Declining Groundwater Level Effects on Supply Well Operations

By

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THESIS

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Abstract

Pumping more from groundwater basins than they can sustainably supply decreases groundwater levels, often by undesirable amounts. Economic impacts from overdraft and drought include increased costs for supplying water and lost revenue from inability to meet water demands. The combination of decreased groundwater level with existing well depth may limit well production as pumping costs increase and wells run dry. Declining groundwater elevations may also incur costs to move pumps deeper in the wells. Further falling groundwater elevation increases costs for production and maintenance, and decreases production capacity, as pumping levels drop into the screened intervals of wells and cause screen clogging and corrosion. In more extreme cases, well replacement costs may be incurred if groundwater drops so low that adequate submergence of pumps cannot be maintained, and wells become unusable. The potential impacts of decreasing groundwater elevation on supply well operations were evaluated for a study area in California's Central Valley (greater vicinity of Tulare, CA). Well construction data from logs provided by the California Department of Water Resources (DWR) were characterized through statistical analysis of the elevations for the tops and bottoms of screened intervals. Groundwater elevation time series were obtained from the DWR Water Data Library. Estimated trends in well capacity loss were developed from estimates of the fraction of wells over time that had standing water levels (minus an estimated pumping drawdown) below 1) the top of the screened interval and 2) the bottom of the screened interval. The end result is a method for estimating the costs of water level declines over time from drought or groundwater overdraft due to effects on proper operation and pumping of wells.

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Chapter 1 – Introduction

Groundwater pumping is the primary cause of groundwater depletion, which often occurs during drought. Some negative effects of groundwater depletion include lowered groundwater levels, reduced streamflows (from greater stream capture), land subsidence, water quality concerns, and increased well operation costs. This thesis focuses on well operation costs**.** As the water table falls, more pumping energy cost is needed per volume of water pumped. This work assesses how lower groundwater levels affect pumping and other supply well operation costs. Through applying costs to various well conditions and rehabilitation methods, we can better understand the impacts of drought on communities that rely on groundwater.

Literature Review: Addressing Overdraft Problems and Groundwater Management

In an average water year, groundwater directly supplies about 30 percent of California's urban and agricultural demand (California 2003). Many communities rely exclusively on groundwater, and it is an essential back-up source of water during droughts when pumping increases significantly to compensate for reduced surface supplies. With continued population growth in California, demand for groundwater will also increase. Groundwater and groundwater basins are valuable resources because of their large quantity of water supply and the capacity for storage and distribution, but groundwater use must be regulated to preserve its value. In many California basins, groundwater use is affected by overdraft and water quality, or limited by a lack of data, management, and coordination among agencies (California 2003). Large lowering of groundwater levels increase pumping costs and can lead to land subsidence. Coastal California basins are also at risk for saltwater intrusion. Consistent lowering of groundwater levels can dry up wells and deplete streams and wetlands. Overdraft also has economic costs from increased well costs and decreased net economic productivity of a region (Harou and Lund 2016).

Water scarcity and other effects of overdraft can be reduced with better groundwater and well management. Groundwater management can be defined as the planned and coordinated monitoring, operation, and administration of a groundwater basin with the goal of long-term sustainability (California 2003). Overdraft is one of the greatest challenges for sustainable groundwater management. Groundwater management can occur at local, regional, and state levels and covers both urban and agricultural use. Integrated water management from economic, environmental, and social perspectives would address challenges in a water supply system. Management strategies for ending overdraft include increased capture, economic or physical depletion, reducing demands, substituting with surface water, and conjunctive use (Harou and Lund 2016).

Harou and Lund (2016) employed hydro-economic optimization in their integrated management model for California's Tulare Basin. The model was used to study how the irrigation-based economy of the region could adapt to a no overdraft policy and found that the least costly form of management would be a combination of reduced demand, surface water substitution, and conjunctive use (Harou and Lund 2016). MacEwan et al. developed a modeling approach that integrates a biophysical response from a hydrologic model into an economic model of groundwater use to evaluate types of groundwater management for basins in the Central Valley (MacEwan et al. 2017). They quantified the costs and benefits of sustainable groundwater management and found that for critically overdrafted basins, losses in crop net revenue are offset by the benefits of energy savings, drought reserve value, and avoided capital costs (MacEwan et al. 2017). In chapters of their masters' theses, Timothy Nelson, Mustafa Dogan, and Ian Buck used the California Value Integrated Network (CALVIN) model—a hydro-economic optimization model of California's water system—to optimize water operations for groundwater management in the Central Valley (Nelson 2014, Dogan 2015, Buck 2016).

The Study Area: Tulare, CA

The California Department of Food and Agriculture (CDFA) funded a research project that evaluated the potential impacts of declining groundwater elevations on well maintenance costs for a combined agricultural/urban study area in Tulare County (Gailey et al. 2016). This area relies on water imports and groundwater pumping and has incurred notable drought impacts. This particular area was chosen because it has good data access and contains a mixture of urban and agricultural water uses to give a representative picture of the larger basin area. Declining depths to groundwater pose challenges for future water supply, especially during dry years. Rob Gailey, who led the CDFA research project, obtained well completion reports for the 27 square mile area from the California Department of Water Resources (CA DWR). Of the 733 well logs obtained and reviewed, 423 contained sufficient information for this analysis, meaning that the well logs were legible and completed.

The city of Tulare is in the Kaweah Subbasin of the San Joaquin Valley Groundwater Basin. About 40% of water use in the southeast portion of the San Joaquin Valley Basin comes from groundwater (DWR 2003). The Kaweah Subbasin is largely agricultural and the largest urban areas in the region are the cities of Tulare and Visalia. During years with low surface water availability, groundwater is important in preventing the loss of permanent crops and agricultural business. The study area lies also within the jurisdiction of the Tulare Irrigation District (the District). The District created its Groundwater Management Plan in 2010, which lists responsibilities including actions to replenish and protect groundwater supply, work with other agencies to manage groundwater, and groundwater assessments. When observing the regional gradients in the area as shown in Figure 1, we can conclude that the study area lies within the bounds of the same groundwater elevation contour region. The CA DWR classified the Kaweah subbasin as critically over-drafted and subject to the Sustainable Groundwater Management Act of 2014 (SGMA), which mandates sustainable groundwater use by 2040 (DWR 2016).

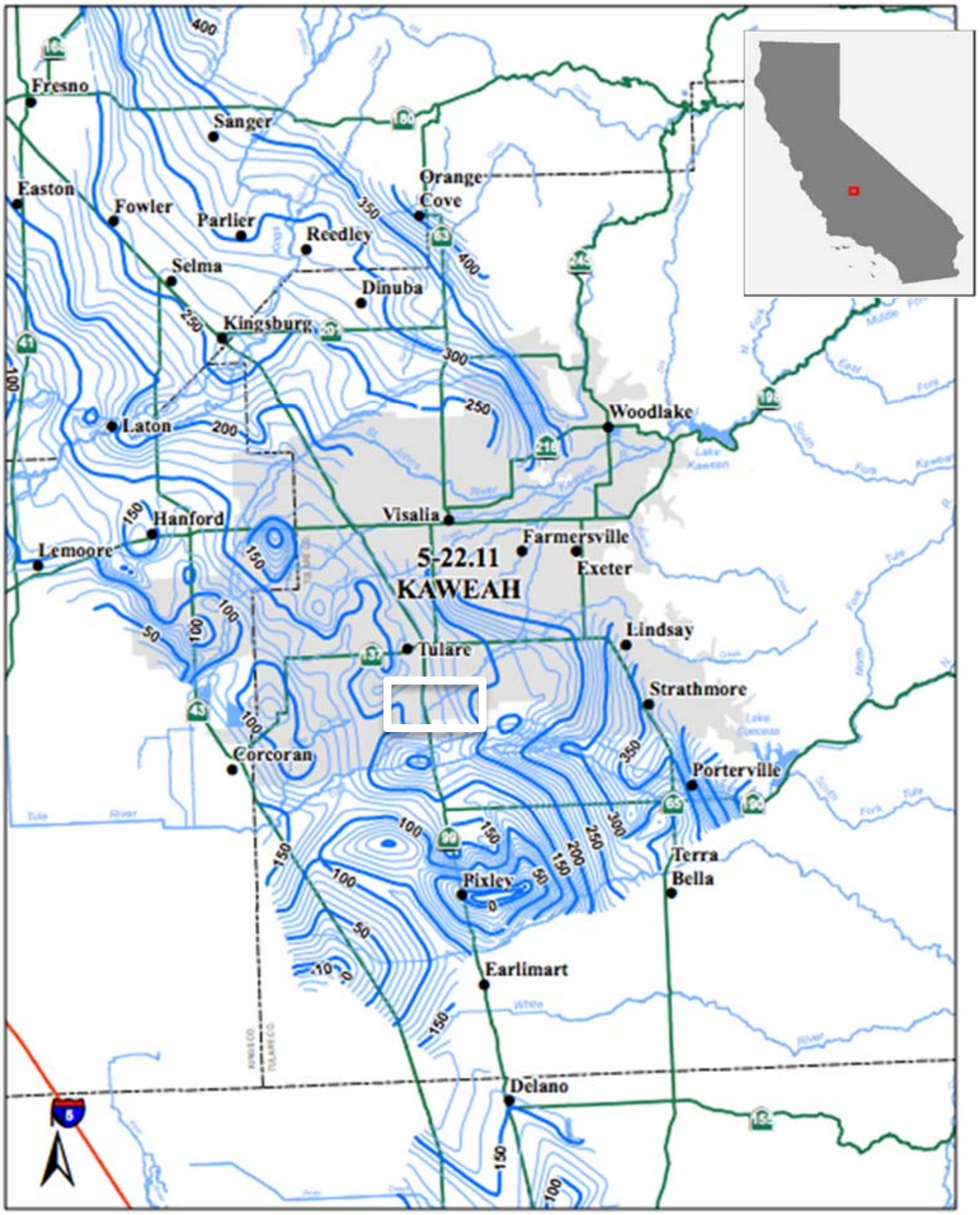


Figure 1. Map of Kaweah Groundwater Basin 5-22.11 (grey area). City of Tulare is identified by the white box. Groundwater elevation contours from wells measured in spring 2011. Water levels are in feet above mean sea level and the data for the map are from the shallowest portions of the aquifer system (Source: CA DWR – South Central Region Office)

Thesis structure

This thesis begins with the methods used to quantify the effects of declining groundwater levels on supply well operations. The methods chapter introduces the data, which are the well completion reports, and describes the equations and model simulation for the analysis. Following are the associated results on the percentages of screen levels above static and pumping groundwater levels and estimated total costs of well treatment for three potential drought periods. The discussion compares the three droughts and their condition percentages and costs. The paper ends with conclusions.

Chapter 2 – Methods

Overview

Water supply wells are constructed to different depths based on a variety of factors, including production and water quality requirements, cost, local hydrogeology, and projections of future conditions and supply needs (Gailey et al. 2016). Depths of existing water supply wells widely vary as construction methods improve to build deeper wells (Gailey et al. 2016). Domestic wells serving drinking water needs of one or a small number of households are typically shallow compared to irrigation wells because of budget constraints and the smaller water demands of domestic households compared to agricultural irrigation enterprises. When water levels in groundwater basins fall, costs often arise to move pumps deeper down wells so the pumps remain adequately submerged below pumping water levels (Gailey et al. 2016). Further elevation decreases may increase costs for production and maintenance as pumping levels drop into the screened intervals of wells and increase screen clogging and corrosion. If groundwater elevations drop so low that pumps become unusable, the wells are unusable and replacement costs may be incurred (Gailey et al. 2016).

Well treatment costs may be estimated by comparing groundwater levels to a well's screened interval (Figure 2). When the water level drops below the top of screen (TOS), rehabilitation may include pump deepening and screen unclogging. When groundwater levels are lower than the middle of screen (MOS), there would be higher costs for screen maintenance. When water levels drop below the bottom of screen (BOS), the well must be abandoned unless corrective actions are taken for local and surrounding groundwater levels to recover. To evaluate the potential for a group of wells in a specified area, the groundwater depths are compared to a statistical summary of the wells' screened intervals (Figure 3) (Gailey et al. 2016).

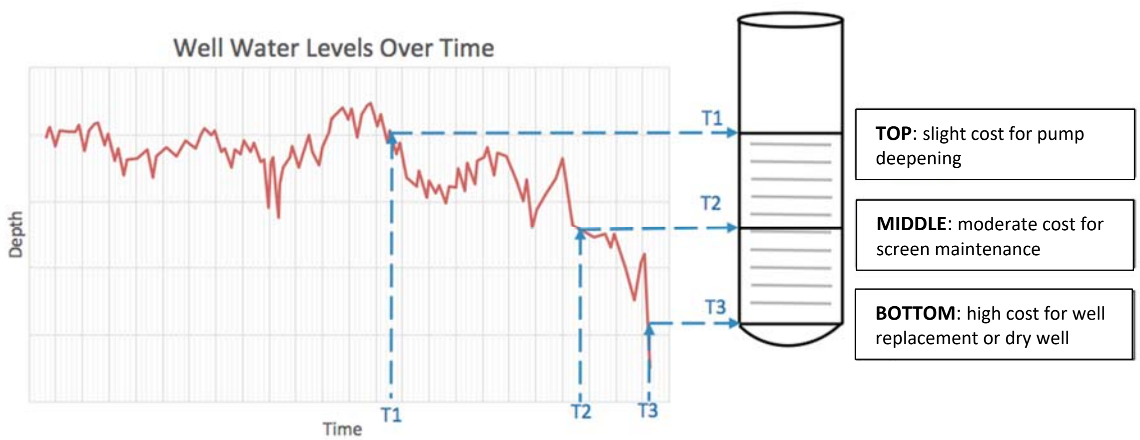


Figure 2: Well screening levels and groundwater level decline in a drought (Figure A-1 in Gailey et al. 2016)

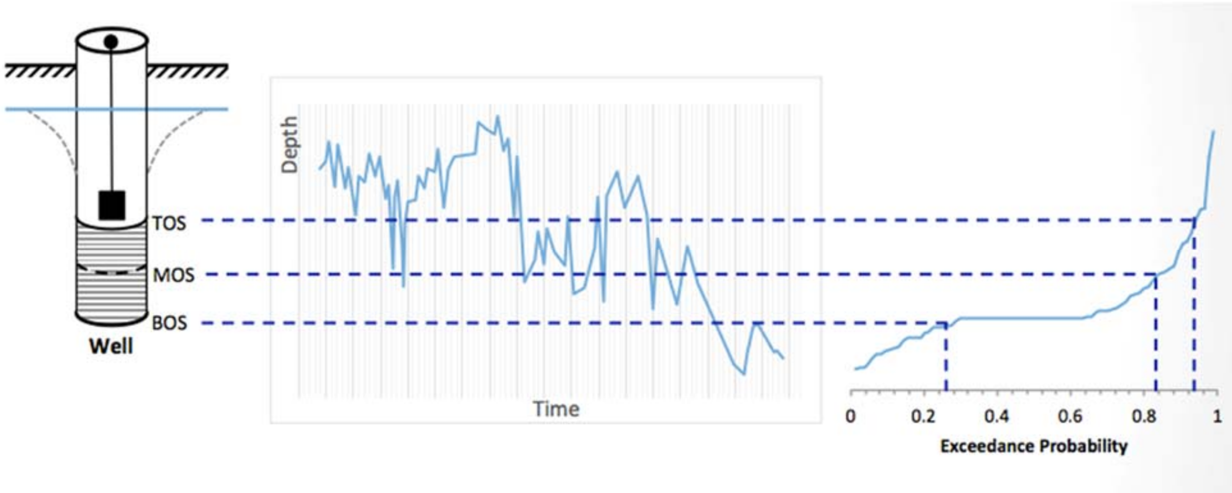


Figure 3: Evaluating the impact of groundwater level decline on a group of wells. Estimated percentage of well (screen) issues based on water levels

Well rehabilitation costs from a particular amount of groundwater level decline can be estimated by assigning expected costs to individual wells based on the severity of each impact and then summing these costs over all wells (Gailey et al. 2016):

$$TC = \sum_{i=1}^{n} W_i * c_i$$

Where, TC, Operating costs ($)
n, number of impact categories from groundwater level decline,
W_i, number of wells in cost category i, and
c_i, expected cost per well for cost category i ($)

Assumptions

To evaluate well issues and well treatment costs, assumptions were made for the analyses outlined above and in the CDFA research report (Gailey et al. 2016). The values presented likely overstate well impacts during drought, but provide useful insights into a "worse case" and general trends (Gailey et al. 2016). Additional data and analysis would be required to address some of these limitations, and to enhance the analysis with more realistic approximations. Analysis assumptions include (Gailey et al. 2016):

- Data from a limited number of locations can characterize groundwater elevations across the study area;
- All wells analyzed for impacts related to well depths are still in service;
- Well construction data in the study area can be grouped into statistical distributions;
- Well performance and treatment costs are directly correlated to specific points in screened intervals (top of screen, middle of screen, and bottom of screen).

Data

Potential impacts of groundwater elevation decline on well operations and maintenance were evaluated for a 27 square-mile region in Tulare County. Most wells were in the city of Tulare. Well completion reports were obtained from the CADWR archives. These reports contain the Township and Range section of the well, a geologic log of the stratigraphy, well use classification, well permit agency information, dates of commencement and completion, and depths of seal, casing, and water levels. Of the 733 well logs obtained and reviewed, 423 provided sufficient information for this analysis. The dataset included 247 domestic wells, 128 irrigation wells, 9 combined domestic/irrigation wells, and 39 well used for industrial, municipal, or miscellaneous public use. Well characteristics obtained from well logs included relative elevations from ground level to screened intervals, particularly top of screen (TOS), middle of screen (MOS), and bottom of screen (BOS). Data from the well completion reports were compiled into a spreadsheet. If a well report contained incomplete records on casing information, screen depths were estimated using the geologic log, which records the type of sediment (clay, sand, gravel) and the range of depth below surface for each sediment layer. Because screens are placed in sand layers rather than clay, screen depths were approximated by assigning the thickness of the sand layer closest to the bottom of the completed well depth or total length of well casing.

Joshua Cho, another member of the CDFA research report team, obtained groundwater elevation time series (well hydrographs) from the CADWR Water Data Library. The groundwater hydrographs from two wells in the study area represented the high and low bounding limits of groundwater levels. A high bounding limit means that the well is more shallow (groundwater levels are commonly higher), and a low bounding limit means that the well is deeper. The well hydrographs were selected because those wells were monitored for a time period spanning multiple droughts. The well water levels were consistently measured twice a year. Changes in potential well impacts, resulting from groundwater depths approaching or exceeding screened intervals over time, were evaluated by identifying temporal intersections of the construction elevation distributions with static and simulated pumping groundwater levels (Gailey et al. 2016).

Model Simulation

For the CDFA report, Robert Gailey created a simple simulation model in Excel to calculate the percentages of wells that have screen depths above static and pumping groundwater level over time (Gailey et al. 2016). Screen depths and standing water levels were given by the well logs and two well hydrographs, and pumping water levels were calculated as described next.

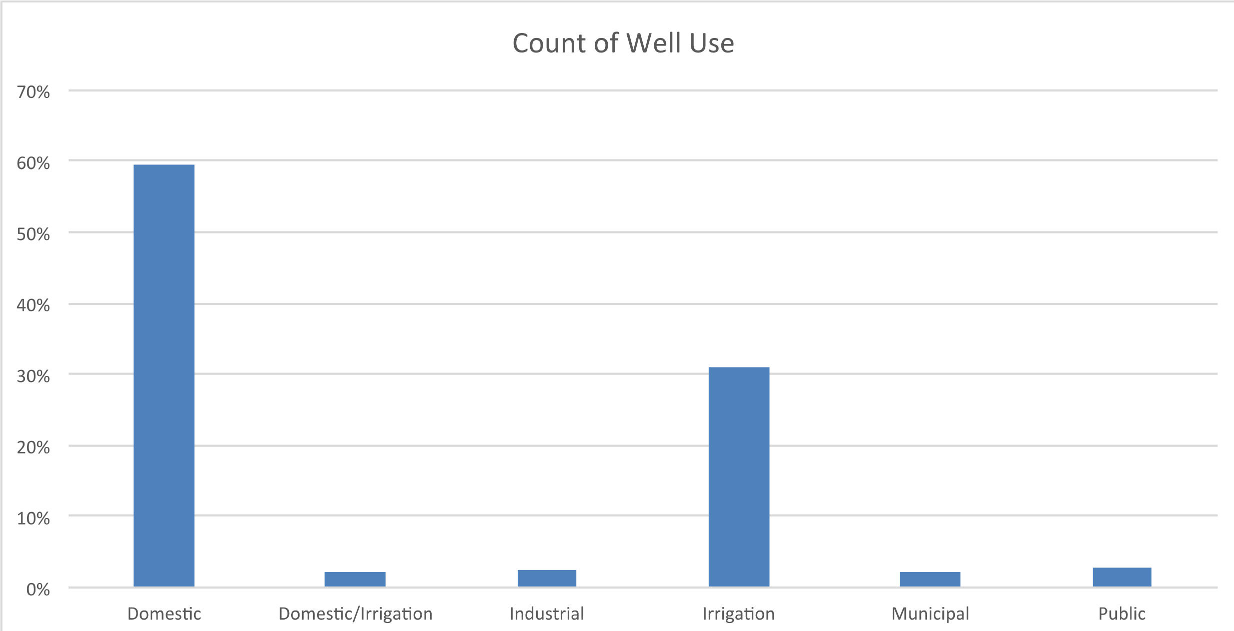
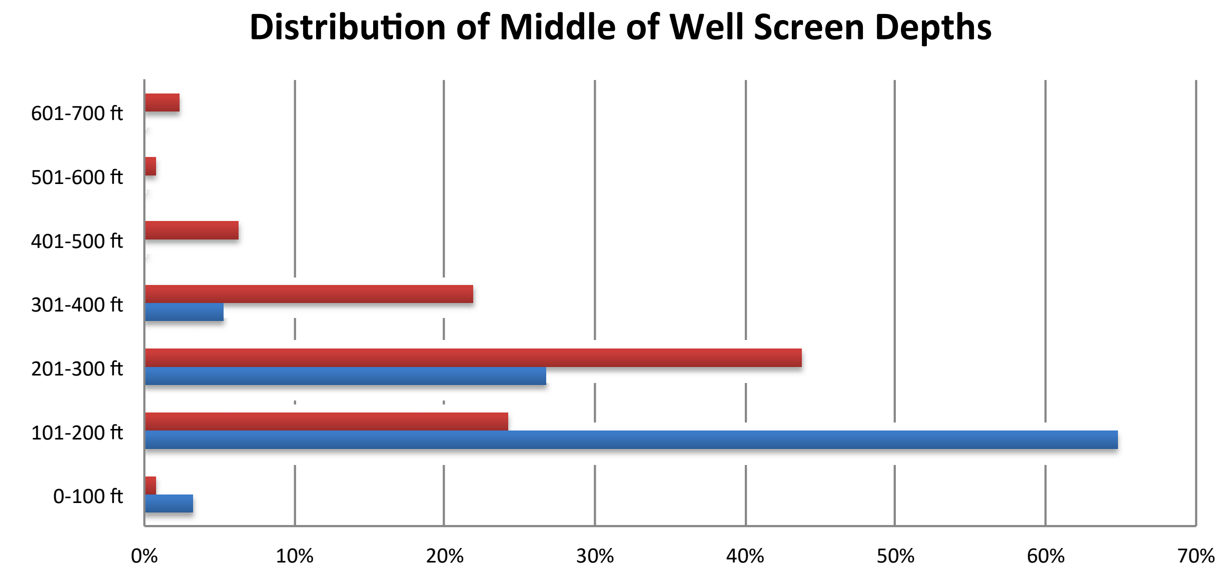


Figure 4: Percentages of each type of well use recorded in the DWR Well Completion Report

Because most well uses in the data set were domestic (247 wells) and irrigation (128 wells), quantifying the effects of declining groundwater levels was only done for those two well use types. The ranges of rates for the pumping simulation were 10 to 20 gallons per minute (gpm) for domestic wells and 500 to 1,000 gpm for irrigation wells (Gailey et al. 2016). Specific capacities were set to 20 to 40 gallons per minute per foot of drawdown (gpm/ft) (Gailey et al. 2016). Pumping rate and specific capacity values were assumed in order to estimate pumping groundwater levels from the standing groundwater level data. Specific capacity is the well pumping rate divided by the water level drawdown. Because the effective coefficient of storativity often decreases with depth due to greater confinement, the specific capacity can also decrease with depth. That is, greater confinement typically produces greater drawdown per unit of pumping. As a result, the domestic and irrigation data may be biased since the domestic wells tend to be much shallower (and hence less confined) than the irrigation wells. Upon observing the typical depths/lengths of the domestic and irrigation wells in the study area, the middle of screen depths for irrigation wells are around 100ft lower than those of the domestic wells. For this analysis, the difference in well casing lengths between the two well uses was not considered in regards to specific capacity changes with depth or bias (see Figure 5 below).



	0-100 ft	101-200 ft	201-300 ft	301-400 ft	401-500 ft	501-600 ft	601-700 ft
Irrigation	1%	24%	44%	22%	6%	1%	2%
Domestic	3%	65%	27%	5%	0%	0%	0%

Figure 5: Plot of distribution of middle of screen depths of all the wells used in the study

The values were paired to create the widest possible range in pumping water levels (i.e., low pumping rate with high specific capacity and vice versa). For domestic wells, the pumping rates and specific capacities were set at 10 gpm and 40 gpm/ft for the high water level and 20 gpm and 20 gpm/ft for the low water level (Gailey et al. 2016). For irrigation wells, the pumping rates and specific capacities were 500 gpm and 40 gpm/ft for the high water level and 1000 gpm and 20 gpm/ft for the low water level (Gailey et al. 2016). The general equation used to calculate pumping water level was:

Pumping level = Standing level – Pumping rate/Specific capacity (Gailey et al. 2016).

Estimated trends in impact were developed by estimating the fraction of wells having standing or pumping water level below the 1) top of screen, 2) middle of screen and 3) bottom of the screened intervals.

Modeling Analysis

The estimated fractions of wells having water levels below specified screen depths were multiplied by the total number of either domestic or irrigation wells to calculate the well counts for top, middle, and bottom of screen exposed. To calculate the relative costs of each incremental effect (TOS, MOS, and BOS), the affected well counts had to be differenced. To avoid double counting, the BOS values were subtracted from the MOS values and the original MOS values were subtracted from the TOS values to get accurate MOS and TOS increments, respectively. By multiplying the incremental well counts by low and high unit cost estimates, we can quantify the total costs for well treatment for drought periods (Gailey et al. 2016).

Chapter 3 – Results

The results break down into two scenarios: Scenario 1 used two monitoring wells that lay outside of the study area and Scenario 2 used two monitoring wells that were inside of the study area (Figure 6 below). The methods for both scenarios were the same, but because the Scenario 2 hydrographs came from wells that were in the study area, the results were more accurate than those of Scenario 1. As a result, Scenario 2 is described in this section and Scenario 1 is discussed in the Appendix and in the CDFA research report (Gailey et al. 2016).

Regional Water Elevations During Drought

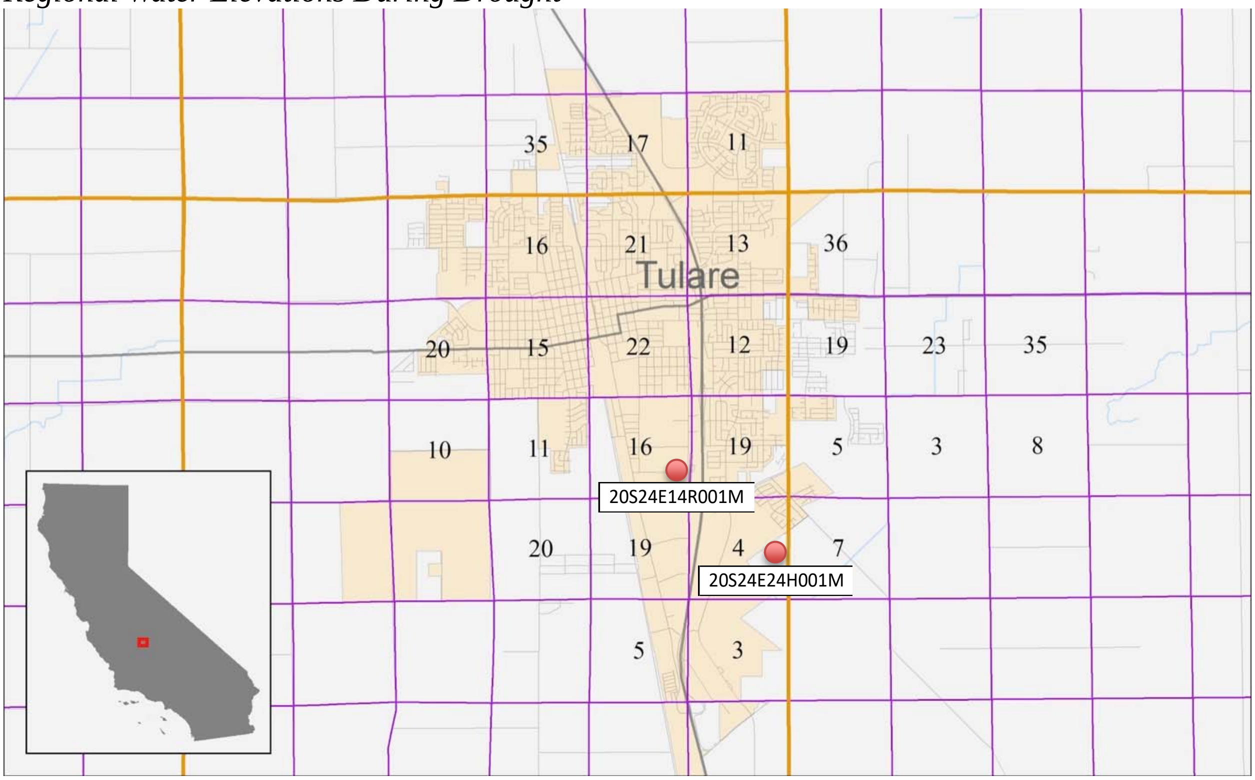


Figure 6: Map of Tulare, CA: Orange lines outline public land survey townships, purple lines outline individual sections within each township. The values within each section indicate the number of well completion reports within that square mile. The two red circles indicate the monitoring wells used in the analysis (Map created by Andy Bell, CDFA Groundwater Report, Gailey et al. 2016)

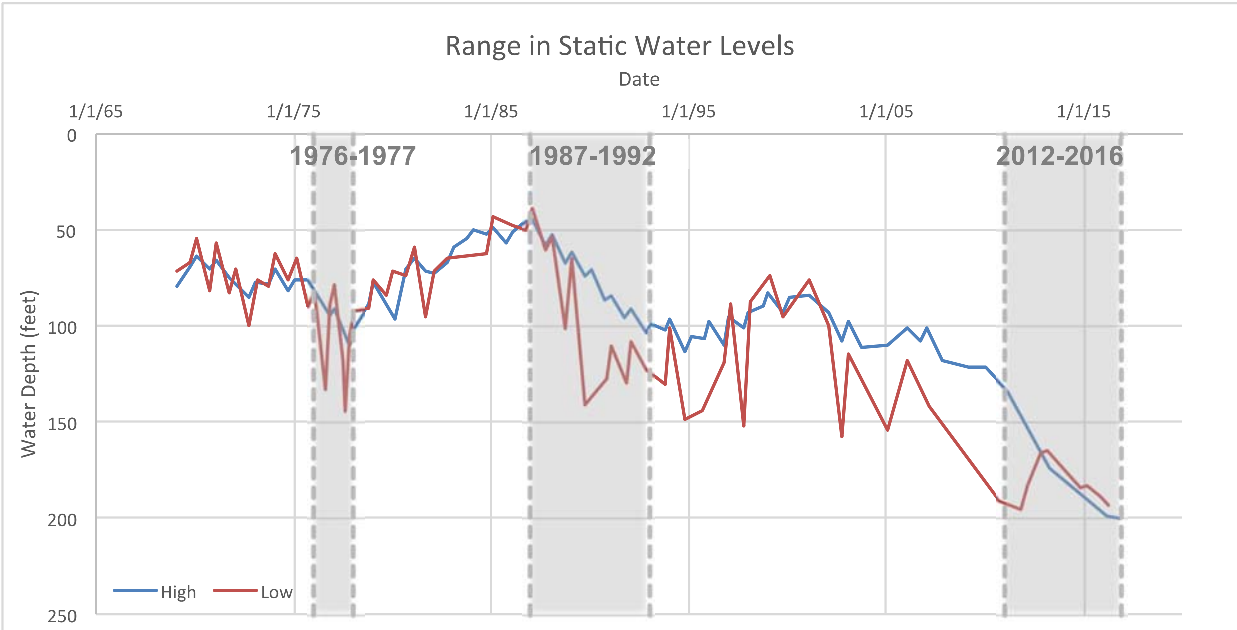


Figure 7: Well Hydrographs of range in static water levels for two field wells (Well IDs: 20S24E14R001M and 20S24E24H001M). Water levels were measured twice a year in the spring and fall.

The figure above displays the hydrographs of the two monitoring wells used in this analysis (Figure 7). As mentioned previously, the study area lies within a uniform groundwater elevation contour, so any monitoring wells in the study area would be representative of the area. Water depth measurements were recorded until the end of 2016, which covers the most recent drought. Downward peaks show the 1976-1977, 1987-1992, 2001-2004, 2007-2009, and 2012-2016 droughts. The gray sections identify the three droughts used in the analysis. Upward peaks in the hydrograph above correlate to notable wet years in 1982-1983, 1997-1998, and 2006-2007.

Percentages of wells with screen depths above static and pumping water levels are shown in Figures 8 through 11. These figures represent all of the different well uses (domestic, irrigation, industrial, municipal, and public), but for calculating costs of well treatment, only domestic and irrigation well uses were considered. Lines marked as the higher bound (blue) indicate deeper groundwater levels and the lines marked as the lower bound (red) indicate shallower water levels. Peaks and valleys in the plots correspond to historical dry or wet years, respectively. The first two large peaks correspond to the 1976-1977 and 1987-1992 droughts. The Central Valley Project (CVP) Improvement Act of 1992 also increased water level drawdown as CVP water users turned to groundwater when a portion of their resources was dedicated to fish and wildlife preservation. The most recent droughts (2007-2009, 2012-2016) have had the greatest effect on the wells, as shown by the large peak at the far right of the graphs.

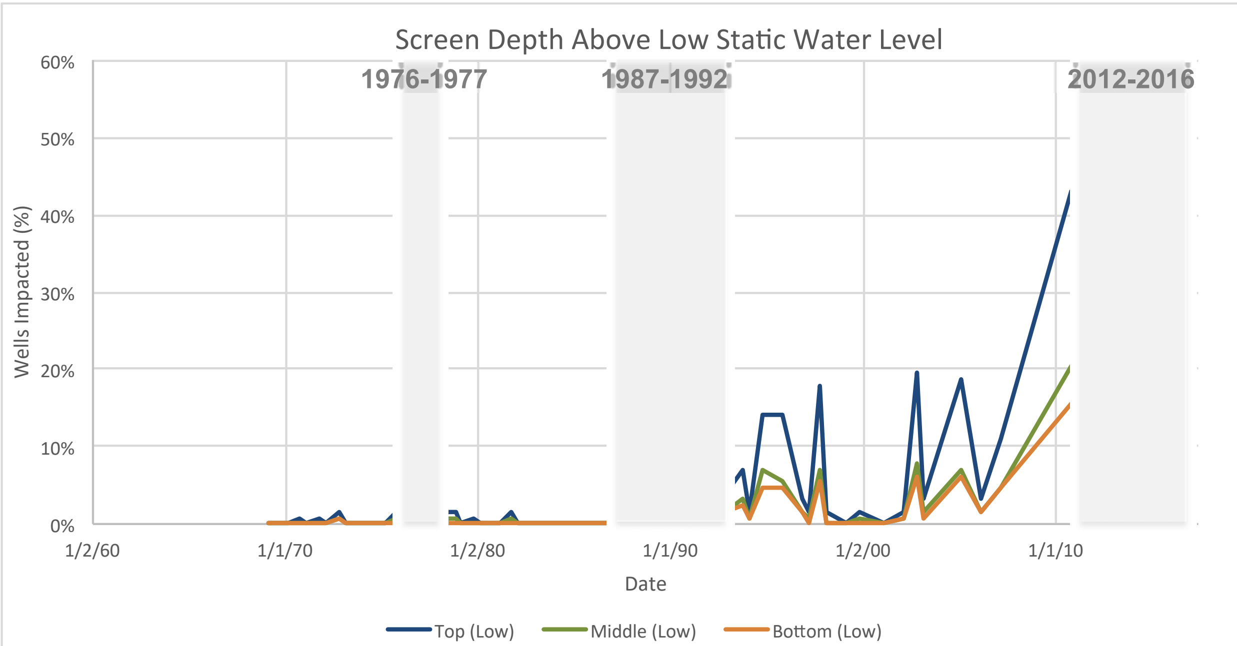


Figure 8: Estimated fraction of total wells with top, middle, and bottom of screens exposed under low static water conditions

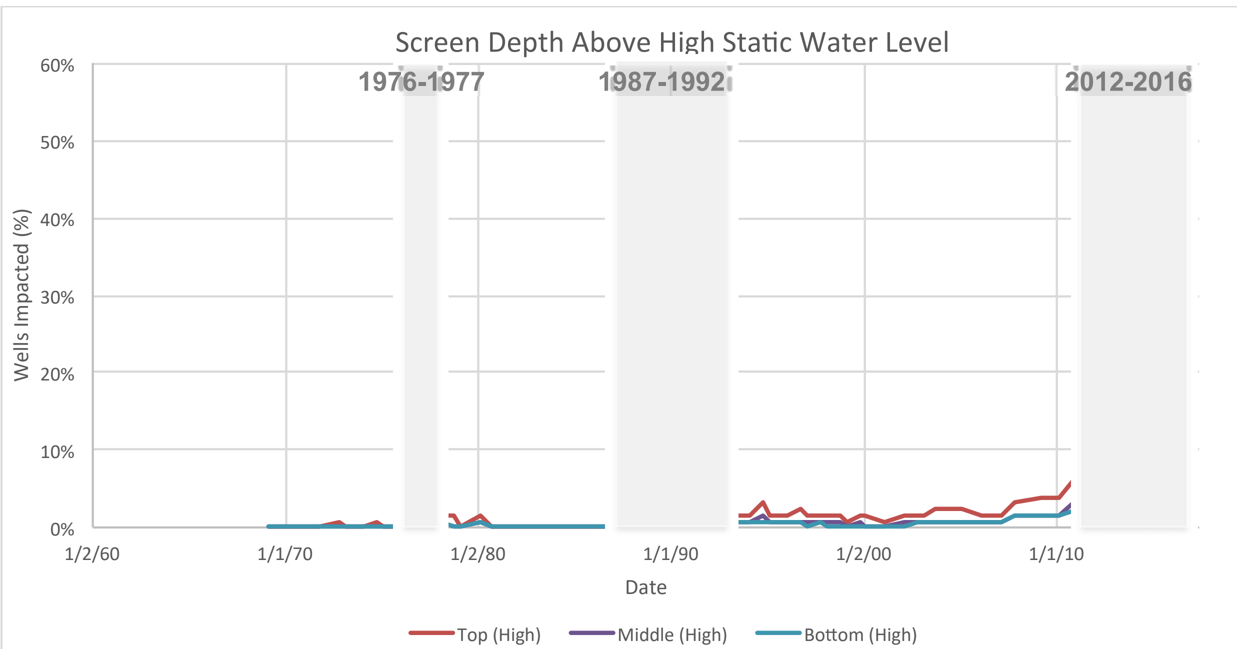


Figure 9: Estimated fraction of total wells with top, middle, and bottom of screens exposed under high static water conditions

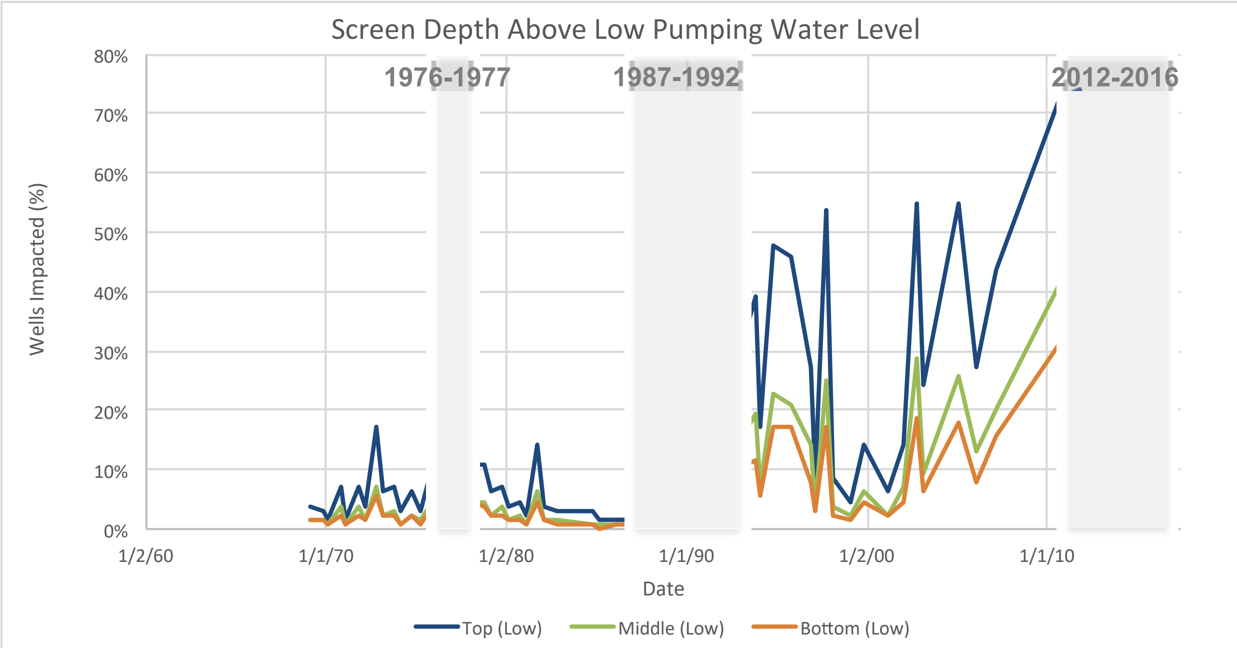


Figure 10: Estimated fraction of total wells with top, middle, and bottom of screens exposed under low pumping water conditions

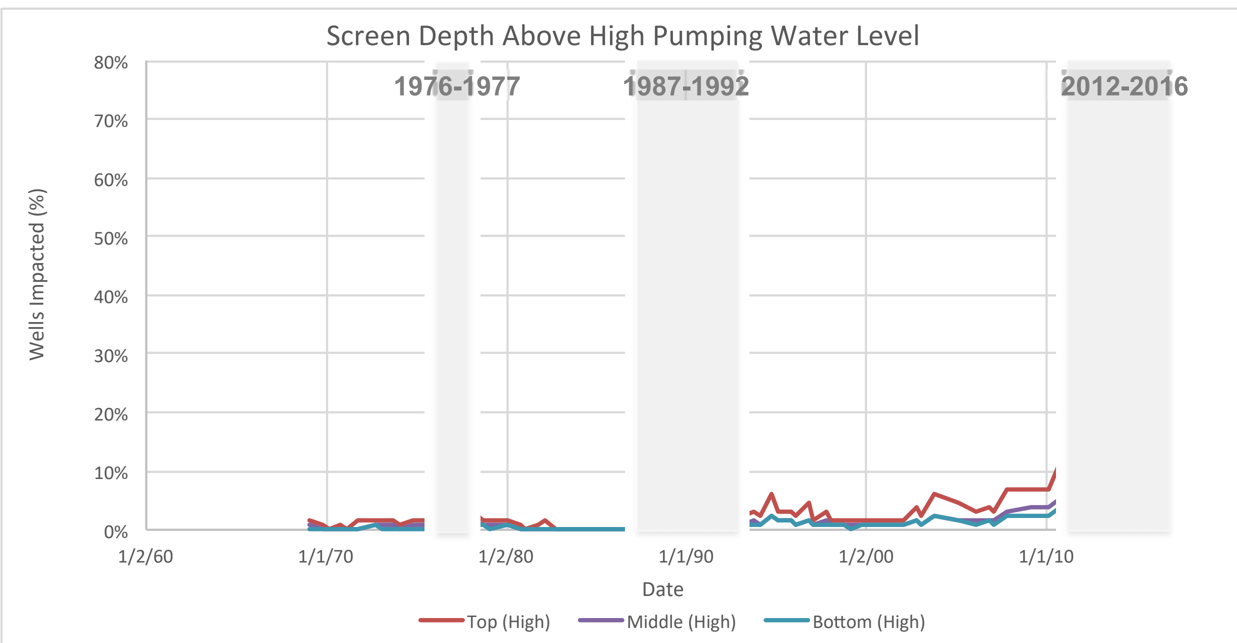


Figure 11: Estimated fraction of wells with top, middle, and bottom of screens exposed under high pumping water conditions

The high static water (Figure 9) shows the lowest peaks (small percentages of well impacted) and the low pumping water (Figure 10) shows the highest peaks (large percentages of wells impacted). The low pumping water level simulation (Figure 10) was assigned a higher pumping rate and a smaller specific capacity than the high pumping water level simulation (Figure 11). For all four scenarios of screen depths in relation to low or high and static or pumping water levels, the top of screen has the highest percentage of wells impacted and the bottom of screen has the lowest. The lower the groundwater elevation—by overdraft or reduced inflow—the higher the peak percent of wells affected. The most drastic difference in peaks among the three droughts is shown in the high static and high pumping water level plots. The 1976-77 and 1987-92 droughts show less than 5% of wells impacted, but the recent drought shows as high as 60% of wells impacted (for top of screen).

Costs of Well Rehabilitation

Estimated costs can be applied to the results in Figures 7 through 10 as described above using the operating costs equation. Table 1 lists estimated unit costs for well treatment, which were incorporated in the total cost calculations[1]. When the water level drops below the top of screen but not the middle or bottom, a common well treatment method is pump lowering. During times of heavier overdraft that lead to the water level dropping below the middle of screen, more costly well rehabilitation actions are needed to restore the well's capacity. In the more extreme cases of overdraft and drought, the water may fall below the bottom of screen. In this case, the well owner may choose to completely replace the well, which is the most costly well treatment option.

Table 1: Estimated Unit Costs for Well Treatment ($1000s) (after Gailey et al. 2016)

	DOMESTIC	IRRIGATION	Trigger Water Level
Pump Lowering:	$2 - 5	$5 - 10	Below Top of Screen
Rehabilitation:	$10 - 30	$50 - 100	Below Middle of Screen
Well Replacement:	$50 - 100	$500 – 1,000	Below Bottom of Screen

Using the deeper estimate of pumping water levels (Figure 11), total cost estimates for the three mentioned droughts (1976-77, 1987-92, 2012-2016) were calculated. Table 2 shows preliminary results of the calculated cost estimates for the three identified droughts. When compared to the values in the CDFA report (Table A-2), the cost estimates of the 1976-1977 drought are similar, but this Scenario 2 estimates $6-12 million less than and $10-20 million more than the research report's estimates of total cost of well treatment for the 1987-1992 and 2012-2016 droughts, respectively (Gailey et al. 2016). The great difference in cost estimates between the two evaluation scenarios for the most recent drought can be explained by the improvement to select hydrographs of monitoring wells located within the bounds of the study area that had water depth measurements recorded to the end of the drought. The two hydrographs used in the CDFA report had measurements until 2013 and 2015, so the total cost estimate of the recent drought did not consider the full length of the 2012-2016 drought period (Gailey et al. 2016).

Table 2: Estimated Total Cost Comparison for the 1976-1977, 1987-1992, and Current Droughts ($ million)

[1] Estimated unit costs are generally based upon experience of Robert M. Gailey, PG, CHG, PhD Candidate (Gailey et al 2016)

	Domestic			Irrigation			
	Pump Lowering	Rehabilitation	Well Replacement	Pump Lowering	Rehabilitation	Well Replacement	TOTAL
1976-1977 Drought	0.03 - 0.085	0.04 - 0.12	0.5 - 1	0.01 - 0.02	0	0.5 - 1	**1.08 - 2.23**
1987-1992 Drought	0.04 - 0.095	0.04 - 0.12	0.3 - 0.6	0.01 - 0.02	0.05 - 0.1	0.5 - 1	**0.94 - 1.94**
Recent Drought	0.006 - 0.015	0.02 - 0.06	5.35 - 10.7	0.16 - 0.31	0.4 - 0.8	9.5 - 19	**15.4 - 30.9**

The above cost estimates only apply to the 27 square mile study area. From the results, the recent drought is an order of magnitude more costly than the 1976-77 and 1987-92 droughts. The largest contribution to the steep rise in estimated cost for the recent drought is due to well replacement costs (groundwater level declines below the bottom of screen). We can expect trends of the most recent drought being the most costly across the groundwater basin, but the costs estimated in this analysis can only be applied to areas of similar size, geology, groundwater elevation, and well use distribution.

Discussion and Application

Table 3. Scenario 2: Percentages of TOS and BOS exposed under static and pumping water conditions for domestic and irrigation wells.

% Wells with Top of Screen Exposed

	Static Water Conditions		**Pumping Water Conditions**	
	Domestic	Irrigation	Domestic	Irrigation
1977 Drought	13-15%	1-2%	13-15%	4-19%
1992 Drought	12-27%	2-4%	12-28%	3-29%
Current (2016)	**74-79%**	**45-54%**	**74-79%**	**59-73%**

% Wells with Bottom of Screen Exposed

	Static Water Conditions		**Pumping Water Conditions**	
	Domestic	Irrigation	Domestic	Irrigation
1977 Drought	3-4%	0-1%	3-4%	1-6%
1992 Drought	2-11%	1-2%	2-11%	1-10%
Current (2016)	**50-61%**	**16-17%**	**50-61%**	**23-31%**

When compared to the 1976-77 and 1987-92 droughts, the most recent drought has the highest percentages of wells with screens exposed (water depth dropped below the stated screen level) for both static and pumping water conditions for the top and bottom of screens. The recent drought is the most costly for well treatment among the three recent major droughts. The difference in percentages (and costs) between the recent drought and the other two droughts is significant, which brings up the concern of over-estimation of the recent drought's values. The difference may be explained by the two years of extremely low precipitation during the recent drought or by an inaccurate assumption. For example, the well owners could have chosen to drill their wells deeper rather than invest in well treatment. The percentages for top of screen exposed are higher than those of the bottom of screen exposed, indicating that there were more instances of the less costly pump lowering than of well replacement for treating wells during these droughts. In Scenario 1, an estimated 22 to 36 percent of domestic wells (between 55 and 89 individual wells) and 6 to 23 percent of irrigation wells (between 8 and 30 wells) analyzed in the area experienced pumping water levels below the bottom of screen in 2015 during the most recent drought, as opposed to a maximum of 26 percent (97 wells) for all pre-2011 historical data. Drought-related data from Tulare County indicates approximately 22-25 domestic well failures in the study area[2]. The well count from Tulare County is less than half of the estimated number of wells from our analysis, which may be related to the assumption that all of the reported wells are still in service (Gailey et al. 2016).

In Scenario 2, an estimated 50 to 61 percent of domestic wells (between 124 and 151 wells) and 23 to 31 percent of irrigation wells (between 30 and 40 wells) experienced pumping water levels below the bottom of screen in 2016 during the recent drought. Scenario 2 is assumed to be more accurate in cost estimates because the two well hydrographs are within the study area and have measurements up to the end of 2016. When once again observing the drought effects status updates from Tulare County for October 2016, it is difficult to estimate the number of well failures in the study area due to overlapping dots that mark reported failures. In general, however, it appears that the reported domestic well count is less than this analysis would estimate. Possible explanations for the lower number of reported failures compared to the analysis estimate include that not everyone reports their well failure and that some owners may use alternative sources or water or fallow.

This is a preliminary analysis, but the methods and results seem mostly reasonable. With better groundwater and well management, drops in groundwater levels and detriment of wells should not be as drastic as the most recent drought. If groundwater agencies and well owners seek management practices such as reduced demand, surface water substitution, and conjunctive use, the cost of well treatment during drought periods can be expected to be lower than the cost of this past drought, assuming that the intensity and length of the drought periods are the same or less than the recent drought.

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[2] http://tularecounty.ca.gov/emergencies/index.cfm/drought/drought-effects-status-updates/

Chapter 4 – Conclusions

This thesis work and the CDFA impact analyses report for both well depths and pumps demonstrate how changes in groundwater levels over time affect well operations. Emphasis was placed on historic and recent drought conditions to quantify conditions when pumps are most active (Gailey et al. 2016). The wells in the study area showed significant potential to contract well maintenance and replacement costs as a result of drought conditions and decreased groundwater levels approaching critical points in the wells' screens (Gailey et al. 2016). The most recent drought may have resulted in several million dollars in well maintenance and rehabilitation costs, though some of these costs may have accumulated as well owners delayed treated their wells.

Impacts of most recent drought on well costs appear likely to be greater than previous recent droughts. This is because the recent drought had California's driest consecutive water years in terms of statewide precipitation (DWR 2015). The 1976-77 drought, though brief in duration, was notable for the severity of its hydrology and the 1987-92 drought was California's first extended dry period since the 1920s-30s (DWR 2015). When comparing the 1976-77 and 1987-92 droughts to the most recent drought, not only did the recent drought have severely dry conditions, but also it occurred at a time of record warmth in California. The combination of extreme conditions and long duration of the recent drought led to greater negative impacts for the wells and thus greater costs for well treatment. In addition, the water levels at the start of the recent drought were much lower than the end of the 1987-92 drought due to other drought periods and poor water level recovery in between. Well pumping costs also indicate cost increases as a result of drought. Representative cost increases for the study area are $1.23/acre annually ($0.39/AF) for the entire hydrograph time period and $5.31/ac ($1.69/AF) during latest drought (Gailey et al. 2016). While these costs are not large on a per acre basis, they may be significant when incurred across large agricultural areas.

Additional study is needed to better assess increases in well maintenance costs during the recent drought. Future work on this topic may include:

- Adjusting the number of wells by obtaining records of well destruction for the study area and constructing a larger data analysis for the study area with more well completion reports and updated hydrograph data;
- Calculating costs for the 2001-2004 and 2007-2009 droughts;
- Considering the effects of specific capacity uncertainty, especially for the deeper irrigation wells;
- Considering the drilling dates and excluding the data for wells not yet constructed in historic droughts;
- Adding the increased pumping costs to the analysis of drought costs;

The research report from which this evaluation draws illustrates that well construction and groundwater hydrograph data can be used to evaluate the impacts to groundwater supply operations caused by declining groundwater levels (Gailey et al. 2016). Governing and managing groundwater are complex activities that depend on both the physical configuration of groundwater structures (ex. wells, pumps, etc.) and an area's reliance on groundwater resources. As California moves towards forming local Groundwater Sustainability Agencies (GSAs) that will develop Groundwater Sustainability Plans (GSPs) under SGMA, it will be interesting to see how more sustainable groundwater management may reduce the cost and need of well treatment for future droughts.

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Appendix

Initial Results and Discussion for Scenario 1

Map of Study Area with Initial Monitoring Well Locations

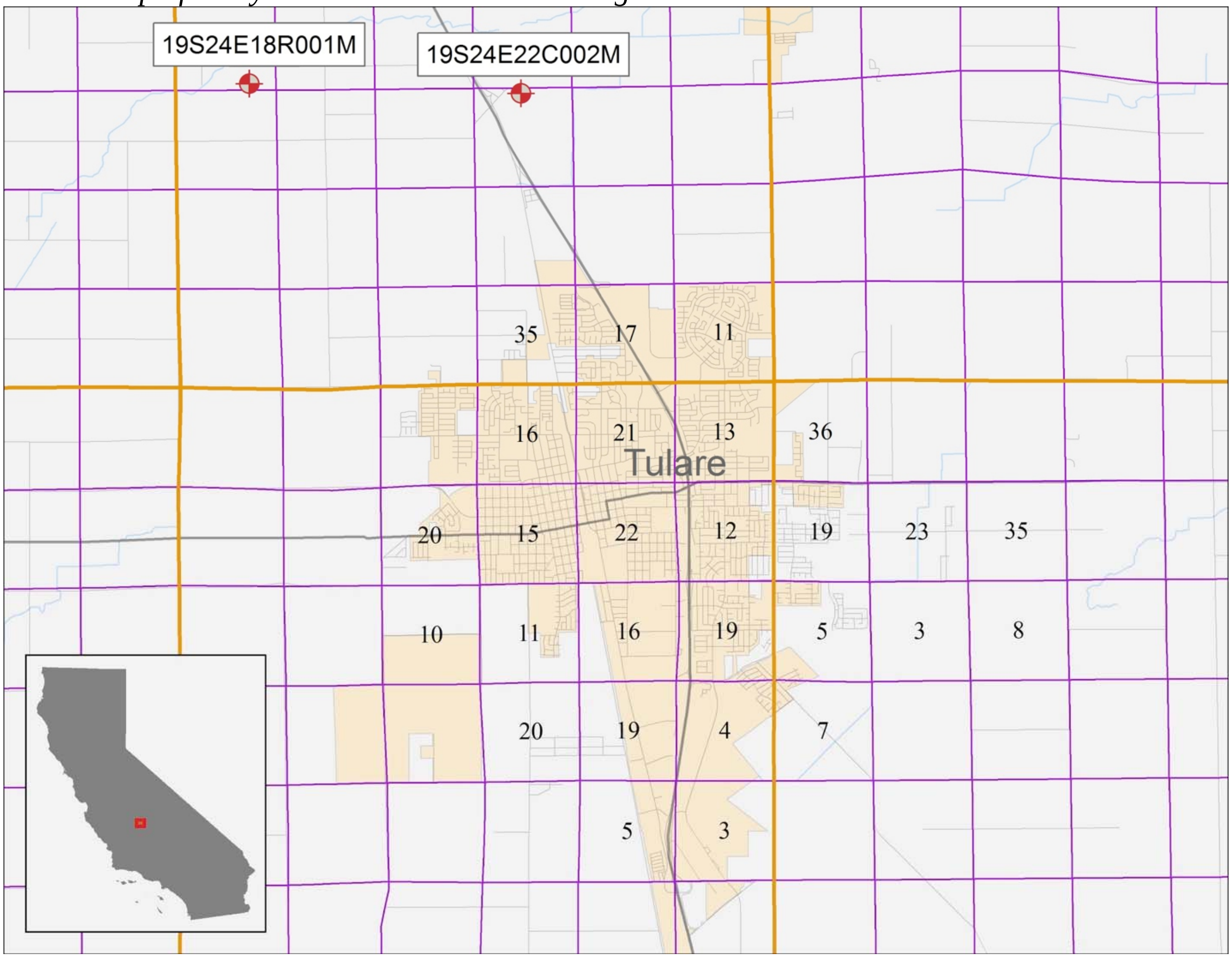

Figure 12: Map of Tulare, CA with well locations: The two red icons at the top of the figure indicate two wells for which groundwater hydrographs were constructed to represent high and low estimates of the water level variations. (from Gailey et al. 2016)

As show in the map figure above, the two monitoring wells used in the initial analysis were located outside of the study area. In an attempt to improve the accuracy of the cost estimates, I searched for hydrograph data from wells that were in the study area that had more recent water level measurement dates. The improved analysis was described in the main text and the initial analysis is shown below.

Regional Water Elevations During Drought

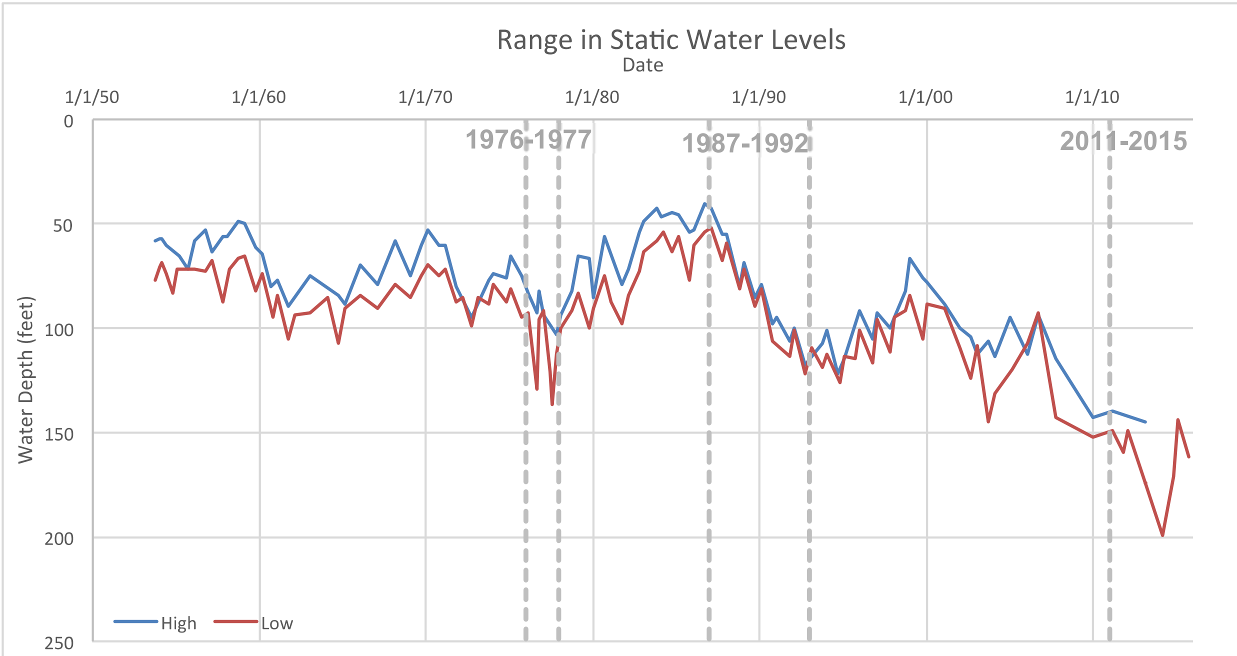

Figure 13: Hydrograph of range in static water levels. Water levels were measured twice a year in the spring and fall.

Figure 13 above shows the hydrographs of the two wells used in the first round of analysis. For the initial results, the water depth measurements stopped at 2015, so the full length of the recent drought was not considered. The dashed gray lines identify the droughts used in the analysis. Peaks in the hydrograph above correlate to notable wet years in 1982-1983, 1997-1998, and 2006-2007. Figures 14 through 17 show percentages of wells with screen depths above static and pumping water levels.

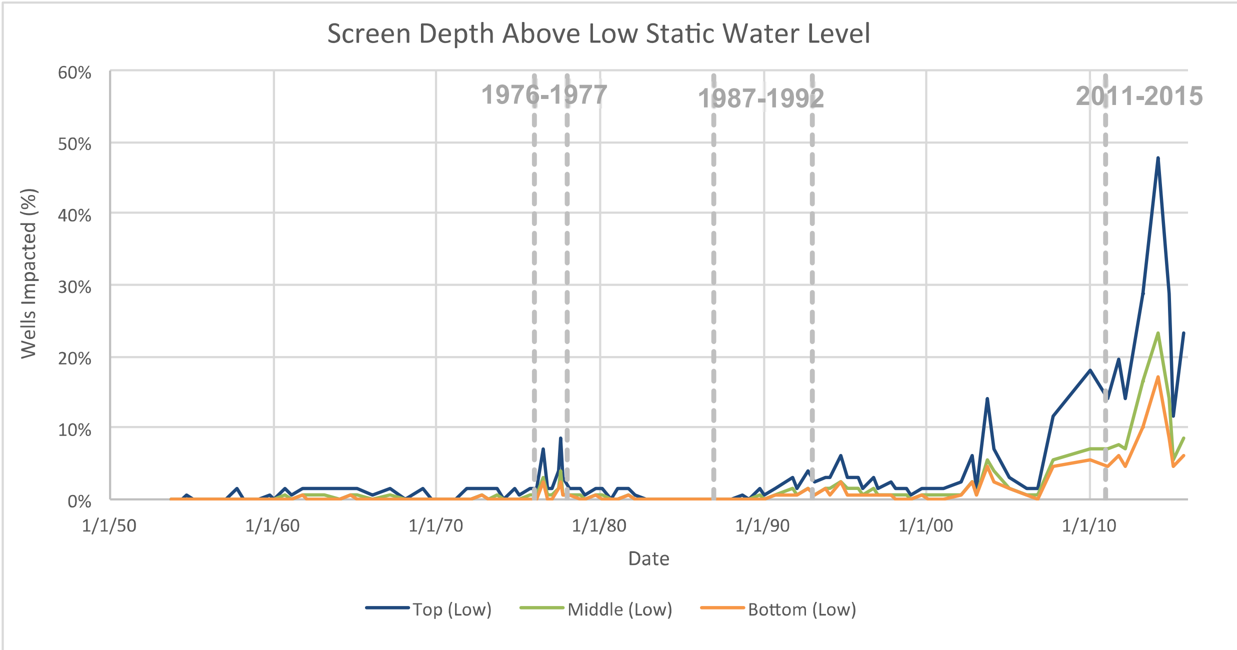

Figure 14: Fraction of wells with top, middle, and bottom of screens exposed under low static water conditions

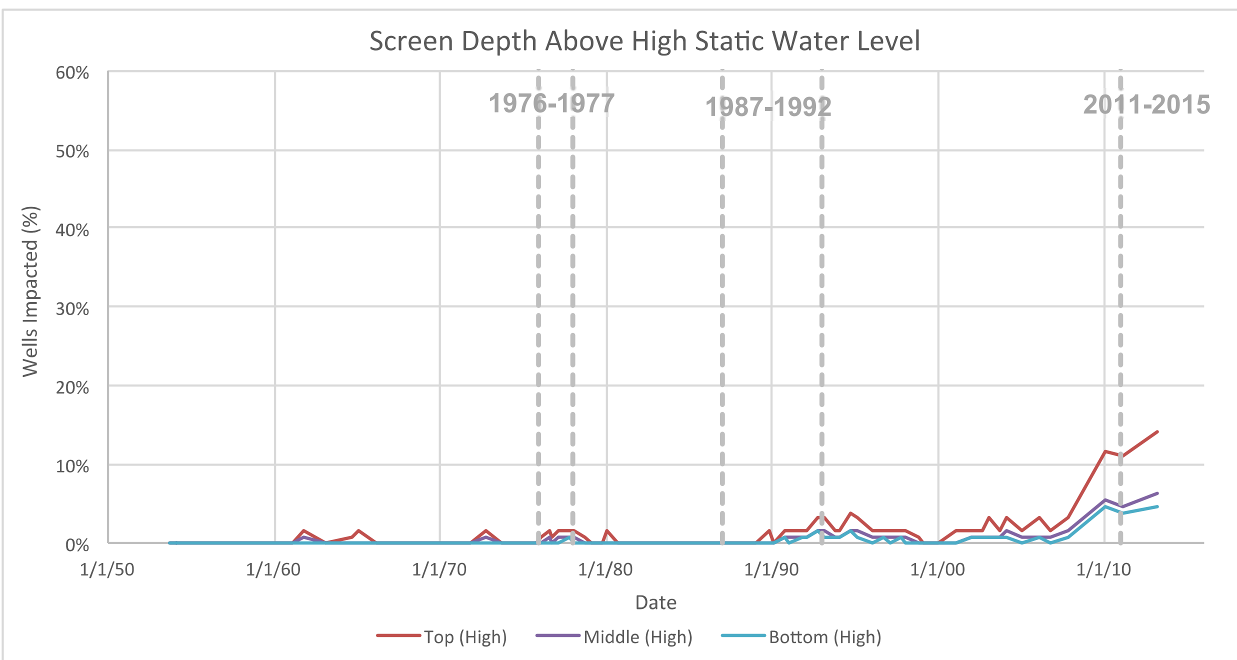

Figure 15: Fraction of wells with top, middle, and bottom of screens exposed under high static water conditions

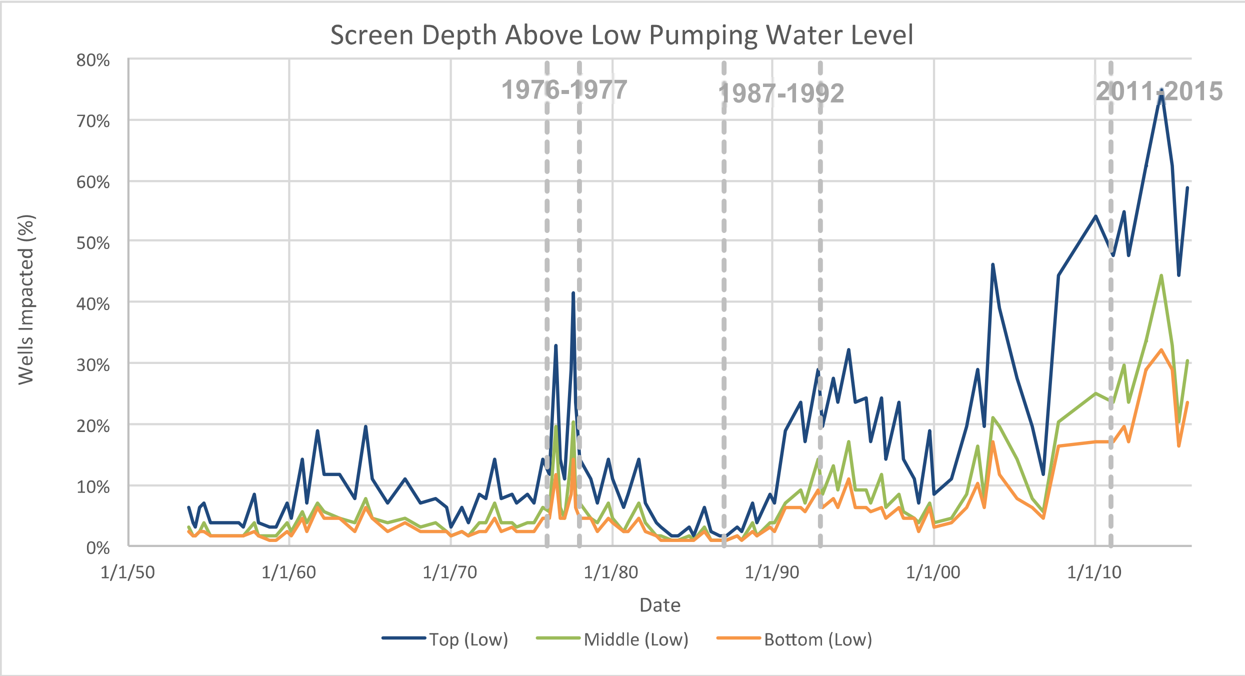

Figure 16: Fraction of wells with top, middle, and bottom of screens exposed under low pumping water conditions

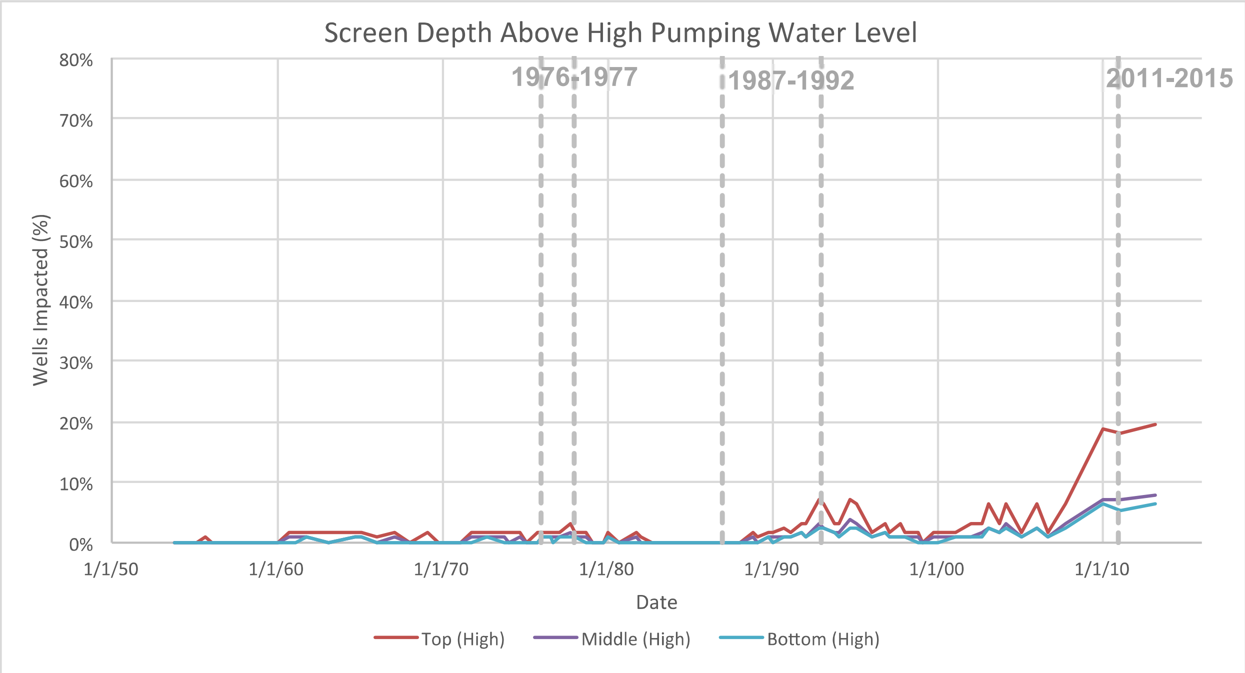

Figure 17: Fraction of wells with top, middle, and bottom of screens exposed under high pumping water conditions

Table 4: Estimated Total Cost Comparison for the 1976-1977, 1987-1992, and Current Droughts

ESTIMATED TOTAL COSTS ($ million)							
	Domestic			Irrigation			
	Pump Lowering	Rehabilitation	Well Replacement	Pump Lowering	Rehabilitation	Well Replacement	TOTAL
1976-1977 Drought	0.04 - 0.095	0.05 - 0.15	0.7 - 1.4	0.06 - 0.11	0.1 - 0.2	1.0 - 2.0	**1.9 - 4**
1987-1992 Drought	0.07 - 0.185	0.01 - 0.03	1.4 - 2.8	0.09 - 0.18	0.3 - 0.6	5.5 - 11	**7.4 - 14.8**
Recent Drought	0.01 - 0.025	0	1.35 - 2.7	0.025 - 0.05	0.05 - 0.1	4.0 - 8.0	**5.46 - 10.8**

**Note: These cost estimates only apply to the 27 square mile study area.

Table 5. Scenario 1: Percentages of TOS and BOS exposed under static and pumping water conditions for domestic and irrigation wells.

	% Wells with Top of Screen Exposed			
	Static Water Conditions		**Pumping Water Conditions**	
	Domestic	Irrigation	Domestic	Irrigation
1977 Drought	12-17%	2-3%	12-17%	3-23%
1992 Drought	19-26%	3-4%	19-27%	7-29%
Current (2016)	**41-52%**	**14-23%**	**41-53%**	**20-59%**
	% Wells with Bottom of Screen Exposed			
	Static Water Conditions		**Pumping Water Conditions**	
	Domestic	Irrigation	Domestic	Irrigation
1977 Drought	2-6%	0-1%	2-6%	1-6%
1992 Drought	8-11%	1-2%	8-11%	2-9%
Current (2016)	**22-36%**	**5-6%**	**22-36%**	**6-23%**

Example of a Well Completion Report:

ORIGINAL
File with DWR
Page 1 of 2

STATE OF CALIFORNIA
WELL COMPLETION REPORT
Refer to Instruction Pamphlet
No. ~~e01033579~~ E0252287

DWR USE ONLY — DO NOT FILL IN
195/24E-34 ... STATE WELL NO./STATION NO.
LATITUDE — LONGITUDE
APN/TRS/OTHER

Owner's Well No. Whitten 1
Date Work Began 1/15/2012, Ended 1/16/2012
Local Permit Agency Tulare
Permit No. 12-0006 Permit Date 1/10/2012

GEOLOGIC LOG

ORIENTATION (✓) ✓ VERTICAL ___ HORIZONTAL ___ ANGLE ___ (SPECIFY)
DRILLING METHOD REVERSE FLUID WATER/POL

DEPTH FROM SURFACE Ft.	to Ft.	DESCRIPTION *Describe material, grain, size, color, etc.*
0	3	TOP SOIL
3	12	SAND
12	16	CLAY
16	43	SAND
43	63	CLAY
63	71	SAND
71	73	HARD
73	88	CLAY
88	91	SAND
91	97	CLAY
97	115	SAND
115	127	CLAY
127	130	SAND
130	150	CLAY
150	158	SAND
158	168	CLAY
168	175	SAND
175	181	CLAY
181	186	SAND
186	189	CLAY
198	218	SAND
218	221	CLAY
221	224	SAND
224	241	CLAY
241	246	SAND
246	462	CLAY
262	255	SAND/GRAVEL
295	347	CLAY
347	361	SAND
361	422	CLAY

TOTAL DEPTH OF BORING 480 (Feet)
TOTAL DEPTH OF COMPLETED WELL 480 (Feet)

WELL OWNER

WELL LOCATION
Address 880' E of North E St 600' N of Zumw alt Ave
City Visalia, CA CA 93277
County TULARE
APN Book 164 Page 050 Parcel 012
Township 19 S Range 24 E Section 34
Latitude ___ DEG. MIN. SEC. Longitude ___ DEG. MIN. SEC.

LOCATION SKETCH
NORTH — WEST — EAST — SOUTH
Illustrate or Describe Distance of Well from Roads, Buildings, Fences, Rivers, etc. and attach a map. Use additional paper if necessary. **PLEASE BE ACCURATE & COMPLETE.**

ACTIVITY (✓)
✓ NEW WELL
MODIFICATION/REPAIR
— Deepen
— Other (Specify)
— DESTROY (Describe Procedures and Materials Under "GEOLOGIC LOG")

PLANNED USES (✓)
WATER SUPPLY
— Domestic — Public
✓ Irrigation — Industrial
MONITORING ___
TEST WELL ___
CATHODIC PROTECTION ___
HEAT EXCHANGE ___
DIRECT PUSH ___
INJECTION ___
VAPOR EXTRACTION ___
SPARGING ___
REMEDIATION ___
OTHER (SPECIFY) ___

WATER LEVEL & YIELD OF COMPLETED WELL
DEPTH TO FIRST WATER ___ (Ft.) BELOW SURFACE
DEPTH OF STATIC WATER LEVEL ___ (Ft.) & DATE MEASURED ___
ESTIMATED YIELD * ___ (GPM) & TEST TYPE ___
TEST LENGTH ___ (Hrs.) TOTAL DRAWDOWN ___ (Ft.)
May not be representative of a well's long-term yield.

CASING (S)

DEPTH FROM SURFACE Ft.	to Ft.	BORE-HOLE DIA. (Inches)	BLANK	SCREEN	CON-DUCTOR	FILL PIPE	MATERIAL / GRADE	INTERNAL DIAMETER (Inches)	GAUGE OR WALL THICKNESS	SLOT SIZE IF ANY (Inches)
0	240	24	✓				STEEL	16	1/4	
240	480	24		✓			STEEL	16	1/4	.090

ANNULAR MATERIAL

DEPTH FROM SURFACE Ft.	to Ft.	CE-MENT (✓)	BEN-TONITE (✓)	FILL (✓)	FILTER PACK (TYPE/SIZE)
0	50	✓			
50	480				GRAVEL

ATTACHMENTS (✓)
— Geologic Log
— Well Construction Diagram
— Geophysical Log(s)
— Soil/Water Chemical Analysis
— Other ___
ATTACH ADDITIONAL INFORMATION, IF IT EXISTS.

CERTIFICATION STATEMENT
I, the undersigned, certify that this report is complete and accurate to the best of my knowledge and belief.
NAME Myers Well Drilling Inc.
(PERSON, FIRM, OR CORPORATION) (TYPED OR PRINTED)
11745 2nd Ave. Hanford CA 93230
ADDRESS CITY STATE ZIP
Signed [signature] 01/24/12 865822
WELL DRILLER/AUTHORIZED REPRESENTATIVE DATE SIGNED C-57 LICENSE NUMBER

DWR 188 REV. 11-97
IF ADDITIONAL SPACE IS NEEDED, USE NEXT CONSECUTIVELY NUMBERED FORM