Appendix 3-C

Vulnerable well impact analysis in the South American Subbasin: well inventory, historical groundwater trends, and analysis to inform Sustainable Management Criteria (October 1, 2021)

Vulnerable well impact analysis in the South American 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 impacts shallow, vulnerable wells and cause dewatering or failure. Relatively shallow residential, agricultural, and public wells (henceforth "vulnerable wells") in the South American Subbasin (SASb) are beneficial uses of groundwater identified by stakeholders in the SASb groundwater sustainability plan (GSP) working group. Residents and water users in the SASb that rely on drinking water obtained from private domestic wells are considered beneficial users of groundwater. The GSP aims to avoid chronic groundwater level decline that leads to significant and unreasonable impacts to vulnerable wells that hamper access to water for drinking, irrigation, and municipal use.

Although shallow wells in the SASb provide beneficial uses of groundwater, the SASb lacks a comprehensive well census (i.e., inventory) and understanding of how sustainable management criteria (SMC) may impact vulnerable wells in the SASb. 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 SASb.

No wells in the SASb 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 SASb 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 SASb from 2005-2018. 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 4 projected groundwater management and climate change scenarios). Finally, we estimate costs to rehabilitate impacted wells and 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 = 2,600), agricultural (n = 532), and public (n = 237) 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

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[1] At the time of writing (2021-06-18), 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.

assumed active wells in the SASb is much lower: domestic (n = 372 - 709), agricultural (n = 72 - 99), and public (n = 62 - 101). An ongoing well "census" would be 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 SASb after four consecutive years of drought and excess pumping to augment lost surface water supply. Data from the DWR and Cal OPR suggests that during this time, no wells in the SASb 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.

Working group input indicated significant and undesirable results to include 5% or more of impacted wells of any type (domestic, agricultural, public). 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 management and climate change scenarios. Results suggest that even assuming a worst-case climate change scenario with no projects and management actions (PMA) – which is unlikely as PMA are already underway – all well types are unlikely to impacted at the 5% undesirable result threshold.

Well protection analysis thus informed the creation of minimum thresholds (MTs) which avoid significant and unreasonable impacts to wells in the basin. Well rehabilitation costs for impacted wells over the implementation horizon, assuming all MTs are reached at all representative monitoring points (RMPs), were estimated at around $300,000 - $700,000 following the cost structure of Pauloo et al. (2021), EKI (2020), and Gailey (2019), but would likely be less, as significant and unreasonable impacts occur when 25% of RMPs exceed MTs.

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.

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[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). Even fewer reside in the South American Subbasin (SASb), 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 SASb, 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 is unlikely to cause widespread and catastrophic well failure in the SASb.

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's Central Valley 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, projects and management actions (PMA), and climate change may impact vulnerable wells in the SASb. 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).

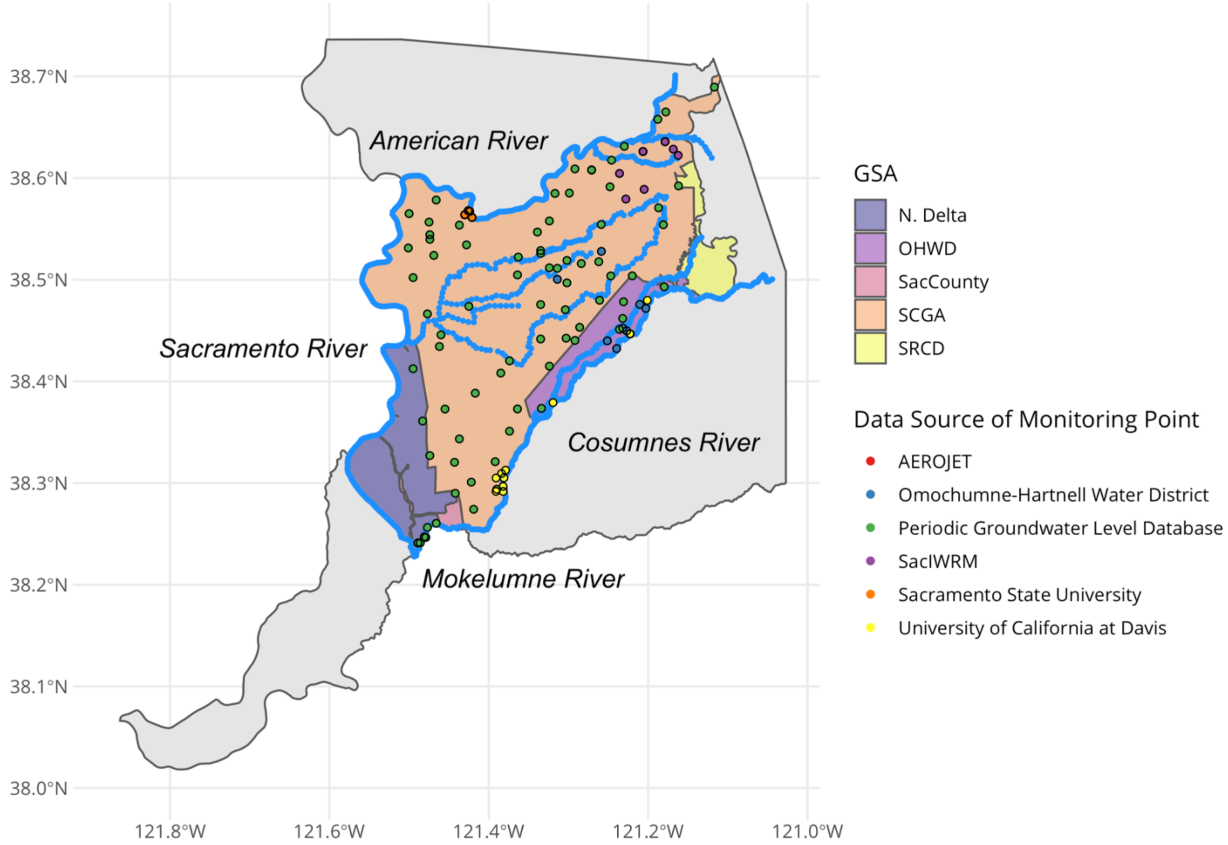

Figure 1. The South American Subbasin is an alluvial aquifer-aquitard system in California's Sacramento County (grey) housing 5 GSAs, and bordered by the American, Cosumnes, Mokelumne, and Sacramento Rivers on the north, east, south, and west boundaries respectively. Representation of these major surface water bodies in the Cosana integrated hydrologic model (including interior creeks) are shown in blue. Groundwater level monitoring points are colored by the data source of the monitoring point. Monitoring points outside of the SASb which were used in the groundwater level interpolation are not shown.

3.1 Groundwater level

Historic and present-day groundwater conditions were analyzed using all available data from six sources (Figure *1*):

(1) California Department of Water Resources (DWR) Periodic Groundwater Level Database
(2) University of California at Davis (UCD) monitoring network
(3) Omochumne-Hartnell Water District (OHWD) monitoring network
(4) Sacramento State monitoring wells
(5) Aerojet
(6) Sac IWRM

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. In the SASb, periodic groundwater level data measurements peak in April and October (Figure 2).

Biannual seasonal groundwater level within the Sacramento Central Groundwater Authority (SCGA) jurisdictional boundary has been measured for decades; these measurements account for most of the spatial spread of groundwater level observations in the SASb and can be found in the DWR Periodic Groundwater Level Database [source (1) above]. Three additional networks, either established or maintained by UCD, OHWD, and Sacramento State all collect high-frequency, 15-minute interval groundwater elevation data. The UC Davis network (2) is situated on land owned by the Nature Conservancy and has collected data fall of 2012, the OHWD network (3) has collected data since fall of 2018, and the Sacramento State network (4) has collected data since spring of 2016. Aerojet monitoring wells (5) used in this study have been collecting data since 1982 and are actively monitored as part of on-site monitoring and remediation actions. Sac IWRM (6) is hydrologic model that includes the SASb and incorporates historic groundwater monitoring data; most of these data are included in (1). 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 2005 to fall 2018 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 2005 and after fall 2018 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.

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

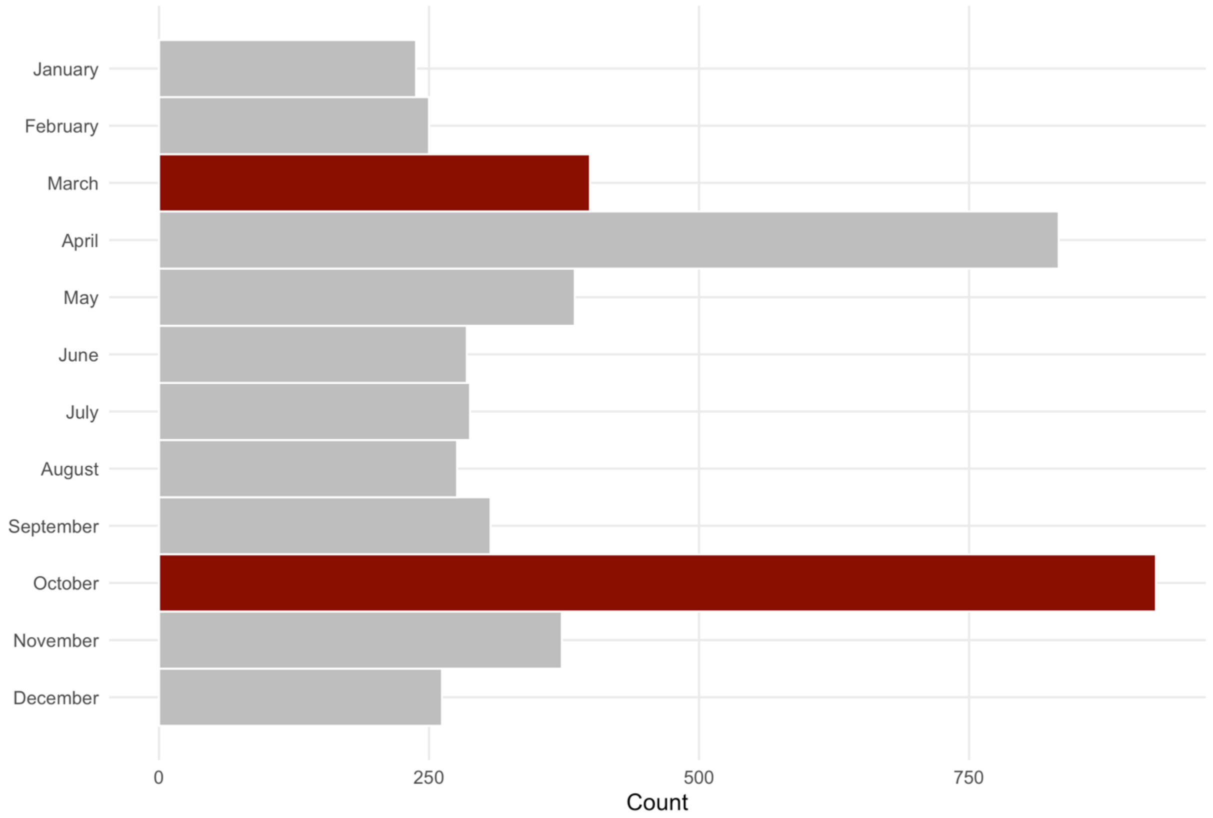

Figure 2: Periodic groundwater level measurements (2000-2021) reported by DWR in the South American Subbasin indicate peaks of seasonal data collection in April and October although DWR Best Management Practices indicate that monitoring wells should collect at least biannual measurements in spring (mid-March) and fall (mid-October) (CA-DWR, 2017). March and October are highlighted in the graph above, and roughly agree with historical data collection trends. It is especially important in dry years to monitor in mid-March, because pumping may begin as early as April; thus, a March measurement in a such a dry year provides a more accurate representation of ambient spring groundwater level. Consistent data collection in March and October ensures data comparability across years.

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 2005-2008 spring level is defined as the average spring groundwater elevation in 2005, 2006, 2007, and 2008. A four-year sliding window was applied to data from 2005 to 2018, resulting in 22 seasonally averaged groundwater elevation conditions (e.g., spring 2005-2009, fall 2005-2009, …, spring 2015-2018, fall 2015-2018). 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 groundwater level surfaces across the SASb at a 500 meter (0.31 mile) resolution. In order to minimize boundary effects, monitoring well data within a 20 kilometer (12.4 mile) buffer of the SASb were included, which effectively incorporates groundwater level data from the Cosumnes and North American subbasins, and Yolo county to the west of the Sacramento river. 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, which are comparable to heads in layers 2-3 of Cosana. All monitoring points were further intersected with the Cosana model grid, and 99.4% of observations at wells occur within the Alluvium, Laguna, and Mehrten layers. 0.6% of observations occur in the Ione and Valley Springs.

3.2 Well Completion Reports (WCRs)

The well completion report database (CA-DWR, 2020) was used to filter and clean WCRs within the SASb. 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 SASb had a total completed depth.

3.4 Projected groundwater management and climate change

Well impacts are characterized in terms of historical data but also in terms of future, anticipated hydrology. Forward-simulated hydrologic conditions using the Cosana groundwater flow model were used to estimate the impact to vulnerable wells from:

- the combined effects of projected water use in the Basin;
- projects and management actions (PMA) already underway (Harvest Water, OHWD[5] recharge, and regional conjunctive use); and
- climate change.

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[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 the South American subbasin and adjacent subbasins, which exhibit relatively continuous geology across borders. 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.

[5] OHWD = Omochumne - Hartnell Water District

Key model outputs include future groundwater basin storage and groundwater level. Storage provides a big picture overview of the change in available groundwater in the basin, and groundwater level shows the spatially distributed result of management actions, which are then used to evaluate well impacts.

In the presentation of results (Section **Error! Reference source not found.**), groundwater level conditions in the current conditions (baseline) are compared to groundwater level conditions in the scenarios evaluated. Five scenarios are compared:

- ***Baseline***: current conditions
- ***Projected***: projected groundwater use (i.e., business as usual with increased demand)
- ***Projected CC***: projected groundwater use with a median climate change warming scenario[6]
- ***Projected PMA***: projected groundwater use considering feasible, in-progress projects and management actions (Harvest Water, OHWD recharge, regional conjunctive use)
- ***Projected PMA CC***: projected groundwater use considering feasible, in-progress projects and management actions (Harvest Water, OHWD recharge, regional conjunctive use) and with a median climate change warming scenario

Differences in groundwater level between each of the scenarios and the "baseline" inform how wells in the basin may respond to projected groundwater management and climate change. These differences are applied to observed data to translate model estimates of change to observed data. For example, to estimate the change in vulnerable well impacts under each scenario, the groundwater level differences implied by each scenario at a Fall 2015 reference point were evaluated by the model, then this difference was applied to the measured and interpolated Fall 2015 level. Fall 2015 was chosen as a reference point because it represents a recent historical minimum in groundwater level across the basin.

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[6] Climate change (CC) scenarios are driven by changes in temperature and streamflow provided by the American River Basin Study (USBR, 2020) "central tendency" scenario, which reflect median temperature and precipitation outcomes.

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[7], 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"[8] to each well, equal to 30 feet above the total completed depth, roughly 3 times the height of water column required to prevent 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 (Figure 3).

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 cost estimate is conservative in this sense.

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[7] 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.

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

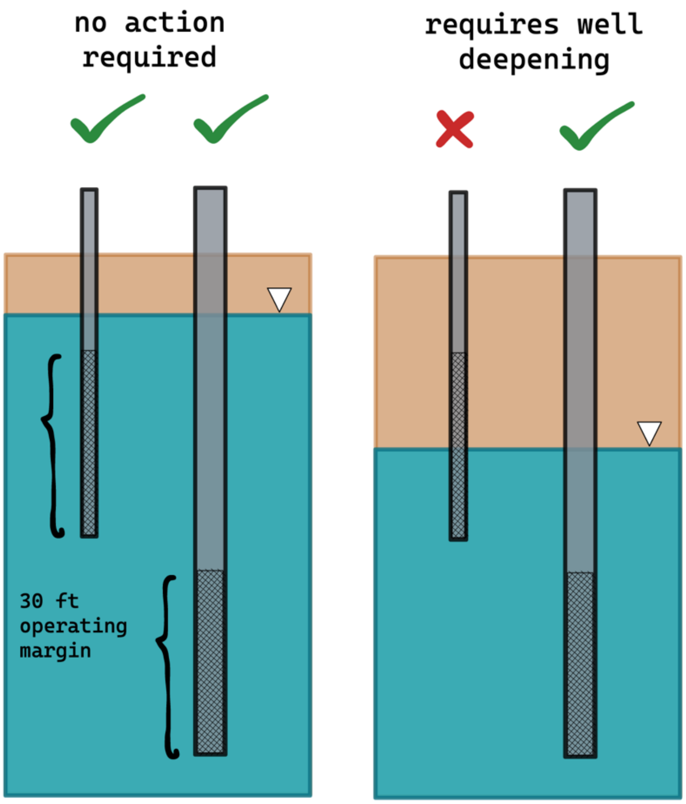


Figure 3: Wells are assigned a 30 foot operating margin above the total competed depth. When groundwater levels are above this "critical datum" at a well, the well is active (left), and the well is impacted when the groundwater falls below the critical datum, which triggers a well deepening event. Note that in reality, cones of depression form around active pumping wells, but are not shown in the figure above for simplicity.

To compute rehabilitation costs, it is assumed that if the groundwater level falls below the total completed depth of the well plus an operating margin of 30 ft, a well deepening rehabilitation event is assumed to take place. Well deepening is estaimted at $21,500 per domestic well, and $100,000 per agricultural and public well. We neglect costs associated with increased lift, as these constitute around 1% of total costs estimated by EKI, 2020. We also neglect costs associated with screen cleaning, as this action is unlikely to yield significant additional water when groundwater levels have fallen below the critical datum.

4. Results

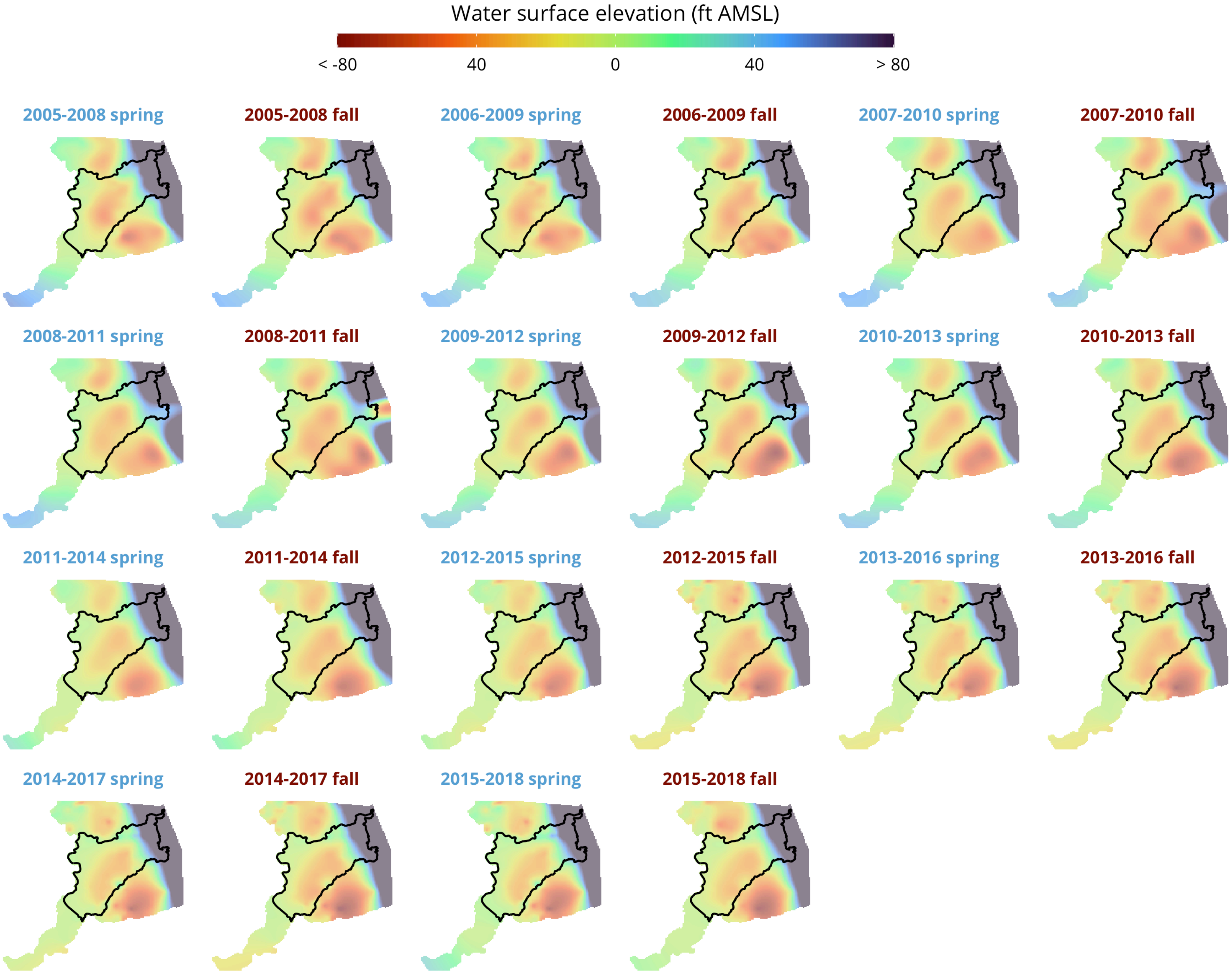
4.1 Groundwater levels

Groundwater level analysis in this memorandum is consistent with that conducted in another technical memorandum attached to Section 3 of the SASb GSP. A detailed treatment of groundwater level results is provided in Appendix C: Interconnected Surface Water (ISW) Section 4.1, and a summary is provided here.

Groundwater elevations show seasonal oscillation (Figure 4, Figure 5) and increasing depth to groundwater in the northeast direction away from the Bay Delta (Figure 6).

Key groundwater levels include the initial condition (spring 2018), and 5 boundary conditions at which well impacts are evaluated. The first boundary condition is the Fall 2015 low, and the remaining four boundary conditions are defined by differences in groundwater elevation projected by the Cosana groundwater level scenarios (see Section 3.4 Projected groundwater management and climate change and Figure 7). The impact of projects and management actions (PMA) on groundwater levels is substantial: Harvest Water accounts for upwards of 25 feet of projected increase in groundwater level in the center of the project area (Figure 8). Importantly, to scope the severity of well impacts at potential MTs, for each scenario and at each location in the SASb, the lower of the Fall 2015 groundwater level and the projected scenario was used as a boundary condition.

Change in basin groundwater storage (Figure 9) indicates that projected management and projected management with PMA increase basin storage over the SGMA implementation horizon, whereas climate change reduces groundwater levels (assuming constant land use and ET commensurate with increased temperature).


Water surface elevation (ft AMSL)
< -80
40
0
40
> 80
2005-2008 spring
2005-2008 fall
2006-2009 spring
2006-2009 fall
2007-2010 spring
2007-2010 fall
2008-2011 spring
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2015-2018 spring
2015-2018 fall

Figure 4: Seasonal, 4 year running mean interpolated groundwater elevations in the South American Subbasin from spring 2005 to fall 2018 show seasonal oscillation, with generally higher (blue) groundwater elevation in spring, and generally lower (red) groundwater elevation in the fall. Groundwater flows from areas of high (blue) to low (red) elevation groundwater elevation. Groundwater elevation mapping indicates groundwater flow inwards towards the center of the basin, coincident with areas of groundwater pumping.

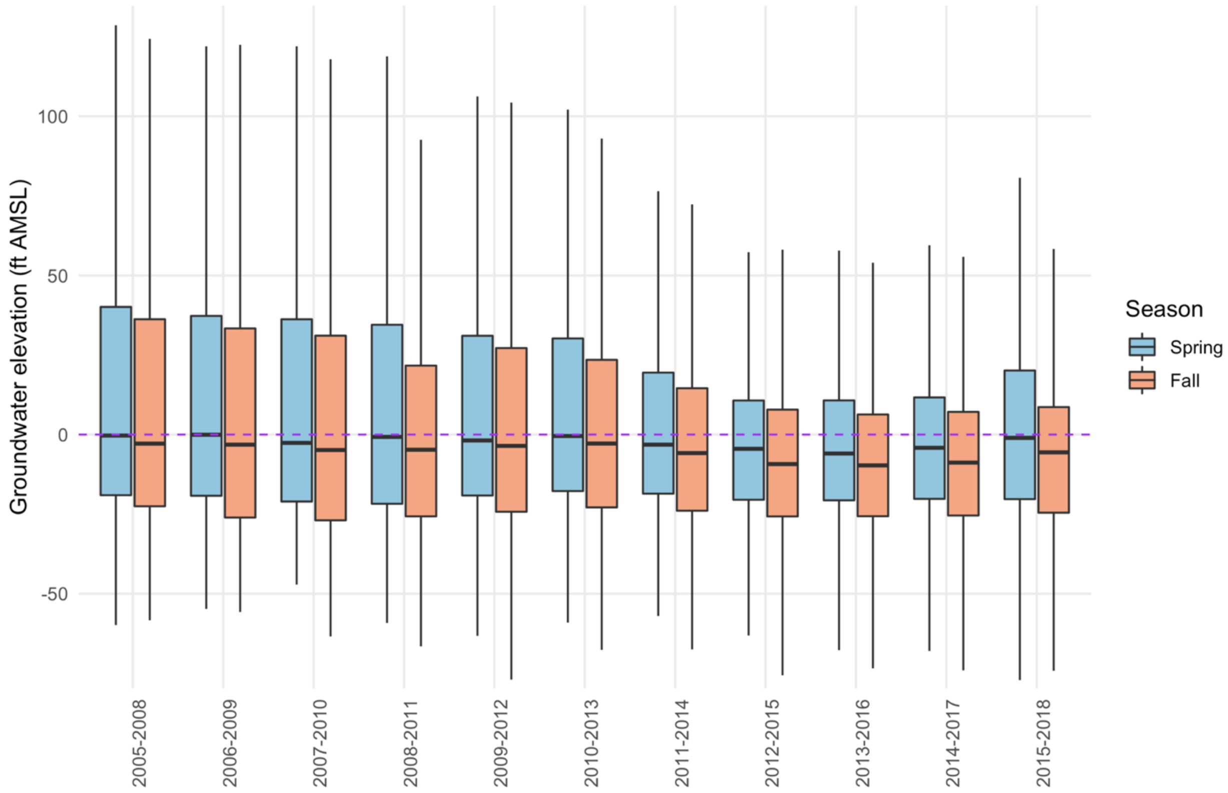

Figure 5: Seasonal summary of interpolated groundwater elevations in the SASb (Figure 4) show oscillating seasonal medians, with consistently higher groundwater elevation in spring, and lower groundwater elevation in fall. Median fall groundwater elevation decreases over the period of record and reaches its lowest value during the average period of 2013-2016 due to the combined impact of 4 years of drought. After this minimum, spring and fall median groundwater levels trend upward. A purple, horizontal dashed line is shown at mean sea level elevation (0 feet) for reference.

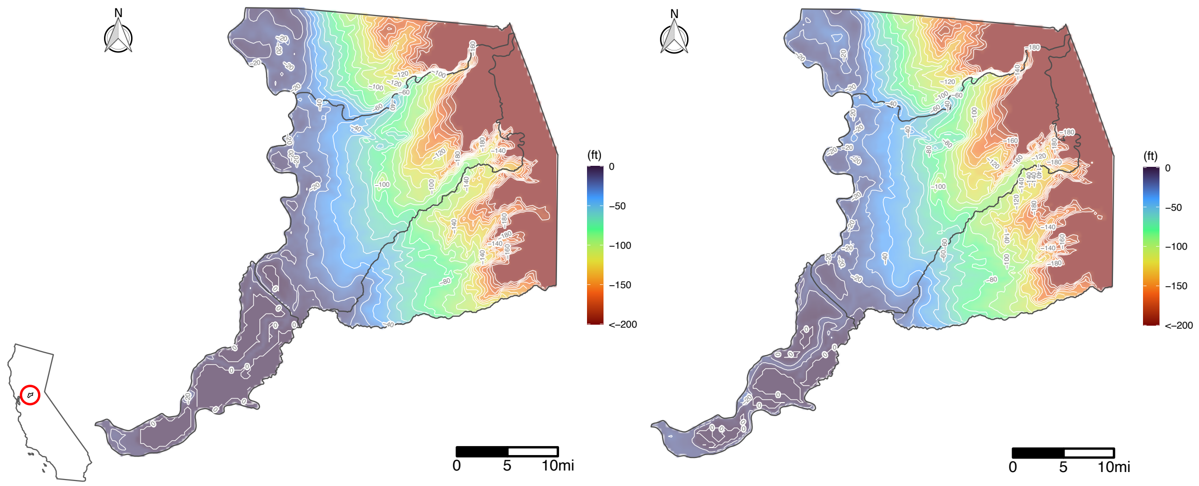

Figure 6: Depth to groundwater in the SASb for average spring (left) and fall (right) conditions across the entire period of record evaluated (2005-2018).

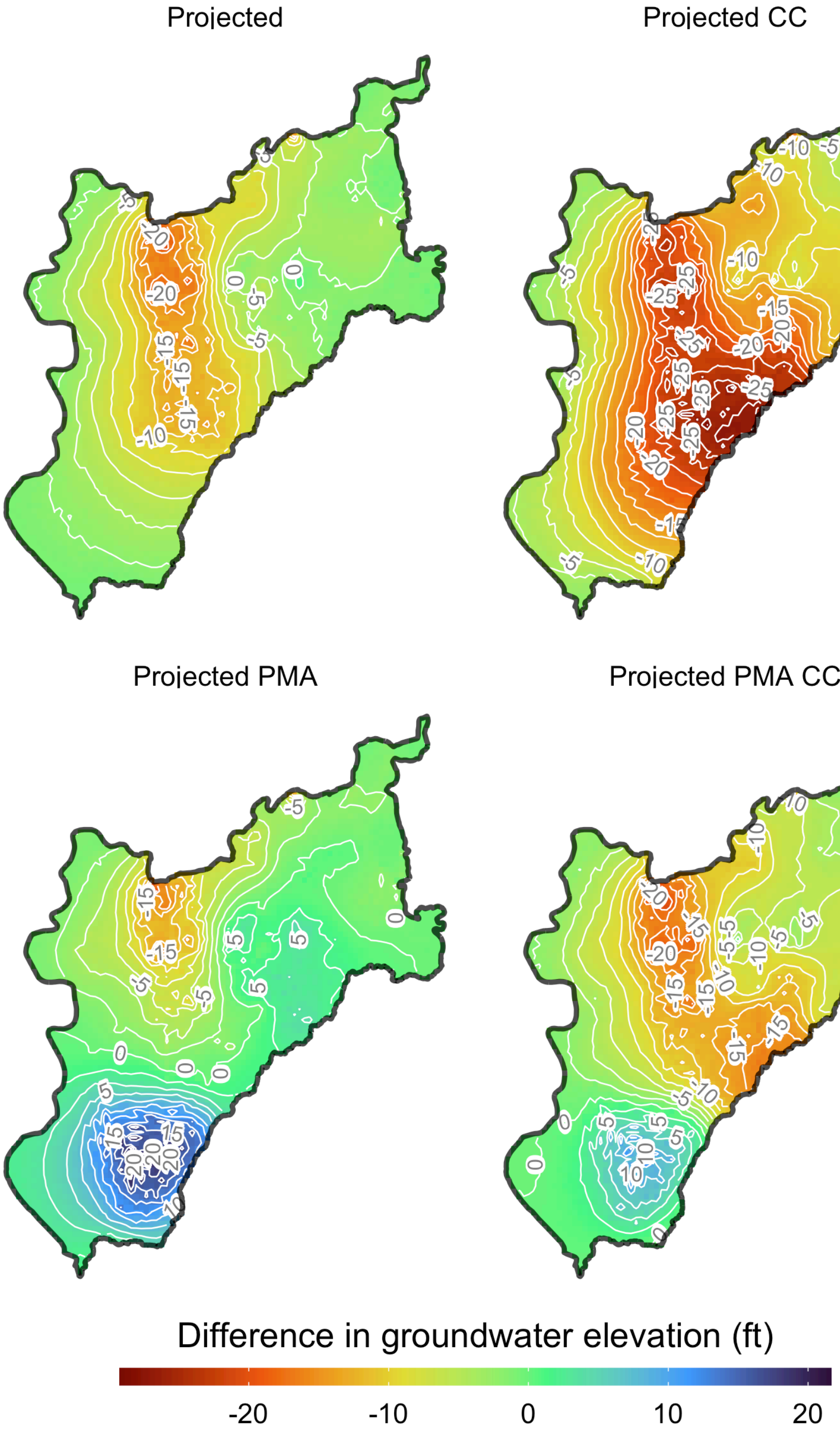

Figure 7: Modeled difference in groundwater level between each of the scenarios and the current conditions baseline at a Fall 2015 benchmark. PMA lead to substantial increases in groundwater level. Climate change projections lead to groundwater level declines, but assume no corrective action or land use change. In reality, climate change would require specialized adaptive management to avoid significant and unreasonable impacts to beneficial users, particularly ISW.

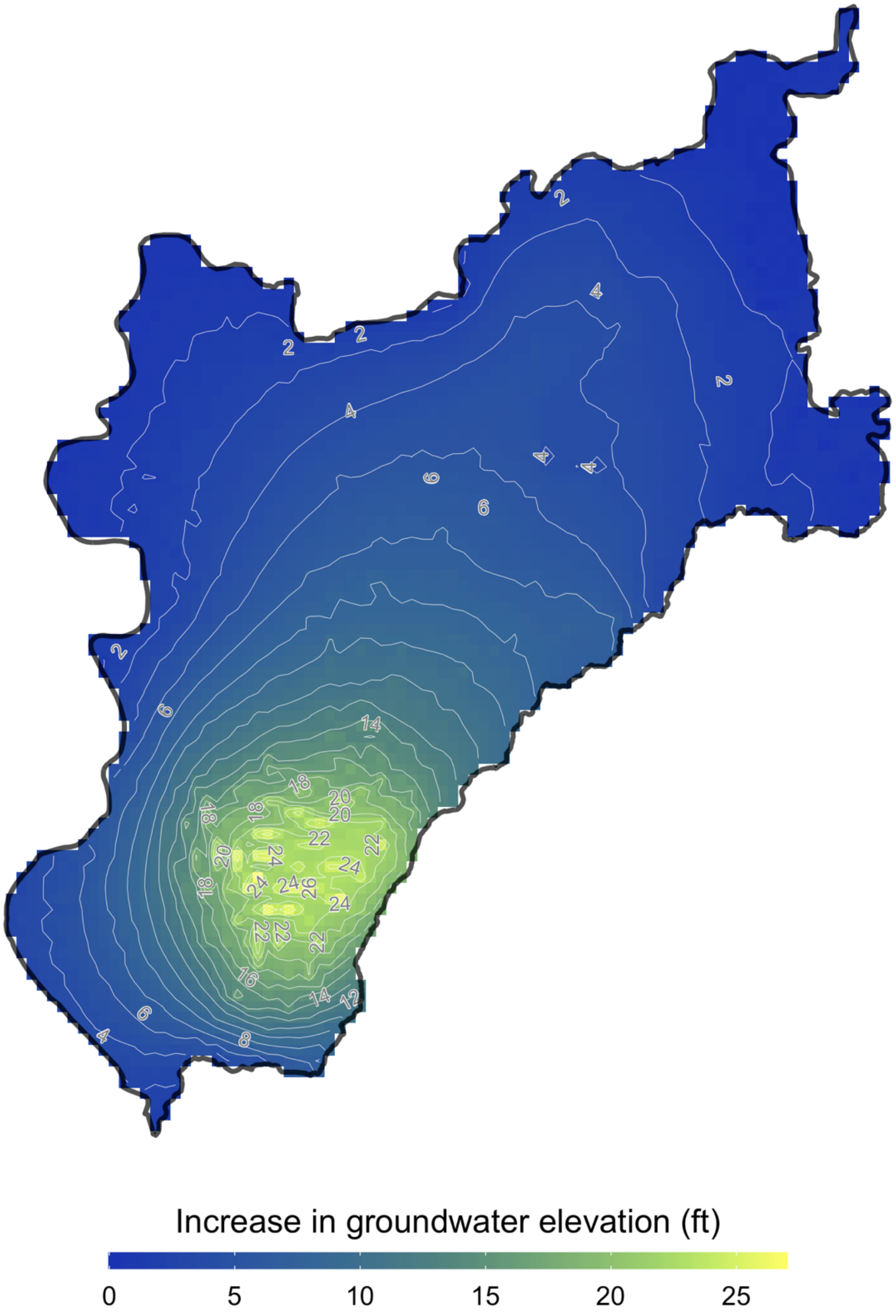

Figure 8: The difference in groundwater elevation between the "Projected PMA" and "Projected" scenarios shows the spatial distribution of groundwater level increases estimated to result from implementing PMA. Increases in groundwater level are observed across the basin and concentrated near the Harvest Water recharge site.

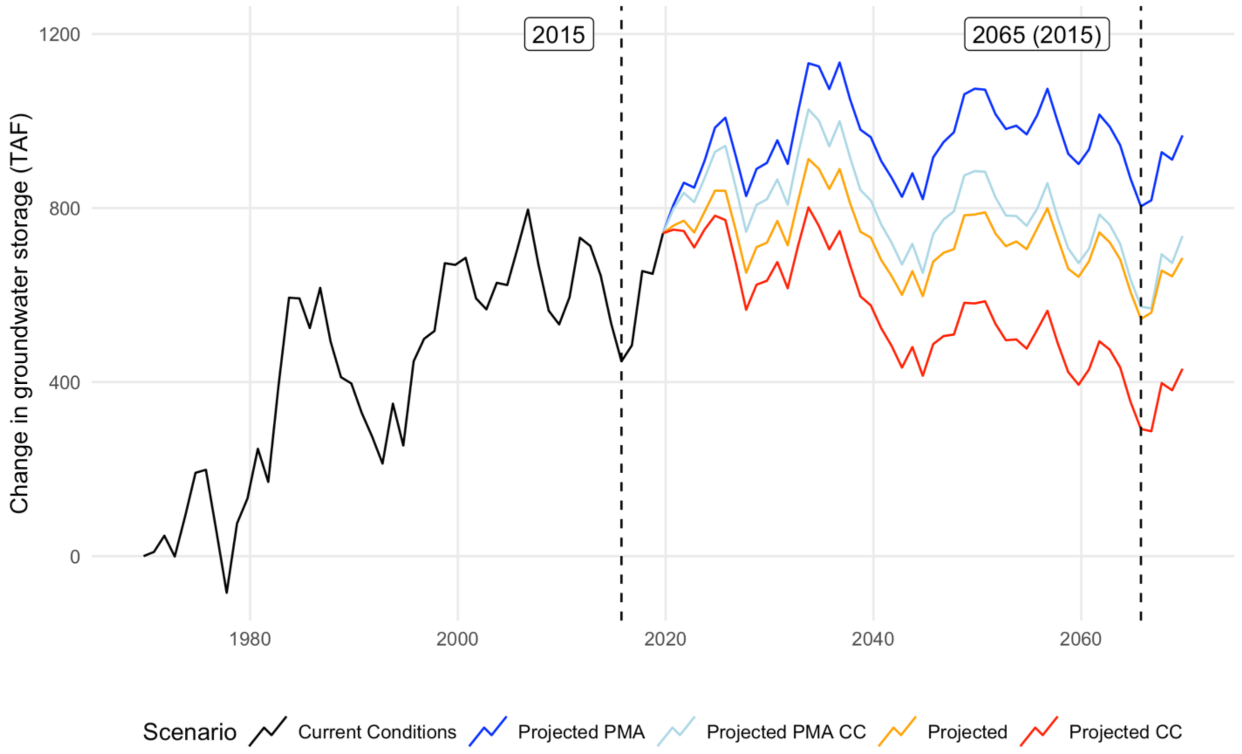

Figure 9: Cumulative change in groundwater storage under the current conditions baseline (black line), and the four scenarios (dark blue, light blue, orange, and red line). Importantly, projects and management actions (PMA) increase storage, and climate change (CC) reduces storage. A black dashed line shows where groundwater level differences are calculated between the projected scenarios and the current conditions baseline (Fall 2015) to maintain consistency.

4.2 Well inventory and characteristics

Results suggest that the most common well types (

Figure 10) with direct beneficial uses are domestic (n = 2,600), agricultural (n = 532), and public (n = 237) wells[9], although the actual number of "active" wells today is likely less due to ageing and well retirement. Assuming 31 to 40 year retirement ages (Figure 11), and that wells with pumps above initial groundwater level conditions are inactive, the number of assumed active wells in the SASb is much lower: domestic (n = 372 - 709), agricultural (n = 72 - 99), and public (n = 62 - 101). Most wells that provide beneficial uses (public, agricultural, domestic) bottom out in the Laguna and Mehrten formations (Figure 12), which constitute a principal aquifer from which transmissivity-weighted heads are extracted from the Cosana model and used to evaluate changes in groundwater level.

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[9] At the time of writing (2021-06-18), 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.

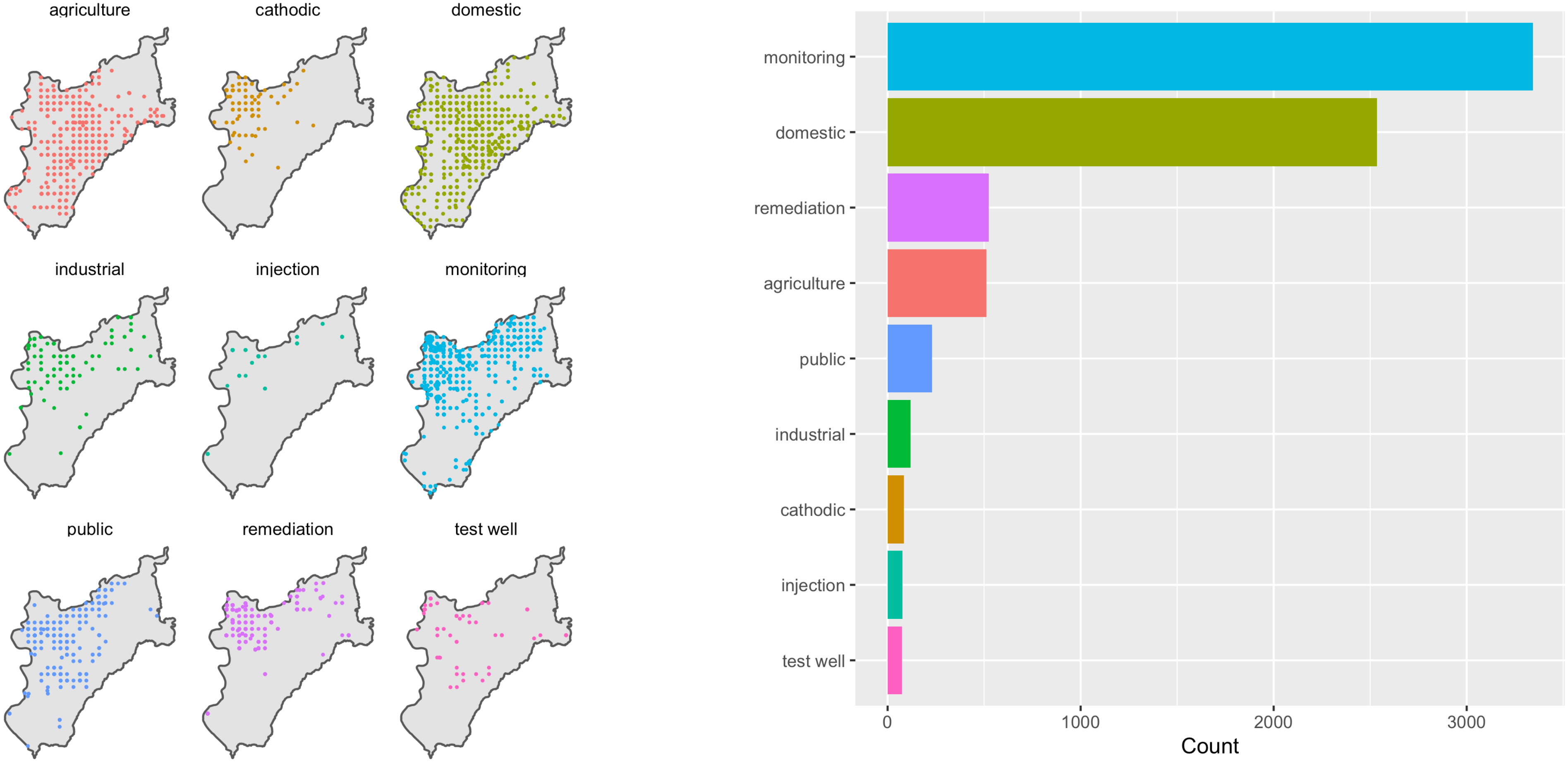


Figure 10: Well inventory of the SASb. Locations and counts do not consider retirement age, thus these wells do not reflect the location and count of active wells, but rather, all wells ever drilled for which records exist. Notice that agricultural, public, and domestic wells are collocated, and that domestic wells outnumber agricultural and public wells. Well locations appear in a grid like pattern because the accuracy of most wells is to the nearest PLSS section (1 square mile grid).

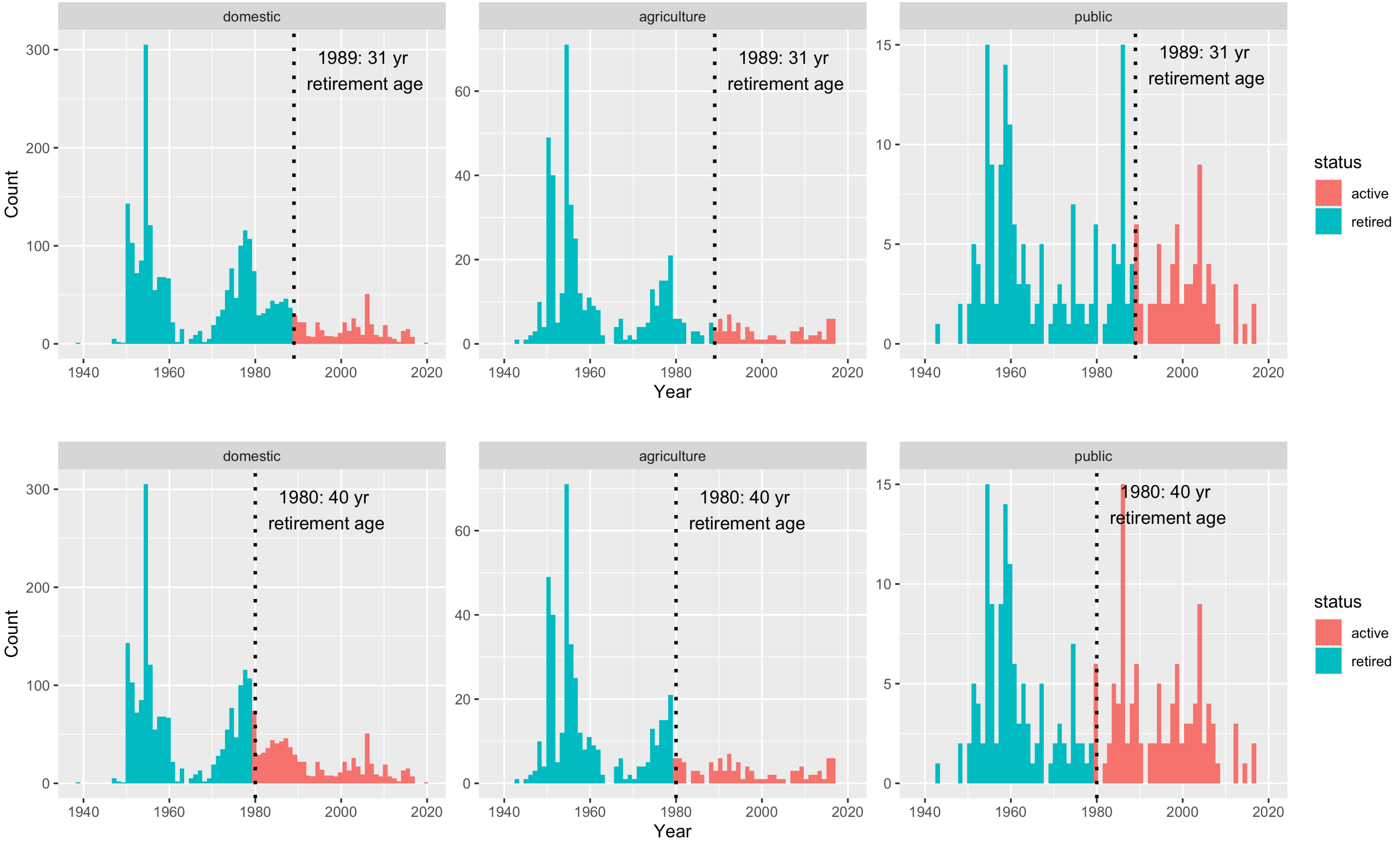
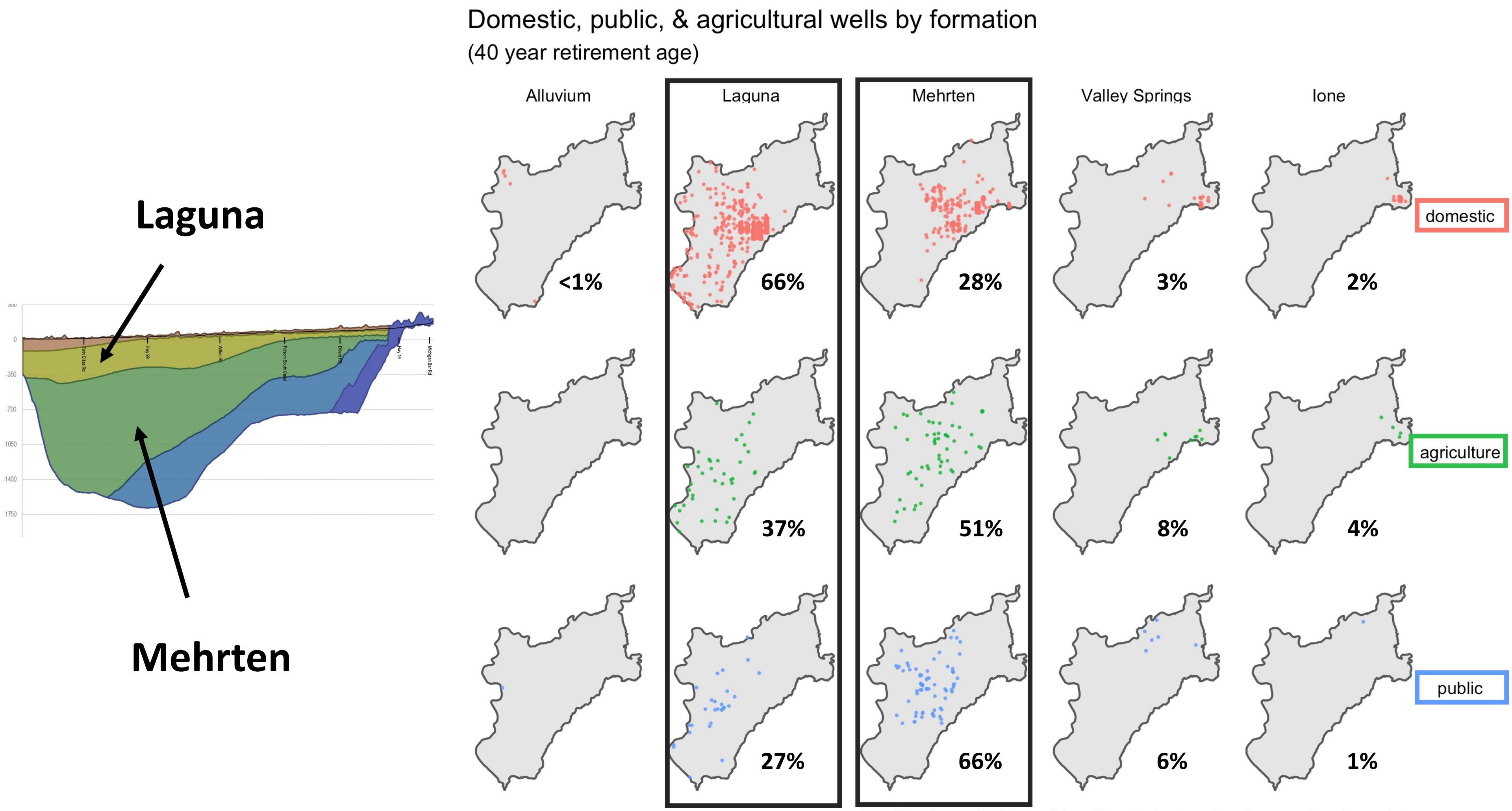


Figure 11: Not all wells drilled are active. Assuming a 31 year (top) and 40 year (bottom) retirement age, different numbers of wells are active.



a minor jitter is applied to well locations to better visualize overlapping points

Figure 12: Most wells that provide beneficial uses bottom out in the Laguna or Mehrten, thus transmissivity-weighted heads from these layers (the principal aquifer) are used to evaluate differences in groundwater elevation implied by the projected scenarios.

Most wells are deeper than long-term average depths to groundwater in the SASb, which suggests a buffer against potential well impacts from declining groundwater levels (Figure 13). Finally, wells tend to be drilled deeper over time (Figure 14), driven by improvements in drilling technology and the need for deeper groundwater unimpacted by surface contaminants and with sufficient transmissivity to support well yield targets.

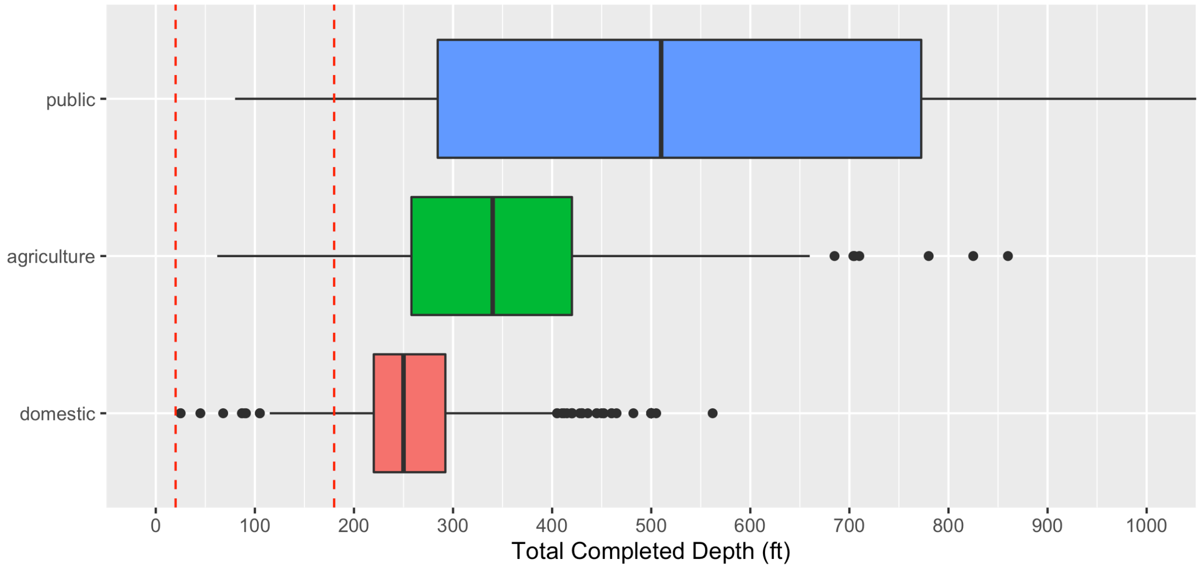


Figure 13: Relative depth distributions of domestic, agricultural, and public wells indicates increasing depth. Red dashed vertical lines are shown at 20 and 180 feet below land surface, which are the approximate modern, long-term depths to groundwater in the SASb (Figure 6)). The 25th percentile of all well depths falls outside of the 20-180 foot envelope, suggesting that many wells are deeper than present day depths to groundwater.

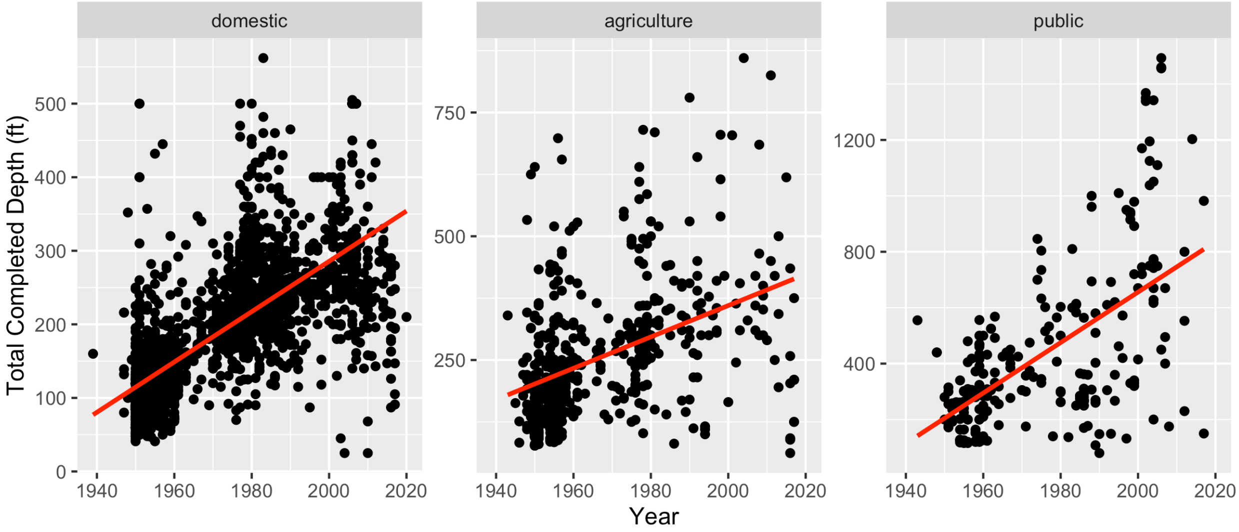


Figure 14: Since 1950, average domestic well depths increased by around 3x; agricultural and public well depths increased by around 2x and 4x respectively.

4.3 Well impacts: location, count, and cost

Fall 2015 groundwater level lows are around 12 feet lower on average compared to near present day groundwater levels. A return to these levels, as well as those implied by projected management, PMA, and climate change show little appreciable difference on well impacts (Figure 15).

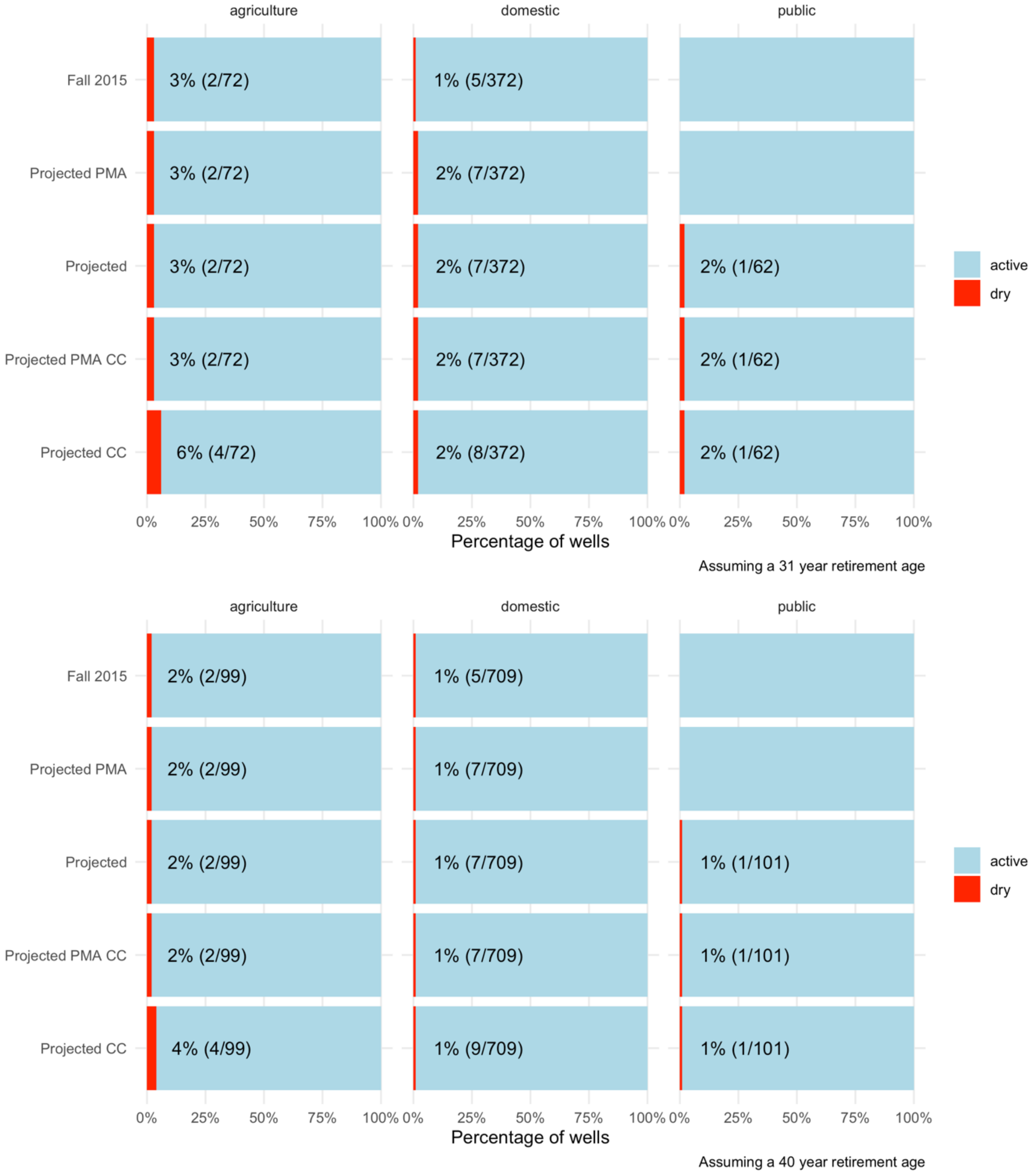
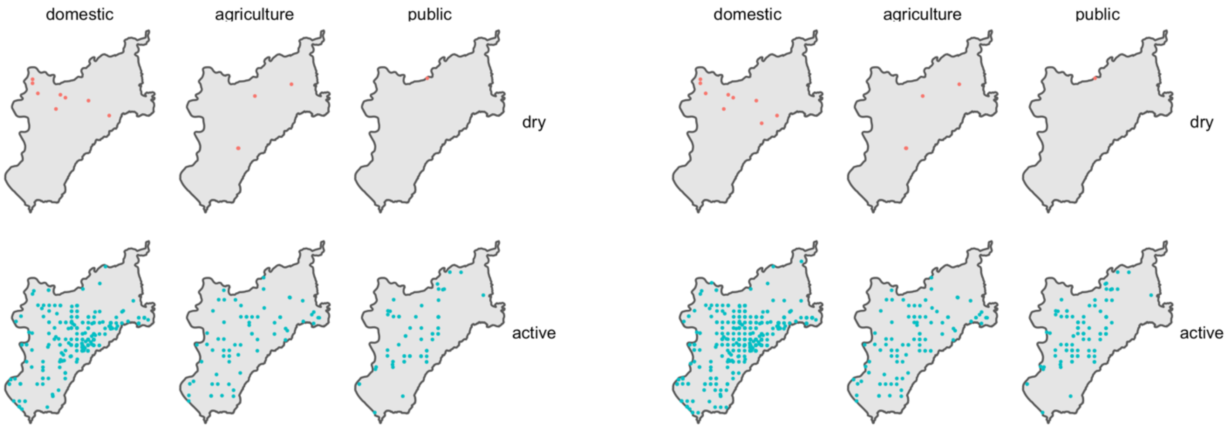


Figure 15: Vulnerable well impact analysis of a Fall 2015 baseline and 4 projected management conditions show little appreciable difference, even when accounting for a 31-year (left) and 40-year (right) well retirement age. Projected = Projected water use in the Basin. PMA = projects and management actions including Harvest Water, OHWD recharge, and regional conjunctive use. CC = climate change. Bar plots show well impact summary statistics for all scenarios and well types. Maps show results for the "Projected PMA CC" scenario on which groundwater level MTs are based.

Consequently, the point patterns of estimated active and dry wells do not appreciably differ among the five scenarios, thus only the most severe case scenario is shown (Figure 16).



Assuming a 31 year retirement age

Assuming a 40 year retirement age

Figure 16: Of the five scenarios evaluated in this study, the Projected Conditions with climate change (and no PMA) result in the most severe well impacts (Figure 15), which are still minimal and close to a 5% impact range in agricultural wells, when accounting for uncertainty in well retirement age.

These results are unsurprising, as well depths are relatively deep compared to groundwater elevations, and the lower of Fall 2015 lows and projected groundwater head conditions do not begin to approach depths that intersect the critical datum of most wells.

4.4 Estimated cost

Costs are estimated informed by the costs put forward by Gailey et al (2019), EKI (2020), and Pauloo et al (2021), which assume well deepening events occur in intervals of 100 feet. For simplicity, domestic wells were assumed to cost $21,500 USD per well replacement, and agricultural and public wells were assumed to cost $100,000 USD per well replacement.

Results across all scenarios evaluated suggest a range of 7-15 wells would be impacted under 31-year and 40-year retirement ages, and accounting for uncertainty in projected management and climate change (Figure 15). For a conservative estimate of PMA with climate change, impacted well count is around 2-3% of domestic wells and 1-2% of public wells, and 1-2% of agricultural wells, primarily near the greater Sacramento urban area. This is explained by groundwater level simulations that indicate drawdown in these areas – areas which are also far away from the agriculture-rural interface where most vulnerable domestic wells are located. These well impact percentages align with GSA-driven definitions of unreasonable results to vulnerable wells.

Further, unacceptable well impacts are defined as dewatering or lost access to groundwater at a well that requires well deepening. Well rehabilitation costs for impacted wells, assuming a return to the MT at all RMPs, were estimated at around \$300,000 - \$700,000 following the cost structure of Pauloo et al. (2021), EKI (2020), and Gailey (2019), but would likely be less, as significant and unreasonable impacts occur when 25% of RMPs exceed MTs, and less expensive rehabilitation costs such as pump lowering may be more appropriate in some situations (e.g., when operating margin exists).

5. Discussion

Vulnerable wells in the SASb 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 are vulnerable when water levels 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 SASb 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 management 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 wells impacted in the worst-case scenario assuming climate change and no PMA results in only one of the well types (agricultural) impacted at 4-6% (accounting for uncertainty in well retirement age). In all other scenarios (many of which are more likely), well impacts for all well types remain below 5%.

Well protection analysis thus informs the creation of 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. Well rehabilitation costs for impacted wells, assuming all MTs are reached at all representative monitoring points (RMPs), were estimated at around \$300,000 -

$700,000, but would likely be less, as significant and unreasonable impacts occur when 25% of RMPs exceed MTs, and if operational space remains in the well, a less costly pump lowering may take place.

6. Conclusion

Well completion reports, and historical and forecasted groundwater levels (using Cosana) were analyzed to estimate groundwater thresholds at which different well types in the SASb reach levels of impact deemed significant and unreasonable. Results suggest that projected groundwater management with PMAs and climate change will not lead to widespread catastrophic well failure in the SASb, and thus groundwater level MTs should be designed according to these levels.

It is advisable therefore, that MTs are based on the lower of the observed fall 2015 groundwater level and any additional decline anticipated under the projected PMA with CC scenario since this represents a likely, but conservative groundwater level scenario with an estimated 1-3% well impact across well types that also fits within the significant and unreasonable 5% impact threshold.

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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