRs)

The well completion report database (CA-DWR, 2020) was used to filter and clean WCRs within the SV. Similar well types were grouped into categories (e.g., "domestic", "private residential", and "residential" were all grouped together) to enable analysis of wells by type. The majority of wells are accurate to the centroid of the nearest section in the PLSS Survey system (1 square mile grid cells). All wells reviewed in the SV had a total completed depth.

3.4 Projected groundwater management

Well impacts are characterized in terms of historical data and future, anticipated hydrology. Forward-simulated hydrologic conditions based on groundwater level MTs were assessed to ensure that MTs would not significantly and unreasonably impact wells.

Differences in groundwater level between each of the scenarios tested (i.e., fall 2015, and the MT scenario) and the "baseline" inform how wells in the basin may respond to historical drought projected groundwater management.

3.3 Classification of failing wells and cost estimate

The initial set of wells to consider are a subset of all domestic wells in the WCR database. Wells are removed based on the year in which they were constructed[5], and their estimated pump location relative to the initial groundwater level condition prior to impact analysis. In other words, wells that are likely to be inactive, or already dry at the initial condition are not considered, and do not count towards the well impact count.

Next, we assign a "critical datum"[6] to each well, equal to 30 feet above the total completed depth, roughly 3 times the height of water column required to prevent

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[5] Two previous studies estimate well retirement ages at 28 years in the Central Valley (Pauloo et al 2020), and 33 years in Tulare county (Gailey et al 2019), thus, we use the average of these two studies and remove wells older than a retirement age of 31 years. To account for uncertainty in the well retirement age, we also consider another well retirement age of 40 years. Importantly, these numbers reflect mean retirement ages in the retirement age distribution. Although some wells in the population may be active for longer than 31 or 40 years, some will also retire before 31 or 40 years. Thus, results should be interpreted as an average estimate of well impacts.

[6] A standard approach for the choice of a critical datum is not well established. Other studies (e.g., Gailey et al, 2019; Pauloo et al, 2020; Bostic and Pauloo et al, 2020; Pauloo et al, 2021) estimate pump locations in different ways. Since considerable uncertainty exists in estimating pumps at a local scale, but WCR data for total completed depth is present and reliable for nearly all wells in the dataset, it is favored. An operating margin of 30 feet added to the bottom of each well's total completed depth is a reasonable

decreased well function and cavitation as calculated by Pauloo et al 2020 using standard assumptions of pumping rate, net positive suction head, barometric pressure head, vapor pressure, and frictional losses (see Pauloo et al 2020, SI Appendix Section S2.3). If groundwater level scenarios imply a groundwater elevation below this critical datum, the well is considered "impacted" and may require pump lowering or well deepening to rehabilitate it (**Error! Reference source not found.**).

In reality, wells dewater and experience reduced yield when the groundwater level approaches the level of the pump. However, for the purposes of this study, we assumed wells maintain the net positive suction head (Tullis 1989) required to provide uninterrupted flow until groundwater falls below the critical datum. At this point, we assume the well needs replacement (i.e., a well deepening event). Therefore, the well impact estimates provided in this study should be interpreted as a worse-case scenario wherein wells can no longer access reliable groundwater and are deepened. In most cases, pumps will be able to be lowered into the 30 foot operating margin prior to a deepening event – this is more affordable than a well deepening, so the impact estimate is conservative in this sense.

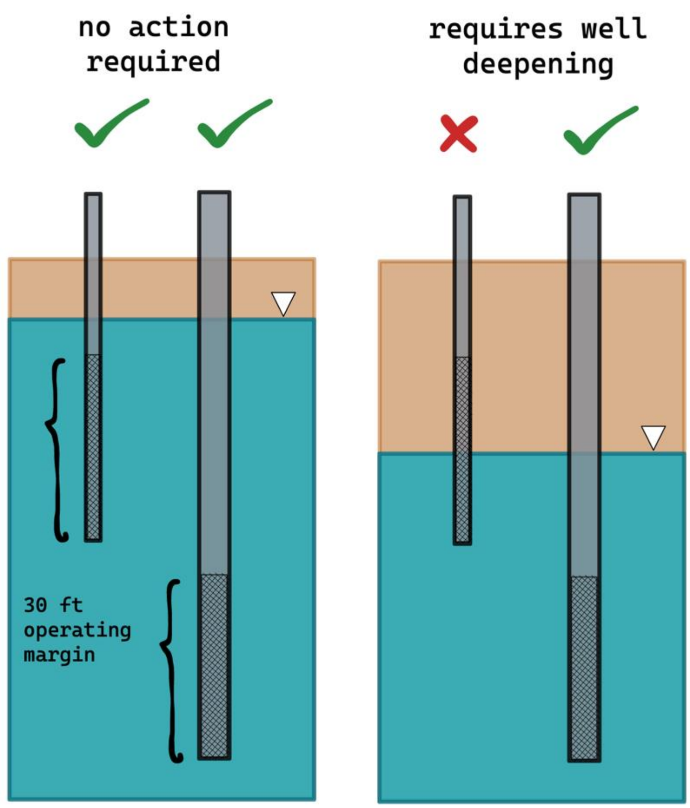

Figure 1: Wells are assigned a 30 foot operating margin above the total competed depth. When groundwater levels are above this "critical datum" at a well, the well is active (left), and the well is impacted when the groundwater falls

column of water necessary for the well to properly function, although wells with greater pumping capacities may require a longer water column.

below the critical datum, which triggers a well deepening event. Note that in reality, cones of depression form around active pumping wells, but are not shown in the figure above for simplicity.

4. Results

4.1 Groundwater levels

Groundwater level analysis in this memorandum is consistent with that conducted in Chapter 2 of the GSP. The lower and upper bookends of the groundwater level estimates (Figure 2 and Figure 3) demonstrate characteristic seasonal oscillation and increasing depth to groundwater in the central portion of the basin used for agricultural purposes.

Key groundwater levels include the initial condition (average 2020 levels), and 2 boundary conditions at which well impacts are evaluated. The first boundary condition is the Fall 2015 low, and the other is the projected MT.

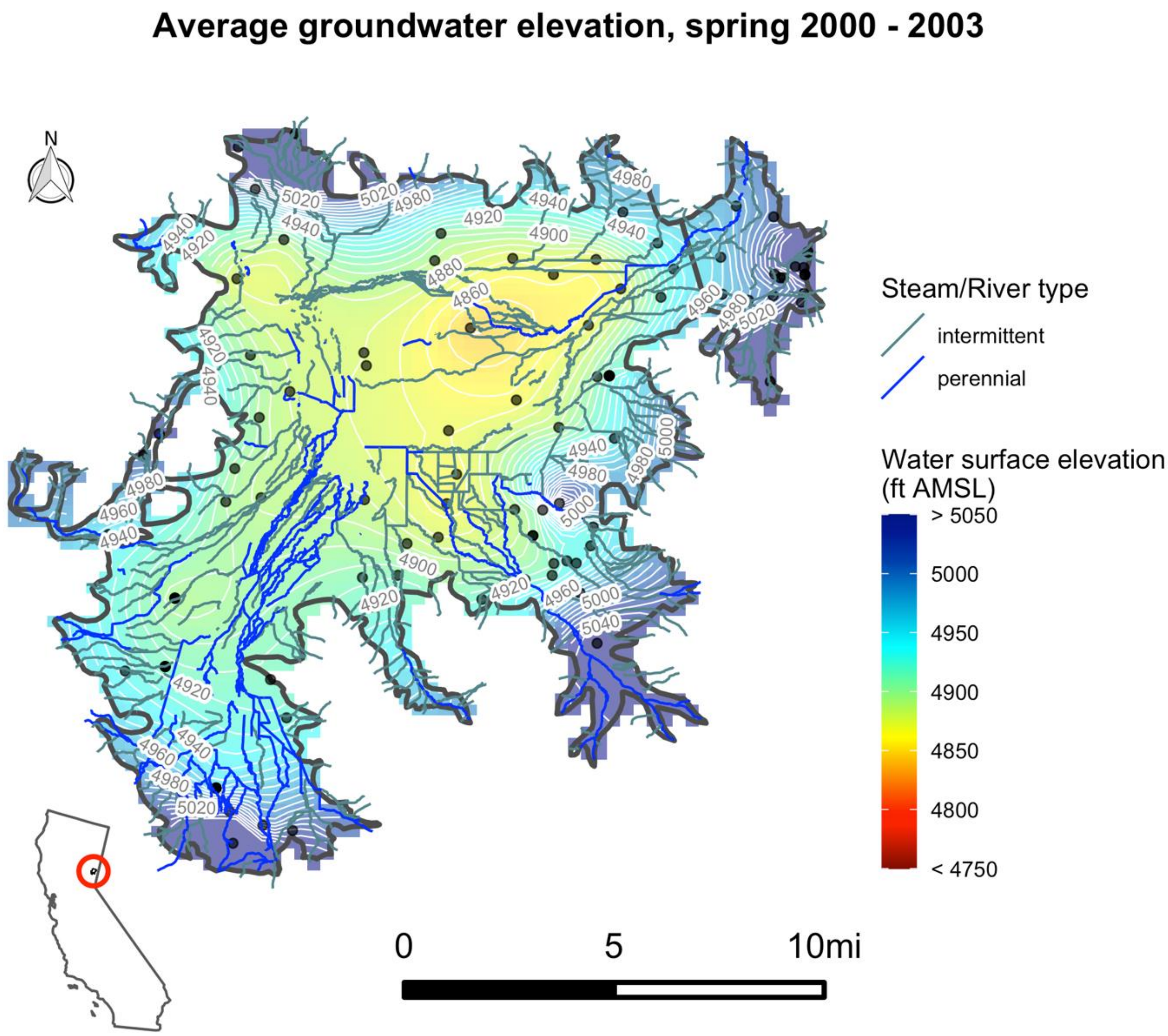

Figure 2: Estimated groundwater elevation for spring 2000 – 2003.

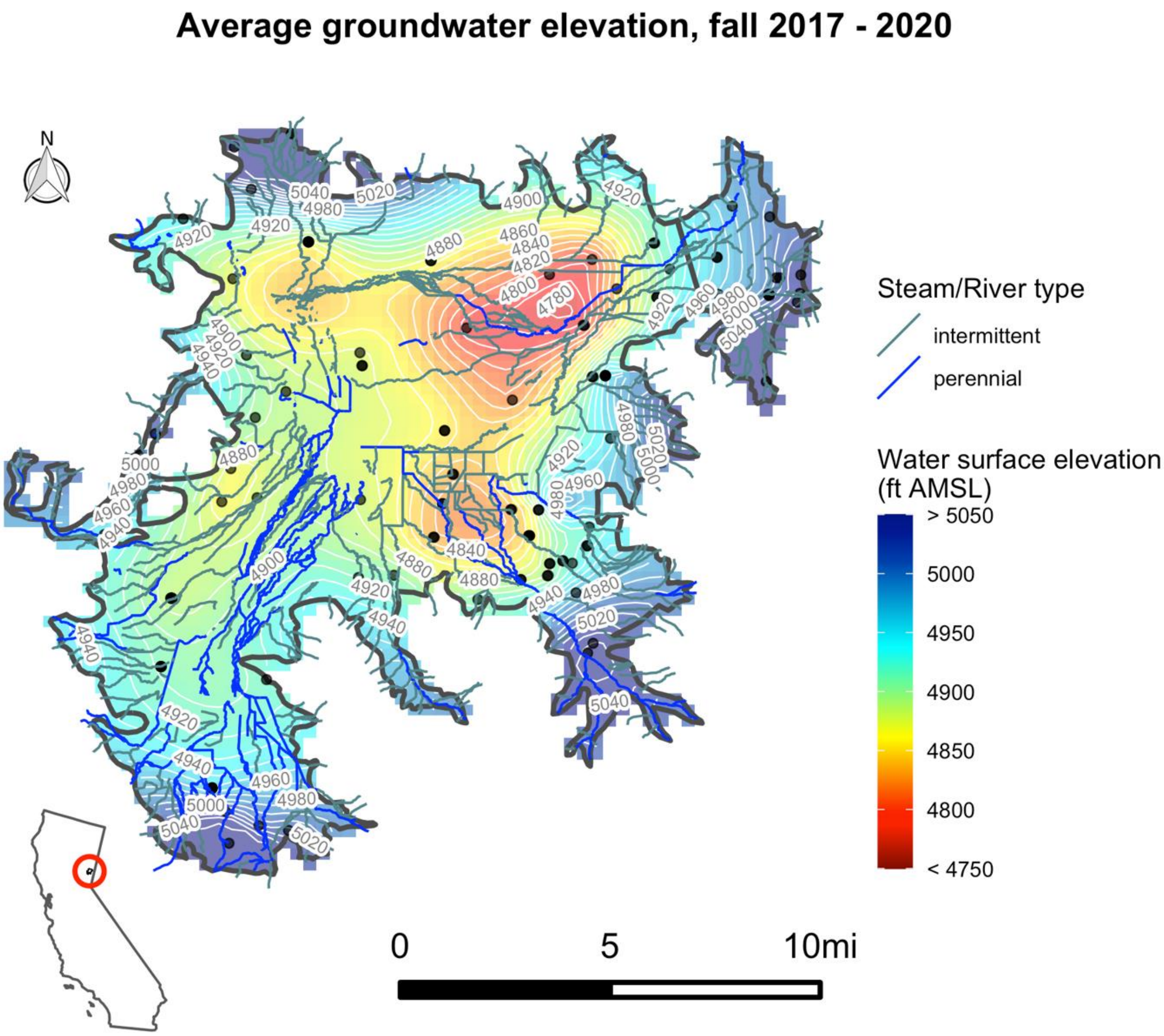

Figure 3: Estimated groundwater elevation for fall 2017 – 2020.

4.2 Well inventory and characteristics

Results suggest that the most common well types (Figure 3) with direct beneficial uses are domestic (n = 540), agricultural (n =105), public (n = 22) and industrial (n = 6) wells , although the actual number of “active” wells today is likely less due to ageing and well retirement. Assuming 31 to 40 year retirement ages (based on Pauloo et al, 2020), and that wells with pumps above initial groundwater level conditions are inactive, the number of assumed active wells in the SV is lower (Figure 5): domestic (n = 325 - 450), agricultural (n = 57 - 61), public (n = 14 - 21), and industrial (n = 1).

Most wells are deeper than long-term average depths to groundwater in the SV (Figure 6) and newer wells tend to be deeper

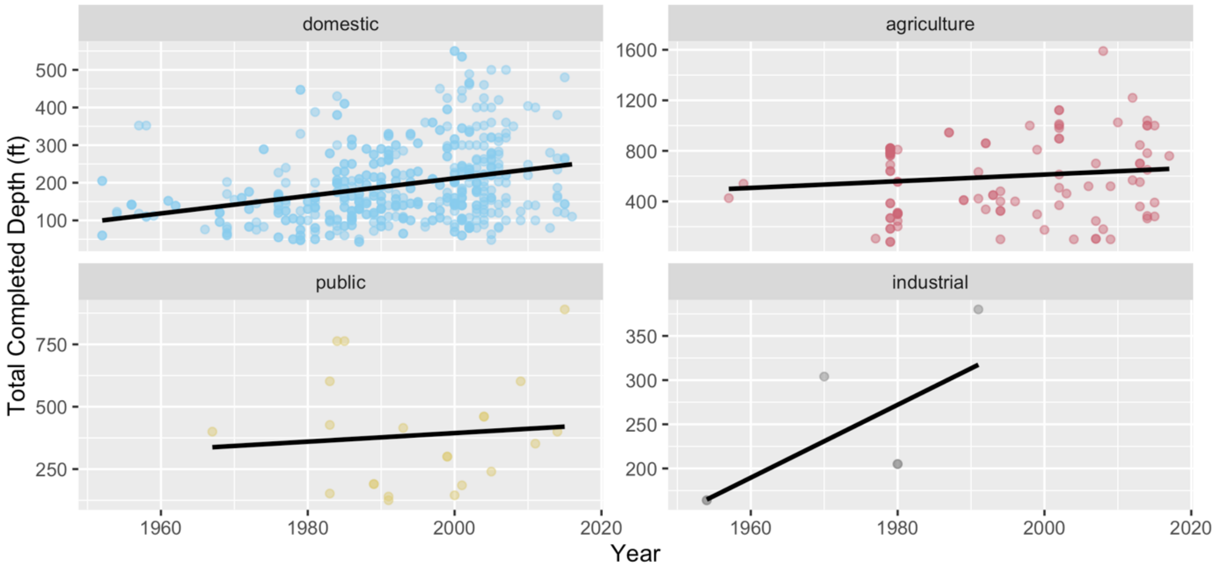

Figure 7), which suggests a buffer against potential well impacts from declining groundwater levels, especially for newer wells. Wells are drilled deeper over time largely due to improvements in drilling technology and the need for deeper groundwater unimpacted by surface contaminants and with sufficient transmissivity to support well yield targets.

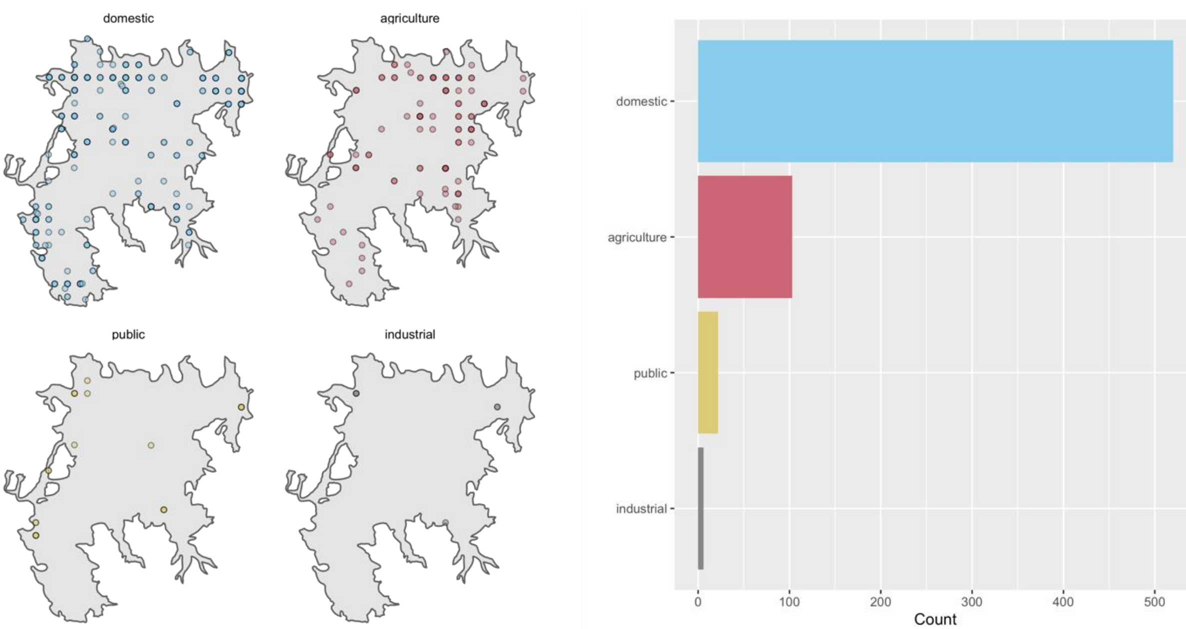

Figure 4: Estimated active well location (left) and count (right) in the Sierra Valley for major well types. Points are semi-transparent to improve visibility. Where points appear more opaque, this indicates multiple wells at the same section centroid.

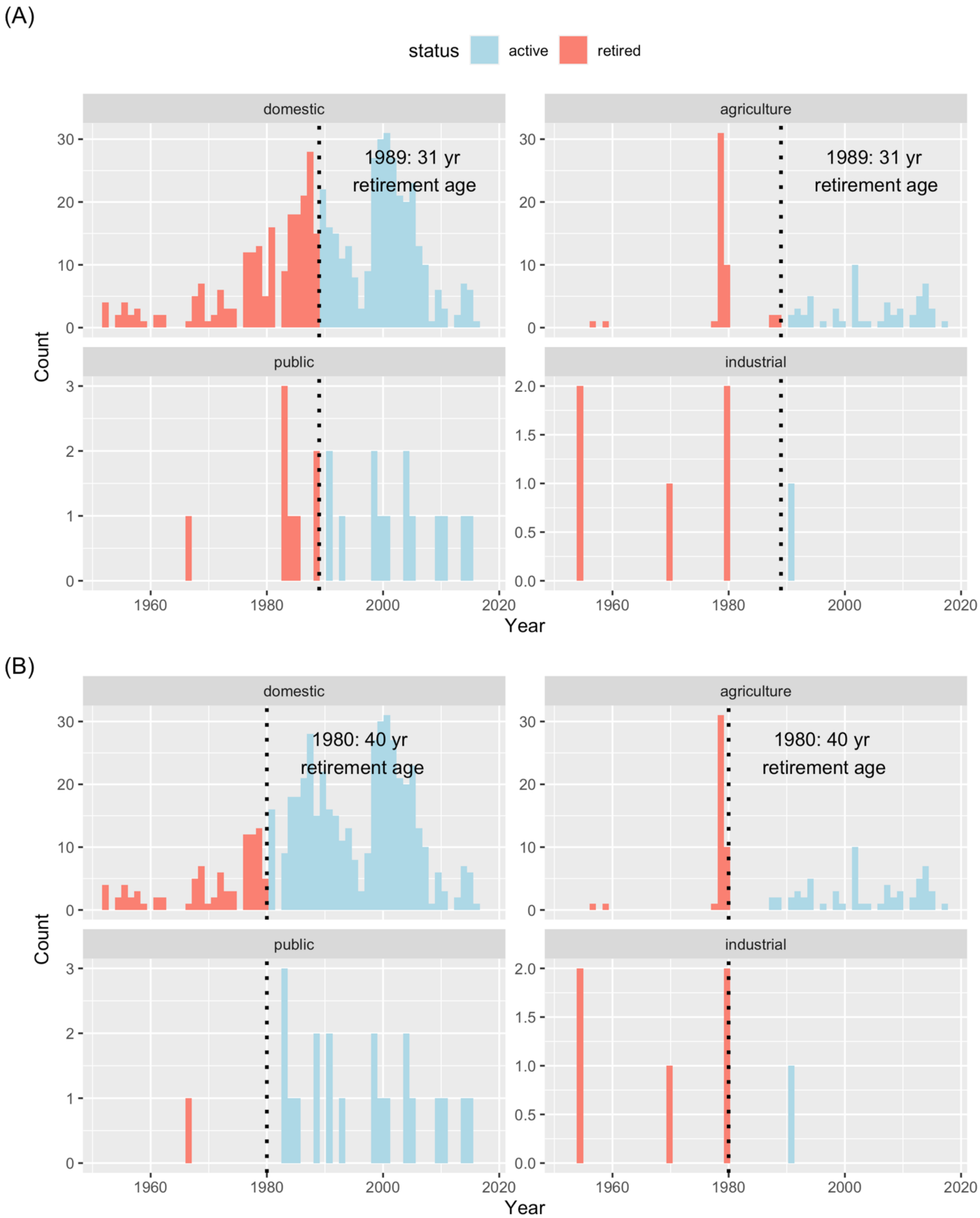

Figure 5: Well retirement ages of (A) 31 years and (B) 40 years were used to determine a likely range of active wells in the basin. The effect of retirement age on the determination of active wells depends on the count of wells drilled per year.

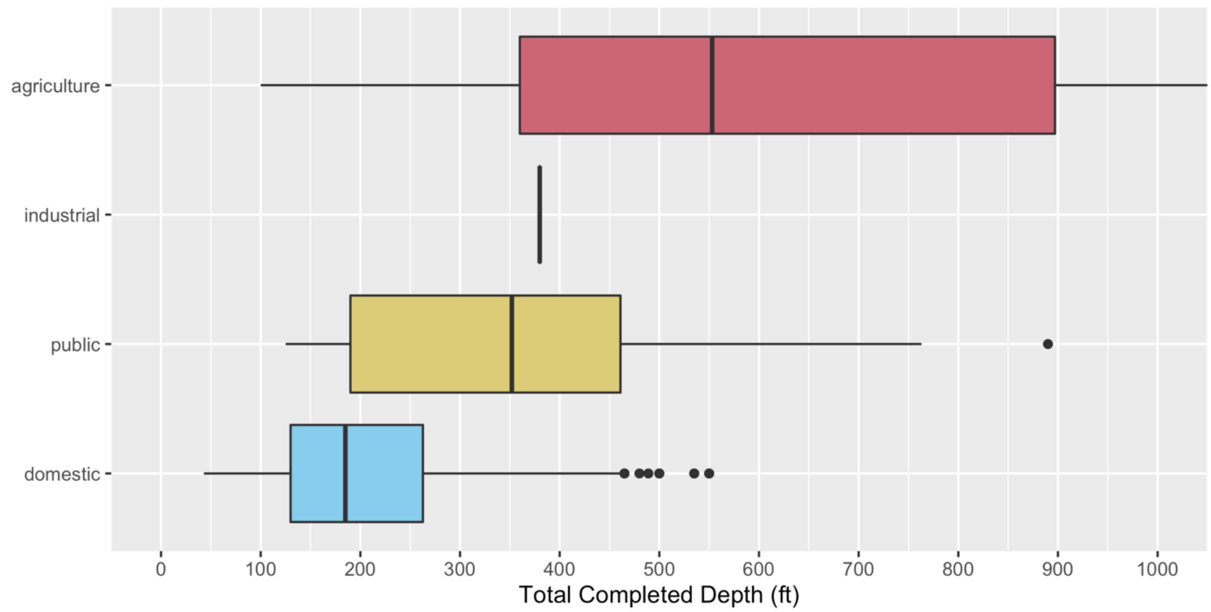

Figure 6: Total completed depth of active wells per well type. Agricultural wells tend to be the deepest, followed by public and domestic wells. Very few industrial wells exist in the basin (n = 7) and of these, only 1 is estimated to be active.

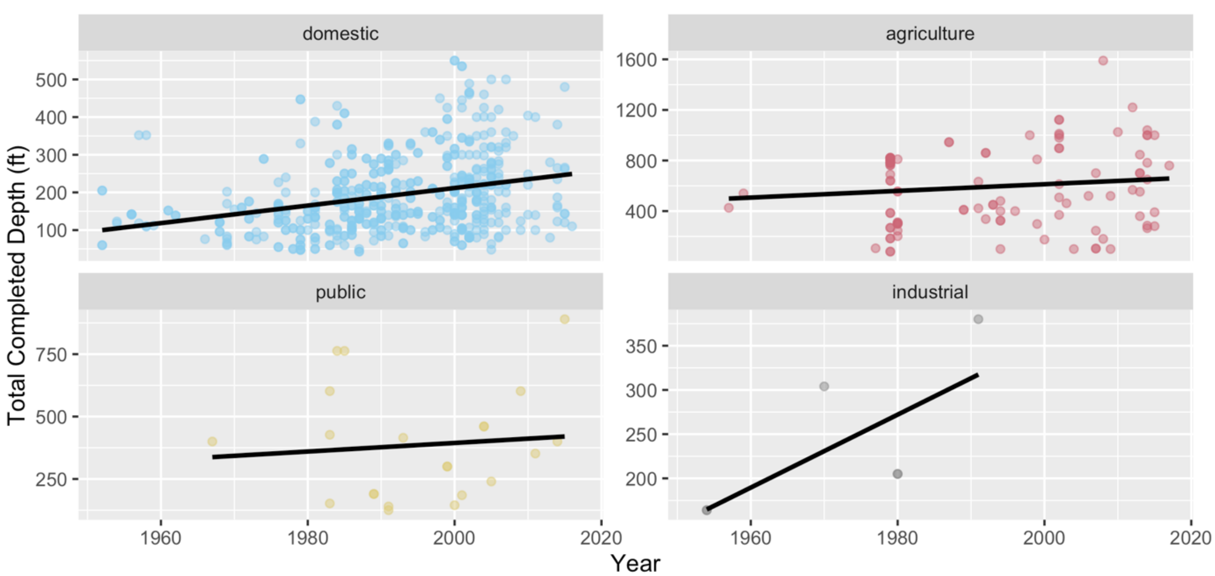

Figure 7: Total completed depth of wells has generally increased over time for all well types.

4.3 Well impacts: location, count, and cost

The difference between roughly present-day groundwater levels (average 2020 levels) and Fall 2015 lows is very similar the difference between present-day conditions and proposed MTs (Figure 8). Thus, a return to Fall 2015 levels, as well as those implied by MTs will likely show little appreciable difference on well impacts. This observation is supported by the well impact analysis, which finds that only 2% of domestic wells (n = 6 -10) are impacted at groundwater level MTs, and that no other well types are impacted (Figure 9 and Table 1). Moreover, the point patterns of estimated active and dry wells do not appreciably differ when considering 31 and 40 year retirement ages, which suggests little dependence of impact on retirement age (Figure 9). Impacted wells are minimal and tend to occur near basin boundaries where groundwater level data is most uncertain, suggesting possible model artifacts.

These results are unsurprising, as well depths are relatively deep compared to groundwater elevations, and MTs do not begin to approach depths that intersect the critical datum of most wells.

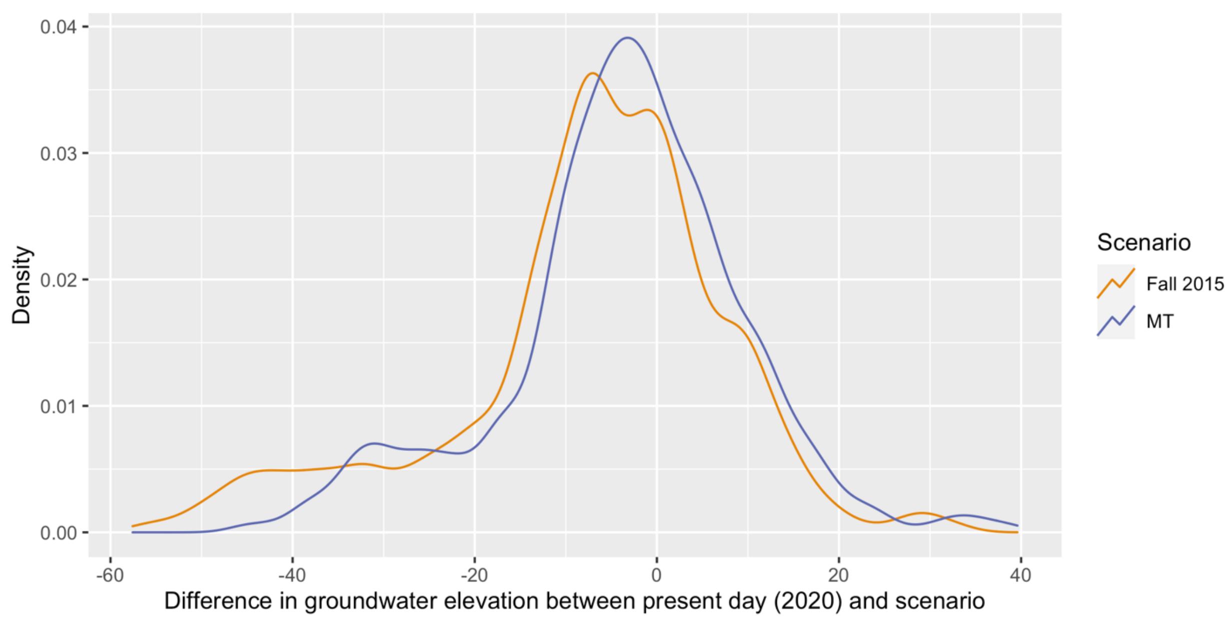

Figure 8: Groundwater level difference between a present day (2020) scenario and both the Fall 2015 groundwater level (orange line) and the MT scenario (blue line) is roughly equivalent, which suggests that groundwater levels do not vary considerably between these where MTs are set and historically observed values.

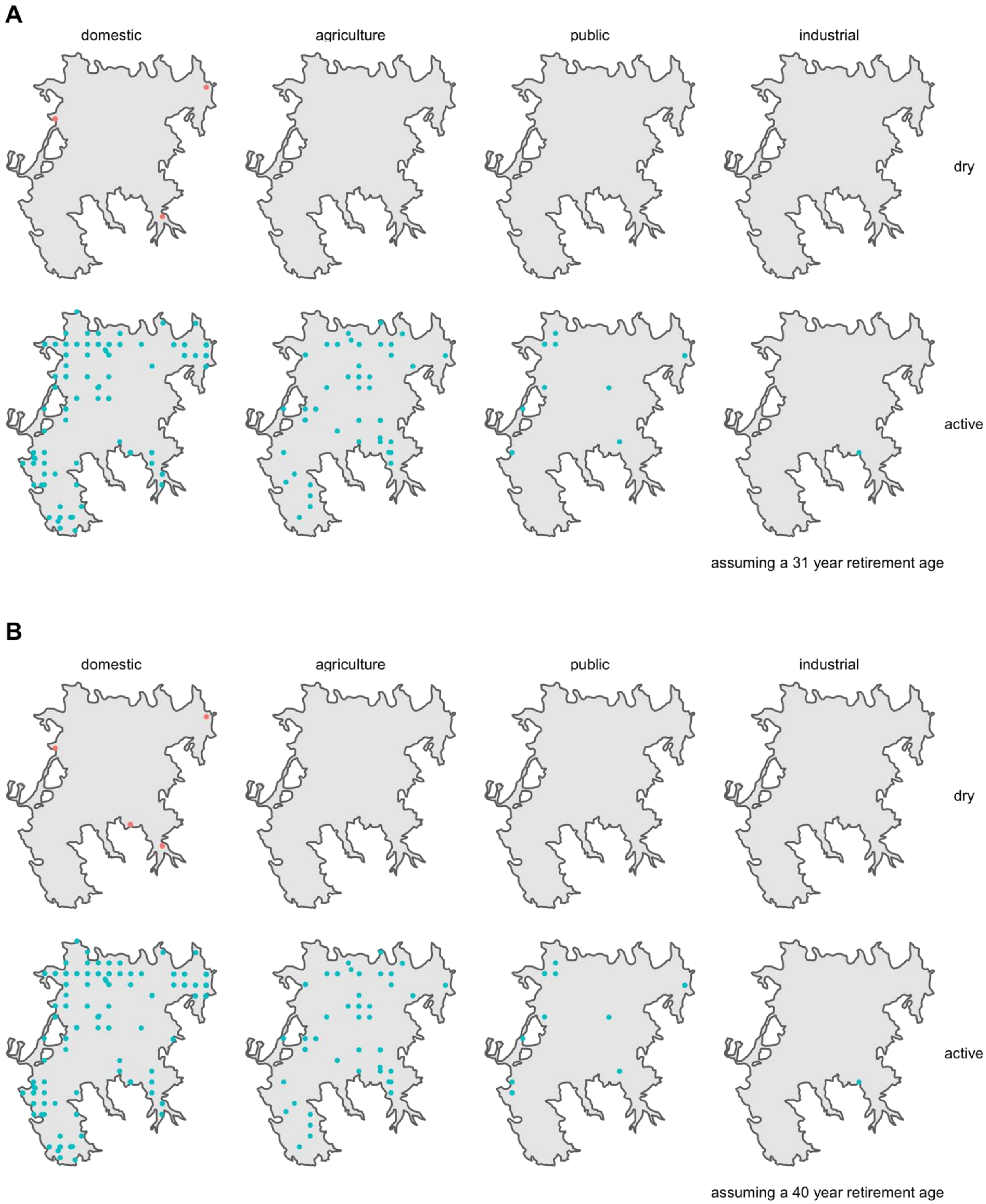

Figure 9: Locations of estimated impacted wells assuming (A) 31 year retirement age and (B) 40 year retirement age.

Table 1: Well impact summary for all well types under 31 and 40 year retirement age assumptions do not exceed 2% relative to the number of initially active wells (n = 325 and n = 450 respectively).

Well type	Impacted well count and percentage (31 yr retirement age)	Impacted well count and percentage (40 yr retirement age)
domestic	6 (2%)	10 (2%)
agriculture	0 (0%)	0 (0%)
public	0 (0%)	0 (0%)
industrial	0 (0%)	0 (0%)

5. Discussion

Vulnerable wells in the SV tend to be privately owned and adjacent to or within areas of concentrated groundwater extraction for agricultural and municipal use. Due to their relatively shallow depth, these wells may be vulnerable when water levels substantially decline due to drought or unsustainable management. With the passage of the Sustainable Groundwater Management Act, local groundwater sustainability agencies will develop sustainable management criteria including minimum thresholds and objectives, measured at monitoring networks that will chart progress towards, or deviance from, sustainability goals. Sustainable management criteria should identify vulnerable wells as beneficial users of groundwater, and hence, identify the quantitative thresholds at which they will be impacted by declining groundwater levels, and the percentages (or count) of impacts above which, local agencies deem significant and unreasonable. The GSP should then set groundwater level MTs according to these thresholds and manage groundwater levels above them to ensure that at MTs, significant and unreasonable impacts occur, and that at MOs, significant and unreasonable impacts are avoided.

Data from the DWR and Cal OPR suggests that during Fall 2015, no wells in the SV were reported dry, even though this period represents a [modern] historic groundwater level low. Results are consistent with this observation and suggest that a return to Fall 2015 groundwater level lows is unlikely to result in catastrophic and widespread impacts to wells. Moreover, additional declines anticipated under projected MTs result in negligible impacts to wells, largely owing to the relatively deep total completed depth of wells compared to present day groundwater levels, and minimal to no groundwater level decline in most parts of the basin. The percentage of domestic wells impacted in the worst-case scenario assuming all RMPs reach MTs simultaneously is 2% (n = 6 - 10), even when considering 31 and 40 year retirement ages. No other well types are impacted.

Well protection analysis thus validates minimum thresholds (MTs) which avoid significant and unreasonable impacts to wells in the basin and allow the basin to achieve projected growth targets within a framework of regional conjunctive use and PMA.

6. Conclusion

Well completion reports and groundwater level data were analyzed to estimate groundwater thresholds at which different well types in the SV reach levels of impact deemed significant and unreasonable. Results suggest that projected groundwater MTs will not lead to widespread catastrophic well failure in the SV.

Well impact analyses depend on reliable data to determine the set of active wells to consider, and their critical datum (the vertical elevation at which a well is estimated to be impacted by declining groundwater levels). Reasonable assumptions are made for modeling purposes, but are not accurate to every well across the basin. Results are sensitive to well retirement age. A “well census” may improve understanding of well retirement and well vulnerability more generally. Such a census, if performed, should take place at the county level; results of the census may be attached to the parcel database used to better inform well protection and rates and fee schedules.

Top-down approaches like the analysis provided herein should be combined with bottom-up approaches. Localized, volunteer-based vulnerable well monitoring may empower point-of-use crowdsourced data and facilitate an early warning system to prioritize well rehabilitation measures before wells go dry. Truly, the best indication of well vulnerability will come from measurements at point-of-use wells. SGMA does not require this level of monitoring or provide guidance on how to achieve it, but GSAs may consider local monitoring programs outside of GSP RMP network to improve communication with well owners and take corrective actions as needed.

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