Decision-Scaling Analysis of California's SGMA Legislation

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Objectives: Water related supply issues due to climate change are a worsening issue for water users and irrigation districts across the world, most notably in drought-susceptible areas such as California's Central Valley region. The objective of this study is to take into consideration climate-informed predictions for future rainfall in the Central Valley to outline the various options and water-related concerns that land holders and agricultural irrigation districts will have to face in the future. This type of decision-scaling analysis will provide an economic approach in dealing with the lasting effects of climate change well into the future. This approach is not a physical model in which a groundwater system is designed, rather a the creation of potential first-order human changes to the groundwater system that could be easily monitored and credited in the already existing groundwater system.

Methods: To create predicted streamflow data, the region's historical data will be altered under a number of conditions to resemble climate change and SGMA legislation that affects groundwater supplies, including altering the rainfall time series so that runoff (coming from the Sierra Nevada snowpack) will arrive at different times of the year at faster rates and in greater concentration. This, and other climate-informed prediction patterns, will be investigated and related to the general outcomes of each decision analyzed in the study.

Results: The results of this study demonstrate that in response to the simulated climate change conditions, net groundwater change responds by decreasing. Alternatively, comparing SGMA legislation with and without the effects of climate change demonstrates predicted decreases of groundwater availability with climate change considered.

Conclusions: The results of this study effectively demonstrate that climate-informed net groundwater changes will translate to worse effects for irrigation districts and farmers in the area. Additionally, the SGMA legislation, which reduces pumping, combined with climate change predicts adverse effects for farmers and irrigation districts. Further research is needed to resolve the extent of these effects.

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1. Introduction

Agricultural production in the arid Central Valley region of California, is dependent on applied irrigation water provided by Sierra Nevada snowpack and large groundwater aquifers. This region's water supply is integrated in a complex surface water distribution network, jointly owned by private interests, the California Department of Water Resources (DWR) and the federal Bureau of Reclamation (USBR). Together, they operate a system designed to store and transport snowmelt to agricultural regions as well as larger cities such as Los Angeles and San Diego. Recent trends towards more valuable permanent crops like almonds and pistachios, have increased the economic productivity of agriculture in the Central Valley (Lund et. al, 2014). During times of drought, most notably the recent drought from 2012-2016, California's third-worst in terms of groundwater decline in 106 years, farmers supply water through groundwater pumping, a process that has until recently for some basins been subject to only limited regulation, resulting in unsustainable, and in some cases, irreversible, reductions in groundwater storage (Sears et. al, 2017).

Commented [HZ1]: Drought is, for all intents and purposes, over now

Commented [HZ2]: Be careful here – not saying you're wrong, but there is not one clear way of judging the magnitude of a drought. It would be good to say what metric it was the third-worst in (groundwater decline? Flow in the Sacramento River? Peak snowpack?)

Commented [HZ3]: Some basins were regulated before SGMA

1.1 California's Sustainable Groundwater Management Act

In response to this, the state of California has passed the Sustainable Groundwater Management Act (SGMA) in September of 2014, requiring farmers and other water users in groundwater basins to form Groundwater Sustainability Agencies to develop and implement Groundwater Sustainability Plans (GSP) that ensure groundwater management practices are sustainable in the future. Though management of the GSPs will be local, they can have wider regional impacts due to effects on stream-aquifer interactions and border surface flows (Dogrul et. al, 2016).

It is widely accepted, even among farmers, that the SGMA legislation will result in less available irrigation water, and therefore less agricultural activity, over time. However, it is not universally accepted how much irrigation water availability will be reduced, and what impact changing climate and hydrology will have on this reduction (Null et. al, 2010). The extent of this decrease is still debated. A large challenge for hydrologic and agricultural based communities is analyzing the effects of climate change on the availability of regional water supplies and irrigated agricultural land (Walthall et al., 2013).

Commented [HZ4]: You want to keep this sentence simple because it's the main 'motivation' for your work. You can just say – its not universally accepted how much irrigation water availability will be reduced, and what impact changing climate and hydrology will have on this reduction. No need to specify individual watersheds either, the CA system is extremely interconnected, and changing conditions in one watershed could impact faraway users (although your analysis is limited to one watershed, water from that reservoir is exported to users in other watershed too.

1.2 The Effect of Climate Change on Snowmelt

The potential for climate change adds uncertainty to the magnitude and timing of flows in snowmelt-dominated systems. Seasonal snowpack and glacier water sources are responsible for providing water supplies to greater than one sixth of the overall global population (Barnett et. al, 2005). The State of California is particularly dependent on snowmelt water resources, where snowpack releases provide much of the water supply during seasons with minimal rainfall (Mote et al., 2005). It is widely accepted that warming temperatures will affect the surface water availability in the Western United States by causing greater amounts of precipitation to fall as rain instead of snow, decreasing the thickness and length of snowfall (Pavelsky et. al, 2011; Aguado et al., 1992; Dettinger and Cayan, 1995; Stewart et al., 2003) and by increasing the rate at which the remaining snowpack will melt.

Increased levels of rainfall means that more runoff will be present during the winter 'rain flood' season, which ranges from November through March. Earlier and faster snowmelt will force the runoff during the snowmelt season, from April to July, to be more concentrated and more prone to flooding. During floods, not all of the water can be productively used for irrigation because of limits to the storage and conveyance systems. If warming temperatures increase the frequency and magnitude of rain floods at the expense of more gradual snowmelt, less overall surface water will be available for irrigation. In the past, irrigators were able to make up for reductions in surface water with groundwater pumping, but SGMA legislation may prevent this in the future.

1.3 California's Central Valley and Millerton Dam

Groundwater usage in the California Central Valley (CV) is widespread, with an estimated total consumptive use by CV users to be ~20 m^3 from the period 2003-2010, in a study using water balance modeling and Gravity Recovery and Climate Experiment (GRACE) satellite data (Famiglietti, 2014). This same study demonstrated that the CV has faced increasing groundwater depletion since 2010, all while having little regional organization in groundwater use monitoring and groundwater storage (Famiglietti et al., 2011). While many studies have created GRACE-based estimates of groundwater depletion, the technology features numerous uncertainties including the limited effective footprint of GRACE, and even so, fewer studies have acknowledged the impact of California's 2012-2016 drought on groundwater availability (Famiglietti et al., 2011;Scanlon et al., 2012; Famiglietti, 2014; Chen et al., 2016; Xiao et al., 2017).

2. Methods

In terms of a more directly financial approach, there are a few methodologies concerning climate change predictions in terms of decision-scaling analyses to predict risk assessment. Essentially, by creating a decision-making framework that links climate-informed water availability predictions with the scaling of climate information required for particular decisions, we can analyze predicted conditions of groundwater levels, for example, that will be beneficiary to water users in the CV (Brown et al., 2012). Decision scaling attempts to discuss downscaling methods, or local-scale weather and climatic surface level Global Climate Models, and their relationships to decisions of interest. Decision scaling is a "bottom-up" risk assessment approach that begins with metrics defined for stakeholders that separate degrees of acceptable system performances (Bussi, et. Al, 2016).

In decision theory, the decision threshold is calculated as the point in which the optimal decision changes as a function of a set of state variables. Thus by assigning the climate conditions as the state variables, the climate state itself can be identified as the range of climate variables that satisfy a certain decision scenario.

After assigning decision thresholds, climate information is used as an indicator of probabilities of attaining these decision-influencing climate states. There are many benefits to estimating probabilities for broad ranges of climate conditions rather than singular climate conditions at a time. According to a study by Mastandrea et al. (2010), decisions which optimize the most likely climate scenarios often produce undesirable outcomes in alternative climate states; these tradeoffs play an important role in considering decisions under great uncertainty. The study also mentions that the lack of specificity of climate information required is greatly reduced, thus cutting back on opportunities for error and making the data more reliable as a whole. The second benefit to widening the range of climate conditions for a wider group is that climate thresholds which would cause a desired change in action can be identifies; that is, it can be determined how drastically a climate state must change in order to effectively change how we respond (Brown et al., 2012). This consideration is significant, as it is useful in not only informing decisions for irrigators but also provides climate scientists and hydrologists with relevant targets to look for in their analyses. The added relevance of this step also makes it easier to analyze how likely one decision state will be over another one.

Commented [HZ5]: This belongs in the methods section. At the end of your introduction here, you need a few sentences about how the issues you've discussed above are related specifically to Millerton Dam and imports from the Friant-Kern Canal. I've written down a few thoughts – don't use them word-for-word but

Commented [HZ6]: You can put the decision-scaling description and citations here

Commented [HZ7]: Lead with the most important reason for evaluating a problem over a broad range of climates – decisions which optimize the 'most likely' climate state often produce undesirable outcomes in alternative climate states – understanding these tradeoffs is crucial to making good decisions under uncertainty. Although they can be good secondary reasons, 'making the analysis easier' is never a good first reason to do something

Commented [HZ8]: This part isn't super clear – what does 'makes the process more relevant to the approach' mean? Is this something like, 'by linking a climate state to a set of decision variables, we can identify the climatic thresholds which would cause a desired change in action'? This is an important point to make, so it should be clear –one of the benefits of decision scaling is that we can identify 'how bad things have to get' in order for it to change how we would respond. This is useful not only for informing our (irrigators) decisions, but also provides climate scientists and hydrologists with relevant 'targets' to look for in their analysis.

2.1 Identifying Thresholds

The first step is to effectively identify climate thresholds, meaning those that cause risks and/or favor a particular decision state over another. In traditional cases, problematic climate states would be reviewed from the history of a location and discussed with stakeholders. The historical record is typically the starting point in identifying how climate has impacted a particular system (Wilby and Dessai, 2010).

Performance indicators must also be identified, which when exceeded mean that the system is in need of adaptive change, or an alternative decision state. In addition, the expected benefit-cost-analysis can also be used to create or specify decision thresholds, as in a study of the Great Lakes by Brown et al. (2011), in which various thresholds for acceptable lake levels were created for stakeholders, only of which some were based on estimated economic effects.

2.2 Risk Discovery

The next step in the process is to characterize the different climate states that have their own defined decision state. This begins with either using a significantly large stochastic series of data, such as a streamflow data series, or through parametrically varying existing climate data to create various samples of different climate possibilities. The main takeaway from this step is that enough climate scenarios must be generated to be paired with their related decision states; at this point, the relative probability of each climate scenario is not important, instead only the variety of scenarios that are available for consideration.

2.3 Defining Climate States Using the Decision Model

In the decision scaling framework, a climate response function is used to find the relationship between the climate state and system performance. Here we use a model of

Millerton reservoir/Friant Kern Canal operations to understand the relationship between reservoir inflow and surface water imports to the Tulare Basin.

The decision analytic framework is used to analyze climate spaces into conditions that satisfy the most efficient decision over those climate states. Another method that can be used is to instead define states according to a decision that is held above a range of included climate states, as used in a weather forecast value analysis and a seasonal forecast value use by Brown in 2004 (Brown, 2004).

Analyzing climate spaces into various states can be beneficial in that for stakeholders, decision-makers, or analysts, the specific climate conditions that pose a particular risk or favor can be more clearly identified.

2.4 Using Climate Information to Influence Decision-Making

The Tulare Basin in California's Central Valley takes advantage of surface water imports to reduce reliance on groundwater for irrigation. One of the largest import projects in the Basin is the Central Valley Project's Friant Division, which uses Millerton Dam and the Friant-Kern Canal to import up to 2.2 million acre-feet of surface water per year to agricultural contractors in region. These surface water deliveries are highly variable and subject to snowpack conditions in the headwaters of the San Joaquin River. The availability of water from the Friant-Kern Canal will be an important factor in determining how irrigators in the Tulare Basin adapt to SGMA legislation, but hydrologic uncertainty related to climate change poses challenges to the planning process.

Here, we present a 'bottom-up' decision scaling approach that attempts to quantify the irrigator actions (fallowing, groundwater recharge) that will need to be taken to meet valley-wide objectives under a range of hydrologic and regulatory conditions. This approach is not a physical model in which a groundwater system is designed, rather a the creation of potential first-order human changes to the groundwater system that could be easily monitored and credited in the already existing groundwater system. It is also important to recognize that groundwater recharge is not being created; ‘natural’ recharge is available from rain and river water that interacts with the aquifer and there are underground flows in the aquifer that can also move groundwater ‘sideways’.

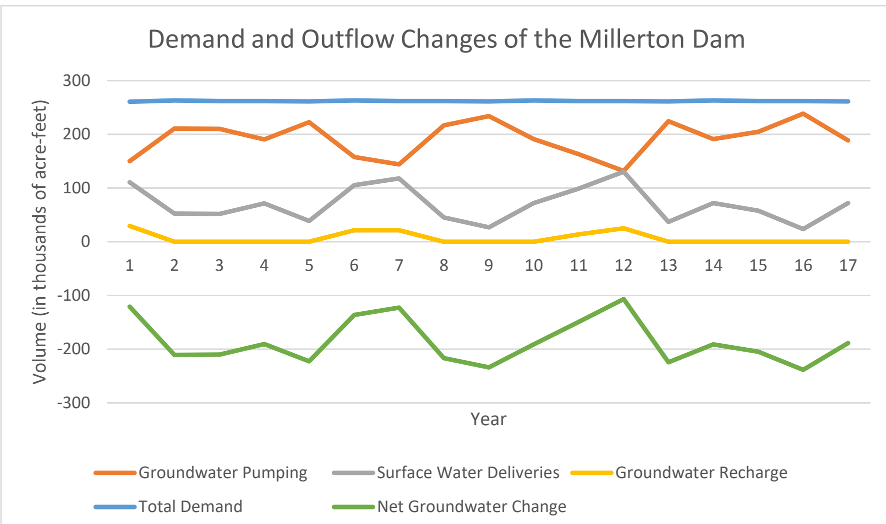

Figure 1: Time series of base streamflow data, broken into groundwater pumping, surface water deliveries, groundwater recharge, total demand and net groundwater change in thousands of acre-feet

The amount of water available for irrigation is found by applying a water balance model of Millerton Lake, which ultimately helps determine how much irrigation water farmers in the region will receive, how much groundwater pumping these farmers will engage in and how much groundwater recharge (excess water supplies stored in recharge pond) is possible. The main outflows for the Millerton Dam consist of environmental releases, flood control regulations, and irrigation, which is dependent on the former two. As part of new legislation known as the new

San Joaquin Restoration Settlement, Millerton Lake must make releases in order to satisfy minimum stream releases, ‘restoring’ the flow downstream in the San Joaquin River, where it has historically been more arid. The sizes of releases are dependent on how much water is expected to be available at the reservoir throughout the year, calculated with the summation of total inflows (this is known as a Perfect Forecast, meaning that subsequent projections are based on a known expectation of available water). In addition, flood control regulations enforce that from mid-October to early March, the lake must maintain available storage space for any flood water that may runoff the surrounding mountains, particularly during a fall or winter rain storm. This requirement in turn limits the amount of irrigation water that can remain available. The flood requirements serve as an important metric to analyze in the case when more precipitation comes in the form as rainwater instead of snow, increasing the size of floods and leaving less runoff for later in the year when snow melts (which is a gradual process, favoring capture and water use for irrigation).

Irrigation requests are additionally considered through requests that the Irrigation District files at the beginning of each year, based on crop water demands of the farmers within the district. While the reservoir may not have the availability to satisfy all irrigation demands, farmers will receive a percentage of their demands. Groundwater pumping occurs when the deliveries from Millerton Lake are not enough to satisfy the total irrigation requirements of the farmers; it is represented by is the difference between irrigation demands and deliveries. Finally, after the water balance occurs, spillage must be accounted for in the case that inflows to the dam surpass available storage or are encroaching on the ‘flood pool’, which needs to be empty during flood seasons. Legislation known as Article 215 Water additionally allows this excess spillage to be utilized by irrigation districts through storage of excess water in groundwater recharge ponds.

Recharge pond storage is calculated subtracting the amount of infiltrated water from the previous days' storage, when the reservoir is at full capacity. It is also important to note that net groundwater changes are calculated by the difference between groundwater pumping and groundwater recharge.

3. Analysis and Results

3.1 Modeling Climate Change's Effect on Net Groundwater Change

Now, taking into consideration the potential effects of climate on groundwater availability, many studies, as previously mentioned, have pointed to two possible effects: that more precipitation will arrive in the form of rain rather than snow during the winter 'rain flood' season, which ranges from November through March, and that earlier and faster snowmelt will cause more inflows to the Millerton Dam prematurely, forcing the runoff during the snowmelt season, from April to July, to be more concentrated and more prone to flooding. These two state variables, named Climate State 1 and Climate State 2 respectively, are investigated in the water balance model, accounting for different ranges of water flow shifting from spring to winter, and for different ranges of water flow shifting from summer to late spring. Average net groundwater change is the most significant metric to follow in determining changes in groundwater availability. Using a base data set of 17 years of streamflow data for the Millerton Dam, staggered levels of the afore mentioned water flow shifts for each of the 2 state variables were simulated for their effects on average net groundwater change; for each shift that defined a State Variable 1 scenario, there exist 5 shifts that define a State Variable 2 scenario.

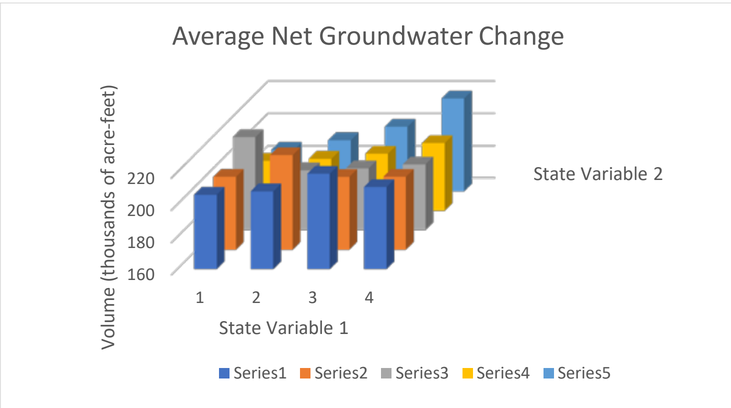

Figure 2 Average net groundwater changes for 20 different climate scenarios (each denoted by one bar). Increasing values of state variable 1 indicate increasing water flow shifts from spring to winter, while increasing series of state variable2 indicate earlier flow of snowpack from summer to late spring months.

The above graph demonstrates average net groundwater changes assuming a base recharge pond area size to be .4 thousand acres and monthly irrigation demands to be current as set by the Irrigation District. However, in order to analyze the effects of changing these two variables, increasing recharge area and reducing irrigation demands, the average net groundwater change is once again investigated. The most extreme (yet still within a reasonable range) case evaluated, in which recharge pond area size is multiplied 10 fold and average monthly irrigation demands are reduced by 30% is considered. The increments of state variables are held the same. Figure 3 shows significantly decreased values of groundwater change in

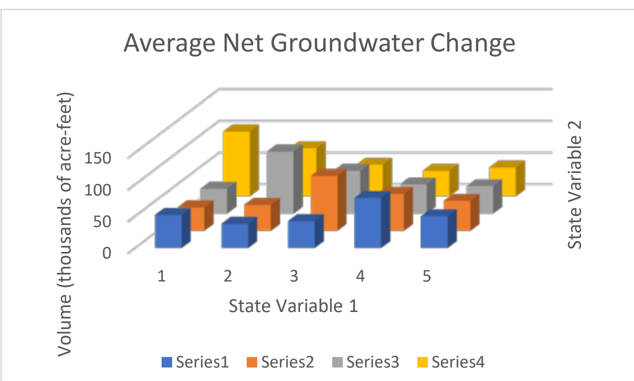

Figure 3 Average net groundwater changes for 20 different climate scenarios (each denoted by one bar). Increasing values of state variable 1 indicate increasing water flow shifts from spring to winter. The recharge pond area size is increased 10 fold, while irrigation demands are reduced by 30% in this simulation.

comparison to the base case for comparison of Figure 2. This will be later discussed in the discussion section.

3.2 Modeling SGMA's Effect on Net Groundwater Change

SGMA's legislation requires cuts in net pumping of approximately 25-30% across the entire Central Valley of California. In terms of the water balance model, the SGMA objectives must be met, and thus the most likely situation of this being possible would be when groundwater changes are lower (from reducing irrigation demands and increasing recharge pond area), however, this is largely dependent on climate change. It is important to recognize that in going forward, future climate change is not predictable with absolute certainty, however it is useful to know, as a starting point, what the best course of action would be for each potential state. Thus, we look at the different combinations of monthly irrigation demand reduction and changes in recharge area availability to observe changes in average net groundwater changes.

Since there exists an expectation that there will be less surface water deliveries in scenarios informed with climate change, a comparison between the base case of data with reduced demands with the most extreme climate-informed scenarios with reduced demands would demonstrate the greatest range of net groundwater change values. The extreme climate-informed scenarios are illustrated using the most extreme combination of both state variables.

Below, Figure 4 illustrates the average net groundwater changes comparing a base case (maintaining a .4 thousand acre recharge pond area) with reduced monthly irrigation demands of 30% in comparison with the most extreme climate-informed case additionally with reduced monthly irrigation demands of 30%. These calculations consider the SGMA reduction of net pumping by 25%. The graph below illustrates greater groundwater changes (increased by approximately 29%) when the most extreme climate state is applied.

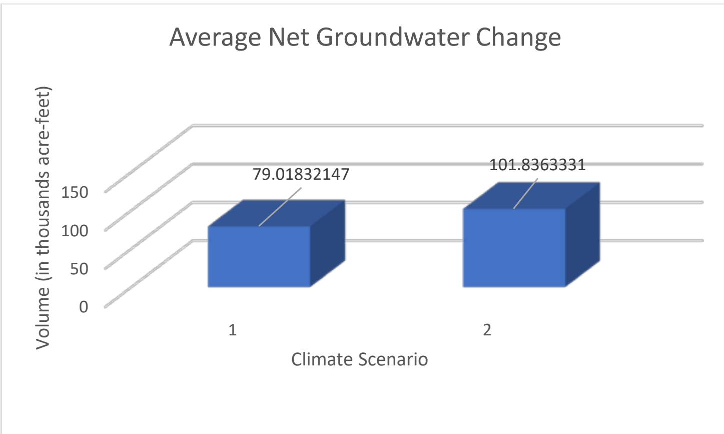

Figure 4: Climate Scenario 1 illustrates simulated average net groundwater change when recharge area= 0.4 thousand acres, no climate change accounted for, and with a 30% reduction in monthly irrigation demands. Climate scenario 2 illustrates simulated average net groundwater change when recharge area= 0.4 thousand acres under the most extreme climate state, and with a 30% reduction in monthly irrigation demands.

Commented [FM9]: Talk about effect of recharge expansion "is it more effective in the climate change scenario?

4. Discussion

Firstly, in comparing data generated in charting the base conditions (maintaining base recharge pond area and monthly irrigation demands) yet under different combinations of the two state variables, we saw very general increases as state variable 2 increased to its fifth increment. However, in comparing this 20-bar data set with an alternate one, in which the recharge pond area is increased 10 fold and the monthly irrigation demands decreased by 30%, in order to simulate a condition when there are greater expectations for available groundwater, we saw that average net groundwater change is significantly diminished aside from a few data points. This demonstrates that in the case where irrigation demands decrease and recharge area increases, more water is available.

Moreover, in terms of observing SGMA's effects on groundwater availability, we reduce net pumping data by 25%, and follow by comparing the effect of climate change on available water when recharge area is held at 0.4 thousand acres and monthly irrigation demands are reduced by 30%. This hydrological case is determined in order to resemble the most likely situation of SGMA demands being met (when groundwater availability is highest). Using climate change as a variable demonstrated higher amounts of groundwater changes, meaning that there would be fewer predicted available amounts of groundwater. This is important to recognize as it shows with the most extreme climate case—in which flow is both shifted from spring to winter months, and excess flow is present in the spring due to more quickly melting snowpack, there will be less available groundwater, which could harm irrigation districts and independent farmers.

5. Conclusions

The results of this study can translate to potential areas of investigation in changing the decisions that farmers and irrigation districts can make in response to changing groundwater availability caused by climate change and SGMA legislation. Cases in which recharge areas increase and demand is reduced offer the optimal scenarios for water users as groundwater availability is expected to be highest then.

In cases where groundwater availability is expected to be lowest, with the advent of SGMA legislation and climate change alike, when considering the best-case scenarios for water availability, when demands are reduced and recharge area has increased, we see that climate change as an isolated variable foreshadows decreased groundwater availability. This can mean that in future climate states in which flow is both shifted from spring to winter months, and excess flow is present in the spring due to more quickly melting snowpack, adverse effects can be seen for water availability, which can deter farmers and irrigation districts from continuing their work in the agriculture industries. However, future research is required in further calculating the effects of climate change and SGMA legislation on the decision making of farmers and irrigation districts in California’s Central Valley.

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