

Economic Tradeoffs in Groundwater Management During Drought: Tulare County, California

By

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ABSTRACT

The 2014 Sustainable Groundwater Management Act (SGMA) requires local groundwater management plans and policies to achieve future sustainability. But, defining groundwater sustainability can be challenging given the various sustainability criteria. Establishing policies in a large existing system of competing users brings further complexity. Before implementing change to current groundwater practices, the effects of proposed policies on users should be evaluated. Policy-makers also may need to consider the needs and interests of different water users.

This thesis focuses on a local groundwater system and evaluates the economic impacts of policy alternatives on two somewhat conflicting user groups. The study analyzes agricultural and domestic groundwater use in Tulare County, California during the 2012-2016 drought. Using hydrologic and crop production data from the drought, agricultural surface water deliveries, crop water demands, and groundwater usage were estimated for the study area. With these data, an agricultural-groundwater profit maximization model was created to relate groundwater use, agricultural profit, and resulting agricultural opportunity costs from water use regulation. An analogous relationship for domestic groundwater users was obtained from an existing domestic well costs model (Gailey et al., 2019). By defining alternative groundwater policies as depth-to-groundwater pumping limits, the models estimated agricultural opportunity and domestic well costs, respectively. The collection of these policy economic impacts on users form a Pareto curve. The groundwater policy which maximizes the total welfare of the two groups was then identified. The additional agricultural groundwater pumping during the drought greatly impacted domestic well users. Since agricultural profit greatly exceeds domestic well costs incurred during drought, an opportunity for negotiating compensation for domestic costs from agricultural users is presented. SGMA policy implementation will require groundwater drawdown recovery by reducing agricultural groundwater pumping and fallowing lower-valued crops following future droughts. Including these recovery costs reduced drought drawdown by agriculture. Limitations of the study, policy implications, and future work also are discussed.

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1. INTRODUCTION AND OBJECTIVES

1.1. Introduction and background

The recent 2012-2016 California drought exacerbated groundwater issues in the state and prompted passage of the 2014 Sustainable Groundwater Management Act (SGMA) (Hanak et al., 2019; Lund et al., 2018). The drought was the warmest and one of the most severe on record, and was especially severe in terms of impacts on soil moisture and snowpack (Lund et al., 2018). Precipitation and subsequent streamflow reached record minimums in some parts of the state (Lund et al., 2018). Consequently, surface water deliveries, particularly from northern California were reduced during the drought which lead to further overdraft of groundwater (Hanak et al., 2019; Lund et al., 2018). The passing of SGMA requires local groundwater management policies to achieve sustainability by 2040 (Hanak et al., 2019). The act defines groundwater sustainability as preventing "...drawing down water levels too far, depleting storage in the aquifer, degrading water quality, allowing seawater intrusion, causing land to subside, or using groundwater in ways that reduce other people's surface water or harm ecosystems," (Hanak et al., 2019). Groundwater sustainability agencies (GSAs), in basins deemed as "critically overdrafted," must submit sustainability plans by 2020 (Hanak et al., 2019).

The SGMA requirement for sustainability policies prompts the need for policy planning tools to evaluate proposed policies for both meeting sustainability and balancing stakeholder and user interests. In regions such as the San Joaquin Valley, where agriculture dominates the local economy and groundwater depletion is highly prevalent, policy planning tools may be helpful (Hanak et al., 2019).

Previous research (Gailey et al., 2019) analyzed the supply impacts on domestic groundwater users in addition to the economic impacts of proposed policies in Tulare County, California during the 2012-2016 drought. Policies were defined as depth to groundwater (DTGW) pumping limitations. The relationship, between economic impact on domestic well owners and DTGW policies, was presented as a domestic well cost curve. While the economic impacts on domestic groundwater users was quantified, economic impacts on agricultural users were only illustrative. To provide a more complete SGMA policy planning tool to evaluate proposed policies, the economic impacts on agricultural users should be quantified.

1.2. Thesis objectives and structure

Focusing on Tulare County, California, during the 2012-2016 drought, this thesis develops an agricultural cost curve, analogous to the existing domestic well cost curve (Gailey et al., 2019), develops Pareto curves of economic tradeoffs for the two user groups, and identifies policies which maximizes the welfare of users. Hydrologic and crop production data, during the drought, is used to estimate agricultural surface water deliveries, crop water demands, and groundwater use. Using these data, an agricultural-groundwater profit maximization model is created to develop the agricultural cost curve. Two additional versions of the model are developed, incorporating additional planting options and groundwater recovery costs to the base model. Using the resulting three agricultural cost curves, with the domestic well cost curve from Gailey et al. (2019), Pareto curves are presented for each different modeling system. The welfare-maximizing DTGW policies, for each modeling system, are identified and compared to the actual drought conditions. Policy implications, alternative policy selection methods, and future work also are discussed. The thesis is organized into sections on methods, results, discussion, and conclusions and future work.

2. METHODS

The following sections detail the study area, analysis period, the methods of the tasks in Figure 1, and key assumptions and limitations. Figure 1 shows the workflow of tasks, labeled as Tasks 1-6. Tasks and methods are defined in the following subsections.

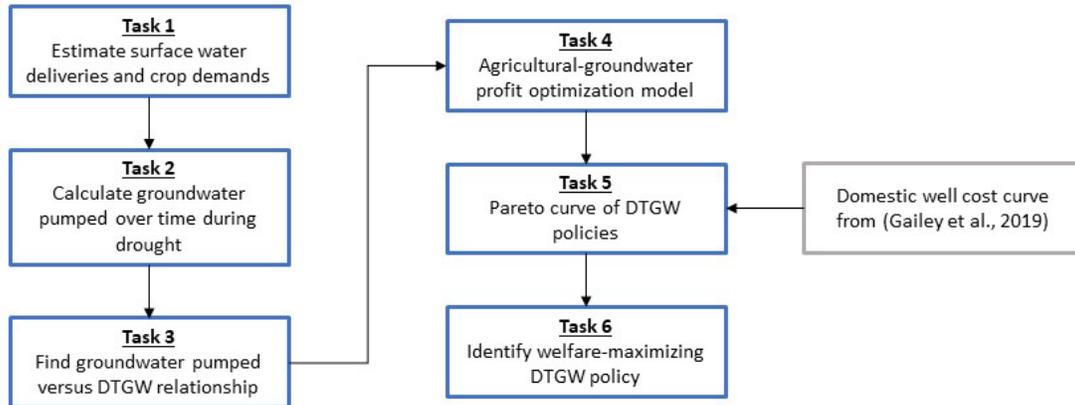


Figure 1. Flow chart of thesis tasks

2.1. Study area and analysis period

The geographical study area, previously used in (Gailey et al., 2019), is shown in Figure 2. The study area includes much of the alluvial Central Valley floor of Tulare County, California (Gailey et al., 2019). Agricultural production is a majority industry in the area and is significant in the local economy (Gailey et al., 2019). This study focuses on the most recent 2012-2016 drought in California. Groundwater decisions and subsequent economic impacts, for agricultural and domestic users, are analyzed by replaying the hydrologic conditions of this drought.

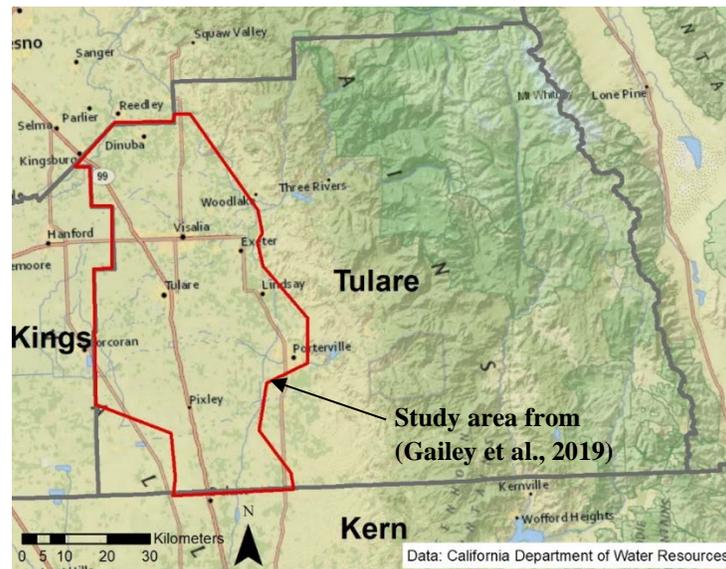


Figure 2. Study area in Tulare County, California

2.2. Task 1: Surface water deliveries and crop demand

In the study area, water supply is primarily from surface water deliveries and groundwater (California Department of Water Resources, 2015). To estimate the groundwater pumped for agriculture in the study area during the drought, surface water deliveries and crop demands were first estimated. Since irrigation districts (IDs) provide much of the surface water to agricultural producers, as farm-gate deliveries, the IDs in the region were identified using geographical information systems (GIS) data from the California Department of Water Resources (California Department of Water Resources, 2018a, 2018b). Approximately 100 IDs were identified in the study area; however, 16 of the largest IDs in the study area

were selected to represent entire study area. The area of the selected IDs is about 90% of the total study area. The select IDs and respective area coverage are shown in Figure 3.

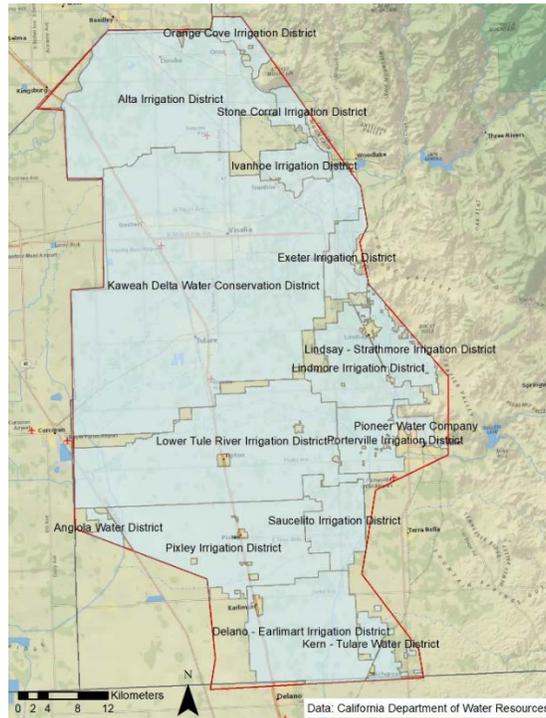


Figure 3. Select IDs in study area

Review of local Agricultural Water Management Plans indicates the main sources of agricultural farm-gate deliveries are local sources, i.e., creeks, rivers, reservoirs, and from the federally-operated Friant-Kern canal. Farm-gate deliveries were obtained for the select IDs from 2011-2016 from the CADWR Water Use Efficiency database (California Department of Water Resources, 2019d). Documentation of farm-gate deliveries for the select IDs was temporally and spatially sparse with the largest coverage consisting of 2013 delivery data for 13 of the selected IDs. These farm-gate deliveries were mathematically scaled-up to reflect farm-gate deliveries for the study area in 2013. An analogous process for Friant-Kern deliveries was done to estimate 2011-2016 Friant-Kern deliveries to the study area using data from the US Bureau of Reclamation (US Bureau of Reclamation, 2019). The temporal trends of Friant-Kern deliveries were used to temporally scale the farm-gate deliveries which are shown in Figure 4.¹ These scaled farm-gate deliveries represent surface water deliveries to the study area from 2010 to 2016.

¹ Friant-Kern and farm-gate deliveries were available for 76% and 85% of the study area, respectively. The Friant-Kern and farm-gate deliveries were divided by 76% and 85%, respectively, to estimate each delivery for the entire study area. The ratio, R , of 2013 farm-gate to Friant-Kern deliveries was used to estimate farm-gate deliveries for each year i of the drought as: $Farmgate_i = R * FriantKern_i$



Figure 4. Friant-Kern and scaled farm-gate deliveries

To estimate crop demand in the study area during the drought, land use was first determined using CADWR land use data for 2014 (California Department of Water Resources, 2019a). After obtaining each land use and respective acreage within the study area, the land uses categories that compose approximately 95% of the land use in the study area were identified. These categories included 12 crops and 2 non-crop types (idle and urban). The non-crop categories were omitted from the crop demand calculation with the simplifying assumption that these non-crop land uses do not require water. Although annual urban water demand for Tulare County is about 134 TAF, annual agricultural water demand is approximately 2690 TAF, according to 2005-2010 data (California Department of Water Resources, 2015). Each of the 12 crops were classified as annual or perennial (Tulare County Agricultural Commissioner, 2016). Using temporal scaling factors from Tulare County Agricultural Commissioner crop reports, crop acreages for each year of the drought were estimated by scaling the 2014 acreage data (Robert Gailey, personal communication, 2019).² The crops and respective acreages from 2011 to 2016 are tabulated in Table 1. Evapotranspiration (ET_c) was calculated using crop coefficients and historical daily reference evapotranspiration (ET_0) during the drought for each of the 12 crops (Doll, 2017). First, crop harvest dates and crop coefficients were used to construct Kc curves for each crop (Nadya Alexander Sanchez, personal communication and spreadsheet, 2018; Doll, 2017; Orang et al., 2013). These Kc curves along with precipitation and daily ET_0 data from 2011-2016, from the Porterville CIMIS station, were used to estimate yearly crop demand for each crop (California Department of Water Resources, 2019b). Total crop demands and total crop acreage per year, for the crops composing the 95% of cumulative acreage, were scaled to represent the entire study area. The scaled total crop demands and scaled total acreage for 2011 to 2016 are shown in Table 1 and Figure 5. The scaled total acreage for annual and perennial crop types, shown in Figure 5, vary throughout the drought. While temporal fluctuations of annual crop type acreage can be attributed to fallowing, temporal fluctuations of perennial crop type acreage is most commonly attributed to fallowing older, less long-term productive perennials and planting new perennials in a given year (Sanchez, 2017).

² Using the Tulare County Agricultural Commissioner crop reports' acreages for each year of the drought and the 2014 DWR Land Use acreages, temporal scaling factors for annual and perennial crop types were estimated for each year. By multiplying the 2014 acreages by the respective temporal scaling factors, acreages for 2011-2013, 2015-2016 were estimated for the study area.

Table 1. Crop acreage and scaled annual crop demand of study area

Top 95% of crop land, acres						
<i>Annual crops</i>	<i>2011</i>	<i>2012</i>	<i>2013</i>	<i>2014</i>	<i>2015</i>	<i>2016</i>
Corn, sorghum, and sudan	184,955	190,863	190,396	151,513	199,938	189,590
Alfalfa and alfalfa mixtures	67,024	69,165	68,996	54,906	72,454	68,704
Cotton	16,177	16,693	16,652	13,252	17,487	16,582
Beans (dry)	9,015	9,303	9,280	7,385	9,746	9,241
<i>Perennial crops</i>	<i>2011</i>	<i>2012</i>	<i>2013</i>	<i>2014</i>	<i>2015</i>	<i>2016</i>
Citrus	71,378	68,847	77,165	81,823	78,190	88,543
Grapes	48,916	47,182	52,883	56,075	53,585	60,680
Almonds	37,741	36,403	40,801	43,264	41,343	46,817
Walnuts	34,272	33,057	37,051	39,288	37,544	42,514
Pistachios	29,469	28,424	31,859	33,782	32,282	36,556
Peaches/nectarines	18,600	17,941	20,109	21,322	20,376	23,073
Plums, prunes, and apricots	10,787	10,404	11,661	12,365	11,816	13,381
Olives	7,652	7,381	8,273	8,772	8,383	9,493
Scaled total crop demand per year, AF						
<i>2011</i>	<i>2012</i>	<i>2013</i>	<i>2014</i>	<i>2015</i>	<i>2016</i>	
1,660,788	1,619,324	1,909,691	1,912,582	2,021,751	2,111,131	

*Scaled total crop demand is the sum of crop demands, for the 12 crops listed above, divided by 95% for each year.

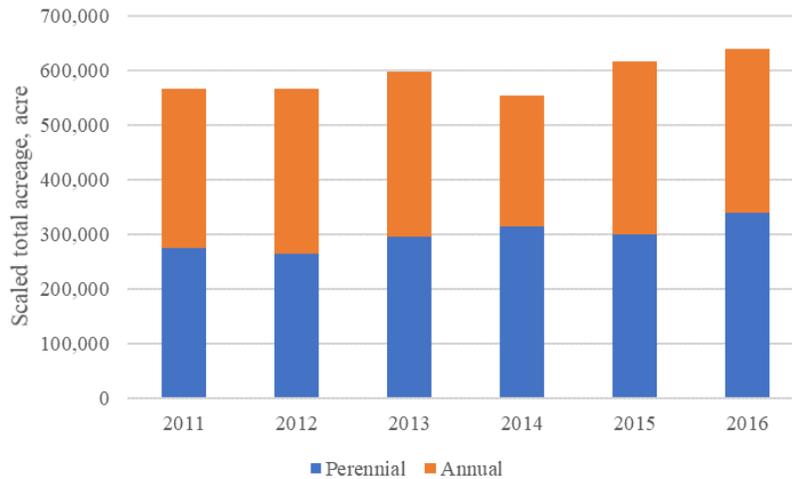


Figure 5. Total scaled crop acreage of study area during drought

2.3. Task 2: Groundwater pumped in study area during drought

The groundwater volume pumped per year in the study area was calculated using Equation 1. Each term in the equation is a volume in units of acre-ft (AF). This relationship assumes that any difference in crop demand and surface water delivery is supplied by pumped groundwater. The groundwater pumped in the study area was calculated for 2011 to 2016, shown in Figure 6.

$$\text{Groundwater pumped} = \text{crop demand} - \text{surface water delivery} \quad \text{(Equation 1)}$$

2.4. Task 3: Groundwater pumped and DTGW relationship

To obtain DTGW values for the study area, a representative well hydrograph was referenced. The same representative well in Gailey et al. (2019), Well 362539N1193051W001, was used for this study. The well hydrograph data, from the CADWR Water Data Library, provided temporally sparse data during the

drought (California Department of Water Resources, 2019c). As assumed in Gailey et al. (2019), this reference well represents the temporal trends of DTGW values for the entire study area. Temporal interpolation of the well hydrograph data allowed calculation of the desired year-end DTGW values during the drought.³ This process assumes that the entire study area has uniform annual DTGW values.⁴ Due to the spatially-varying hydrogeological and pumping complexities of groundwater systems, these DTGW values are simplified estimations of real-world conditions in the study area. Figure 6 shows groundwater pumped and well hydrograph DTGW values during the drought. To estimate the relationship of DTGW and groundwater pumped during the drought in the study area, a regression of the DTGW values versus cumulative groundwater pumped was performed. The graphical relationship and mathematical regression appear in Figure 10.

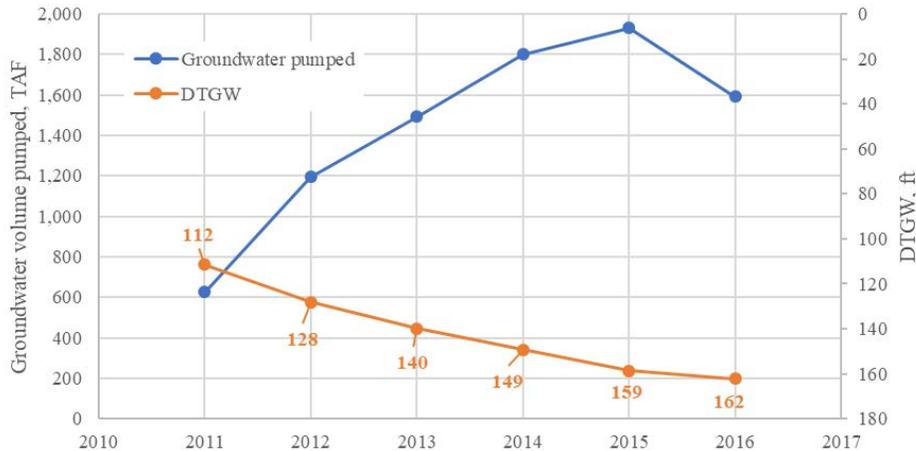


Figure 6. Groundwater pumped and well DTGW values during drought

2.5. Task 4: Agricultural-groundwater profit optimization model

A relationship between agricultural opportunity cost and DTGW within the study area, analogous to the domestic well cost curve from Gailey et al. (2019), was required to create a Pareto curve of policies to represent agricultural and domestic cost tradeoffs. Each policy explored in this study is a DTGW threshold that users cannot exceed by pumping groundwater. To obtain a relationship between agricultural opportunity costs and DTGW policies, an agricultural-groundwater profit optimization model was developed. Three versions of the model were created representing different crop planting options and groundwater pumping costs. The base model is defined in the following Section 2.5.1 with the additional variations of model 2 and 3 discussed in Sections 2.5.3 and 2.5.4, respectively.

2.5.1. Base model formulation

The mathematical model formulation and model variables are defined in Figures 7 and 8. The model objective is to maximize agricultural profit, from crop production, during the drought by selecting annual groundwater pumping volumes. The objective function uses a specified discount rate (0, 3, 6%) to discount agricultural profit for each respective annual time step. The model is subject to constraints of DTGW policy compliance, initial and upper limit crop acreages, and non-negativities. DTGW policy compliance is determined using the relationship between groundwater pumped and DTGW described in Section 2.4. For each model simulation, a DTGW policy is specified. The model considers two crop types: (1) annual and (2) perennial. Net returns for each crop type were estimated by obtaining historical

³ To be consistent with groundwater pumped data, temporal interpolation of the well hydrograph data was performed to estimate DTGW values for the end of each year of the drought, i.e., December 31st for each year.

⁴ These DTGW value assumptions for the study area apply only to the agricultural opportunity cost curve and not the domestic well cost curve from Gailey et al. (2019).

net returns for crop sub-types from UC Cooperative Extension Cost and Return Studies and weighting by 2014 acreages (University of California Cooperative Extension, 2019). Net return for annual and perennial crops were estimated as \$180 and \$2085 per acre, respectively.⁵ Annual crop demands were estimated for 2012-2016, using the work discussed in Section 2.2, by classifying each of the 12 crop types as either annual or perennial (Tulare County Agricultural Commissioner, 2016). Actual annual and perennial crop acreages were estimated by scaling 2014 acreages using temporal scaling factors from Tulare County Agricultural Commissioner crop reports, as discussed in Section 2.2.⁶ The upper limit for annual crop type acreage was the actual annual crop type acreage for the respective year. The upper limit for perennial crop type acreage was the modeled perennial crop type acreage of the previous time step. The perennial crop type acreage upper limit accounts for the fact that once fallowed, newly planted perennials are not immediately profitable and thus are not successively fallowed and re-planted in a short time period, as opposed to annual crops which may be successively fallowed and re-planted (Sanchez, 2017). Total water available in each time step includes the estimated surface water delivered and the groundwater pumped. The total water available is proportionally allocated between the two crop types based on water available and respective crop type demands in the 2011 base year.

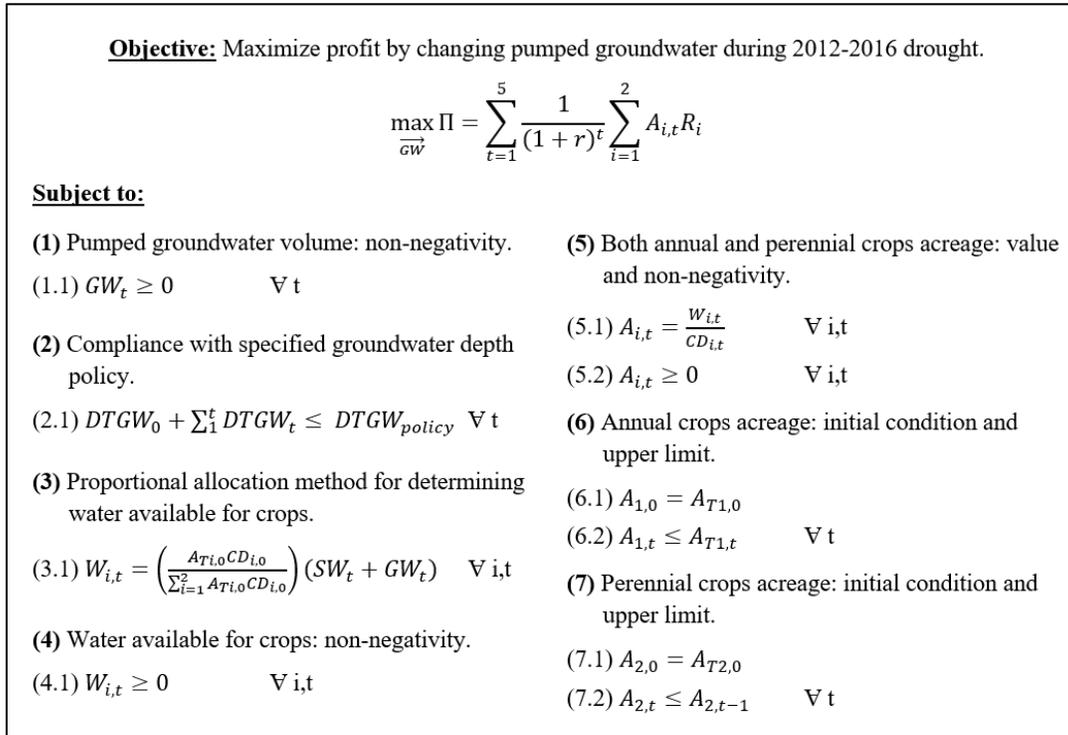


Figure 7. Agricultural-groundwater profit base model formulation

⁵ Before weighting net return by crop acreage, net returns for each crop were estimated by averaging the non-negative “net returns above total cost” during the drought. “Net returns above total cost” for each crop were obtained from UC Cooperative Extension Cost and Return Studies.

⁶ Like the method described in Section 2.2, temporal scaling factors for annual and perennial crop types, based on 2014 DWR Land Use data, were used to estimate annual and perennial acreage for 2011-2013 and 2015-2016.

t	years (1-5)	$DTGW_t$	depth to groundwater change from year $t - 1$ to t , [ft] <i>note: $DTGW_t = func^{-1}(GW_t)$</i>
i	crop (1: annual, 2: perennial)	$DTGW_{policy}$	allowed maximum total increase of DTGW, [ft]
Π	profit from year $t = 1$ to $t = 5$, [\$]	$DTGW_0$	initial DTGW, [ft]
\vec{GW}	groundwater pumped from year $t = 1$ to $t = 5$ (vector of GW_t), [AF]	$W_{i,t}$	water available for crop i in year t , [AF]
r	discount rate (0, 3, 6), [%]	$CD_{i,t}$	water demand per acre of crop i in year t , [AF/acre]
$A_{i,t}$	acreage of crop i in year t , [acre]	SW_t	surface water available in year t , [AF]
R_i	net return per acre of crop i , [\$/acre]	$A_{Ri,t}$	total available acreage of crop i in year t , [acre]

Figure 8. Agricultural-groundwater profit base model variable definitions

2.5.2. Model results processing

The model is formulated as a non-linear optimization problem. For each model run, a DTGW policy and discount rate were input and vectors of pumped groundwater volumes and total agricultural profit were output for the 2012-2016 annual time steps. To estimate agricultural opportunity cost, each modeled agricultural profit was subtracted from the maximum agricultural profit. The maximum agricultural profit was estimated from the model run of the largest DTGW policy threshold which was derived by relaxing constraint (2.1) until it was non-binding. The agricultural opportunity costs and respective DTGW policies were compiled to form the agricultural opportunity cost curve, shown in Figure 12.

2.5.3. Model 2 version details

Model 2 has the same formulation as the base model; however, model 2 allows for the planting of annual crops to replace fallowed perennial crop acreage in each time step. During the drought, fallowed annual and older perennial acreage commonly were replaced with new perennials which require less water (Sanchez, 2017). Constraint (6.2), shown in Figure 7, which states the upper limit of annual crop acreage is updated as follows:

$$(6.2) \quad A_{1,t} \leq A_{T1,t} + \sum_1^t F_t \quad \forall t$$

The new term, $\sum_1^t F_t$, represents the cumulative fallowed perennial crop acreage from year 1 to year t . The same method of results processing for the base model, discussed in Section 2.5.2, was performed for model 2. The agricultural opportunity cost curve for model 2 is shown in Figure 13.

2.5.4. Model 3 version details

Model 3 has the same formulation as model 2; however, model 3 accounts for a groundwater recovery cost for the volume of pumped groundwater that exceeds a base volume. Since SGMA requires sustainable groundwater use, e.g., lack of drawdown or overdraft, a groundwater recovery cost is added to simulate the costs associated with recovering overdraft. This addition attempts to encompass the recovery costs related to drawdown after the modeling time period. The agricultural user group is assumed responsible for the groundwater recovery cost. To implement this addition, the objective function, shown in Figure 7, is updated as follows:

$$\max_{\vec{GW}} \Pi = \sum_{t=1}^5 \frac{1}{(1+r)^t} \left(\sum_{i=1}^2 A_{i,t} R_i - C_w X_t \right)$$

The new term, $C_w X_t$, denotes the groundwater recovery cost, in units of dollars, and is subtracted from the crop profit term. Specifically, C_w , is the unit groundwater recovery cost per volume, in dollars per AF and X_t is the pumped groundwater volume exceeding the base volume in year t , in units of AF. Different values of C_w were used in the model runs, ranging from 300, 600, and 900 dollars per AF, and is denoted in Figure 14. C_w can be considered in a couple ways: an excess groundwater pumping fee, amount of dollars per AF to purchase and recharge a basin, and a proxy for future agricultural opportunity costs due to the water scarcity caused by current management decisions. These C_w values are exploratory and were not chosen from any specific basis. Model 3 results are processed the using the same method as the base model and model 2.

2.6. Task 5: Pareto curve of DTGW policies presenting agricultural and domestic costs

With the agricultural opportunity cost curves developed from the optimization models, described in Section 2.5, and the domestic well cost curve, from Gailey et al. (2019), for the range of DTGW policies, a Pareto curve of respective agricultural and domestic costs for each DTGW policy is formed. The Pareto curves for the three versions of the agricultural opportunity cost curves are respectively shown in Figures 12-14.

2.7. Task 6: Least-total cost DTGW policy

Using the economic concept of welfare, the DTGW policy that maximized welfare (minimized total cost) of the two user groups was identified for each of the three model systems (Gailey et al., 2019). Maximum welfare, as used in this study, is defined as the policy scenario in which the minimum total cost is incurred for the composite of the two user groups (Gailey et al., 2019). To estimate this DTGW policy, the total cost (agricultural and domestic cost) was calculated for each DTGW policy. The DTGW policy, to the nearest ft, that corresponded to the minimum total cost, was identified as the welfare-maximizing DTGW policy. The welfare-maximizing DTGW policies for each of the three model systems are respectively identified in Figures 12-14 and Table 2.

2.8. Assumptions and limitations

The following section outlines key assumptions and limitations of the methods used in this analysis. Most assumptions result from data and modeling simplifications. Although not performed for this study, a sensitivity analysis, which may include some structural adjustments to the model, could be used to determine the significance of assumptions.

2.8.1. Negligible drawdown effect from domestic groundwater pumping

One major assumption throughout the analysis is that domestic groundwater pumping is a negligible portion of total groundwater use and has little effect on the drawdown in the study area. Specifically, the relationship between pumped groundwater and the DTGW values throughout the drought is based solely on agricultural groundwater pumping estimates. This assumption was used because agricultural groundwater pumping has historically been significantly larger than domestic groundwater pumping (Gailey et al., 2019). Assuming each of the 5,774 domestic wells in the study area supports one household, with an annual water demand of about 0.89 AF, the estimated annual domestic water demand for the study area is about 5.1 TAF (California Department of Water Resources, 2014; Gailey et al., 2019). Compared to the average annual agricultural groundwater pumped during the drought, about 1,602

TAF, the domestic water demand is minimal.⁷ However, with this assumption, uncertainty is introduced into the analysis as the relationship between pumped groundwater and DTGW values may not sufficiently represent the effects of domestic groundwater pumping on drawdown.

2.8.2. Limitations of pumped groundwater and DTGW regression

Due to groundwater pumping and DTGW assumptions, discussed in Sections 2.4 and 2.8.1, and the choice to use a linear regression to represent the groundwater volume and drawdown relationship, the regression model does not fully encompass the complexity of the aquifer system of the study area. Since the mathematical relationship is based on data estimations of pumped groundwater and DTGW values, the regression does not account for all groundwater flow dynamics, hydrogeological processes, and other aquifer specific characteristics. However, as shown in Figure 10, the linear regression yields an R^2 value of 0.937, suggesting a satisfactory fit of the data. Additionally, pumping occurring outside the study area influences the drawdown effects inside the study area. This leads to an overestimation of drawdown from pumping within the study area.

2.8.3. Agricultural-groundwater profit optimization model limitations

The main assumptions of the agricultural-groundwater profit model are fixed crop net returns and the crop water allocation method. The crop net return values, described in Section 2.5.1, were fixed for the modeling period by weighting historical crop net return values by respective acreage during the drought. By using fixed net return values, real-world temporal fluctuations in crop yield and market price were not considered in the modeling scheme. In addition, the crop water allocation method, described in Section 2.5.1, was assumed to be proportional based on 2011 crop demands. This simplified method allowed for a consistent allocation rule; however, this method may not reflect all real-world allocation conditions and decisions.

Four limitations of the agricultural-groundwater profit model are simplified crop types, the preliminary crop acreage decision method, the assumption of full irrigation, and the limited modeling time period. The model considers only two crop types, annual and perennial crops, when allocating water and acreage. By limiting crop types, the model may not fully reflect the real-world crop varieties. In addition, as shown in Figure 7 as constraint (5.1), the primary method to determine crop acreage, is based on water allocated to the crop and respective crop demand. Although the model versions have different crop acreage constraints, the primary method remains consistent. This method is solely mathematically-driven and may not accurately reflect real-world planting decisions. Incorporated in constraints (3.1) and (5.1), crop demands are assumed to be fully satisfied, i.e., the model does not consider deficient irrigation, which may occur during drought. Lastly, the limited 5-year modeling time period, may introduce uncertainty in agricultural opportunity cost results as perennials could produce and be profitable for up to 20 years.

⁷ The average annual agricultural groundwater pumped during the drought was estimated from the 2012-2016 groundwater pumped values in Figure 9.

3. RESULTS

3.1. Estimated pumped groundwater during drought

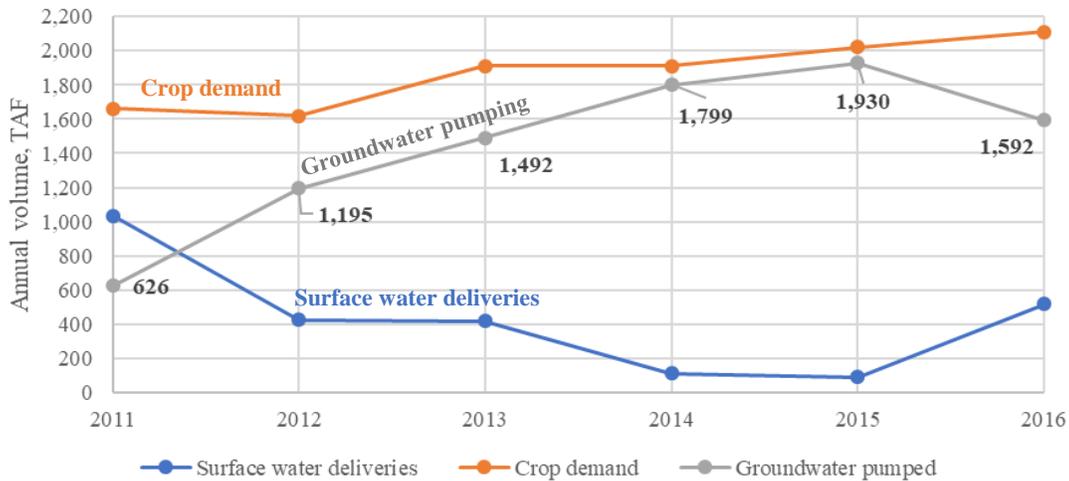


Figure 9. Groundwater pumped, crop demand, and surface water deliveries

Figure 9 shows pumped groundwater, crop demand, and surface water deliveries during the drought. Surface water deliveries decreased from pre-drought 2011, reached a minimum in 2014 and 2015, and slightly increased in 2016 at the end of the drought. Crop demand steadily increased, which may in part be attributed to crop demand hardening as a result of increased perennial planting. As shown in Figure 5, perennial and total crop acreage increased, in general, in the study area during the drought. So groundwater pumping increased throughout the drought and reached a maximum in 2014 and 2015. The estimations and trends of pumped groundwater, crop demand, and surface water appear to reflect actual drought conditions (Gailey et al., 2019).

3.2. DTGW and pumped groundwater relationship during drought

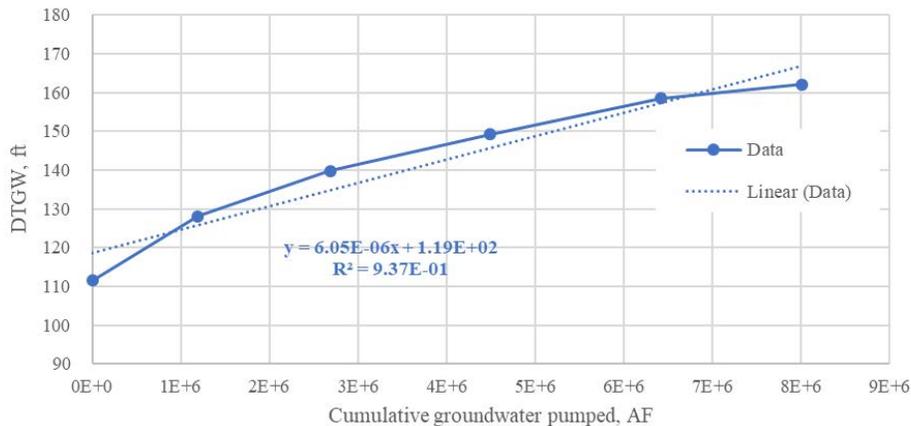


Figure 10. DTGW versus cumulative groundwater pumped data and regression

Figure 10 shows the relationship between cumulative groundwater pumped and DTGW values from 2011 to 2016. The relationship is represented by the linear regression shown in Figure 10. As expected, with increasing cumulative groundwater pumping, DTGW values increase. The slope of the regression, 6.05×10^{-6} , represents the DTGW decrease per unit of cumulative groundwater pumped. This slope was

used in the agricultural-groundwater profit model to provide a relationship between groundwater pumped and subsequent DTGW decrease to determine DTGW policy compliance.

3.3. Agricultural cost curves and Pareto curves of DTGW policies

The spatial distribution of domestic wells and reported service outages during the drought appear in Figure 11 from Gailey (2018). Figures 12-14 show the agricultural cost curves, for each model version, respectively, the domestic well cost curve from Gailey et al. (2019), total cost curves, and resulting Pareto curves. The cost curves are presented for DTGW policies ranging from 112 ft to 200 ft. The initial DTGW value was 112 ft and the actual maximum DTGW during the drought was 162 ft. Each model system used a discount rate of 3% excluding model 2 which used three different discount rates, as shown in Figure 13. As noted in the figures, the agricultural and domestic costs are presented in units of billions and millions of dollars, respectively.

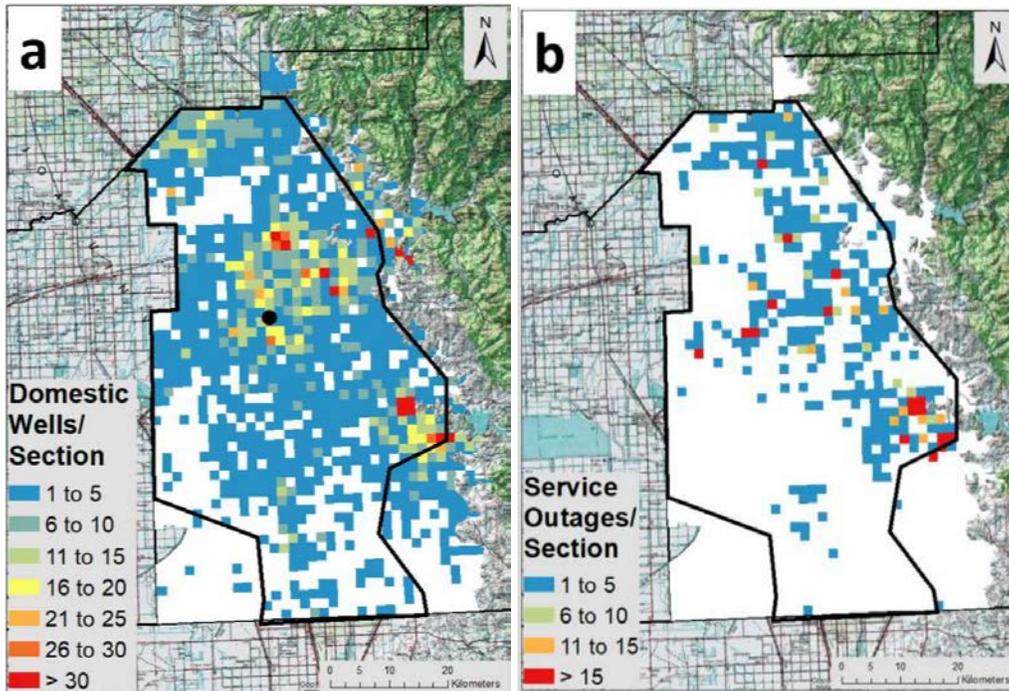


Figure 11. (a) Domestic wells and (b) service outages during drought (Gailey, 2018)

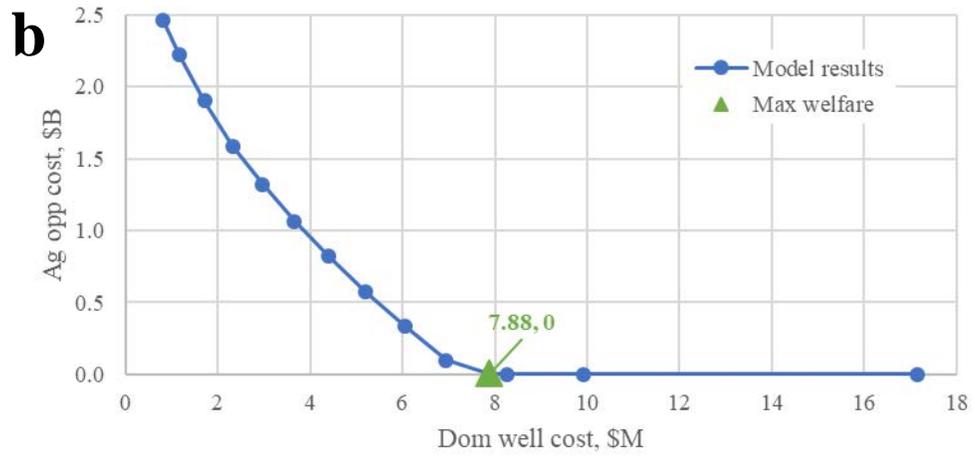
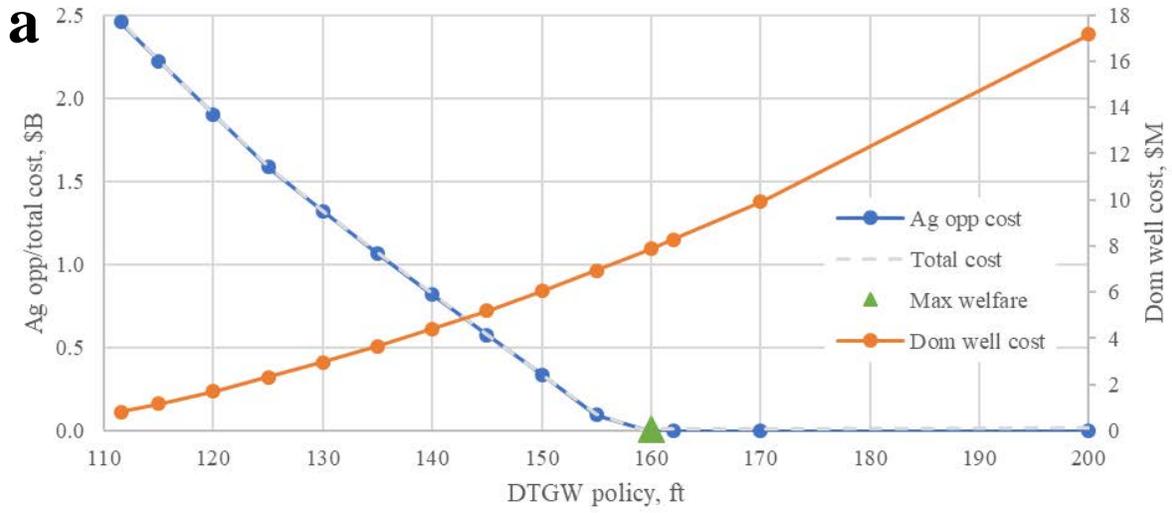


Figure 12. (a) Base model agricultural cost curve (\$B), domestic well cost curve (\$M), total cost (\$B), and (b) Pareto curve with $r = 3\%$

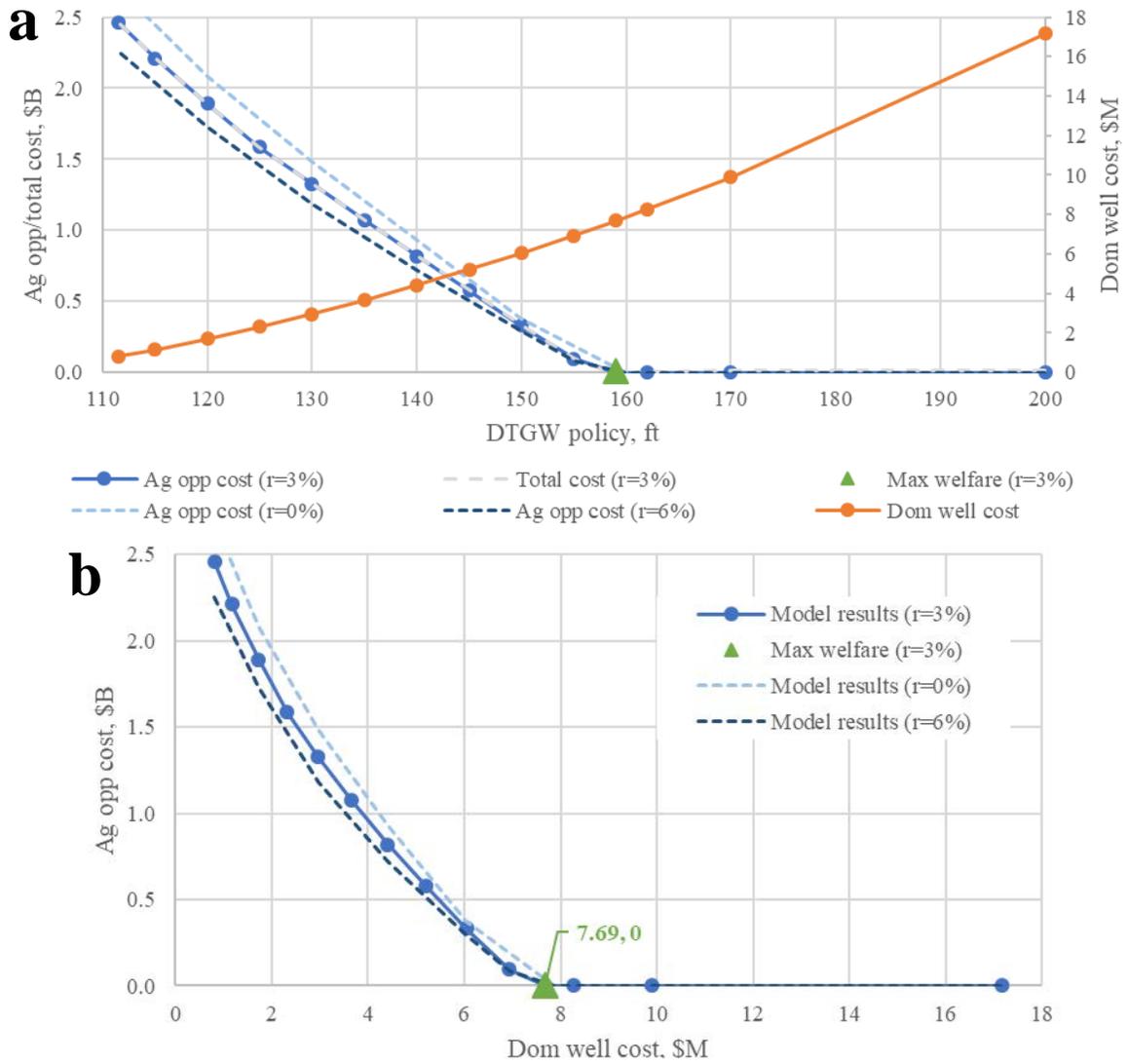


Figure 13. (a) Model 2 agricultural cost curve (\$B), domestic well cost curve (\$M), total cost (\$B), and (b) Pareto curve with varying r values

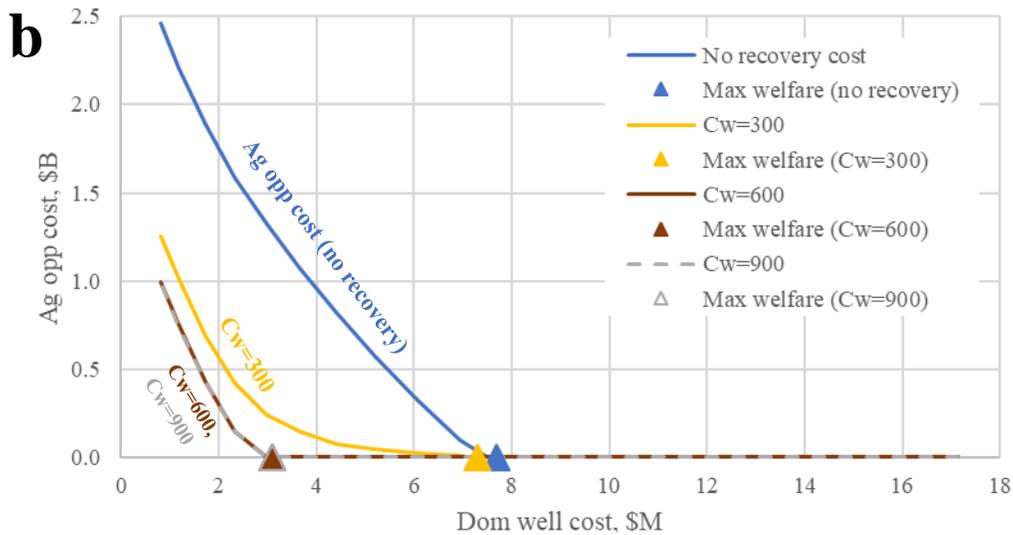
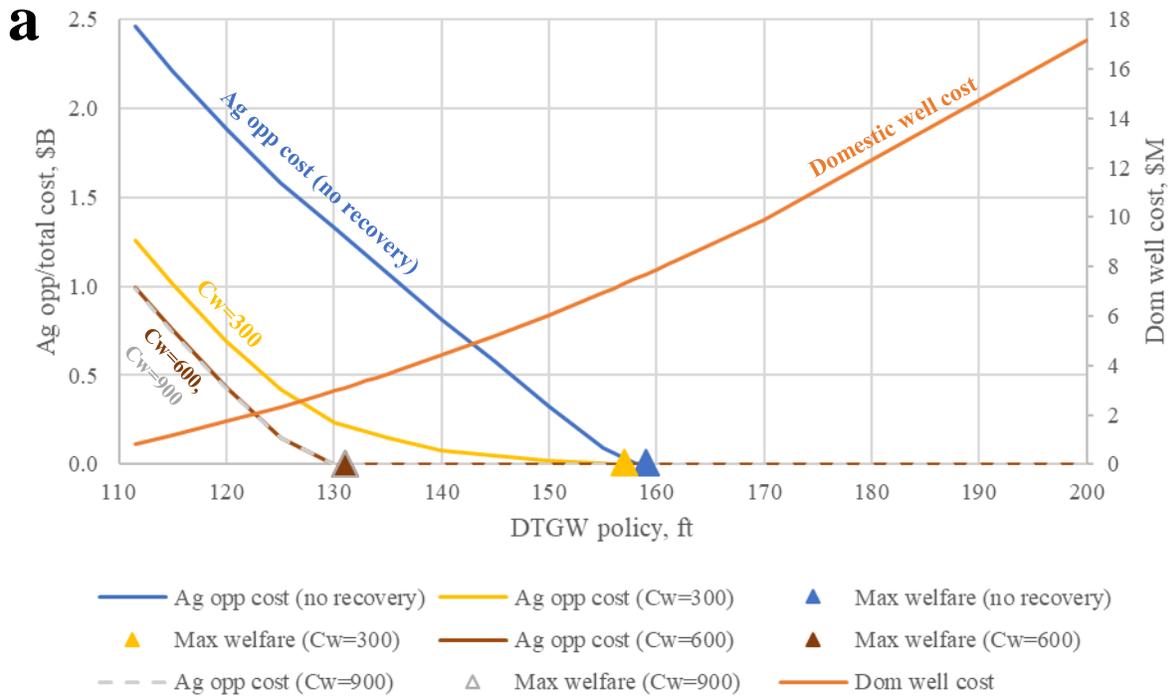


Figure 14. (a) Model 3 agricultural cost curve (\$B), domestic well cost curve (\$M), total cost (\$B), and (b) Pareto curve with $r = 3\%$ and varying C_w values

3.3.1. Agricultural cost curves and total cost curves

For all model versions, less allowable drought drawdown increases agricultural costs and reduces domestic well costs. Agricultural costs increase because reduced groundwater availability reduces crop production and profits. Domestic well costs decrease because the DTGW increase is minimal and thus supply shortages and accompanying costs from groundwater drawdown are less (Gailey et al., 2019). Conversely, with greater DTGW policy values, agricultural costs decrease and domestic well costs increase. For all model versions, the total cost curves are highly influenced by the agricultural costs due to their larger order of magnitude than domestic well costs.

Comparing results from the base model to model 2, the agricultural cost curve, and subsequently the total cost curve, begin to shift to the left, i.e., slightly less agricultural cost is generated for lesser DTGW policy values. This shift occurs because model 2 allows for planting annual crops to replace fallowed perennial acreage which provides an opportunity to increase agricultural profit. However, the base model and model 2 results are similar. As shown in Figure 13, model 2 results remain consistent with changing discount rates which suggests that the model is not very sensitive to the discount rate.

Figure 14 shows the agricultural and total costs curves from model 3, which incorporates a groundwater recovery cost. Agricultural cost curves, with varying unit groundwater recovery costs ($C_w = 300, 600, 900$ dollars per AF), are plotted along with respective total cost curves. In addition, the agricultural cost from model 2 is included as a base case in which no groundwater level recovery (and cost) is required, i.e., $C_w = 0$. Recall, the groundwater recovery cost applies solely to agricultural users. Although previous model versions yielded similar results, model 3 results change significantly. The added recovery cost reduces maximum agricultural profit as C_w increases, shown in Table 2. With the added groundwater recovery costs, the agricultural cost curves reach thresholds in which the recovery costs to pump more groundwater are greater than the profit gained with the extra groundwater pumped. These model results suggest that with SGMA implementation, e.g., penalty for excess groundwater pumping, drawdown and domestic well costs are reduced.

3.3.2. Pareto curves

Pareto curves for each model are presented in Figures 12-14. The Pareto curves plot corresponding agricultural and domestic costs for each respective DTGW policy. As mentioned previously, the agricultural and domestic costs are in units of billions and millions of dollars, respectively. The Pareto curves were utilized to determine the welfare-maximizing DTGW policies, discussed in Section 3.4.

3.4. Welfare-maximizing DTGW policies from Pareto curves

The welfare-maximizing DTGW policies, total cost, cost breakdown between users, maximum agricultural profit, and total groundwater recovery cost for each model system are shown in Table 2. The unregulated case contains results from the base model for a DTGW policy of 162 ft, which was the actual maximum DTGW value during the drought.

Table 2. Welfare-maximizing DTGW policies for the three model systems with $r = 3\%$

	<i>Unregulated (uses base model)</i>	<i>Base model</i>	<i>Model 2</i>	<i>Model 3 ($C_w=0$)</i>	<i>Model 3 ($C_w=300$)</i>	<i>Model 3 ($C_w=600$)</i>	<i>Model 3 ($C_w=900$)</i>
<i>DTGW policy, ft</i>	162	160	159	159	157	131	131
<i>Total cost, \$M</i>	8.27	7.88	7.69	7.69	7.31	3.10	3.10
<i>Domestic cost, \$M</i>	8.27	7.88	7.69	7.69	7.31	3.10	3.10
<i>Max. agricultural profit, \$B</i>	2.85	2.85	2.85	2.85	1.65	1.38	1.38
<i>Ag. opp. cost, \$M</i>	0	0	0	0	0	0	0
<i>Total GW recovery cost, \$M</i>	N/A	N/A	N/A	0	1,291	0.17	7.1×10^{-4}

<i>Total ag. GW pumped, TAF</i>	8,343	8,013	7,847	7,847	7,225	3,218	3,132
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The welfare-maximizing DTGW policy is estimated by identifying the DTGW policy that yields the minimum total cost for the two users. The welfare-maximizing DTGW policies are identified on the total cost curves and Pareto curves of the three model systems in Figures 12-14. As discussed previously, the total cost curve is highly influenced by the agricultural cost curve due to the large order of magnitude difference as compared to the domestic cost curve. Subsequently, the welfare-maximizing DTGW policy heavily weights minimizing agricultural cost which can be seen in the total cost breakdown in Table 2 (agricultural opportunity cost equals \$0). In addition, a major cost to agricultural users during drought is the energy cost for groundwater pumping. Embedded conceptually within the agricultural-groundwater profit model, the energy cost is considerable but not substantial enough to reduce groundwater use.

When comparing the welfare-maximizing DTGW policies for the base model and model 2, the DTGW policy for model 2 is reduced. This reduction in welfare-maximizing DTGW policies in successive models comes from greater flexibility in crop planting which yield greater profit and possible reduction in groundwater usage. The results for the base model and model 2 are similar; however, the welfare-maximizing DTGW policy value changes significantly with model 3. As C_w increases, the welfare-maximizing DTGW policy decreases until a minimum of 131 ft for both C_w values of 600 and 900 dollars per AF. The matching results, for the C_w values of 600 and 900 dollars per AF, suggest that 131 ft is the threshold at which the profit gained from pumping more groundwater does not outweigh the recovery costs incurred. Allowing a sizable amount of drought drawdown is tremendously valuable for agriculture, even if that drawdown must be recovered at a high cost after the drought. The total groundwater recovery costs significantly decrease with increasing C_w due to the decrease in groundwater pumping, i.e., the decrease in optimal DTGW policy. Consistent with previous observations, the total agricultural groundwater pumped decreases with the decrease in optimal DTGW policy. The total agricultural groundwater pumped begins to plateau for C_w values of 600 and 900 dollars per AF, which reflects the suggested DTGW threshold of 131 ft. For all model systems, the welfare-maximizing DTGW policies are less than the unregulated 162 ft DTGW observed during the drought which aligns with the prediction stated in Gailey et al. (2019).

The difference in orders of magnitudes for the two users creates a mathematical limitation for the welfare-maximization approach. In general, a welfare maximizing DTGW policy minimizes the total cost of the system (Gailey et al., 2019). This occurs when the absolute values of the slopes of the agricultural and domestic cost curves are equal (equal marginal costs for agricultural and domestic well users).⁸ Inspection of Figures 12a, 13a, and 14a, recalling the different orders of magnitudes of the cost curves, reveals that the slopes are never equal. Equivalently, the agricultural opportunity cost from shorting a unit of water is far greater than the domestic well costs incurred from agricultural users using that unit of water. An alternative economic concept to account for the difference in magnitudes is discussed in Section 4.

4. DISCUSSION

The following section discusses influences of market forces on groundwater pumping and crop planting decisions, an alternative economic concept that allocates total cost between the two user groups, and insights of groundwater usage with SGMA implementation.

⁸ Using the first-order optimization criterion, $\frac{d(\text{total cost})}{d(\text{DTGW}_{\text{policy}})} = 0$. Defining total cost as the sum of agricultural opportunity and domestic costs and rearranging yields: $\left| \frac{d(\text{ag opp cost})}{d(\text{DTGW}_{\text{policy}})} \right| = \left| -\frac{d(\text{dom cost})}{d(\text{DTGW}_{\text{policy}})} \right|$ which is never equal.

4.1. Market forces in groundwater pumping and crop planting decisions

Agricultural market forces heavily influence groundwater pumping and subsequent crop decisions (Lund et al., 2018). In a globalized economy, such as in California, agricultural prices and revenue are driven by market forces largely unaffected by a local drought (Lund et al., 2018). These global market forces may motivate groundwater pumping and crop decisions that do not reflect reduced groundwater use and crop planting that one may predict with drought (Lund et al., 2018). As shown in Table 1 and Figure 5, total crop acreage and crop water demand increased during the drought. Although the rate in annual volume of groundwater pumped slowed, the annual volume of groundwater pumped continued to increase during the drought, as shown in Figure 9. Market forces that drive prices and subsequent revenues were likely influential in these groundwater use and crop planting decisions. As discussed in Section 2.8.3, one limitation of the agricultural-groundwater profit model is the lack of changing crop net return values with time. Due to this limitation, the influence of market forces observed during the actual drought are not fully reflected in the model.

4.2. Negotiated cost allocations between agricultural and domestic user groups

As mentioned in Section 3.3.1, the total cost curves and subsequent welfare-maximizing DTGW policies are heavily weighted to avoid agricultural losses which can greatly exceed domestic well user costs. As shown in Table 2, the unregulated case and all welfare-maximizing policies have almost no agricultural costs. The least cost method was used to identify the welfare-maximizing policy (Gailey et al., 2019). However, negotiated cost allocations between user groups may be more appropriate (Gailey et al., 2019).

Since domestic costs are much less than agricultural costs, agricultural users could compensate domestic users at a negotiated percentage of domestic costs (Gailey et al., 2019). For example, using the Pareto curve from the model 2 system, a 1:1 line is extended from the maximum-welfare DTGW policy to the agricultural costs axis to represent 0-100% compensation, respectively, in Figure 15. The bounds on the Pareto curve plot axes are reduced to better view the negotiated cost allocation line.

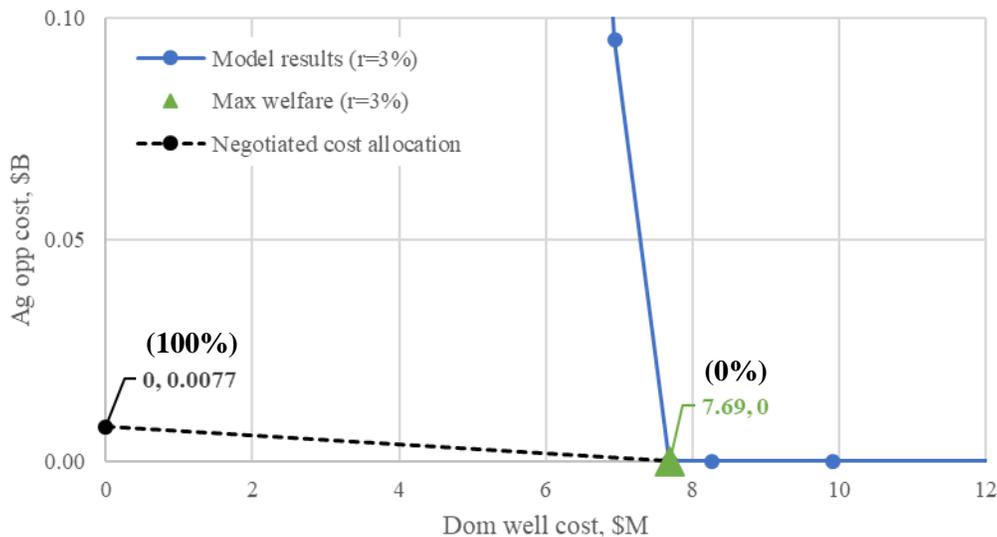


Figure 15. Negotiated cost allocation of welfare-maximizing policy for model 2 system

The cost allocation line is referred to as “negotiated” because the percentage of compensation provided by agricultural users may be a matter of negotiation involving user groups and regulatory authorities. Consistent with Gailey et al. (2019), one potential method to estimate a socially-equitable cost allocation is to model the groundwater drawdown caused by agricultural and domestic users and allocate costs

proportionally to drawdown impacts, respectively. One method to implement cost allocation is to create a compensation fund with revenues from excess pumping fees.

4.3. Insights of groundwater usage with SGMA implementation

SGMA implementation will require management to achieve groundwater sustainability. Model 3, which includes a groundwater drawdown recovery cost, provides insights on groundwater use and drawdown for this potential management strategy. As shown in Table 2, higher values of C_w reduce both groundwater volume pumped and drawdown. These results, while location-specific and using a particular management strategy, illustrate potentially successful outcomes of SGMA implementation for achieving sustainability and reducing drought impacts on domestic well users.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

This study produced three major conclusions:

- (1) Additional agricultural groundwater pumping, to compensate for reduced surface water supplies, greatly impacted domestic well users during the drought. With unregulated pumping yielding a DTGW of 162 ft in the study area, the economic impact on domestic well users largely outweighed that on agricultural users.
- (2) Modeled agricultural costs avoided greatly exceeds domestic well costs during drought. This presents an opportunity for compensation of domestic well costs from agricultural users.
- (3) With SGMA policy implementation to achieve sustainability, requiring groundwater recovery to pre-drought levels (avoiding overdraft), will provide long-term groundwater availability to all system users. Groundwater recovery can be accomplished by reducing groundwater pumping to avoid excess pumping penalties, purchasing water for basin recharge, and fallowing of lower-valued crops.

The analysis presented in this study can help in SGMA policy planning for GSAs and regulatory authorities. The study provides a modeling example in which the economic impacts of proposed policies on competing groundwater users are quantified. These modeling results can supplement discussions of proposed policies. As discussed previously, various definitions of sustainability and different sustainability criteria may be applicable. Although this study chose DTGW policies as the sustainability metric, based on earlier work (Gailey et al., 2019), different criteria could be explored in the modeling scheme.

This study acknowledges that users in a groundwater system often have somewhat different needs that must be recognized and balanced when considering potential policies. Likewise, this study introduces the discussion about different approaches for selecting policies, i.e., welfare-maximizing, profit-maximizing, positive economic, social equity, etc. Nonetheless, SGMA implementation policies will bring change to long-established and complex systems.

5.2. Future work

Future work, to expand this study, largely includes additional model complexities and applications of different approaches for selecting policies.

5.2.1. Additional model complexities

As discussed previously, the agricultural-groundwater profit model uses a linear regression of groundwater pumped volumes and DTGW data as a relationship between groundwater pumped and subsequent drawdown. A more accurate relationship could be developed that includes aquifer specific parameters and groundwater flow principles. Additional model complexities could be incorporated such

as further crop type options and planting decisions, more accurate land use data, and temporally changing revenue data. More details regarding perennial fallowing and the impacts on future profit could be added along with distributions of perennial plant ages. Moreover, this study only considers agricultural and domestic user groups; however, additional users and stakeholders, such as the environment and industry, could be considered.

5.2.2. Different approaches for selecting policies

While the study focused on the economic concept of welfare-maximizing to select optimal policies, additional approaches, such as profit-maximizing and social equity, could be simulated. As proposed previously (Gailey et al., 2019), negotiated cost allocations between users may provide additional insights for selecting optimal policies. In addition, with further modeling of user-created drawdown, specific percentages of cost allocations may be suggested.

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