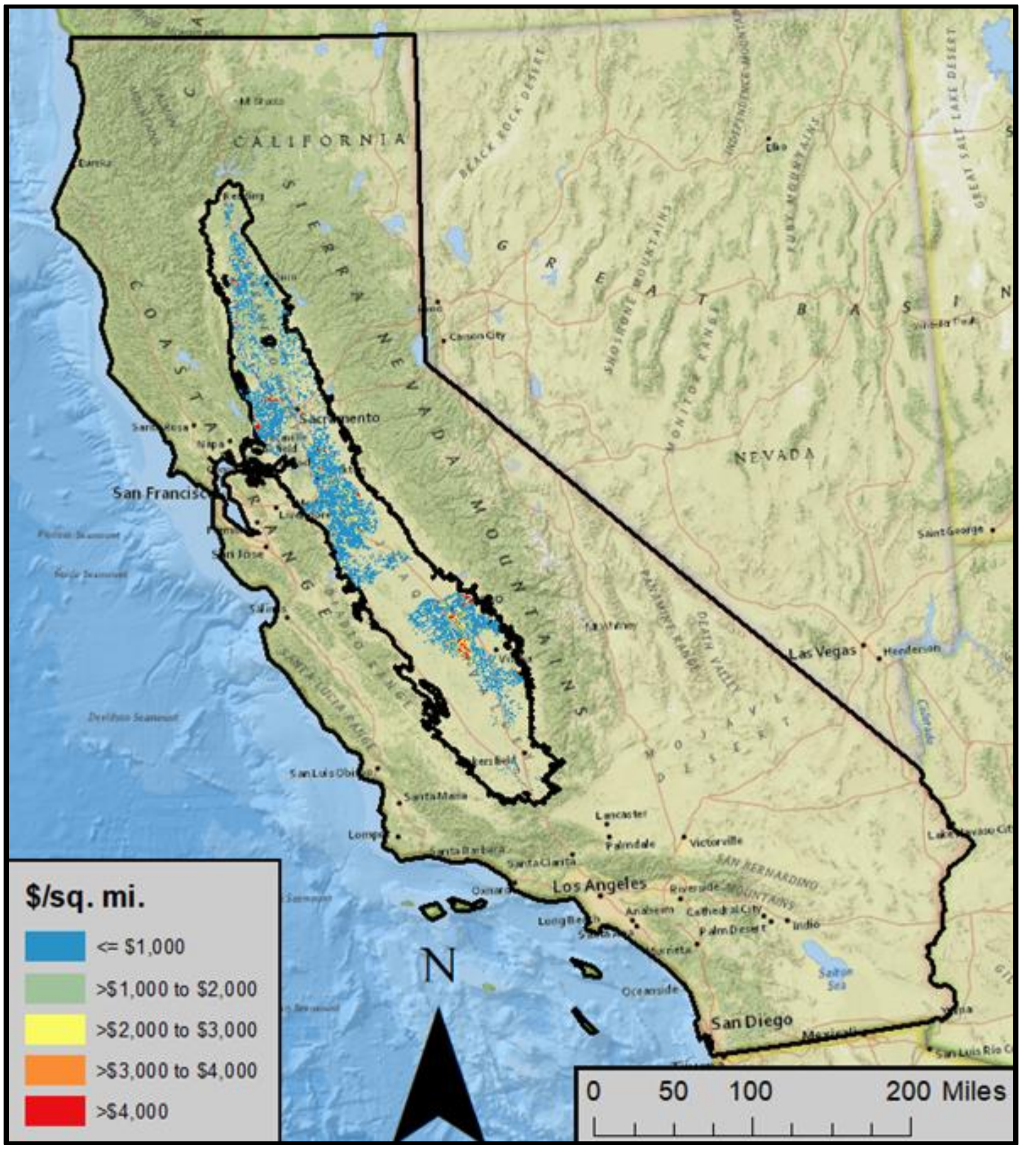
Robert M. Gailey, P.G., C.HG.
Consulting Hydrogeologist PC

CALIFORNIA SUPPLY WELL IMPACT ANALYSIS FOR DRINKING WATER VULNERABILITY WEBTOOL



Prepared for:
Community Water Center

Prepared by:
Robert M. Gailey Consulting Hydrogeologist PC

January 14, 2020

415-407-8407 · rob@rmgailey.com · www.rmgailey.com

Robert M. Gailey, P.G., C.HG.
Consulting Hydrogeologist PC

January 14, 2020

Ms. Adriana Renteria
Community Water Center
900 West Oak Avenue
Visalia, CA 93291

Re: California Supply Well Impact Analysis for Drinking Water Vulnerability Webtool

Dear Ms. Renteria,

Please find enclosed the final report for the above-referenced project. The report and supporting analysis was performed by Robert M. Gailey Consulting Hydrogeologist PC under a contract to the Community Water Center executed on October 26, 2018. This was an ambitious scope of work for the allocated budget and the concluding section suggests potential tasks to enhance the results.

Sincerely,

Robert M. Gailey, P.G., C.HG.

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1.0 INTRODUCTION

This report was prepared by Robert M. Gailey Consulting Hydrogeologist PC (RMG) under a contract to the Community Water Center (CWC) executed on October 26, 2018[1]. The work product presented here is part of larger CWC project for developing a web platform to evaluate drinking water supply vulnerability in California with a focus on domestic wells and wells of community water systems serving populations less than 10,000.

The limited scope of work for an initial budget included the tasks listed below. Updates on progress for tasks 1 through 3 were provided by RMG in the form of webinars and written feedback was provided by CWC. In addition to this report, results of the analysis performed by RMG were provided to CWC as GIS layers and spreadsheet tables.

- Task 1 – Develop method
- Task 2 – Develop datasets
- Task 3 – Perform analysis and create GIS layers
- Task 4 – Finalize analysis and GIS layers
- Task 5 – Prepare report

The following report sections briefly address the approach, data, assumptions and limitations, results, conclusions and potential extensions, as well as general limitations that apply to this work. Additional exploration of the results beyond that presented here, including higher-resolution viewing of results for specific areas within the larger study area, is possible through the CWC Drinking Water Vulnerability Webtool that will be launched soon.

2.0 ANALYSIS APPROACH

The analysis is based on the approach presented in Gailey et al. (2019)[2]. Some modifications have been made based on recent applications to groundwater sustainability planning conducted in response to requirements of the Sustainable Groundwater Management Act (SGMA)[3]. For this work, the wells considered were domestic (Dom) and those owned by community water systems serving less than 10,000 people (CWS).

This approach addresses water quantity and considers how declining groundwater elevations might reduce well production potential as well as what mitigation measures might be required to maintain supplies. Impacts are predicted and tracked, then mitigation measures are posed and the resulting costs estimated. Impacts considered are: increased pumping lift, pump cavitation, well screen clogging and wells running dry. Mitigation measures considered are: pumping against increased

[1] The contract acknowledges that RMG conducted similar work for others while performing this work for CWC and is free to perform similar work for others in the future.

[2] A similar, possibly more easily accessed, presentation appears in Chapter 4 of Gailey (2018).

[3] Existing computer codes, developed for previous research and other consulting projects, were applied for the work presented in this report.

lift, lowering the pump in the well, cleaning (or rehabilitating) the well screen and replacing a dry well with a deeper well.

Figures 1 through 4 illustrate the impacts and mitigations considered for each well in the analysis. Information on both the well structure and pump, including an estimated initial installed depth, are considered (Figure 1). Accounting for pumping drawdown and required pump submersion, a maximum depth to water in the well (MDTW) is determined and compared to the static (non-pumping) water depth. As groundwater levels decline (Figure 2a), the MDTW threshold is exceeded, production potential is impacted and pump lowering becomes necessary[4]. In some cases, continued groundwater level decline may result in water levels contacting the screened (or perforated) interval of the well (Figure 2b). Under such conditions, a combination of physical, chemical and biological processes may result in well screen clogging and require cleaning. Finally, groundwater levels may decline so much that, for shallower wells, it may not be possible to lower the pumps farther[5] (Figure 2c) and a deeper, new well would be required. Combinations of these impacts and mitigation measures may occur for a well (Figure 3).

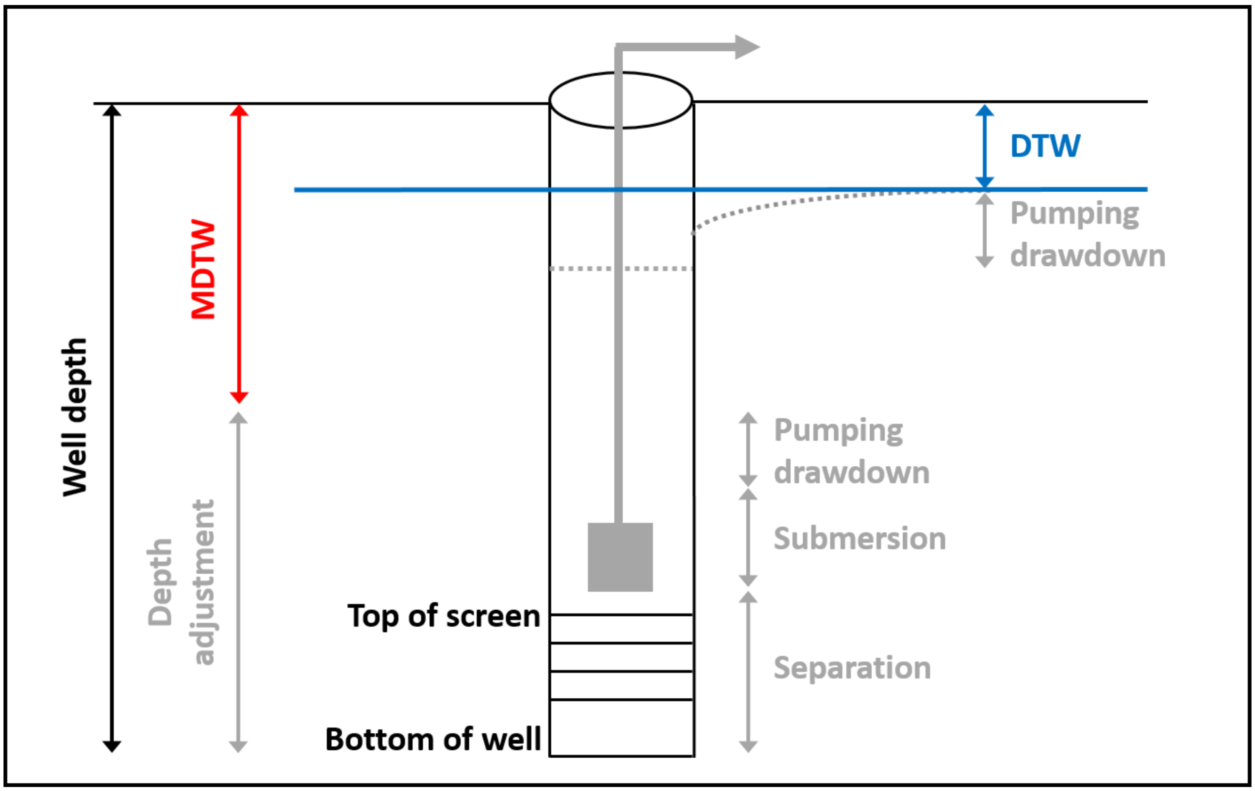

Figure 1: Typical well configuration considered in the analysis. DTW is Depth to Water. MDTW is Maximum Depth to Water. Note that Separation is measured from the bottom of the well screen since space in the well that extends below the bottom of the screen is usually not appropriate for pump placement.

[4] The MDTW value is updated when the pump is lowered.

[5] This would occur when some minimum separation distance between the pump intake and the bottom of the well screen, resulting from sediment accumulation, was reached.

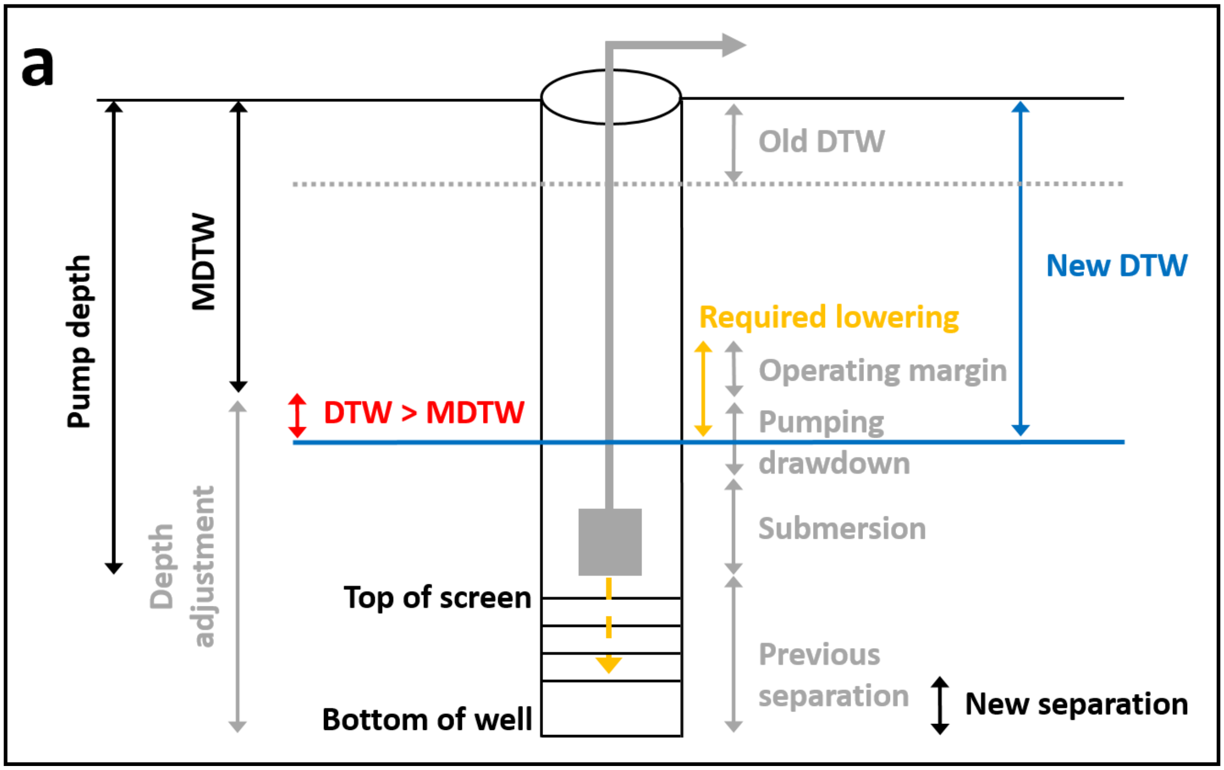

Figure 2a: Conditions resulting in corrective actions: pump lowering when DTW is greater than MDTW and there is room to lower the pump. DTW is Depth to Water. MDTW is Maximum Depth to Water.

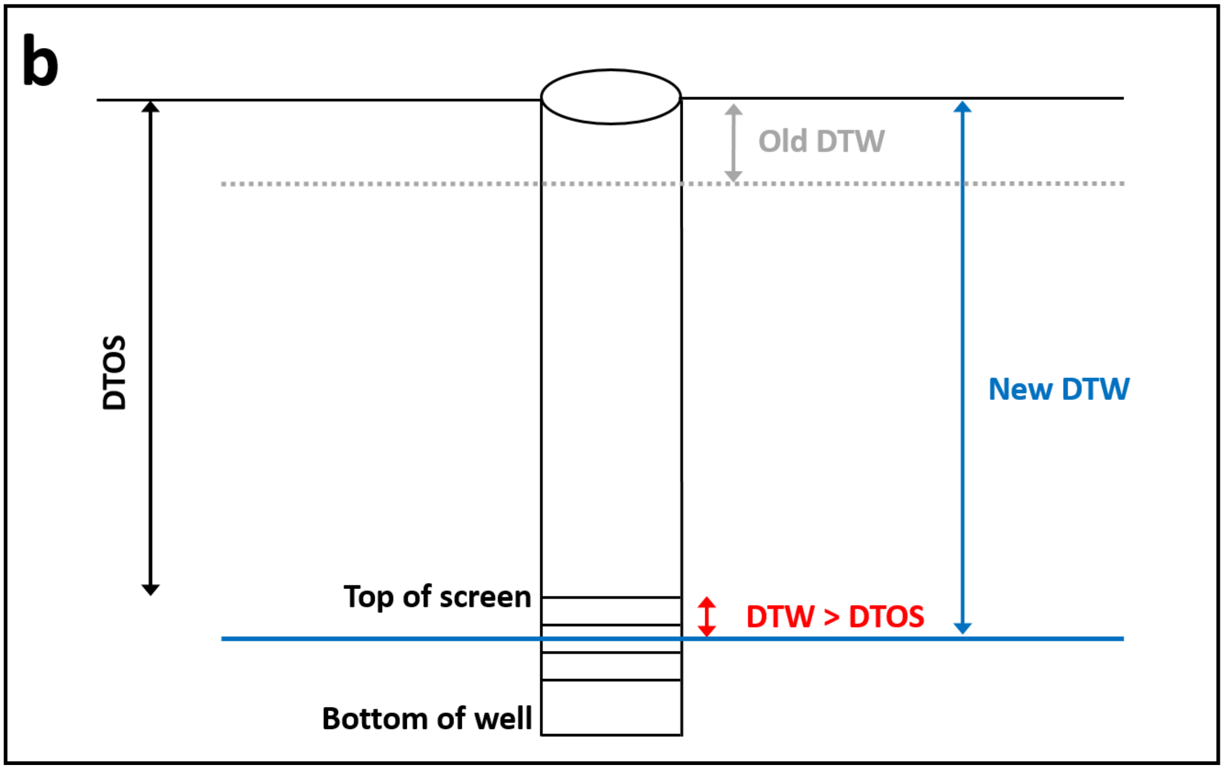

Figure 2b: Conditions resulting in corrective actions: well screen rehabilitation when DTW is greater than DTOS. DTW is Depth to Water. DTOS is depth to top of screen.

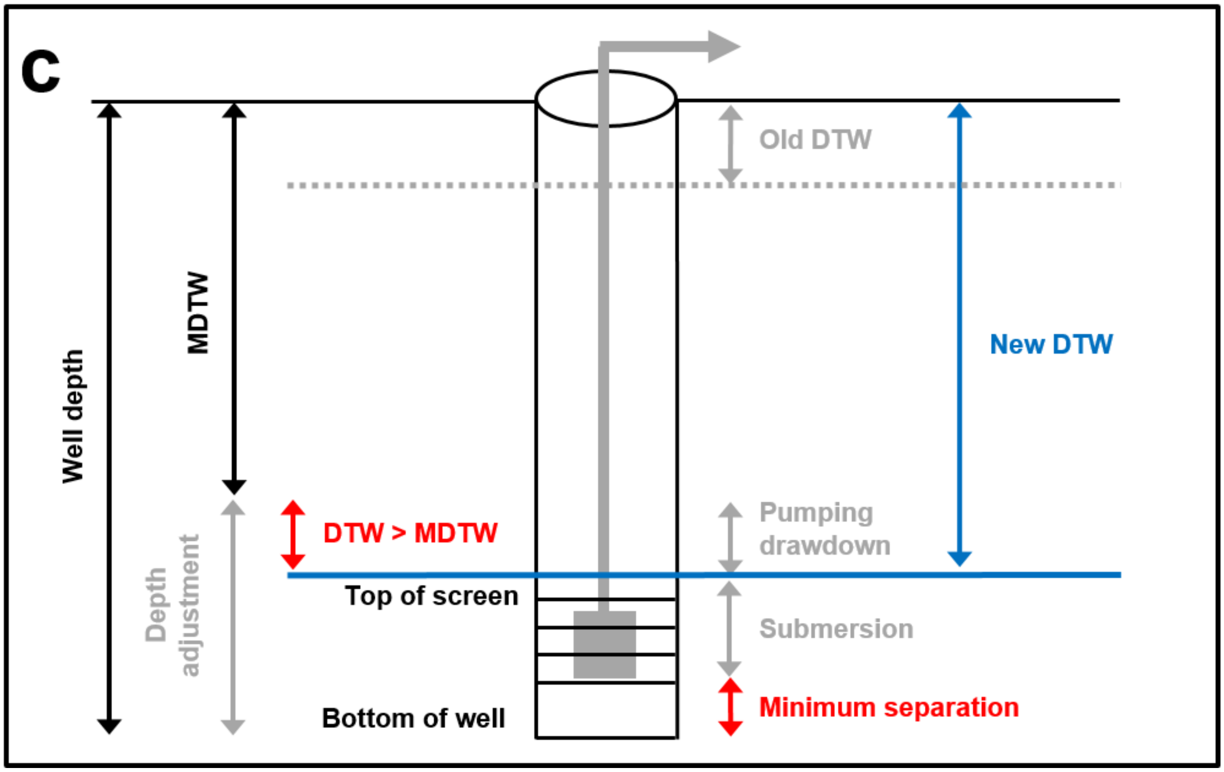

Figure 2c: Conditions resulting in corrective actions: well failure and replacement when DTW is greater than MDTW and there is no room to lower the pump (condition of minimum separation exists). DTW is Depth to Water. MDTW is Maximum Depth to Water.

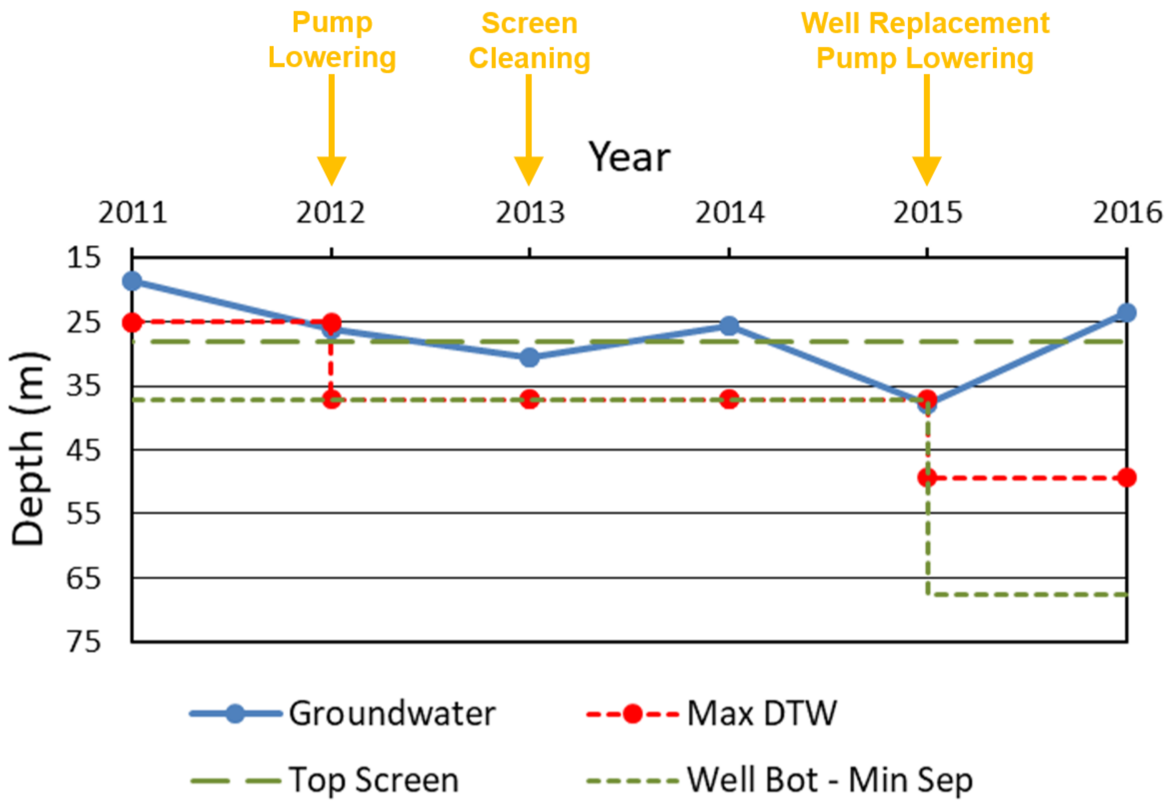

Figure 3: Example results for a single well simulating timing of mitigation measures during recent drought. Max DTW is Maximum Depth to Water. Well Bot – Min Sep is Well Bottom minus Minimum Separation.

The historic inventory of domestic well construction data (locations, year constructed, and depths to tops and bottoms of well screens) is aggregated and mapped onto the US Public Land Survey System (PLSS) section grid. This is done for two reasons. First, the State of California limits well location information to this grid in response to well owner privacy concerns. Second, it is necessary to compare the well constructions to groundwater levels that represent some minimum areal extent and grouping the wells by PLSS section grid is consistent with this requirement. After analysis is performed at the PLSS section level, higher-level aggregation to a geographic area of interest is possible and the aggregate effects on groups of wells can be considered (Figure 4).

Groundwater level decline scenarios considered in this work are based on observations from the 2012 to 2016 drought. As explained in Section 3.2, groundwater level declines that occurred during the drought throughout the study area are scaled by a drought factor to create scenarios for analysis.

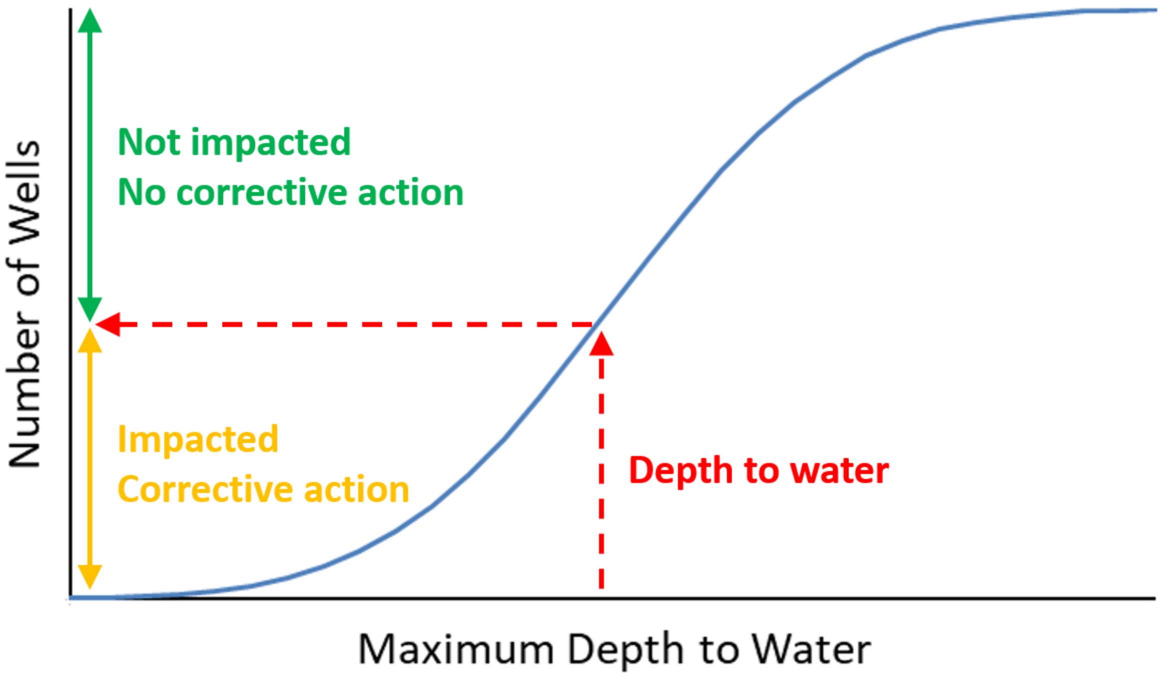

Figure 4: Conceptual representation of impact and mitigation measure simulation for a group of wells.

3.0 DATA SOURCES, PREPARATION AND MODEL PARAMETERIZATION

3.1 DATA SOURCES

Well construction information (including location by PLSS section, completion date, and depths to top and bottom of screened interval) were obtained from the California Department of Water Resources (CDWR) Online System of Well Completion Reports (OSWCR) database[6]. Groundwater depth information was obtained from the CDWR Groundwater Information Center Interactive Map Application[7]. Groundwater sustainability agency (GSA) boundary information was obtained from the CDWR SGMA Data Viewer with modification by CWC[8]. Boundary information for small CWS service areas was obtained from the Tracking California Water Boundary Tool with modification by CWC[9]. Details regarding mitigation measures and unit costs

[6] Downloaded on 11/16/18 from https://dwr.maps.arcgis.com/apps/webappviewer/index.html?id=181078580a214c0986e2da28f8623b37

[7] Downloaded on 11/16/18 from https://gis.water.ca.gov/app/gicima/

[8] Downloaded by CWC on 10/7/19 from https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#boundaries
The Exclusive GSAs Master Shapefile was modified by CWC so that unique GSA names were available for searches in the webtool.

were obtained during the Fall of 2018 through a consulting survey performed by RMG for another project in the Tulare Lake Basin[10].

3.2 DATA PREPARATION

The well construction and groundwater depth data were processed before use. The processing generally entailed:

- Selecting data located within the study area where both well construction and groundwater depth data were available
- Removing records for wells that were
  - Not related to supply (i.e., monitoring wells)
  - Incomplete with respect to location or construction
  - Expected to be dry at the beginning of the analysis time period
- Developing groundwater levels for scenarios to be analyzed

The following paragraphs discuss the details of the data preparation.

The well construction records were processed to select well types and locations applicable to the project and filter out incomplete data. Of approximately 980,000 total records statewide in the OSWCR database, there were approximately 420,000 water supply wells with complete location information. Approximately 158,000 of these records were for locations in the Central Valley[11] with the following distribution of well types:

- Domestic: 104,610 (66%)
- Municipal/Public: 3,877 (2.4%)
- Agricultural: 49,767 (31.4%)
- Unspecified: 288 (0.2%)

A common spatial domain for the well constructions and groundwater depths was determined by comparing the spatial extents of the well location and groundwater depth data. For domestic wells, PLSS sections were identified where both well location and groundwater depth data requirements were met. A total of 68,138 domestic well constructions were retained after this data processing step. For CWS wells (taken as those designated as municipal or public in the OSWCR database and located within the CWS service area), PLSS sections within a 1-mile buffer[12] of CWS

[9] Downloaded by CWC on 12/10/2018 from www.trackingcalifornia.org/water
CWC joined service area boundaries with CWS attributes from the State Water Resources Control Board and selected non-wholesale CWSs that serve 10,000 people or fewer.

[10] See Table 2. The survey entailed conducting telephone interviews with contractors that perform well services (pump service, well rehabilitation and constructing new wells) in the Tulare Lake Basin. Unit costs suggested by the contractors differed based on a variety of factors including project-specific experience and cost estimation assumptions. RMG applied professional judgement in selecting values from the range of survey results for use in the analysis. Because tabular summaries of results for this work, discussed in Section 5.1, include totals for the different mitigation measures, the effects of using different unit costs may be evaluated. However, as noted in Section 7, any post-processing of project results must be approved by RMG in writing in order to provide for correct calculations.

[11] The Central Valley was the focus of this work since geographically extensive groundwater depth data were readily available from CDWR.

boundaries were identified where both well location and groundwater depth data requirements were met. A total of 1,479 municipal/public well constructions were retained after this data processing step. Figures 5 A through D present the spatial distributions of wells and groundwater depth data[13].

Two additional steps in the data preparation process were implemented in the code that performs the impact analysis. First, records with incomplete well construction data (depths to top and bottom of screened interval) were filtered out (domestic: 36,105 or 53%; municipal/public: 491 or 33%). After this step, 32,033 domestic and 988 municipal/public wells remained. Figures 6 A and B summarize this step. The final processing step included 1) mapping the groundwater depth contours to the PLSS section grid, 2) comparing the groundwater depths to the well constructions and depths required for operation (Figure 2C), and 3) removing well constructions when the depth requirements for operation were not met (domestic: 2,736 or 9%; municipal/public: 15 or 2%). Figures 7 A through F summarize this step. Ultimately, 29,379 domestic and 973 municipal/public wells were retained for analysis over a 4,982 square-mile area. Table 1 summarizes the well data preparation steps and results.

Table 1: Well Data Preparation Steps and Results

Preparation Steps	Well Count	
	Domestic	Municipal/Public
Locations in Central Valley	104,610 (100%)	3,877 (100%)
Groundwater Depths Available near Well	68,138 (65%)	1,479 (38%)*
Complete Screened Interval Information	32,033 (31%)	988 (25%)
Can Operate under Fall 2014 Groundwater Depths	29,379 (28%)	973 (25%)
Total Excluded	75,313 (72%)	2,904 (75%)
Total Carried Forward for Analysis	29,379 (28%)	973 (25%)

* This step also entailed selecting only those municipal/public wells located within CWS service areas with boundaries adjusted to include a 1-mile buffer.

Groundwater depth data were processed for each the scenario chosen for analysis. Groundwater level decline was based on four scaled versions of the 2012 to 2016 drought (drought factors of 0.0, 0.5, 0.75 and 1.0; see Figure 8A). The starting time for scenario analysis was subject to data availability and specified as Fall 2014 (generally the deepest point in annual groundwater level fluctuation resulting from seasonal pumping that was closest to the beginning of the SGMA responsibility period of 1/1/15). The drought amplitude was defined by Fall 2011 (pre-drought) and Fall 2016 (late drought). The groundwater declines were applied over the responsibility/compliance and management periods as defined in the SGMA regulations and indicated on Figure 8B[14].

[12] A 1-mile buffer around the CWS boundaries was used to account for the potential that some CWS wells might be located outside the water system service areas. All wells located within a buffered CWS service area were considered as potential CWS wells.

[13] Areas that contain no data (where the base map is visible through the color flood presentation) do not contain all of the required well and groundwater level information.

Finally, weights were developed to aggregate analysis results obtained for each PLSS section to geographic areas of interest[15]. When the PLSS sections span boundaries between adjacent areas (GSAs, counties or buffered CWS service areas), the results must be weighted so that they are not counted multiple times. The weight for a PLSS section is based on the number of geographic areas that share the grid cell. For example, results for a grid cell shared by two areas receives a weight of ½.

[14] As indicated on Figure 8B, pumping lift increases as groundwater level decline progresses and, therefore, additional lift cost increases during the responsibility/compliance period. Other mitigation measures (lowering pump cleaning well screen and replacing well) and associated costs are considered to occur once at the point in time when maximum groundwater decline has occurred. The calculations allow for cost inflation and discounting over time; however, the interest rates have been set equal in this work (See Section 3.3) such that the effects cancel.

[15] The domestic well results are aggregated to the boundaries of GSAs and counties, while the municipal/public wells are aggregated to CWS service areas with 1-mile buffers.

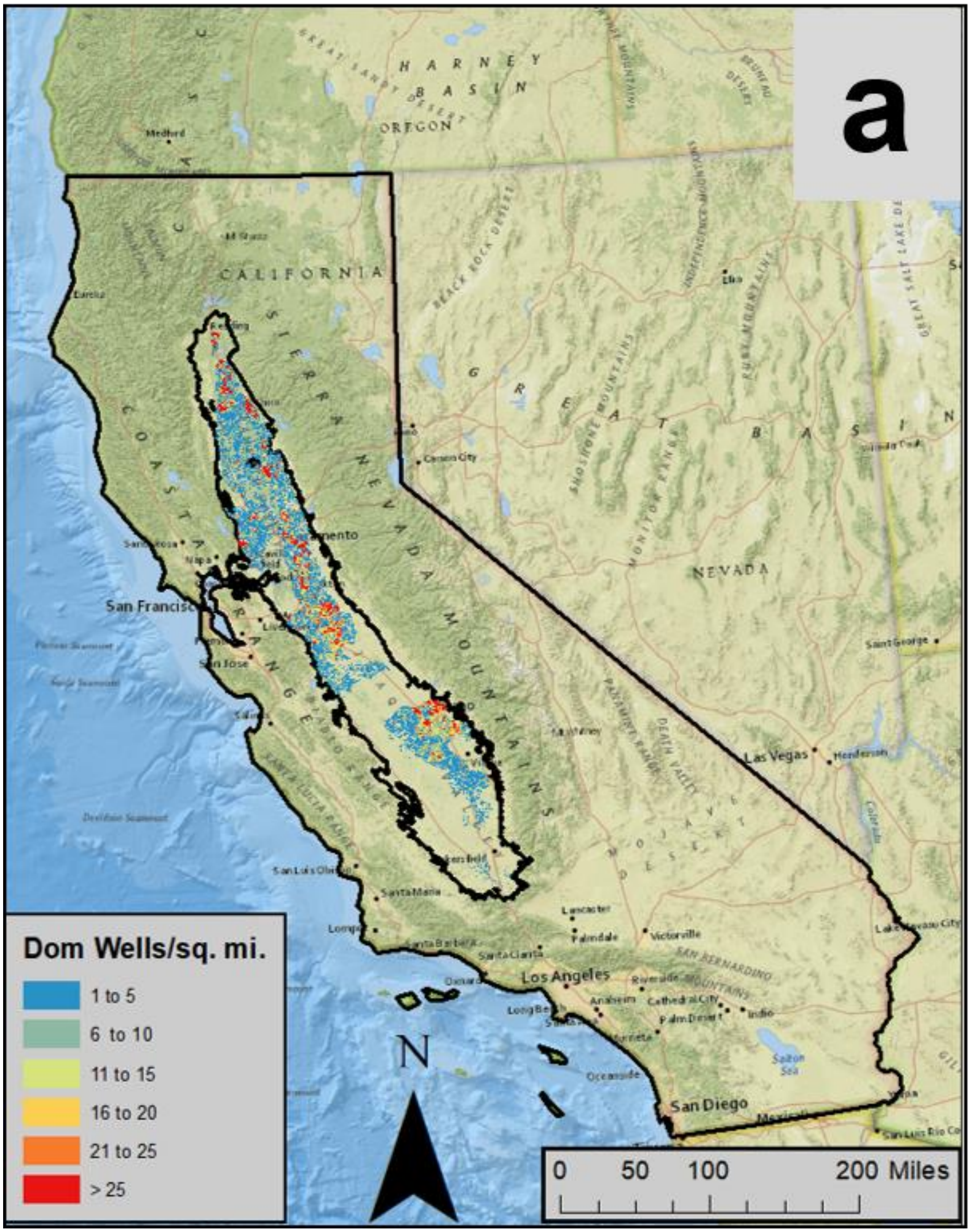

Figure 5a: Spatial distribution of wells and groundwater depth data presented by PLSS section (per square mile): domestic wells where both well and groundwater depth requirements were met (N = 68,138 wells). Sq. mi. is square mile.

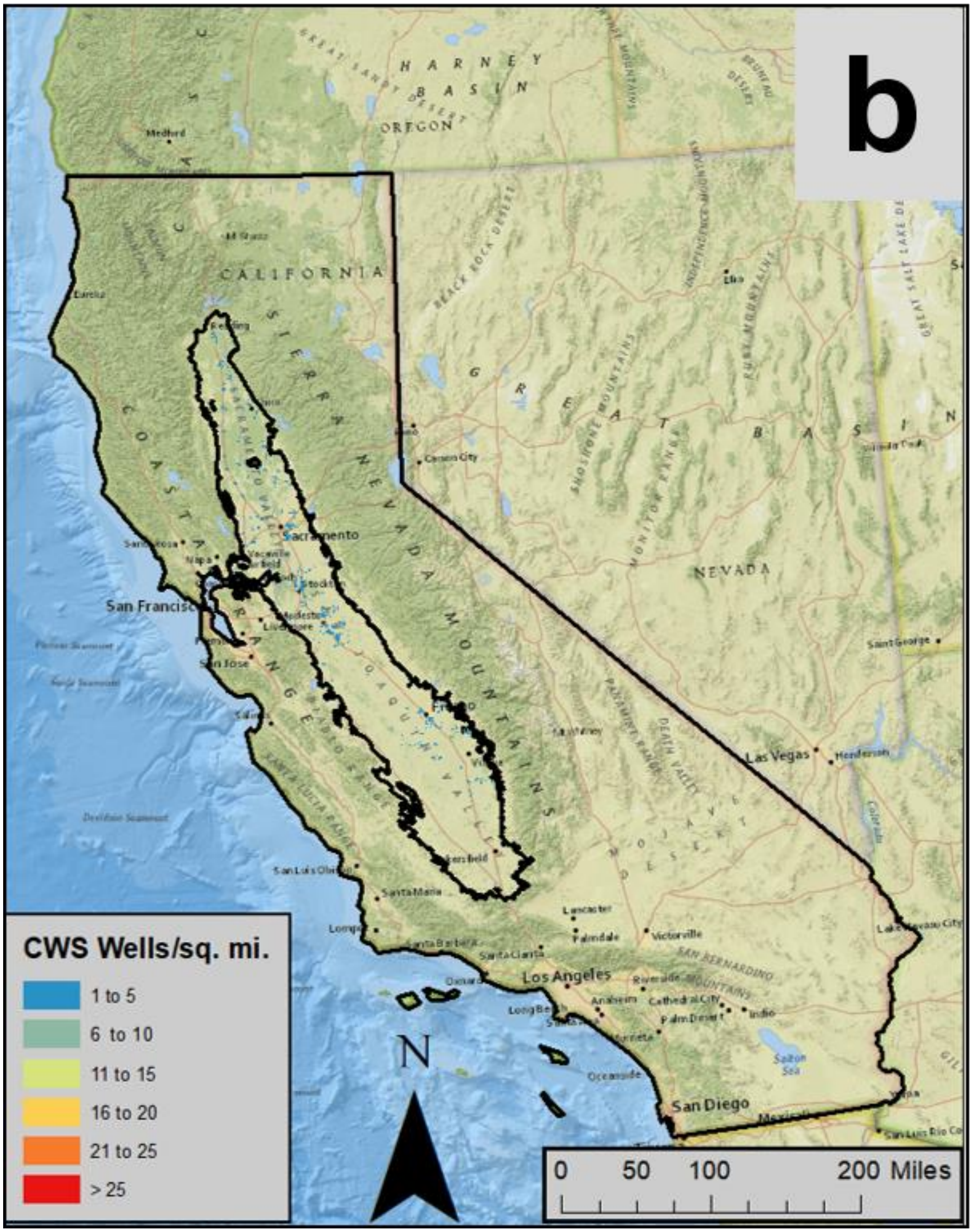

Figure 5b: Spatial distribution of wells and groundwater depth data presented by PLSS section (per square mile): municipal/public wells located within 1-mile buffered service areas for small CWS (less than 10,000 people served) where both well and groundwater depth requirements were met (N = 1,479 wells). Sq. mi. is square mile.

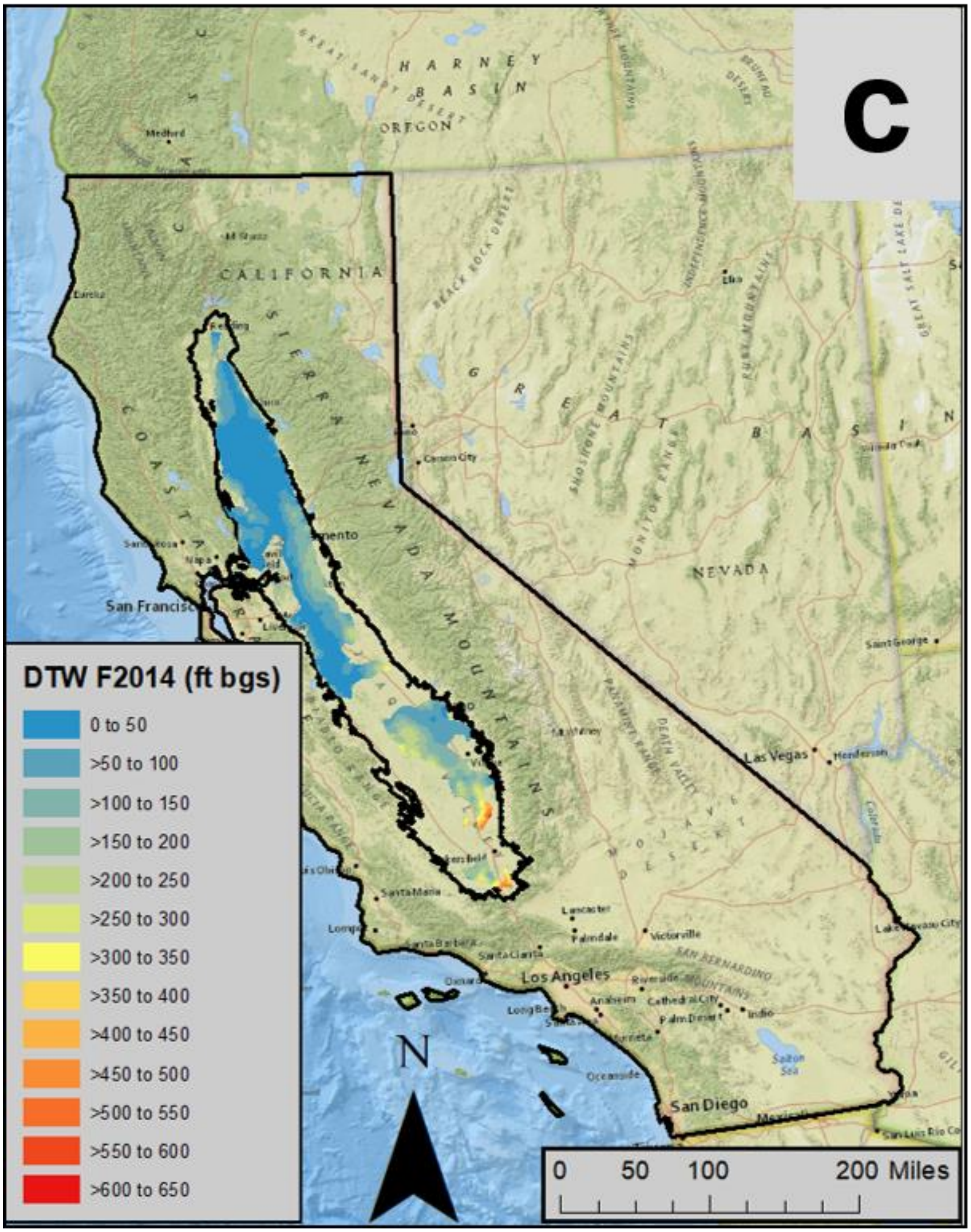

Figure 5c: Spatial distribution of wells and groundwater depth data presented by PLSS section (per square mile): Fall 2014 groundwater depths taken as the beginning of SGMA responsibility/compliance period. Ft bgs is feet below ground surface.

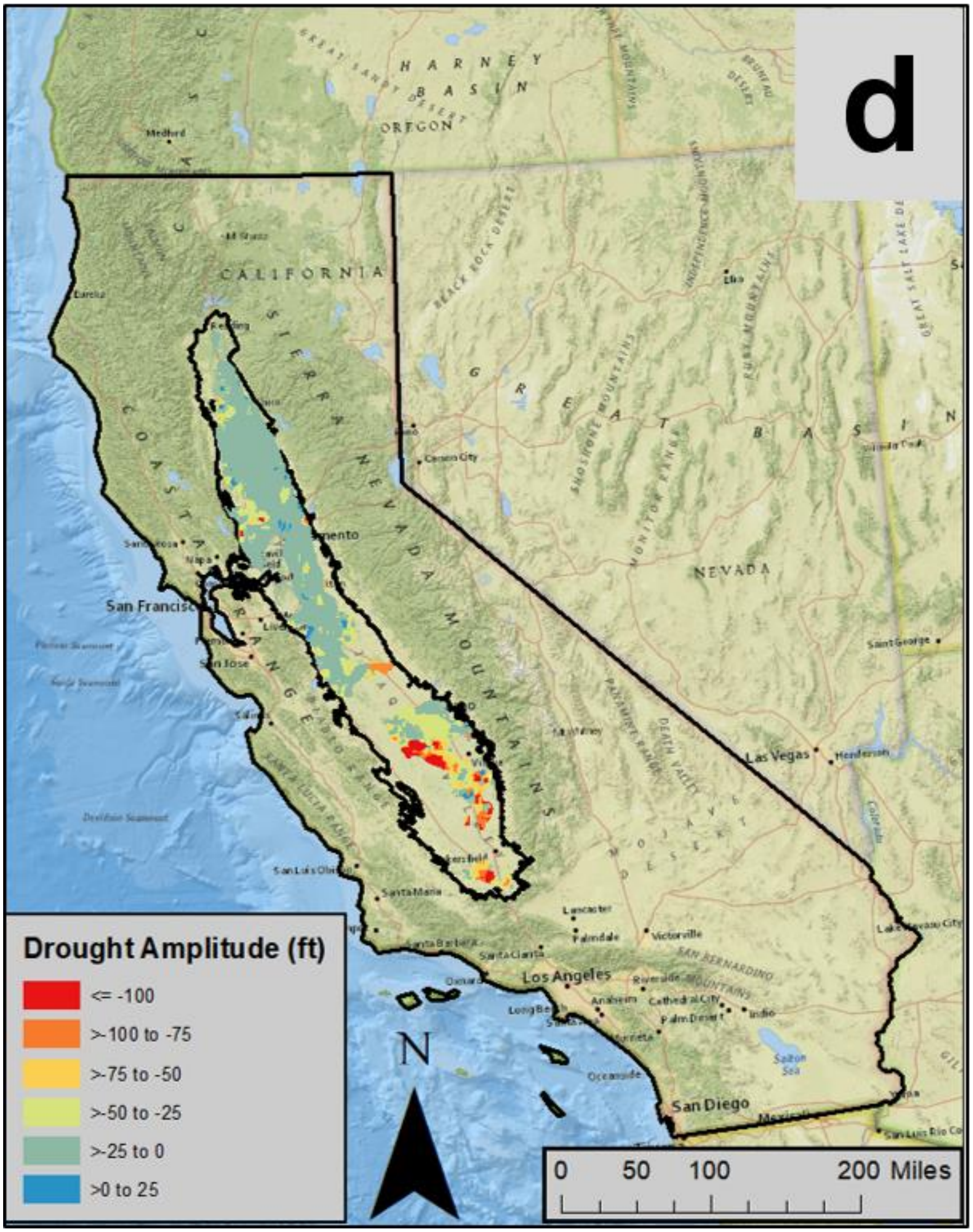

Figure 5d: Spatial distribution of wells and groundwater depth data presented by PLSS section (per square mile): 2012 to 2016 drought amplitude. Ft is feet.

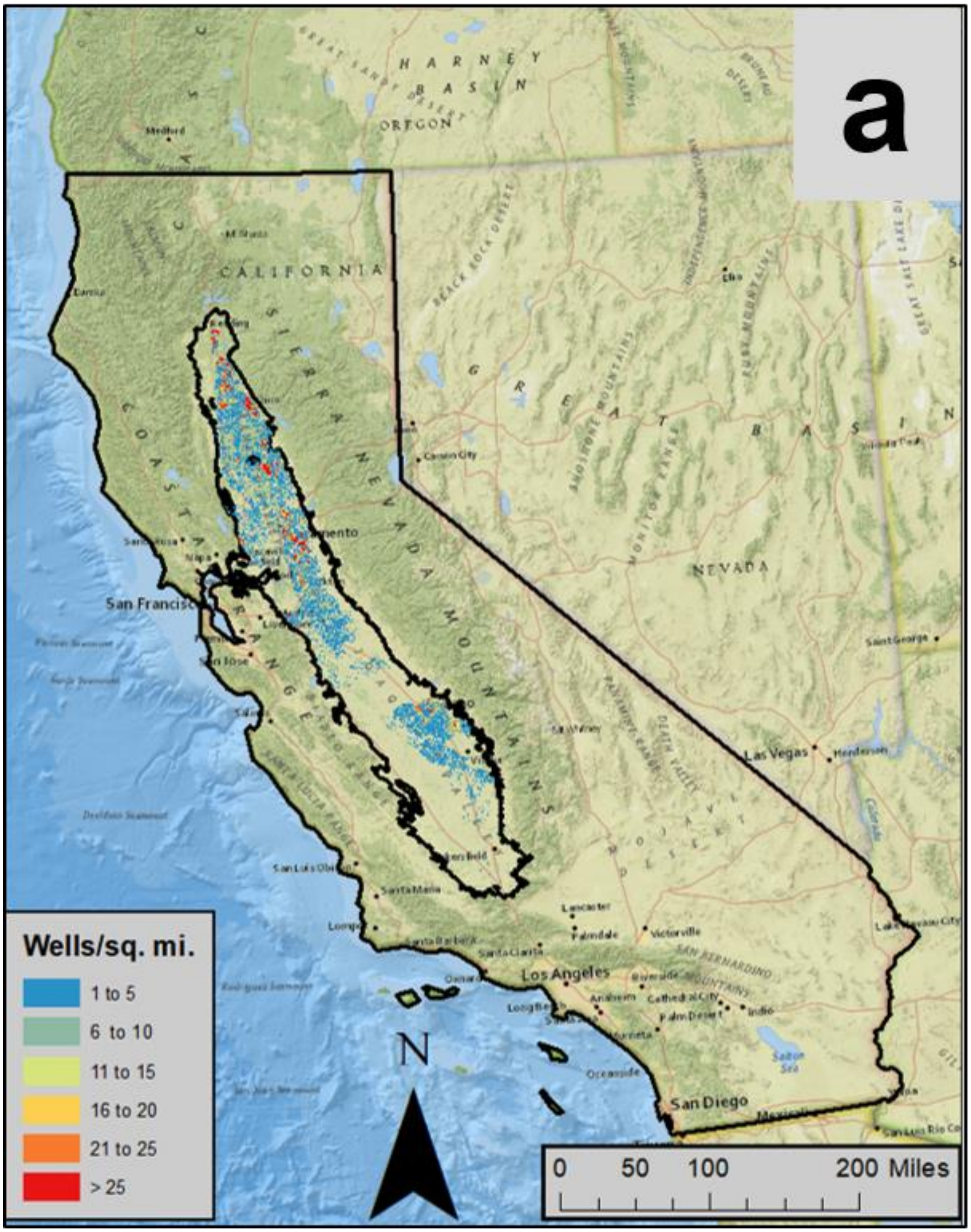

Figure 6a: Spatial distribution of wells removed from analysis because of incomplete screened interval data: domestic wells by PLSS section (N = 36,105 wells).

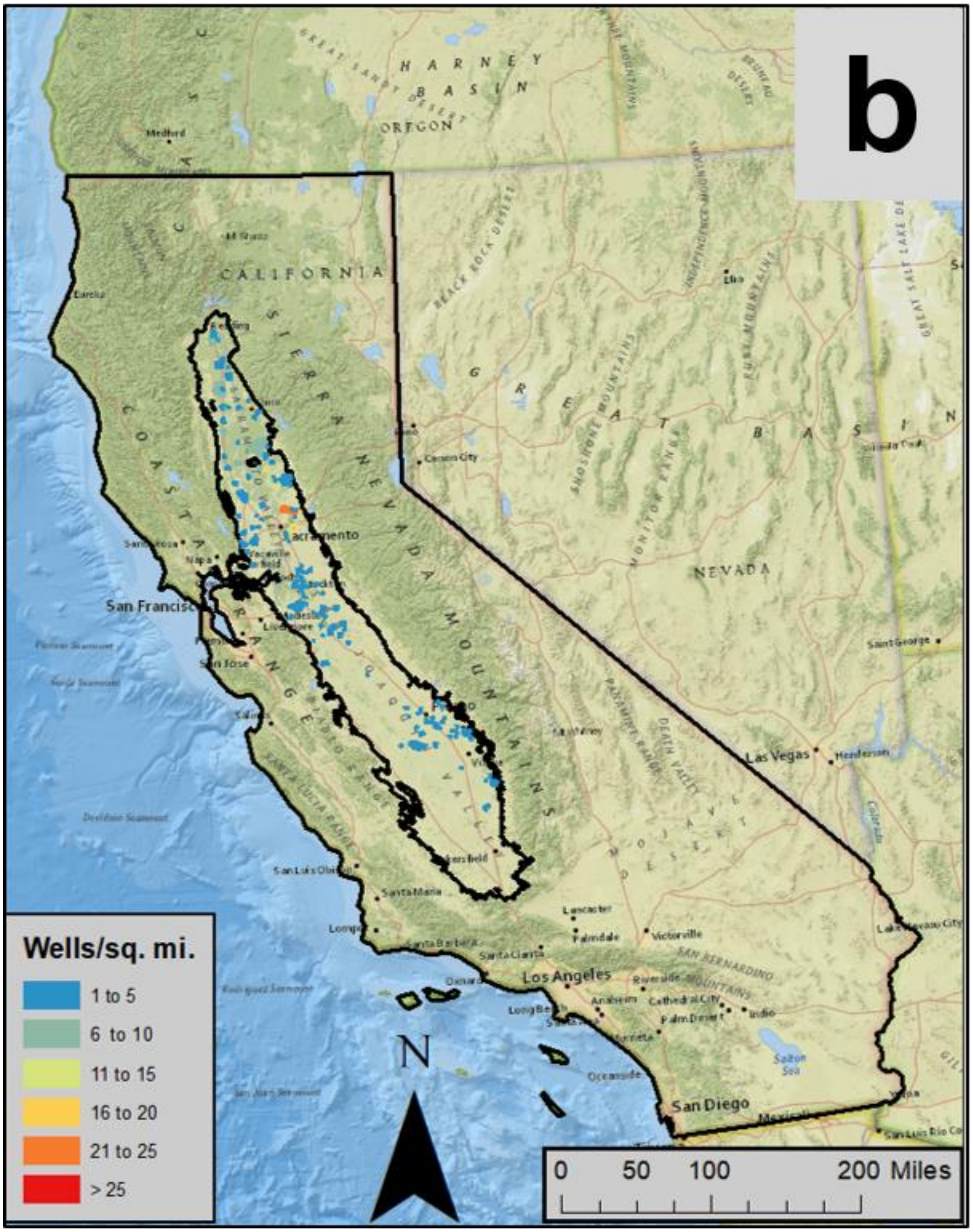

Figure 6b: Spatial distribution of wells removed from analysis because of incomplete screened interval data: municipal/public wells by buffered CWS service area (N = 491 wells).

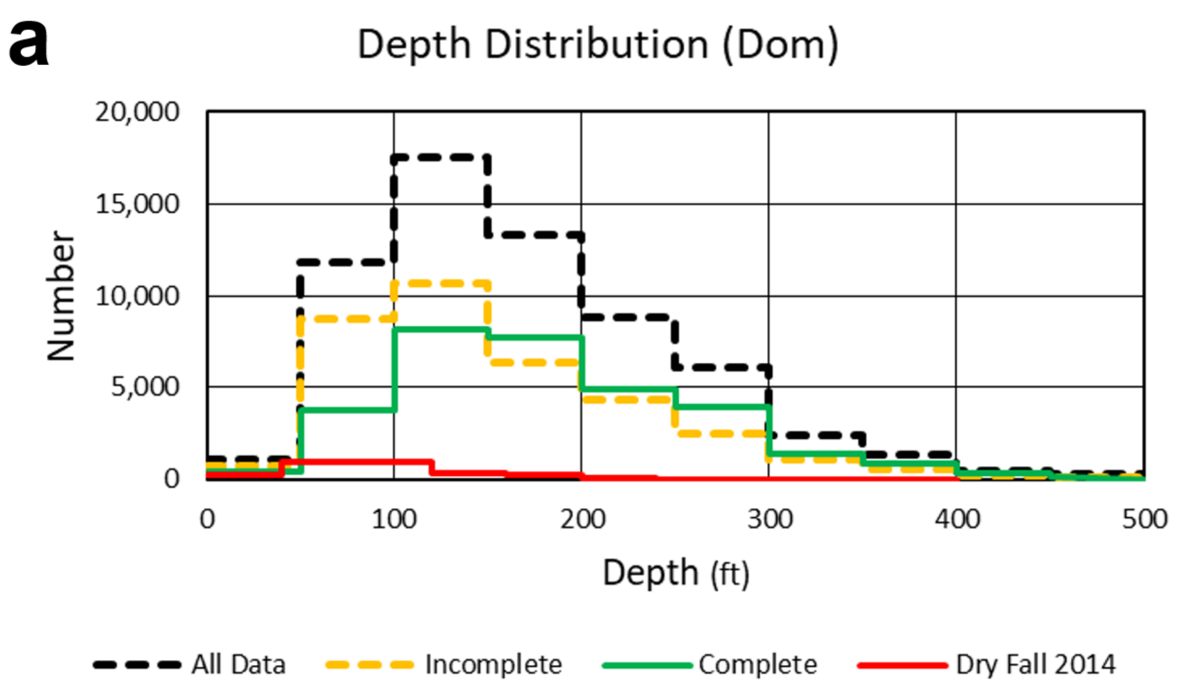

Figure 7a: Wells removed from analysis because they were too shallow to operate relative to Fall 2014 groundwater depths: domestic well depth distribution (N = 2,736). Dom is domestic wells.

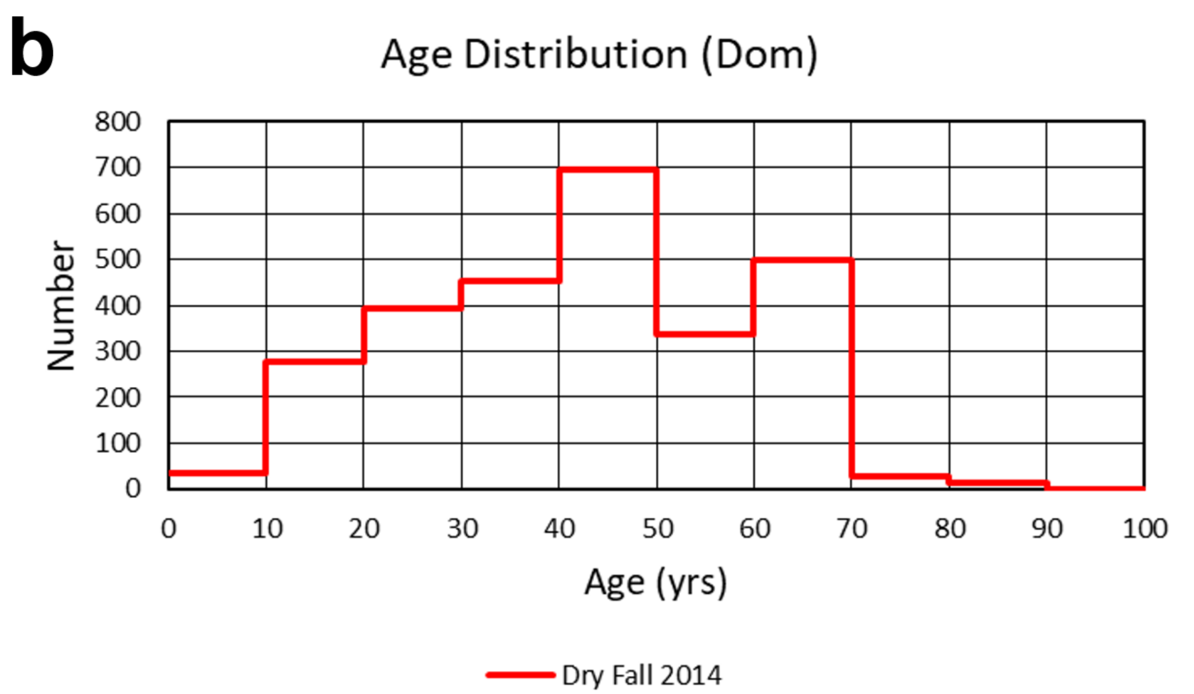

Figure 7b: Wells removed from analysis because they were too shallow to operate relative to Fall 2014 groundwater depths: domestic well age distribution (N = 2,736). Dom is domestic wells.

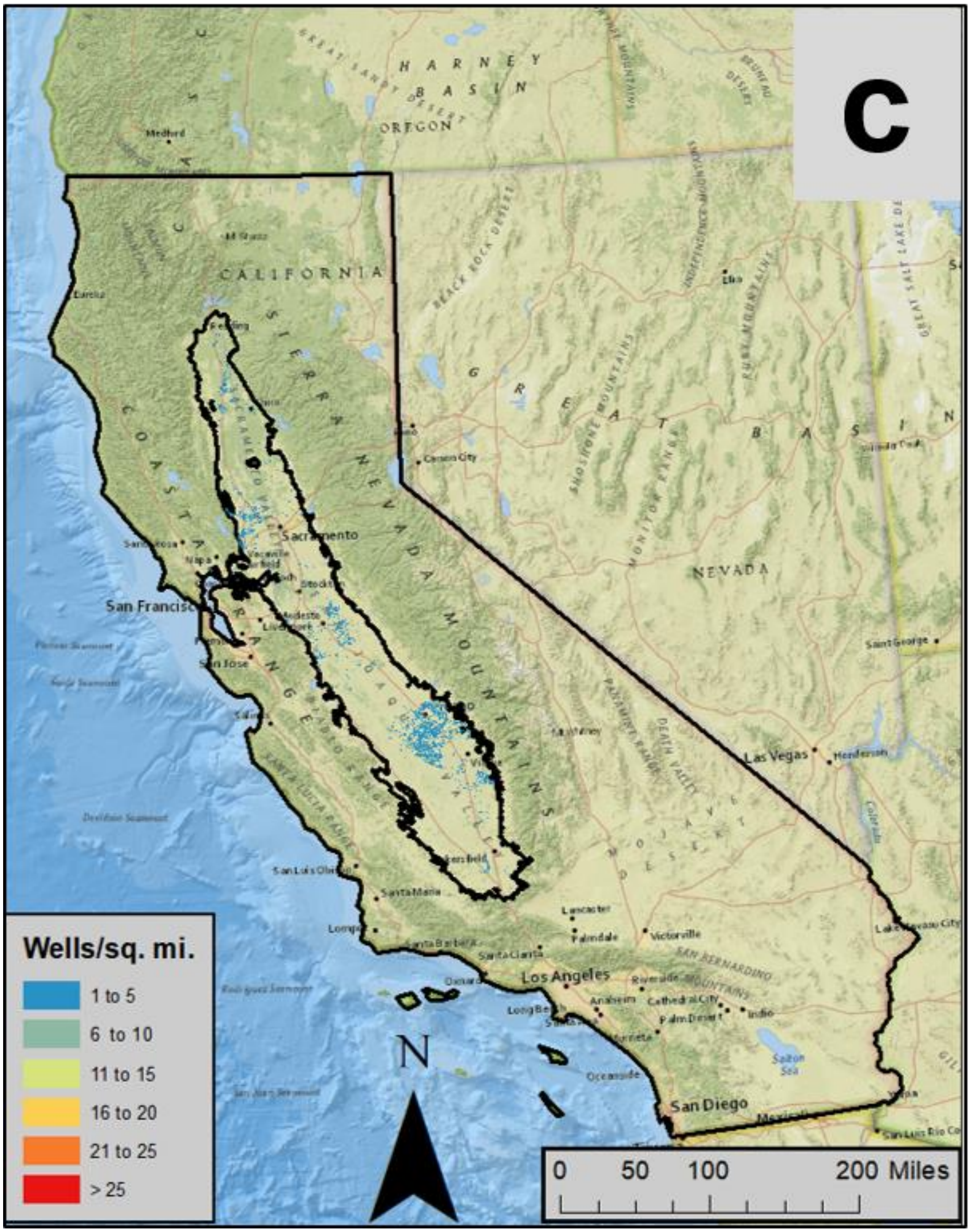

Figure 7c: Wells removed from analysis because they were too shallow to operate relative to Fall 2014 groundwater depths: domestic well spatial distribution by PLSS section (N = 2,736).

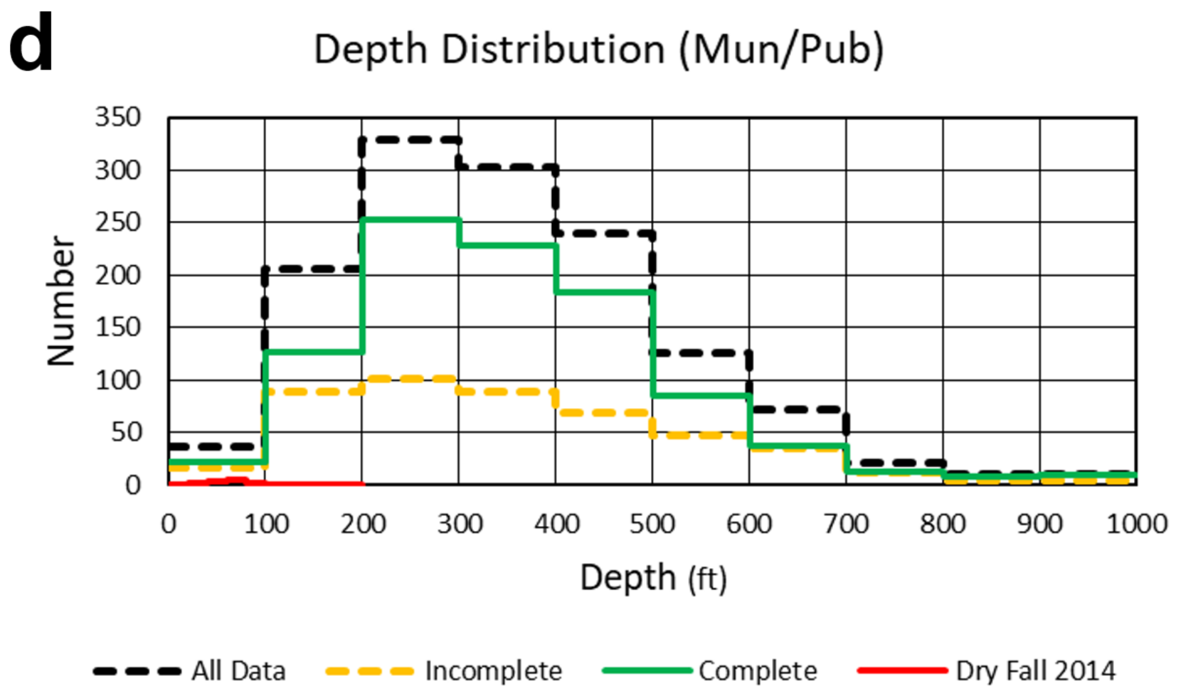

Figure 7d: Wells removed from analysis because they were too shallow to operate relative to Fall 2014 groundwater depths: municipal/public well depth distribution (N = 15). Mun/Pub is Municipal/Public wells.

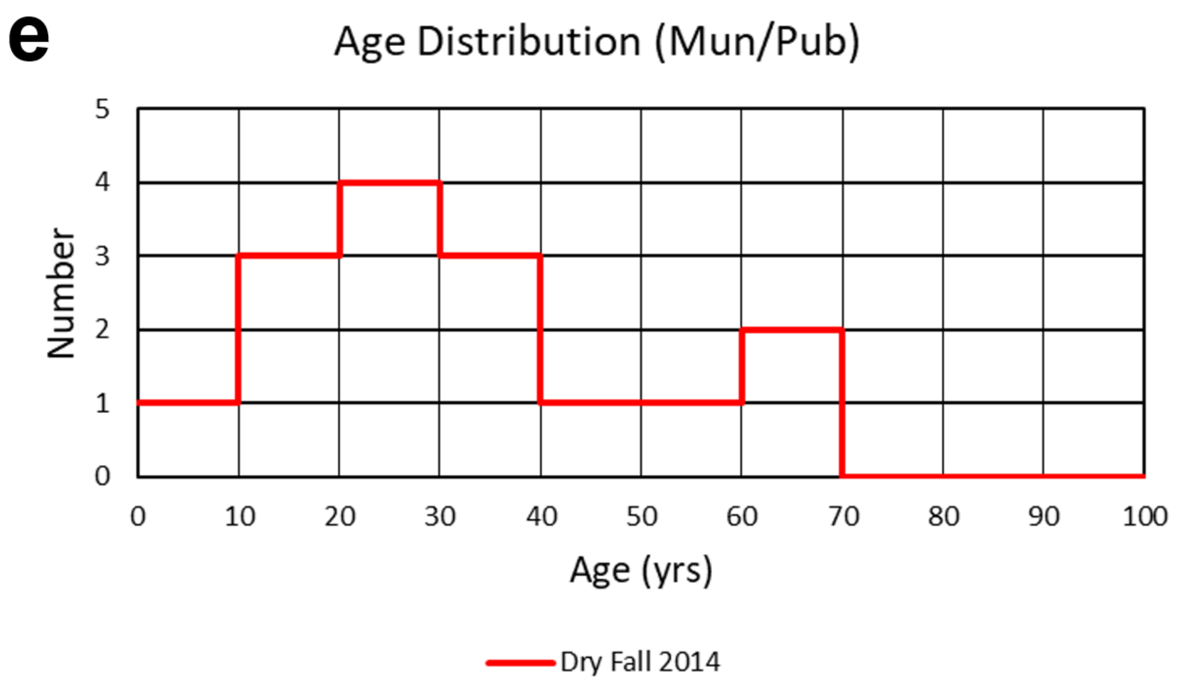

Figure 7e: Wells removed from analysis because they were too shallow to operate relative to Fall 2014 groundwater depths: municipal/public well age distribution (N = 15). Mun/Pub is Municipal/Public wells.

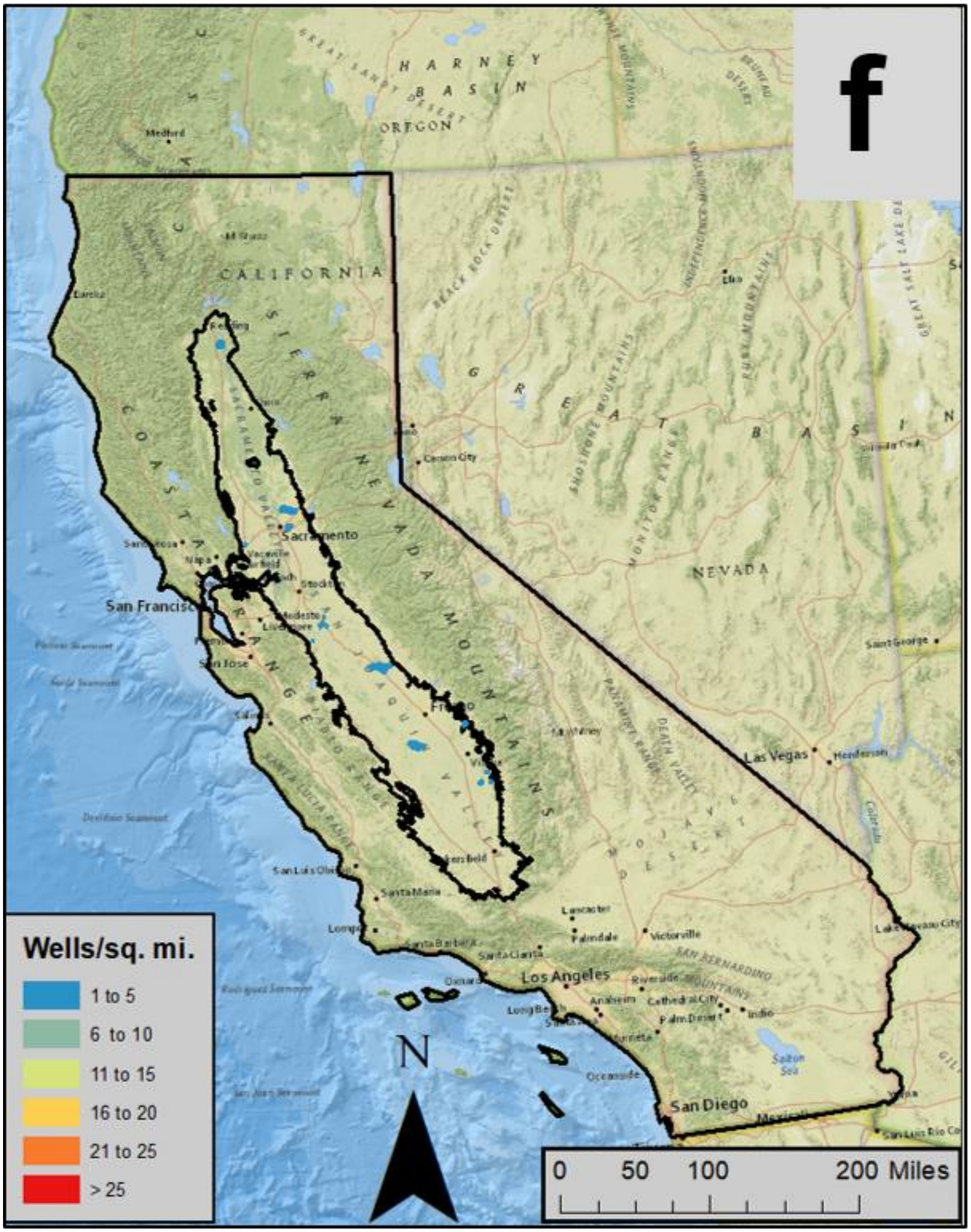

Figure 7f: Wells removed from analysis because they were too shallow to operate relative to Fall 2014 groundwater depths: municipal/public well spatial distribution by buffered CWS service area (N = 15).

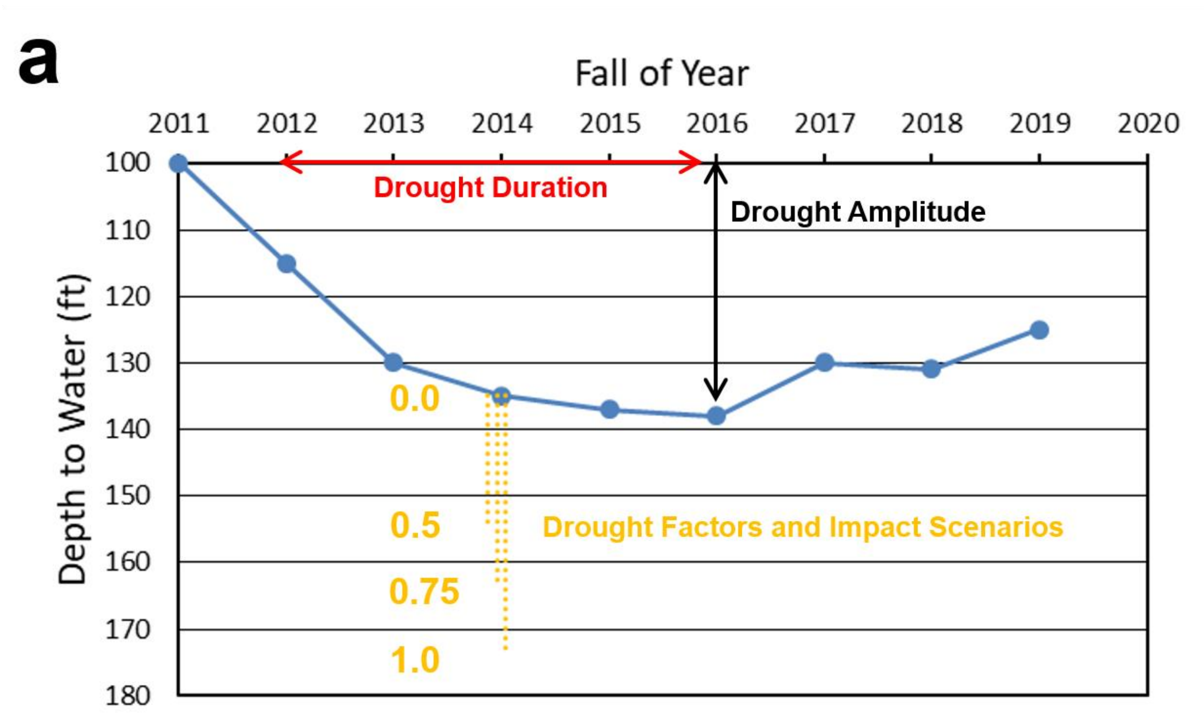

Figure 8a: Groundwater level decline scenarios: total decline based on scaled versions of 2012 to 2016 drought.

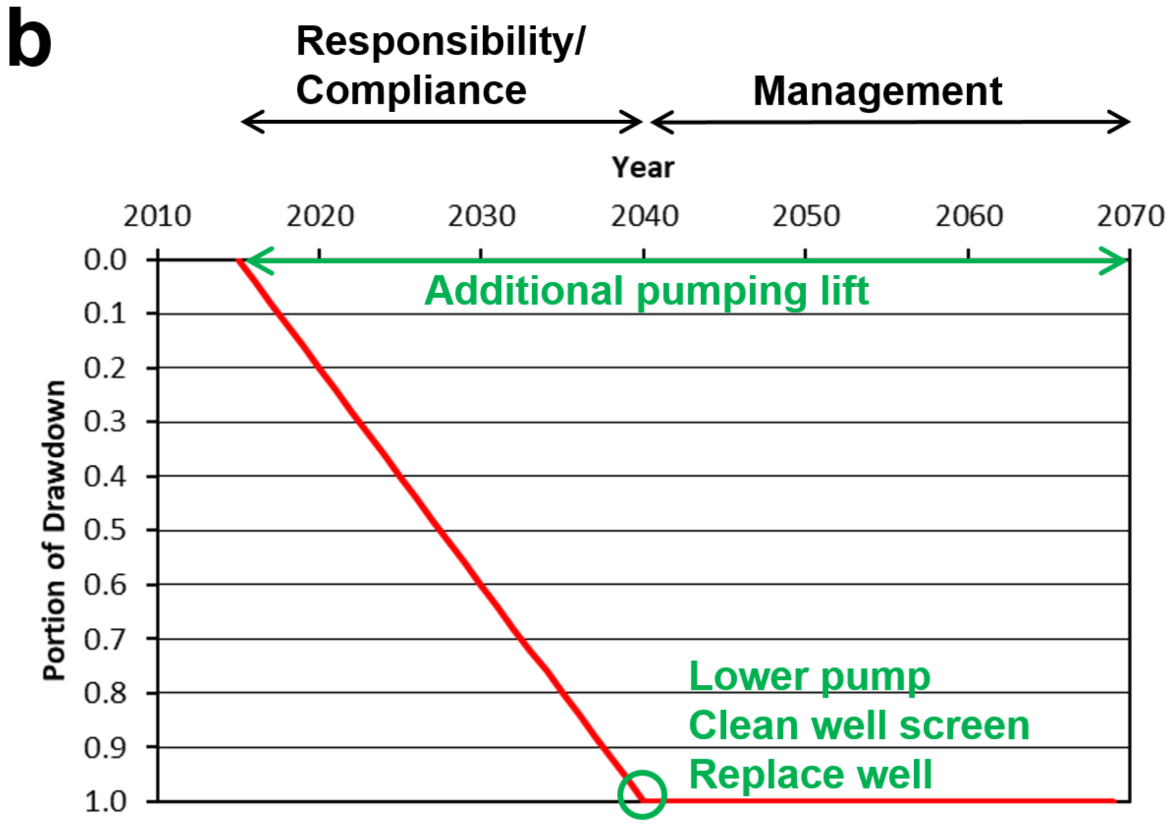

Figure 8b: Groundwater level decline scenarios: declines applied over SGMA responsibility/compliance and management periods.

3.3 MODEL PARAMETERS

Table 2 summarizes the parameters used in the calculations. The most significant and uncertain values are for the initial pump depth below static water depth and well retirement age. A value of 60 feet was chosen for initial pump depth and no well retirement was considered[16]. For initial pump depth, a small value (shallow initial pump depth setting) would make more wells vulnerable to groundwater level decline and result in high predictions of well operations impacts and pump lowering costs, while a large value (deep initial pump depth setting) would result in low predictions. Conversely for well retirement age, a large value (wells not retired until old) would increase the population of wells potentially impacted and result in high predictions of well operations impacts and the full range of potential costs, while a small value (wells retired earlier) would result in low predictions[17]. Uncertainty resulting from these parameter selections is discussed in the following sections.

[16] The CWC Technical Advisory Committee requested that no well retirement be considered in the analysis so that all well data would be used.

[17] This sensitivity to the parameter value is enhanced when, as is the case for this work, the older wells tend to be shallower.

Other parameter values (pumping rate, pumping volume, specific capacity, pump submergence, plant efficiency and minimum pump separation) are expected to vary from well to well. Given the limited information available for these parameters, RMG selected representative values based on professional judgement. Cost information was collected as described in Section 3.1. Interest rates were set to nominal, generally representative, values.

Table 2: Model Parameter Summary

Parameter	Domestic Wells	Municipal/Public Wells
Initial pump depth below static water	60 ft	60 ft
Well retirement age	None	None
Pumping rate	5 gpm	500 gpm
Pumping volume	0.5 ac-ft/yr	120 ac-ft/yr
Specific capacity	20 gpm/ft	50 gpm/ft
Pump submergence	5 ft	5 ft
Plant efficiency	60%	60%
Minimum pump separation	20 ft	20 ft
Cost for increased lift	0.16 $/kW-hr	0.16 $/kW-hr
Cost to lower pump	2,000 $/20 ft	15,000 $/20 ft
Cost to clean well screen	$10,000	$200,000
Cost to replace well	115 $/ft	500 $/ft
Inflation rate	3%	3%
Discount rate	3%	3%

4.0 ASSUMPTIONS AND LIMITATIONS

Figure 9 summarizes the steps in the data preparation and analysis described in Section 3.2. As is the case for any quantitative analysis, assumptions are made so that the calculation tasks are achievable and the analysis can be accomplished with limited data. The most important assumptions and limitations for this analysis are discussed below.

The approach may tend to overestimate impacts and costs since all well constructions are used regardless of installation date (no well retirement considered) and there is the potential that some wells may no longer be in service. However, as indicated for Step 3 on Figure 9 and discussed above, wells that are too shallow relative to groundwater depth at the beginning of the analysis are removed from consideration (see Figure 7). This adjustment should significantly temper the potential for over-estimation. For the municipal/public wells, some overestimation may also have occurred since all wells located within the buffered CWS service areas were retained in the analysis[18].

[18] Some wells located within a CWS service area, as well as the 1-mile buffer, may not be operated by the CWS. Therefore, over-estimation could occur.

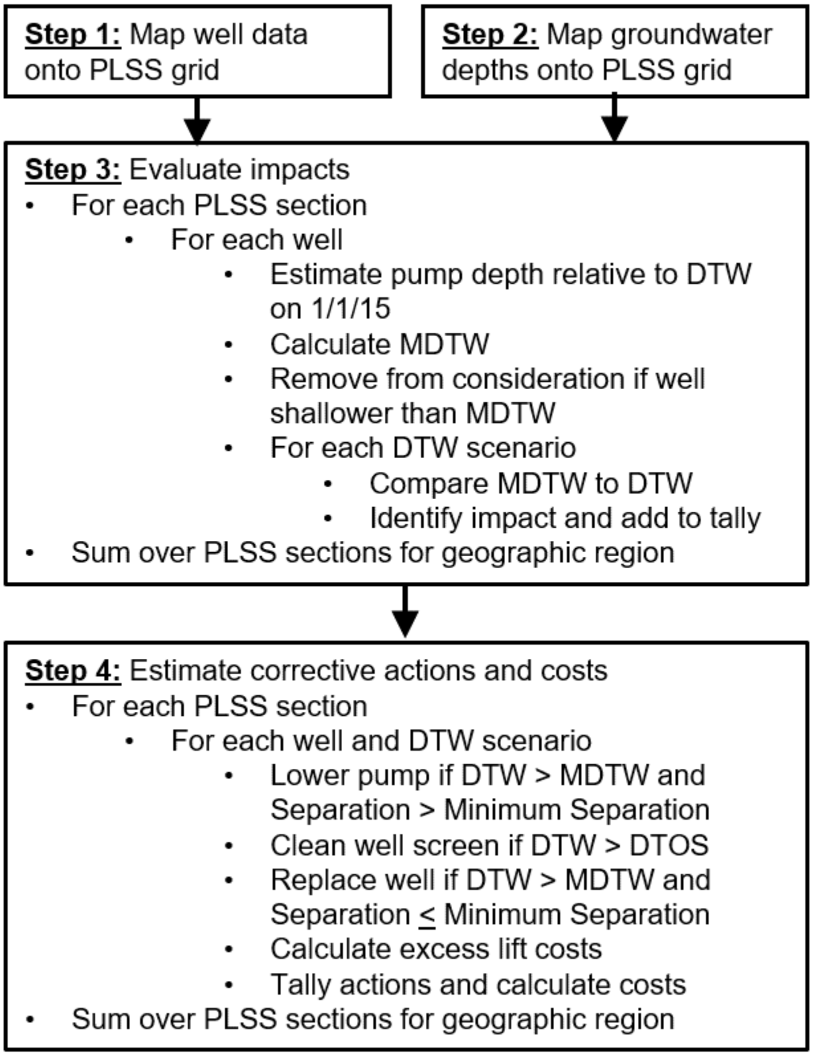

Figure 9: Summary of data preparation and analysis steps. The mapping of data onto the PLSS grid (Steps 1 and 2) involves the processing approach discussed in Section 3.2.

The physical and financial parameters used in the calculations (Table 2) are represented as spatially constant for each of the two well types instead of varying. However, the analysis retains a significant amount of spatial variability since the well construction and groundwater depth[19] data that drive physical aspects of the analysis do vary with location. Model prediction uncertainty analysis (Section 5.3), including evaluation of sensitivity to the pump depth parameter, provides

[19] It should be noted that the groundwater depth contours that form the basis of the impact scenarios provide only a rough approximation of field conditions and may affect prediction accuracy. Gailey et al. (2019) provide additional discussion of this point.

an indication of the potential range in predictions stemming from physical parameters in the model. Also, as indicated in Footnote 10, the tabular results may be used to further evaluate the sensitivity of results to cost parameter values.

Data gaps exist in the primary datasets used in this work. Missing groundwater depth data results in much of the well construction dataset being discarded. For domestic wells, the groundwater depth data requirements for the analysis could not be met for 4,756 (41%) PLSS section grids that contained well construction data and 36,472 well construction records (35%) could not be evaluated. For the municipal/public wells, the groundwater depth data requirements for the analysis could not be met for 2,971 (36%) PLSS section grids that contained well construction data and 2,398 well construction records (62%) could not be evaluated. Missing well construction data was also a consideration with missing well screen depths being the most prevalent gap (domestic: 36,105 or 53% of remaining data; municipal/public: 491 or 33% of remaining data).

The groundwater level decline scenarios included in this work are based on conditions that occurred during the 2012 to 2016 drought and do not necessarily reflect management decisions that may be made in the future. Changes in cropping and pumping patterns, as well as new efforts to perform aquifer recharge, may occur to varying degrees at different locations within the study area. As a result, the state-wide distribution and timing of groundwater level declines may be different than represented.

Finally, the maximum horizontal resolution for this study is limited to one square mile because well location information is limited to the PLSS section grid. Notwithstanding these considerations, this approach provides analysis where none was previously available, provides some analysis to evaluate uncertainty in the results, allows for flexibility in future application and adds insight regarding water supply vulnerability for areas where data are available.

5.0 RESULTS

A brief summary of results for domestic wells (by PLSS section) and CWS wells (by buffered service area) is presented here with additional exploration, including higher-resolution viewing of results for specific areas within the larger study area, possible through the CWC Drinking Water Vulnerability Webtool that will be launched soon. Results aggregated to geographic areas of interest (GSAs and counties for domestic wells, and CWS service areas with 1-mile buffers for municipal/public wells) are only presented in the webtool[20].

There are four drought intensity scenarios (Figure 8A). The base case (2012 to 2016 drought amplitude scaled by zero) is not presented since it merely provides a check on calculations to verify

[20] Care should be exercised when reviewing the aggregated results. The areal extent of data available for the analysis should be reviewed relative to the aggregation area (GSA, county or buffered CWS service area). In some cases, the data do not cover the entire area of interest and aggregated results could be misleading. For example, well data are available for the northwest part of Tulare County; however, no groundwater depth data are available for that area and potential well impacts cannot be included in the analysis. Therefore, aggregation of results for Tulare County may underestimate magnitudes of impact because some of the well data was not included in the analysis.

that impacts and costs predicted for conditions present on January 1, 2015 (beginning of SGMA responsibility period) are properly removed from the results. Results for the remaining three drought intensity scenarios (2012 to 2016 drought amplitude scaled by drought factors of 0.5, 0.75 and 1.0) are presented in terms of spatial distribution and magnitudes for the entire study area.

5.1 SPATIAL DISTRIBUTION OF IMPACTS AND COSTS

There are three maps per drought scenario that tally results by PLSS section for domestic wells or buffered CWS service area for municipal/public wells: 1) impacts other than additional pumping lift (since additional lift applies at all locations where there is data support), 2) costs for impacts other than additional pumping lift and 3) costs for additional pumping lift.

For domestic wells, Figures 10 A through C present results for the 0.5 drought factor, while Figures 11 A through C and 12 A through C present results for the 0.75 and 1.0 drought factors. Impacts other than additional pumping lift are most pronounced south of Fresno with additional clusters near Modesto, west of Sacramento and west of Chico. Additional pumping lift occurs throughout the study area.

For CWS wells, Figures 13 A through C present results for the 0.5 drought factor, while Figures 14 A through C and 15 A through C present results for the 0.75 and 1.0 drought factors. Impacts other than additional pumping lift are most pronounced south of Modesto and Fresno with additional clusters west of Sacramento and west of Chico. Additional pumping lift occurs throughout the study area.

The information presented in this section was also aggregated by GSA and county (for domestic wells) and by CWS. The tables that contain these results are large and not presented in this report. Instead, they are to be made available through the CWC Drinking Water Vulnerability Webtool that will be launched soon.

Figure 10a: Spatial distributions of impacts and costs for domestic wells with a 0.5 drought factor: impacts other than additional pumping lift (pump lowering, well screen rehabilitation, well replacement). Tallies by PLSS section.

Figure 10b: Spatial distributions of impacts and costs for domestic wells with a 0.5 drought factor: costs for impacts other than additional pumping lift. Tallies by PLSS section.

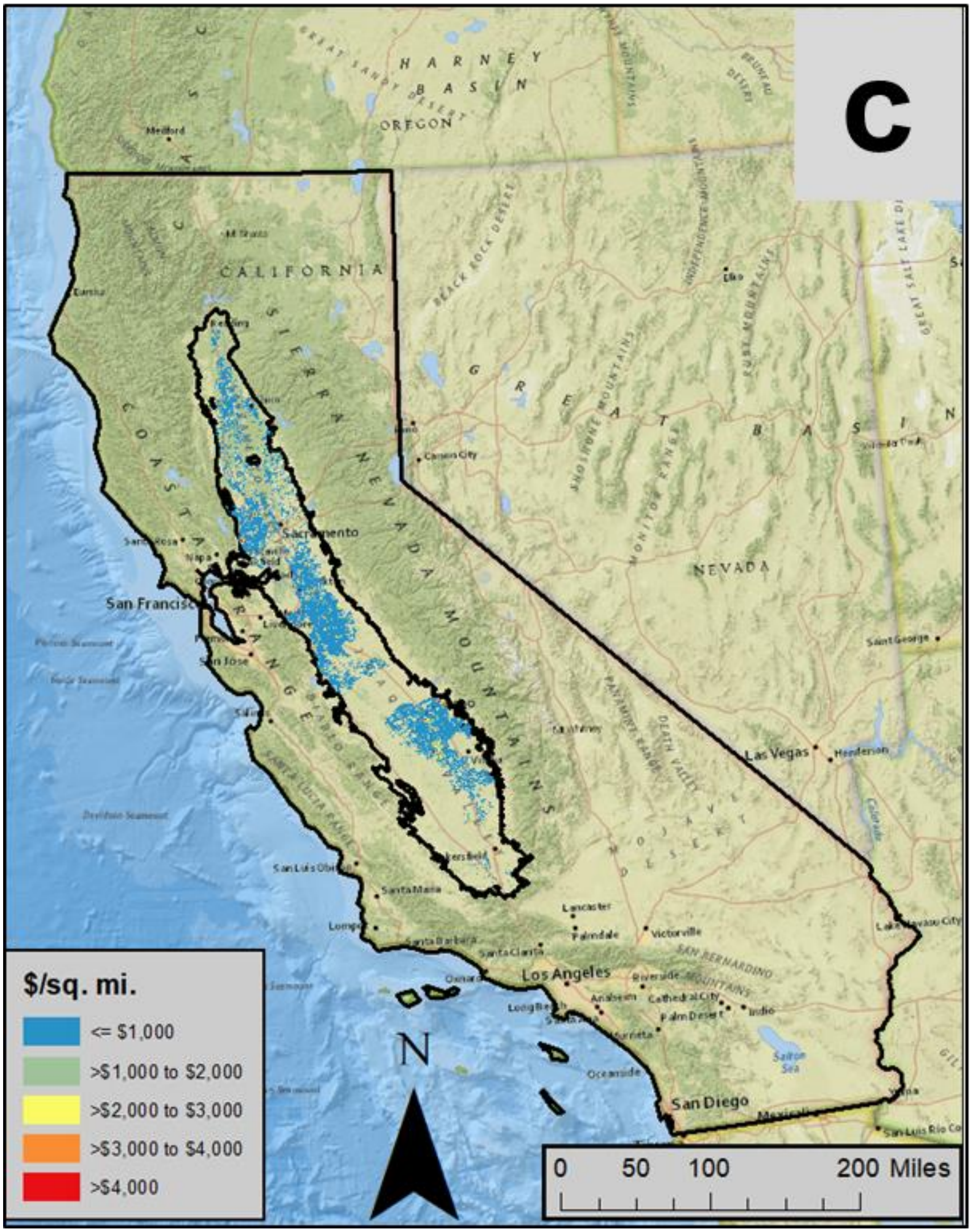

Figure 10c: Spatial distributions of impacts and costs for domestic wells with a 0.5 drought factor: costs for additional pumping lift. Tallies by PLSS section.

Figure 11a: Spatial distributions of impacts and costs for domestic wells with a 0.75 drought factor: impacts other than additional pumping lift (pump lowering, well screen rehabilitation, well replacement). Tallies by PLSS section.

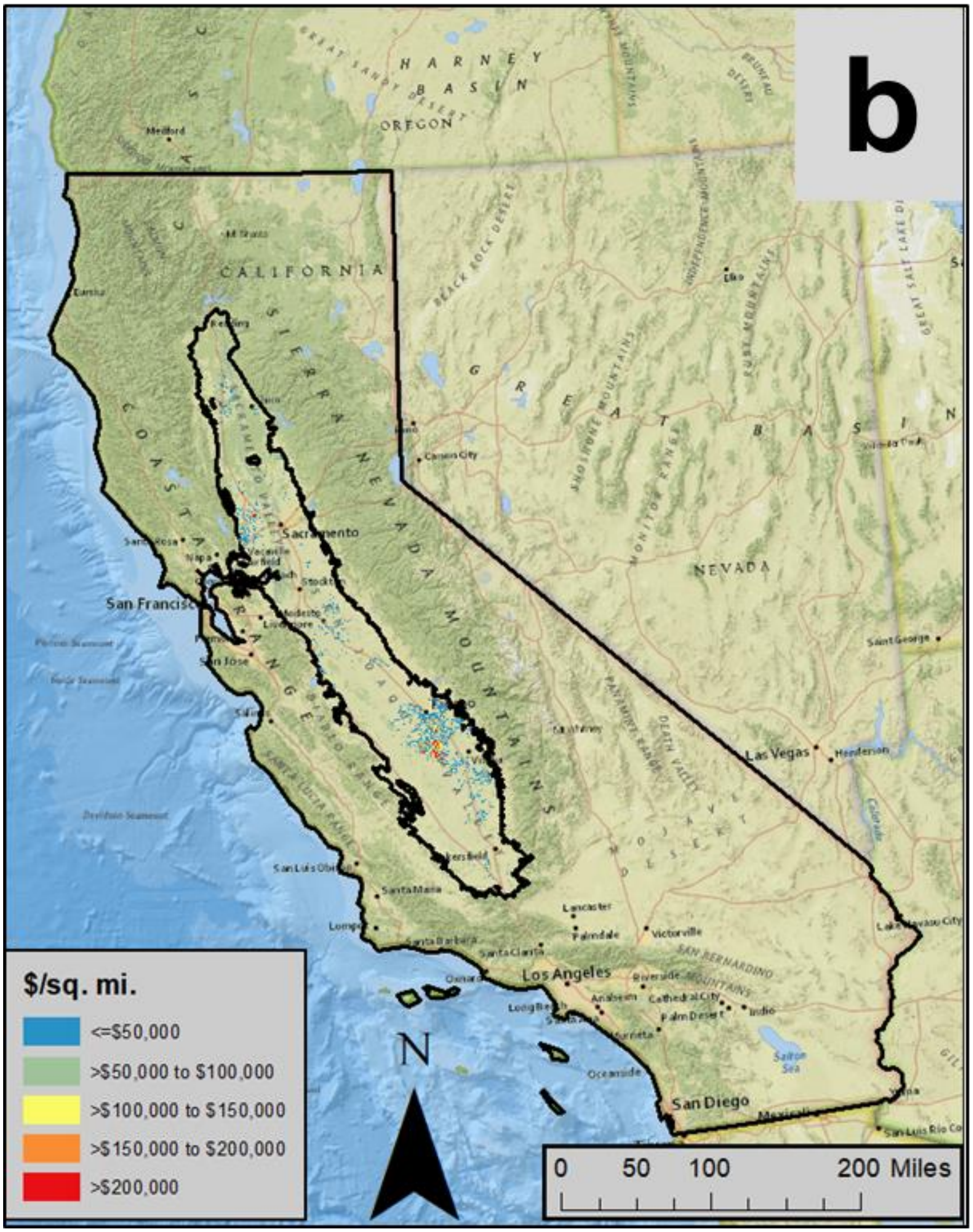

Figure 11b: Spatial distributions of impacts and costs for domestic wells with a 0.75 drought factor: costs for impacts other than additional pumping lift. Tallies by PLSS section.

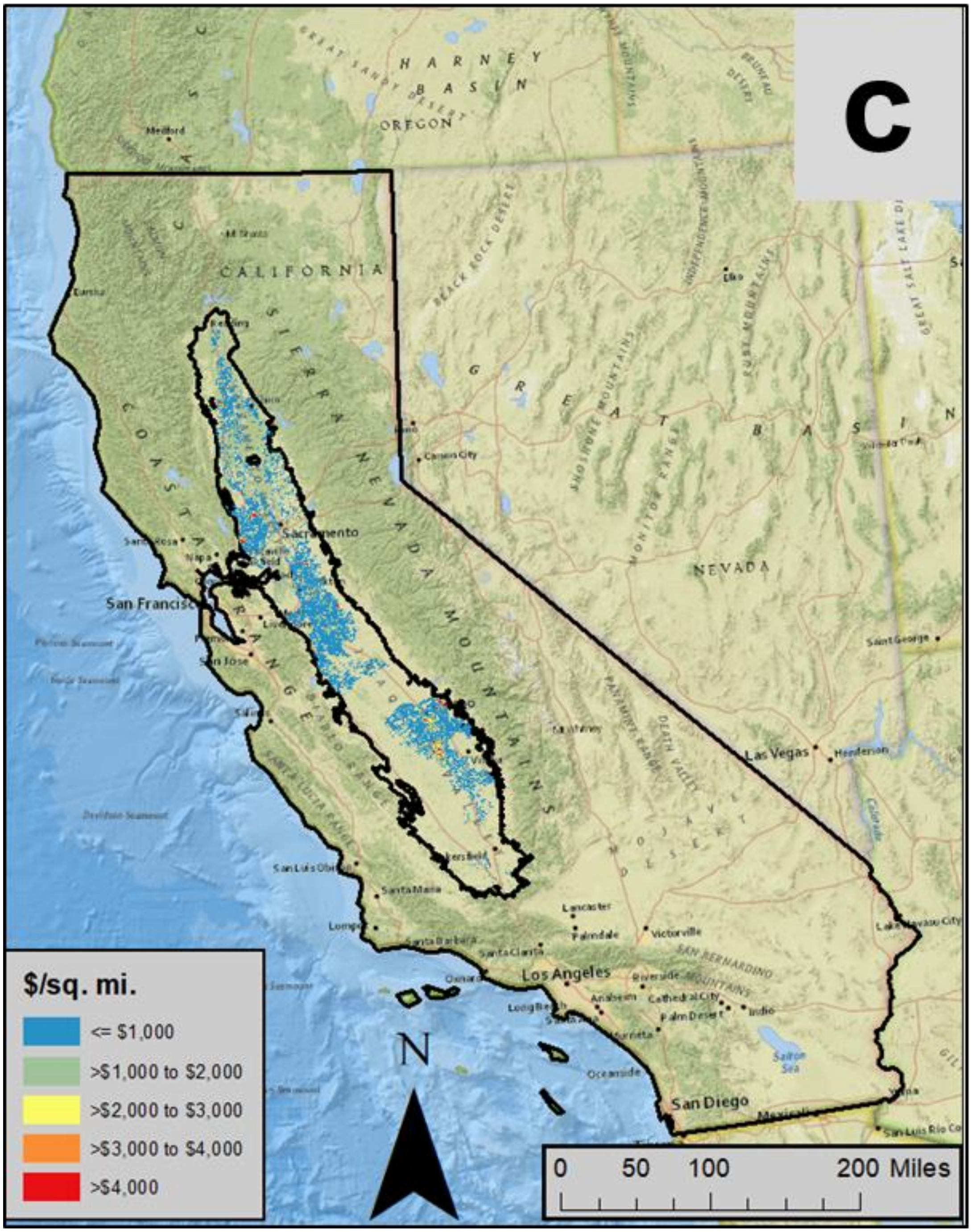

Figure 11c: Spatial distributions of impacts and costs for domestic wells with a 0.75 drought factor: costs for additional pumping lift. Tallies by PLSS section.

Figure 12a: Spatial distributions of impacts and costs for domestic wells with a 1.0 drought factor: impacts other than additional pumping lift (pump lowering, well screen rehabilitation, well replacement). Tallies by PLSS section.

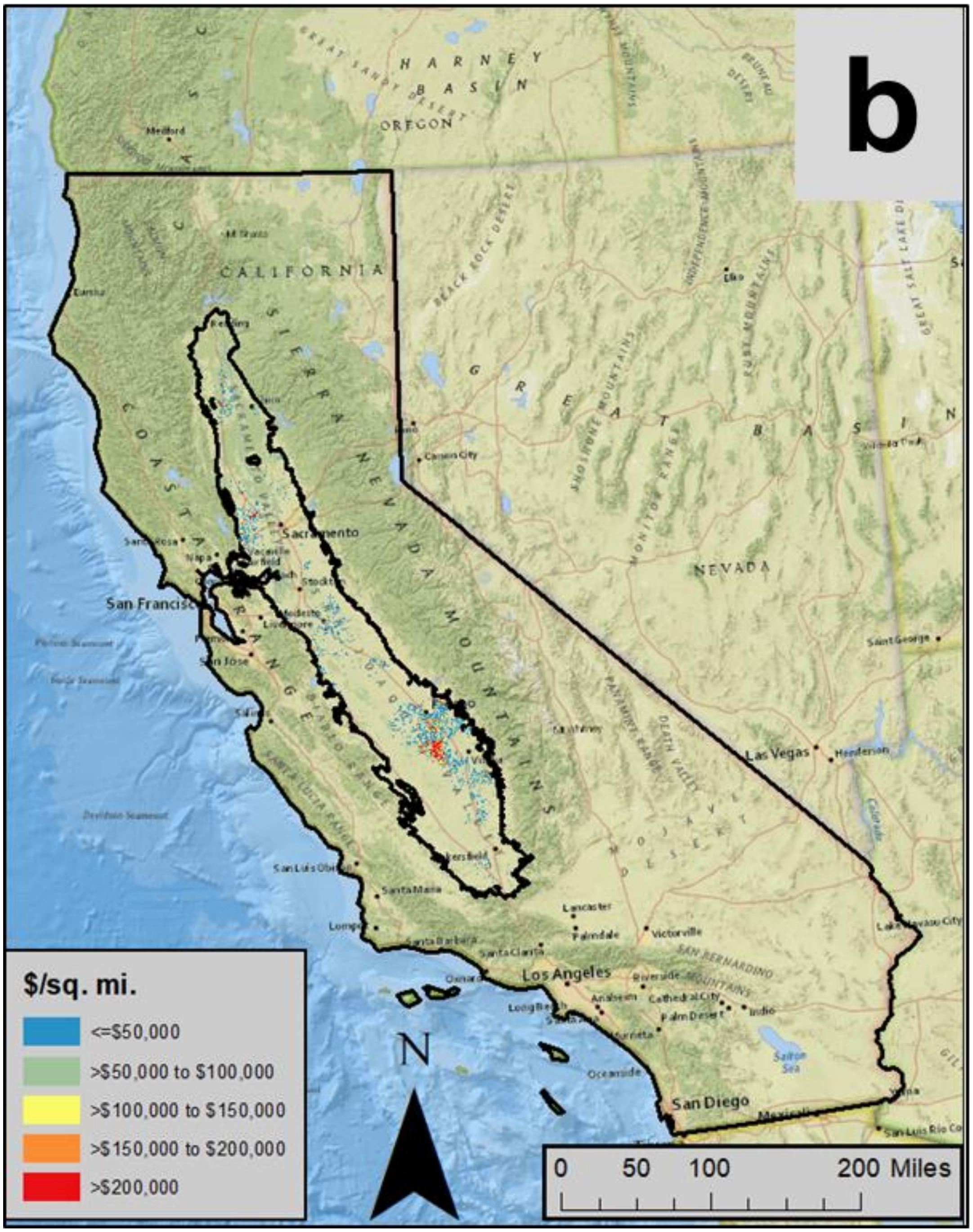

Figure 12b: Spatial distributions of impacts and costs for domestic wells with a 1.0 drought factor: costs for impacts other than additional pumping lift. Tallies by PLSS section.

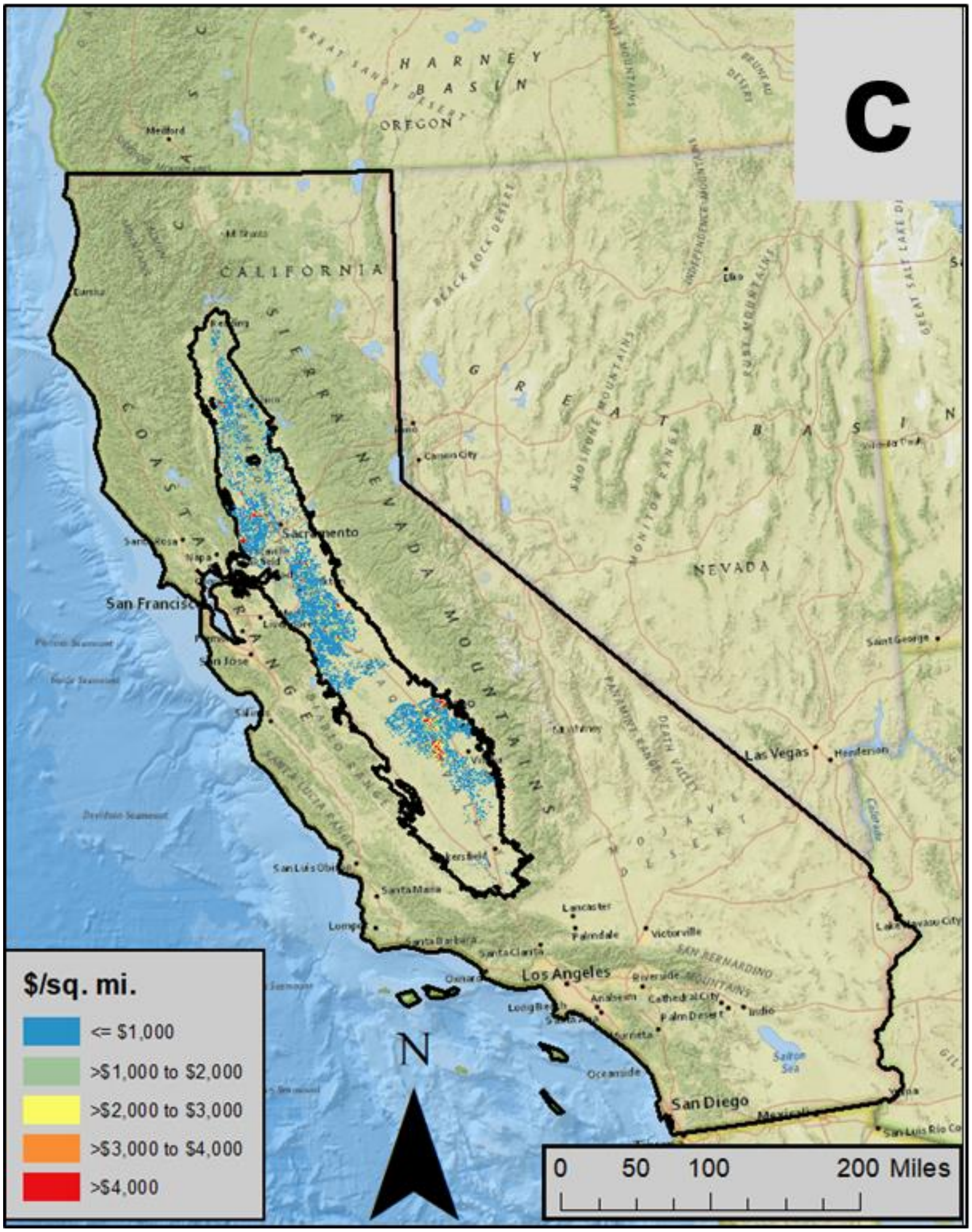

Figure 12c: Spatial distributions of impacts and costs for domestic wells with a 1.0 drought factor: costs for additional pumping lift. Tallies by PLSS section.

Figure 13a: Spatial distributions of impacts and costs for CWS wells with a 0.5 drought factor: impacts other than additional pumping lift (pump lowering, well screen rehabilitation, well replacement). Tallies by buffered CWS service area.

Figure 13b: Spatial distributions of impacts and costs for CWS wells with a 0.5 drought factor: costs for impacts other than additional pumping lift. Tallies by buffered CWS service area.

Figure 13c: Spatial distributions of impacts and costs for CWS wells with a 0.5 drought factor: costs for additional pumping lift. Tallies by buffered CWS service area.

Figure 14a: Spatial distributions of impacts and costs for CWS wells with a 0.75 drought factor: impacts other than additional pumping lift (pump lowering, well screen rehabilitation, well replacement). Tallies by buffered CWS service area.

Figure 14b: Spatial distributions of impacts and costs for CWS wells with a 0.75 drought factor: costs for impacts other than additional pumping lift. Tallies by buffered CWS service area.

Figure 14c: Spatial distributions of impacts and costs for CWS wells with a 0.75 drought factor: costs for additional pumping lift. Tallies by buffered CWS service area.

Figure 15a: Spatial distributions of impacts and costs for CWS wells with a 1.0 drought factor: impacts other than additional pumping lift (pump lowering, well screen rehabilitation, well replacement). Tallies by buffered CWS service area.

Figure 15b: Spatial distributions of impacts and costs for CWS wells with a 1.0 drought factor: costs for impacts other than additional pumping lift. Tallies by buffered CWS service area.

Figure 15c: Spatial distributions of impacts and costs for CWS wells with a 1.0 drought factor: costs for additional pumping lift. Tallies by buffered CWS service area.

5.2 MAGNITUDES OF IMPACT/COST AND DISTRIBUTION OF COST TYPE

The magnitudes of impact and costs, as well as distribution of cost types, were evaluated for the study area as a whole. Figures 16 A through C summarize the impacts and Figures 17 A through C summarize the costs. Impacts to domestic wells are much larger and more sensitive to drought intensity than for CWS wells (Figure 16) because there are many more domestic wells in the study area (29,379 domestic versus 973 CWS wells, see Section 3.2) and domestic wells tend to be shallower. Cost magnitudes and sensitivities also differ between the two well types (Figure 17A) and the types of costs experienced are quite different (Figures 17 B and C). These results stem from characteristic differences between the well types. Domestic wells tend to be shallower and more susceptible to requiring mitigation measures that involve work on the well structures (pump lowering, well screen rehabilitation and well replacement). CWS wells tend to be deeper, larger and produce at much higher flow rates. While structural mitigation measures can be expensive because the wells are larger, the most costly effect of drought is additional pumping lift.

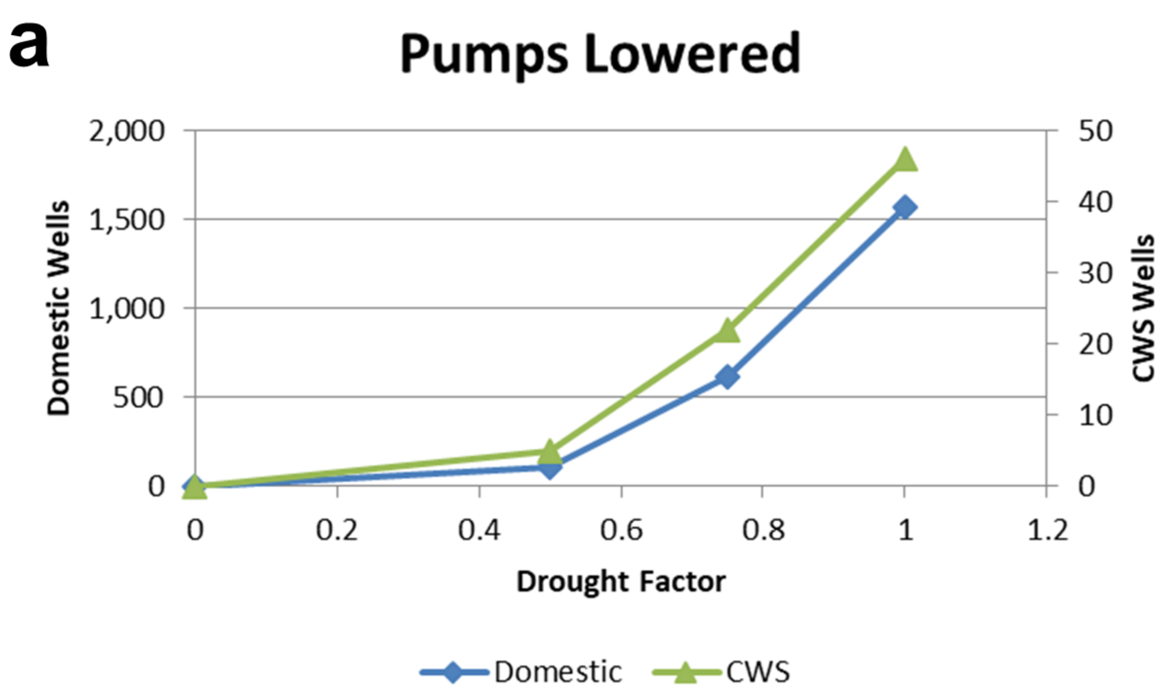

Figure 16a: Impacts for study area as a whole: pumps lowered.

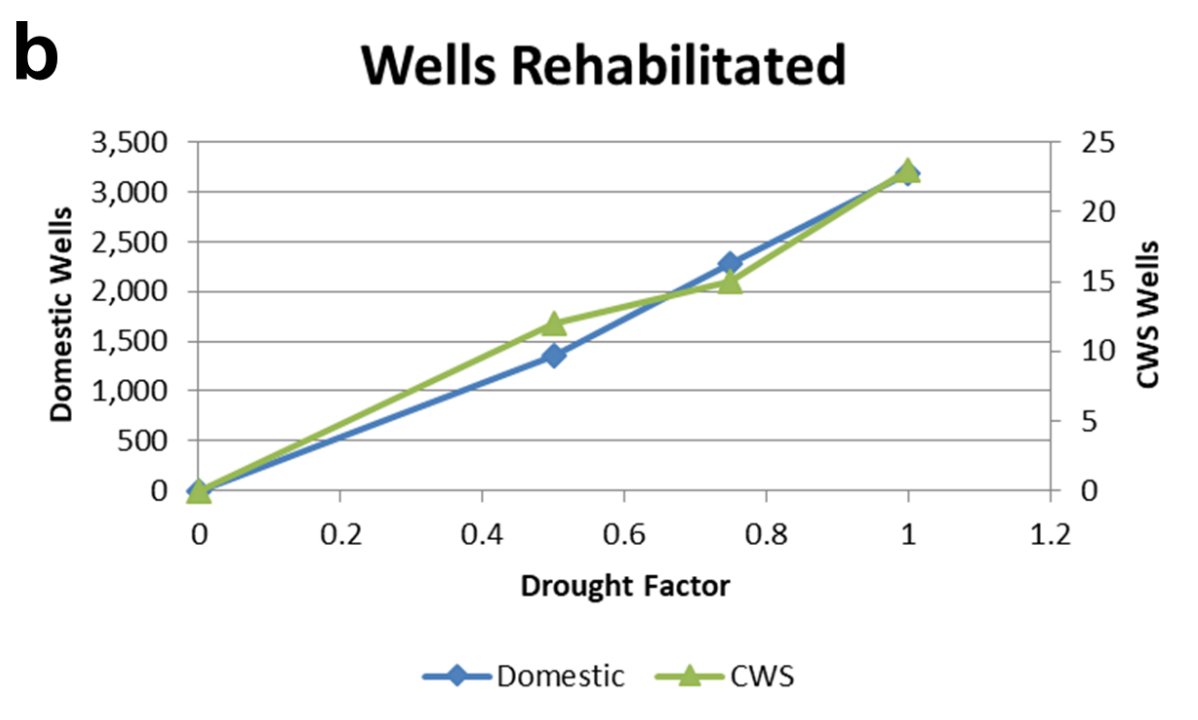

Figure 16b: Impacts for study area as a whole: wells rehabilitated.

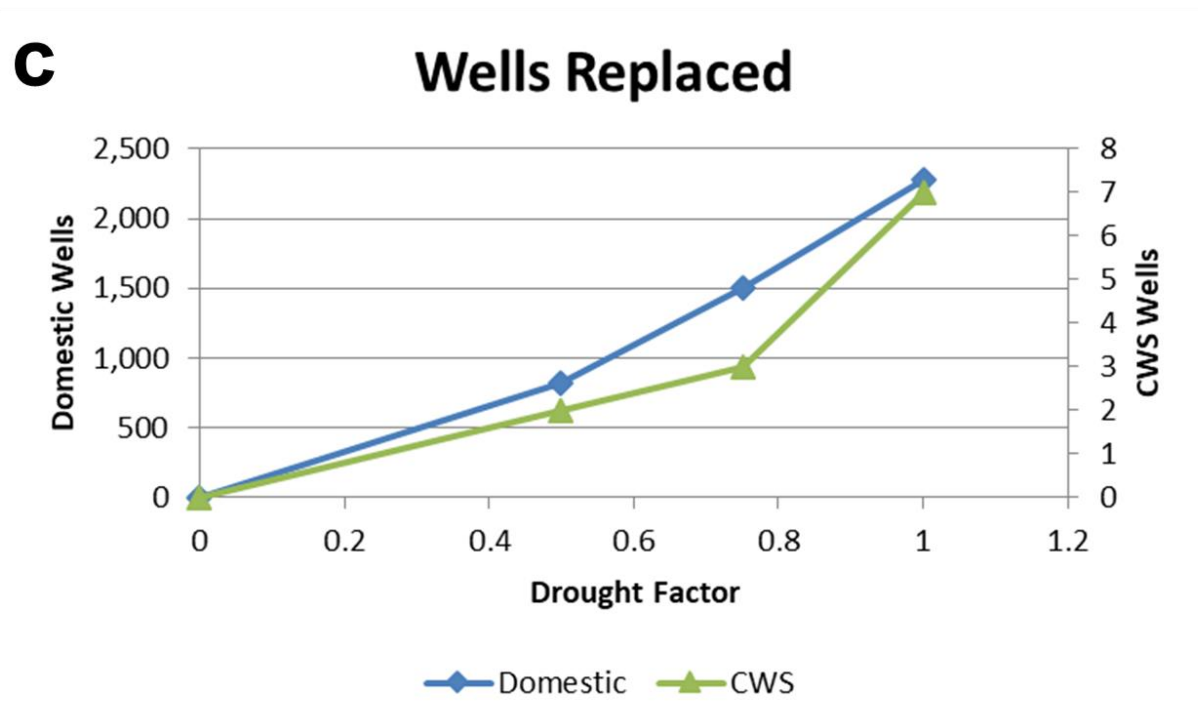

Figure 16c: Impacts for study area as a whole: wells replaced.

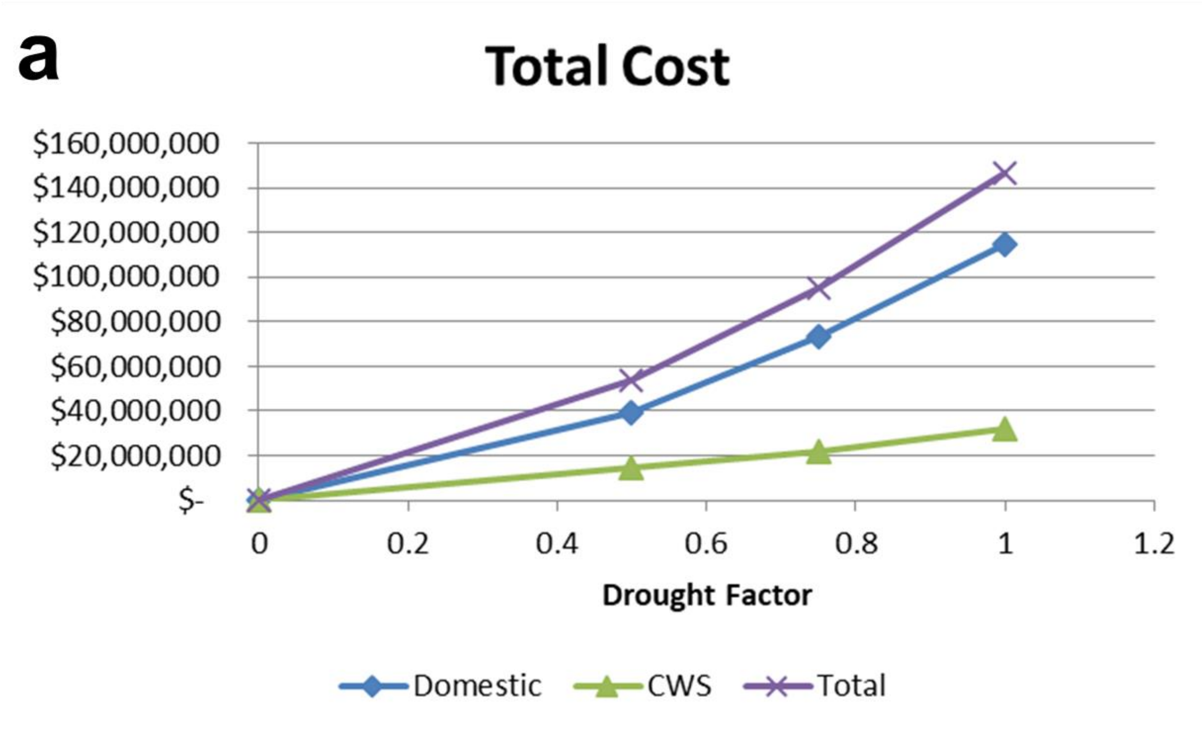

Figure 17a: Costs for study area as a whole: total cost.

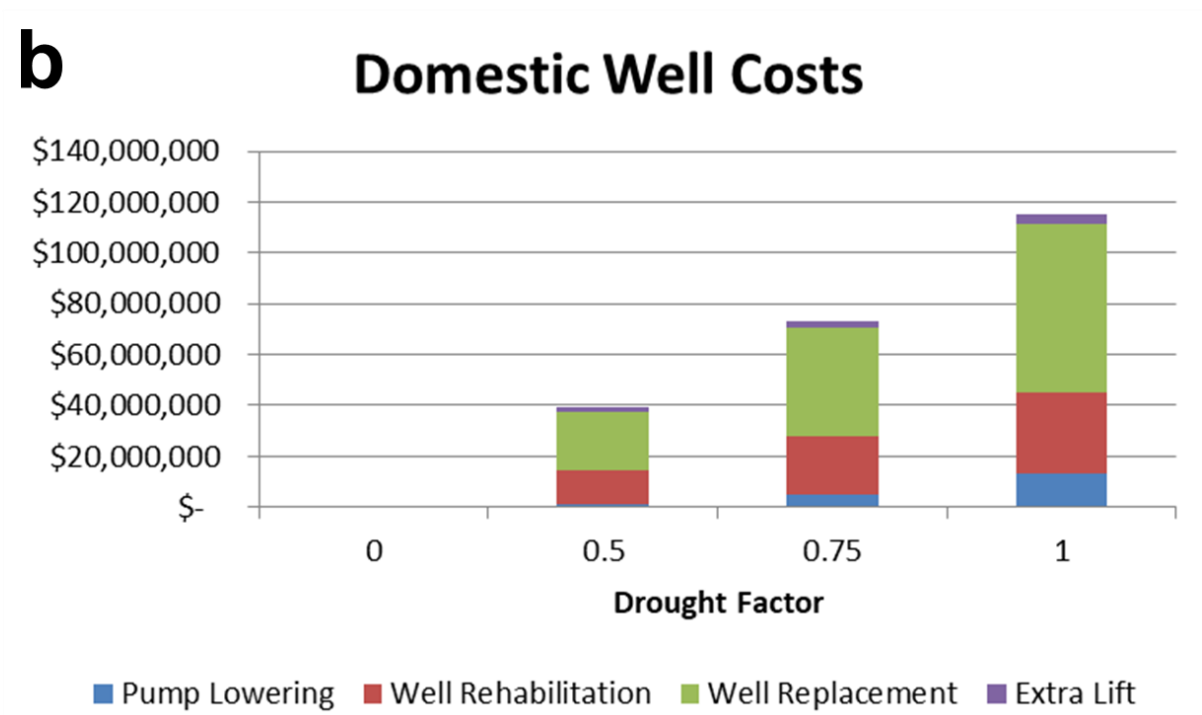

Figure 17b: Costs for study area as a whole: domestic wells.

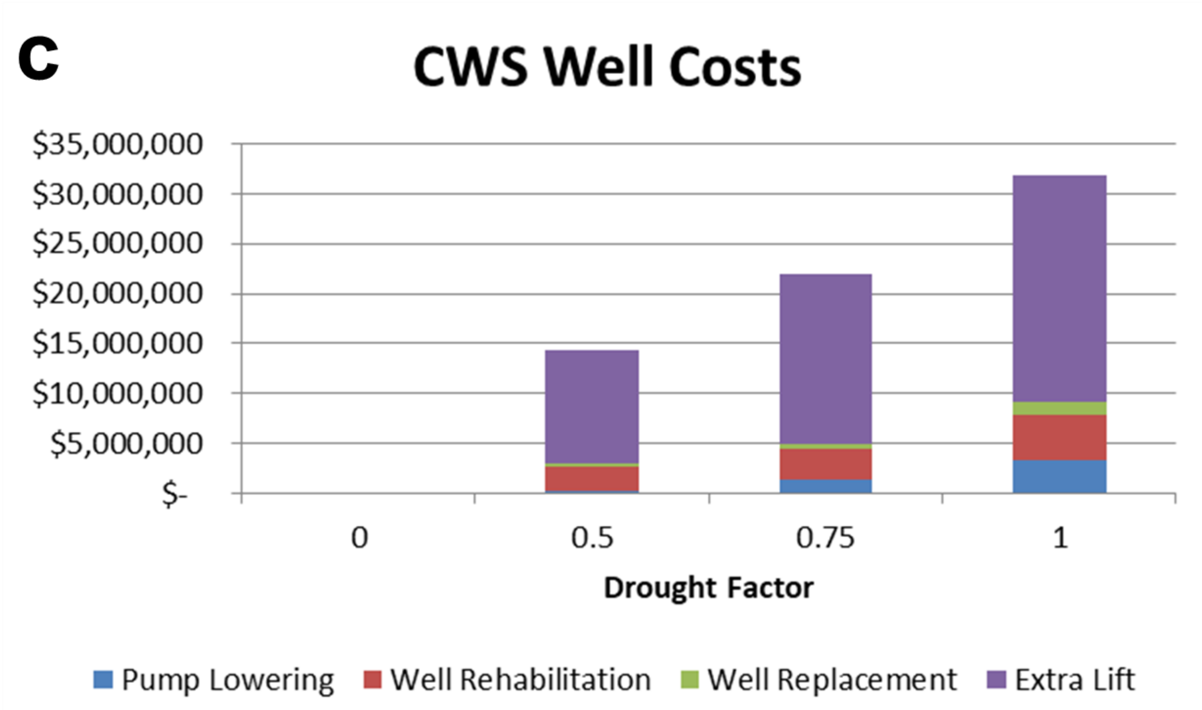

Figure 17c: Costs for study area as a whole: CWS wells.

5.3 UNCERTAINTY

Results for the sensitivity analysis on initial pump depth are summarized on Figures 18 A through D. The pump depth was varied 20 feet around the base case of a 60-foot depth. Moving the pump to a shallower depth increases the need for pump lowering and enlarges the corresponding cost component. The results are more sensitive to moving the pump to shallower depth. The 40-foot value may be a realistic lower limit for this parameter value; therefore, the upper curves on Figures 18 B and D were taken as the upper bound of a roughly defined uncertainty band for (Figures 19 A and B). The lower uncertainty bound was defined by a 26 percent reduction in the base case results as discussed by Gailey et al. (2019).

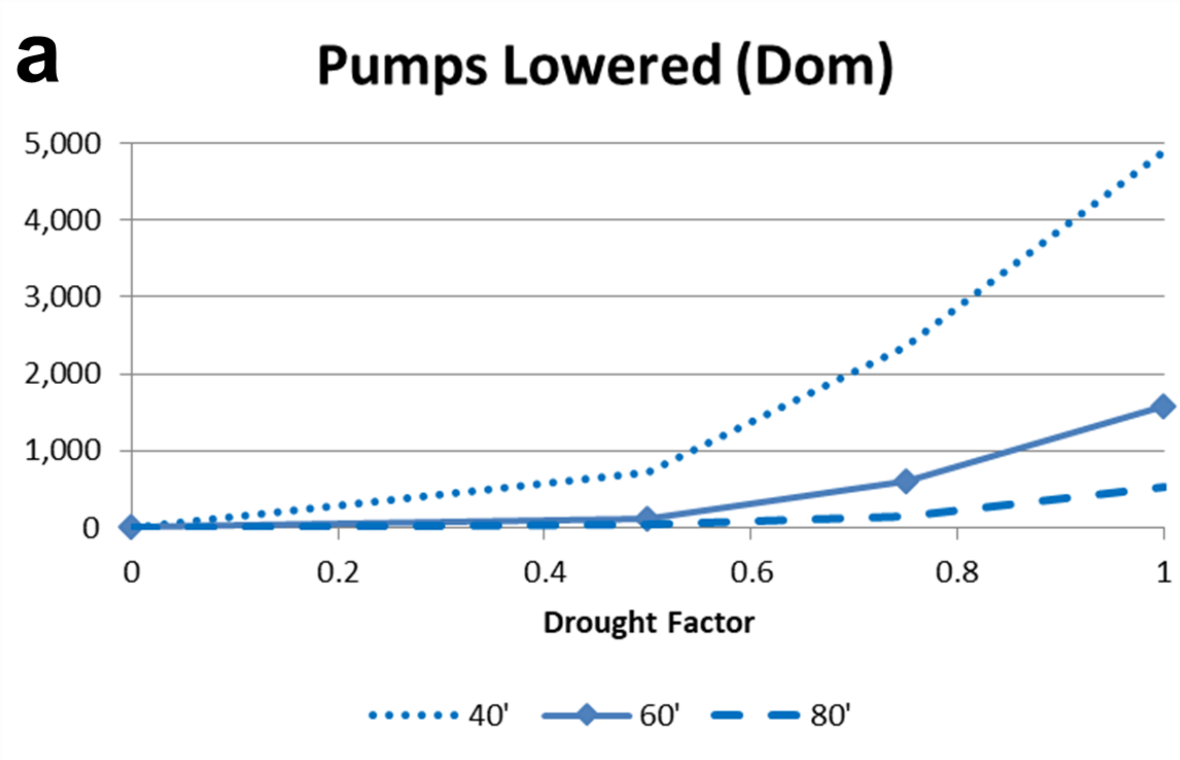

Figure 18a: Sensitivity to initial pump depth: domestic well pumps lowered. Solid line for 60-foot initial pump depth represents the base case. Dom is domestic wells.

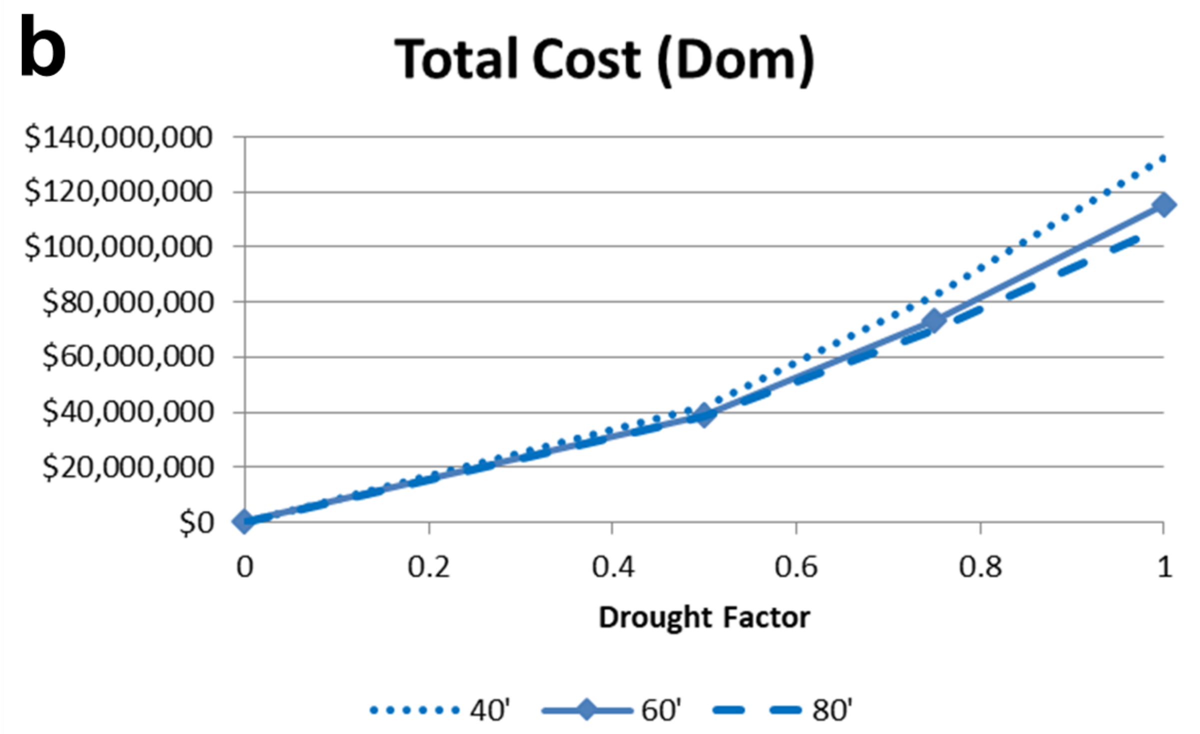

Figure 18b: Sensitivity to initial pump depth: domestic well total costs. Solid line for 60-foot initial pump depth represents the base case. Dom is domestic wells.

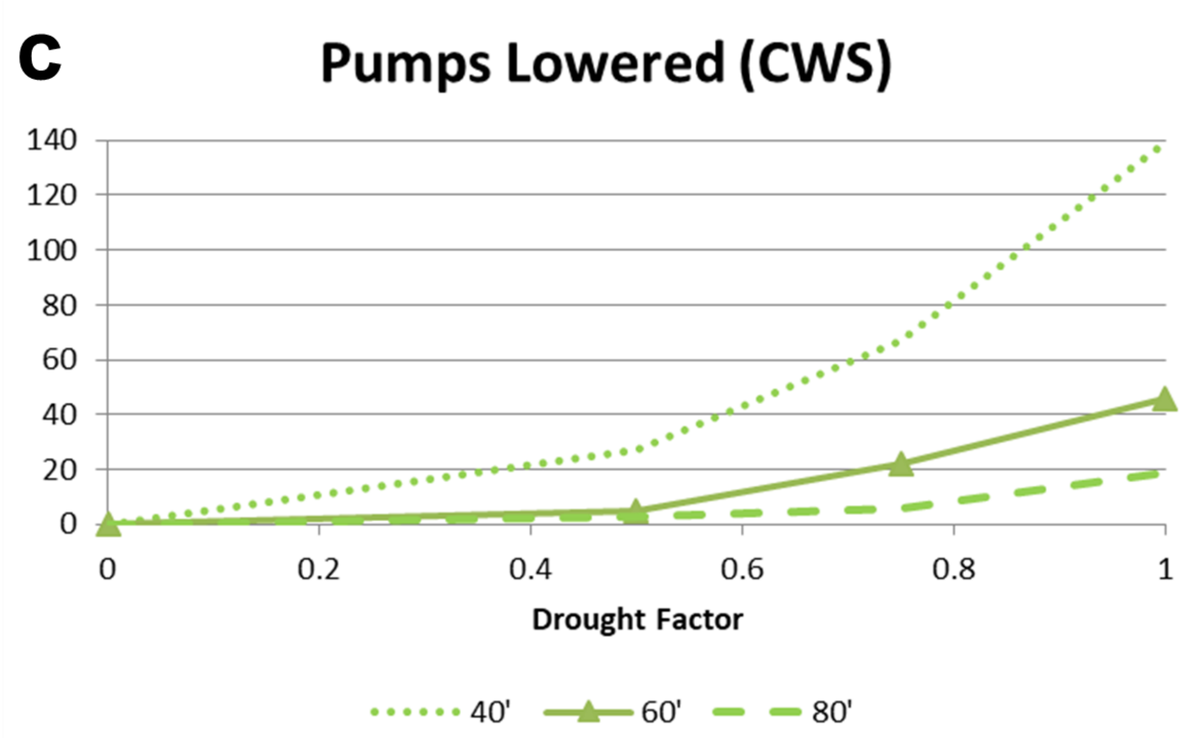

Figure 18c: Sensitivity to initial pump depth: CWS well pumps lowered. Solid line for 60-foot initial pump depth represents the base case. CWS is CWS wells.

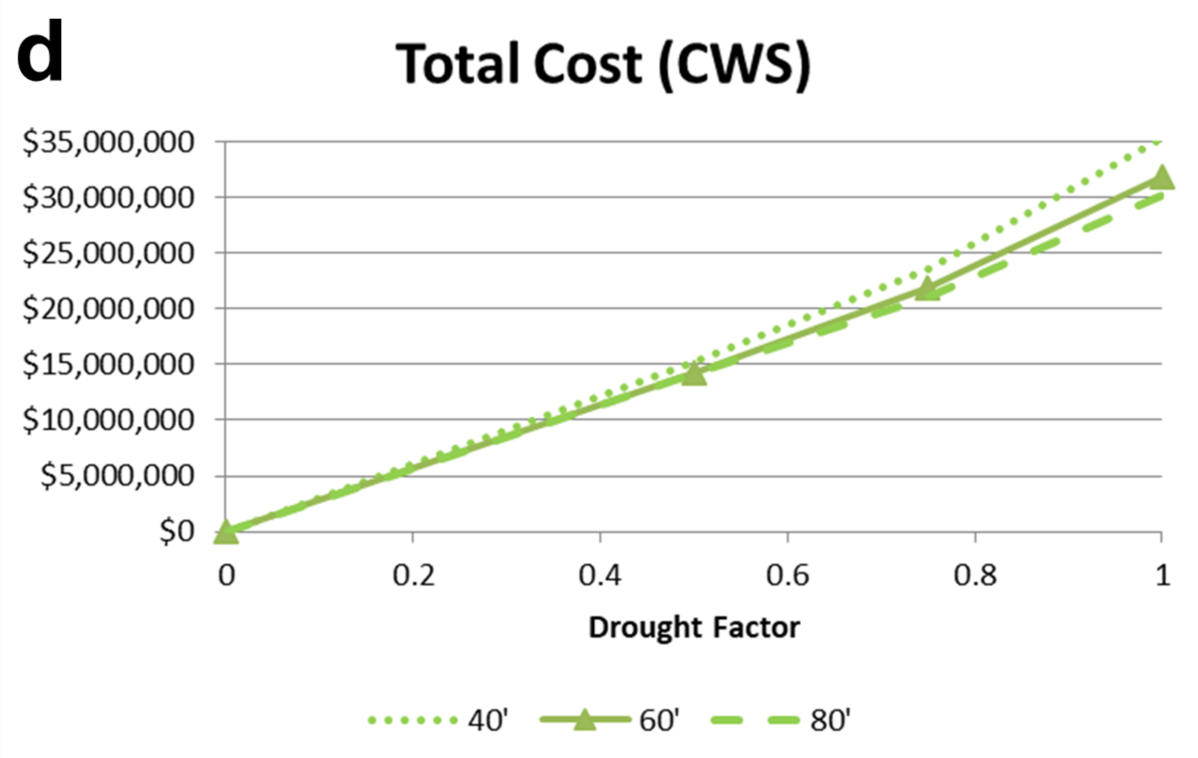

Figure 18d: Sensitivity to initial pump depth: CWS well total costs. Solid line for 60-foot initial pump depth represents the base case. CWS is CWS wells.

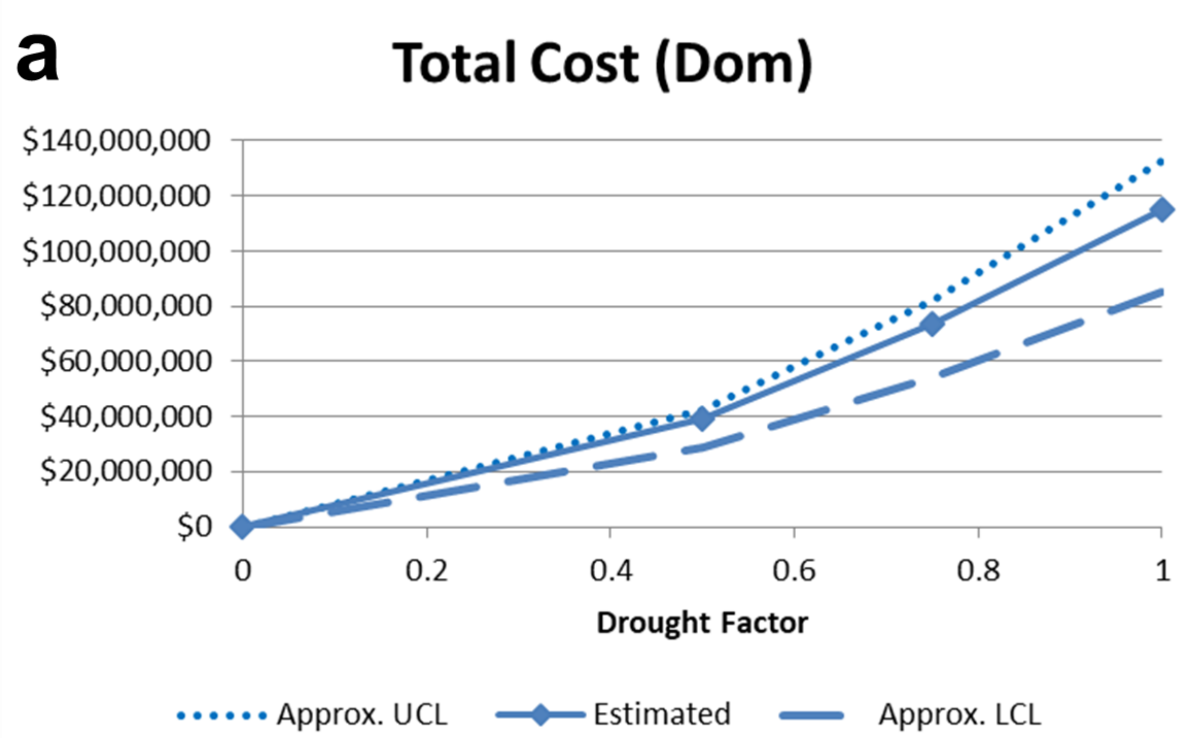

Figure 19a: Uncertainty bounds for total cost: domestic wells. UCL is upper confidence limit and LCL is lower confidence limit. Dom is domestic wells.

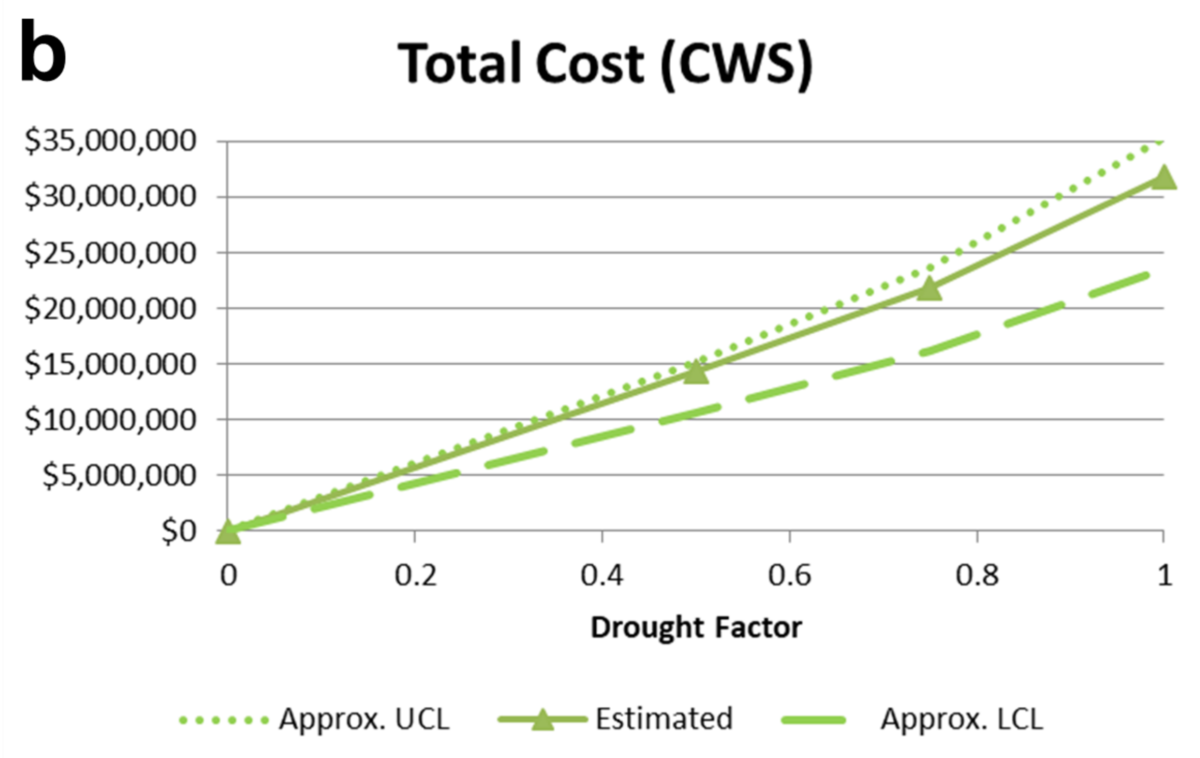

Figure 19b: Uncertainty bounds for total cost: CWS. UCL is upper confidence limit and LCL is lower confidence limit. CWS is CWS wells.

6.0 CONCLUSIONS AND POTENTIAL EXTENSIONS

The evaluation performed as described in this report provides indications of drinking water supply vulnerability for people served by some well types at certain locations within California. Specifically, domestic wells and wells used by community water systems serving populations less than 10,000 people were considered for parts of the Central Valley where sufficient data were available to conduct the analysis. A detailed set of results was produced for 29,379 domestic and 973 municipal/public wells over a 4,982 square-mile area. While a brief summary of results is presented in this report, additional exploration of the results, including higher-resolution viewing of results for specific areas within the larger study area, is possible through the CWC Drinking Water Vulnerability Webtool that will be launched soon.

Some indications of impact include:

- Domestic Wells: Impacts are most pronounced south of Fresno with additional clusters near Modesto, west of Sacramento and west of Chico. Because domestic wells tend to be shallower, they are more susceptible to requiring mitigation measures and costs that involve work on the well structures (pump lowering, well screen rehabilitation and well replacement). Additional pumping lift occurs throughout the study area.

- Community Water System Wells: Impacts are most pronounced south of Modesto and Fresno with additional clusters west of Sacramento and west of Chico. Because municipal/public wells tend to be deeper, larger and produce at relatively high flow rates, the most costly effect of drought is additional pumping lift. Structural mitigation measures, while expensive because the wells are larger, occur less often. Additional pumping lift occurs throughout the study area.

Given the information and experience developed during this project, extensions of the results could be accomplished cost-effectively. Potential extensions of this work could include:

- Increasing the spatial extent of analysis: Adding groundwater depth data for areas where it was not available for this work would allow similar analysis to be performed where well construction data are currently available. This includes areas in both the Central Valley and other parts of the state. As described in Section 4, some 35 and 62 percent of domestic and municipal/public well construction data in the Central Valley were excluded from the analysis because groundwater depth data were not available. Additional groundwater depth data might become available in the near future as groundwater sustainability plans (GSPs) required by SGMA are finalized.

- Considering additional groundwater level decline scenarios: Considering location-specific planning scenarios may more accurately reflect future conditions in different basins across the state. As described in Section 4, the scenarios included in this work use past conditions from the 2012 to 2016 drought, may not reflect management plans currently being developed in GSPs, and the spatial and temporal distributions of groundwater level declines may be different than assumed. Additional information might become available in the near future as GSPs are finalized.

- Considering different parameter values: Considering location-specific values for the parameters listed in Table 2 may more accurately reflect conditions for some parts of the study area. Such information may be developed as part of the SGMA planning process.

7.0 GENERAL LIMITATIONS

This document, as well as associated work products including GIS layers and tabular results, was prepared specifically for the use of CWC with the purposes of documenting the analysis performed by RMG and supporting development of the CWC Drinking Water Vulnerability Webtool. The results of this work should be considered and interpreted within the context of data availability and assumptions, both indicated in this report and generally understood for the practice of hydrogeology. These results are intended to be considered in their entirety. No modification or excerpting of this report may be performed unless approved in writing by RMG. Given the complexity of data processing and calculations made for this work, this requirement also applies to any processing of the above-referenced associated work products. If any unapproved use of the report or associated work products occurs, it shall be at the user's sole risk without liability to RMG.

These results are intended to assist CWC personnel and its contractors in applying their own professional judgment for displaying information in the CWC Drinking Water Vulnerability Webtool. RMG cannot guarantee the completeness or accuracy of information provided to RMG by other parties, including CWC and State agencies, even where efforts were made by RMG to verify such information. RMG has exercised professional judgment, consistent with the survey-level scope of work authorized by CWC, to collect information and present results of a scientific and technical nature. The results are based on existing conditions at the time RMG performed the work as well as assumptions specified and implied. RMG cannot guarantee that future conditions will not change and affect the validity of the information presented here. No warranty or guarantee, whether expressed or implied, is made by RMG with respect to the data, observations, findings, assumptions, results, work products, conclusions or recommendations.

8.0 REFERENCES

Gailey, R.M. 2018. Approaches for Groundwater Management in Times of Depletion and Regulatory Change. PhD Dissertation, University of California, Davis. (https://watershed.ucdavis.edu/shed/lund/students/GaileyDissertation2018.pdf)

Gailey, R.M., J.R. Lund and J. Medellin-Azuara. 2019. Domestic Well Reliability: Evaluating Supply Interruptions from Groundwater Overdraft, Estimating Costs and Managing Economic Externalities. Hydrogeology Journal, 27(4):1159-1182, doi: 10.1007/s10040-019-01929-w (https://link.springer.com/article/10.1007/s10040-019-01929-w)