MODERNIZING IRRIGATION SYSTEMS FOR A WATER SECURE CENTRAL VALLEY

FINAL REPORT

Client: The Natural Resources Defense Council (NRDC)

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1. Introduction

California's agriculture powerhouse is a multi-billion-dollar industry centered in the Central Valley, which alone produces one-fourth of the nation's food on less than 1% of US farmland (Faunt et al, 2009). However, this high food productivity uses significant volumes of water; in fact, 80 percent of California's developed public water supply is diverted to agriculture (Mount et al, 2016). But California's water supply is threatened by unpredictable precipitation patterns and rising temperatures resulting from climate change, making it a challenge to ensure enough water is available to maintain agricultural productivity and to supply water for drinking water and other critical human uses. As a result, efforts to conserve water and use current supplies more efficiently are critical. Ultimately, efficient use of water supplies will be dictated by how suppliers manage consumption and convey water to farmers. However, our analysis suggests that the type of distribution system used to supply water is potentially a major factor in determining overall water use efficiency. Based on this research, irrigation management and distribution networks that are adjusted to fit crop water demands, rather than networks that supply water on fixed schedules, are the optimal ways to potentially decrease water use while maintaining crop yield.

California's current agricultural water distribution system was almost 100 years ago without considering water conservation practices. Many water suppliers, or irrigation districts, still use delivery infrastructure that mostly relies on gravity to feed water through dirt-lined canals. Farmers who receive water from those canals have traditionally employed flood irrigation, a form of irrigation that inundates crops with water, and is vulnerable to evaporation and percolation into the ground during conveyance and irrigation. Without substantial system retrofits, traditional gravity fed distribution systems are incompatible with modern on-farm water saving technologies, like pressurized micro-drip irrigation. This lack of compatibility partially explains why flood irrigation still accounts for 43 percent of total irrigated crop area in California (Tindula et al, 2013[1]).

During the last drought, however, there was less surface water available to employ these conventional irrigation methods, and thus farmers increasingly extracted groundwater – which involves intensified pumping and pressurizing practices (Faunt and Sneed, 2015) but also allows farmers to implement their own water-efficient systems. Many farmers also rely on groundwater to irrigate crops at the proper time, as an antiquated distribution system may not deliver water when needed (Playan et al, 2006). These factors, in part, characterize the

[1] Tindula et al, 2013 excludes water used to irrigate rice. USGS recently reported that flood irrigation accounts for 44% of total irrigated crop area.

Central Valley's significant consumption of groundwater reserves and subsidence in large parts of the Valley (Dale et al, 2013; Lo and Famiglietti, 2013).

There is potential for the agricultural sector to install more efficient water delivery systems, but implementing those new water systems is a political, financial, and environmental challenge. Even still, opportunities for water conservation exist in California that could make serious progress towards water security. This project assessed current techniques and opportunities for upgrading outdated irrigation conveyance for pressurized delivery systems and estimates what effects water delivery infrastructure upgrades may have on water use practices. The project also proposes solutions for surface water conservation and water efficiency, while also noting potential regulatory challenges, environmental impacts, and capital costs.

2. The Central Valley

1. Surface Water

<u>1.1 Supply</u>

Most of the Central Valley's surface water is stored in snow that covers the Sierra Nevada Mountains each year. Precipitation falls as snow during the winter to build up an annual snowpack. Then, in the springtime, the snow melts and flows down through rivers, including the Sacramento and San Joaquin Rivers, where it is impounded behind a series of dams before being distributed through systems of canals or other infrastructure. These delivery mechanisms eventually carry the water to a farm or other end user. However, climate change is increasing temperatures and causing unpredictable precipitation patterns, which prompts the Sierra snowpack to melt earlier in the year and before peak growing seasons (Maurer, 2007; Anderson et al, 2008; Taylor et al, 2013). Instead of storing the earlier runoff, California's dams may ultimately release the water to maintain safe levels during the spring storm season for flood protection purposes (USACE, 2018). The disconnect between the timing of the growing season and the snow melting poses water distribution, storage, and management challenges for farmers and water suppliers. Additionally, the San Joaquin and Sacramento River Basins, which cover a majority of the Central Valley, are projected to receive 27-30 percent less annual surface water runoff by 2050 due to the effects of climate change (Pagán et al., 2016). This decrease jeopardizes the certainty of surface water supply that farmers need to continue crop production.

<u>1.2 Distribution – The Central Valley Project and an Overview of Surface Water Rights</u>

Central Valley farmers and residents mainly receive surface water from the Central Valley Project (CVP), a federal water infrastructure project constructed primarily to serve the agricultural industry (Grantham et. al, 2014). The CVP, through a series of dams and reservoirs, diverts water from the Sacramento-San Joaquin Delta to irrigation districts in agricultural counties from Glenn County in the north to Kern County in the south. The CVP distribution system is shown in Figure 1. Irrigation districts receive water allocations from the CVP and then deliver that water to individual farms. The water is distributed via surface delivery canals, which traditionally transport water along open-water channels powered by gravity (Cantoni, 2007). Water losses in the distribution process account for most of the water lost in irrigation; at least 15 percent of water in conveyance is estimated to be lost to evaporation or percolation into the ground (See, e.g., Cantoni, 2007).

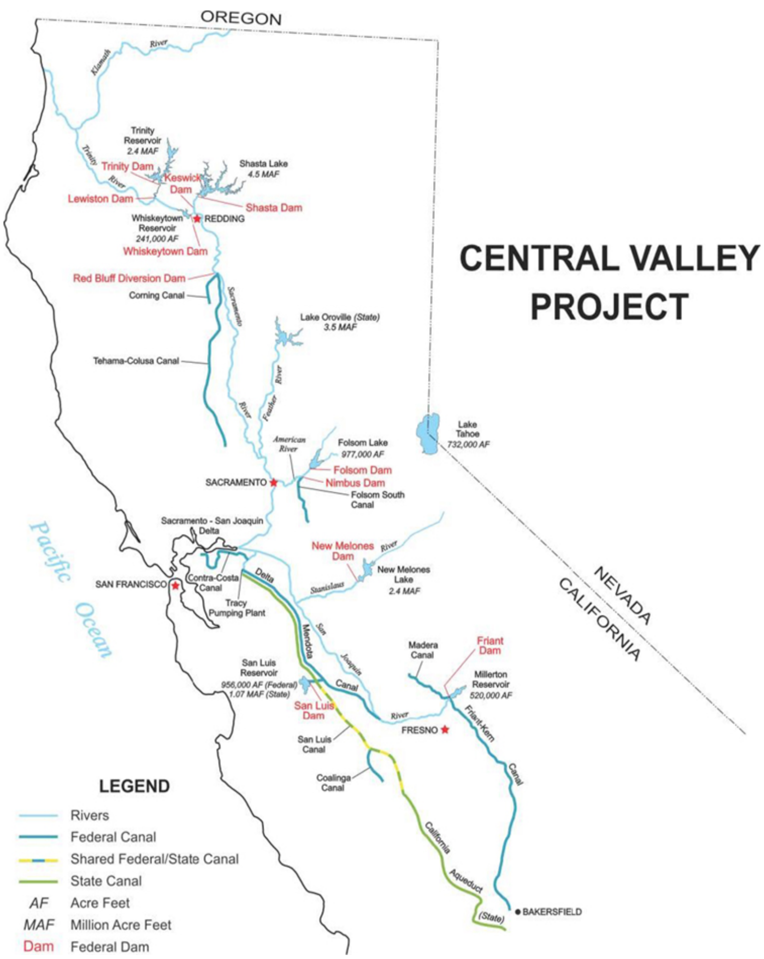


Figure 1: Central Valley Project

Farmers in the Central Valley receive surface water from the CVP and other sources based on a complex hierarchy of water rights administered by the state. These rights determine how much surface water irrigation districts can receive from the CVP. The overall framework of water distribution is based on seniority (SWRCB, 2018). There are two main types of water rights in California: riparian and appropriative. Riparian water rights refer to the use of naturally occurring water in streams, lakes, rivers, or other bodies of water. These rights are usually held by the landowner of the adjacent land. On the other hand, appropriative water rights govern the use of water which has been diverted from its natural source. In order to obtain appropriative rights, a permit must be granted by the State Water Board, unless a landowner claimed water rights before the State Water Board was established in 1914. Moreover, there are two main types of appropriative rights. Those granted before 1914 are often referred to as senior water rights, while those granted post-1914 are considered junior water rights; senior rights holders take priority over junior rights holders and have higher priority to receive water allocations every year, even during times of drought and water shortage, though all water rights may be curtailed in severe droughts.

Historically, a provision in the California Water Code, colloquially known as “use it or lose it”, states that appropriative water rights holders must use their full allocation towards a “beneficial use,” or the unused portion of their water right may be revoked and given to another user (Lustgarden, 2015). This policy (California Water Code 1011a) has been considered by the agricultural industry and the public as an obstacle towards water conservation (Lustgarden, 2015; California State Water Code, Stats. 1999, Ch. 938, Sec. 2); as there was no perceived incentive for districts and farmers to implement water conservation practices. However, as of January 2000, California State Water Code 1011b details that reducing water use for conservation is considered a beneficial use, thereby protecting rights for water users even if they do not use all the water allocated to them (California State Water Code, Stats. 1999, Ch. 938, Sec. 2). The code therefore allows for water to be reallocated towards conservation purposes, and it also allows for the sale of saved water to other users or for use in groundwater recharge efforts.

2. Groundwater

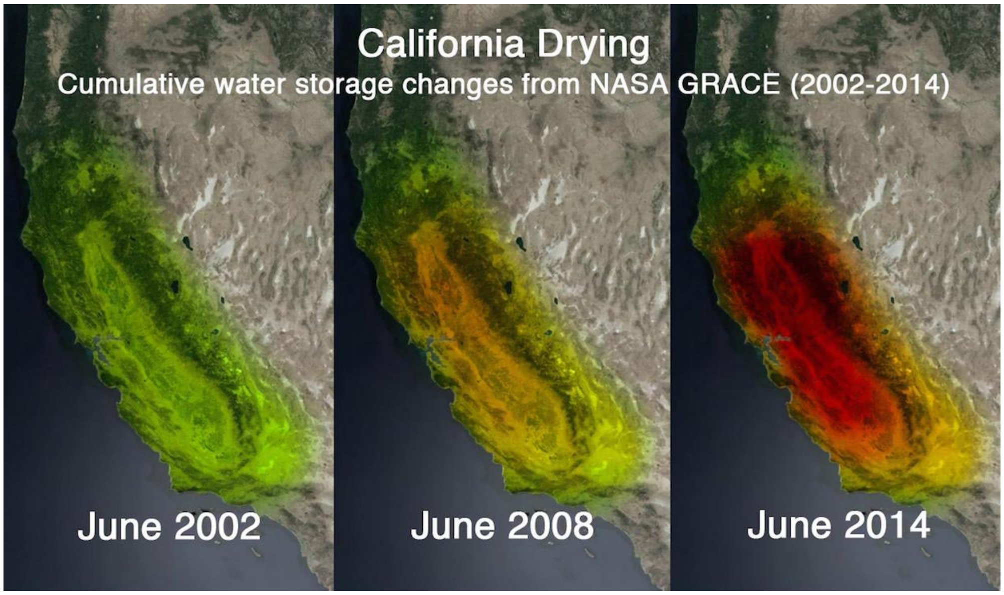
2.1 Supply and Extraction

Due to uncertain surface water supplies, Central Valley farmers often rely on groundwater reserves to meet their irrigation needs, and models suggest that more groundwater will be dedicated to maintain current agricultural productivity in the future (see, Hayhoe et al, 2004; Lo and Famiglietti, 2013; Famiglietti et al., 2011; Taylor et al., 2013; Famiglietti, 2014). As shown in Figure 2, the Central Valley’s groundwater aquifer system contains four sub basins: the Sacramento Valley, Sacramento-San Joaquin Delta, San Joaquin Valley, and Tulare basins. The Redding Basin, although part of the Northern California basin, also feeds into the Central Valley region (Williamson et al. 1969). The water table in the aquifer system can be as shallow as 500 feet or reach depths up to 3,500 feet.

Figure 2: Central Valley Basins (USGS, n.d.)

2.2. Consequences from Over-extraction

Twenty-one out of 525 total groundwater basins in the state are labeled "critically overdrafted," because withdrawal rates have far exceeded natural recharge rates (Chappelle et al., 2017), and "continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts." (California Department of Water Resources, n.d.) Groundwater is heavily over-extracted throughout the Central Valley (See, Figure 3). Excessive withdrawals have caused water tables to decline throughout the San Joaquin Valley by over 400 feet, and groundwater levels are expected to continue to drop at rates of up to 0.3 cubic feet per second (Faunt and Sneed 2015). In some Central Valley agricultural regions, groundwater overdraft, or a condition where more water is withdrawn from an aquifer than replenished naturally, averages 2 million acre-feet per year (Faunt, 2009).



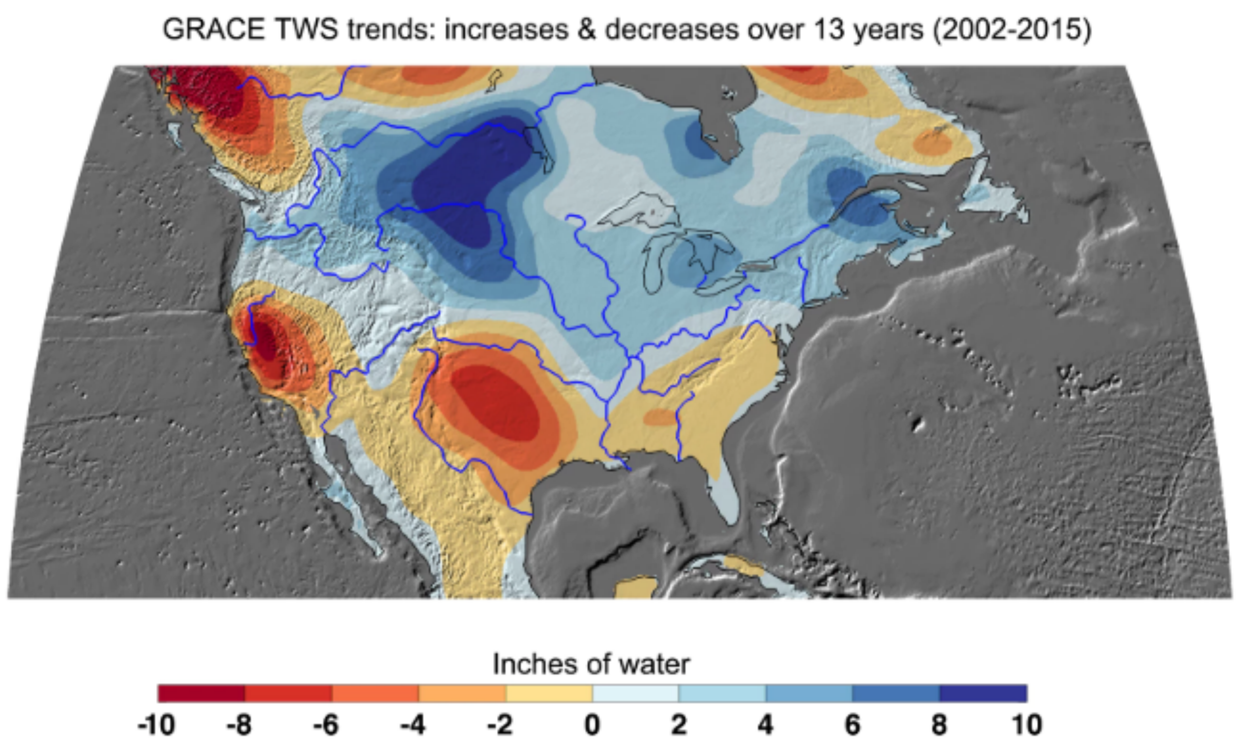
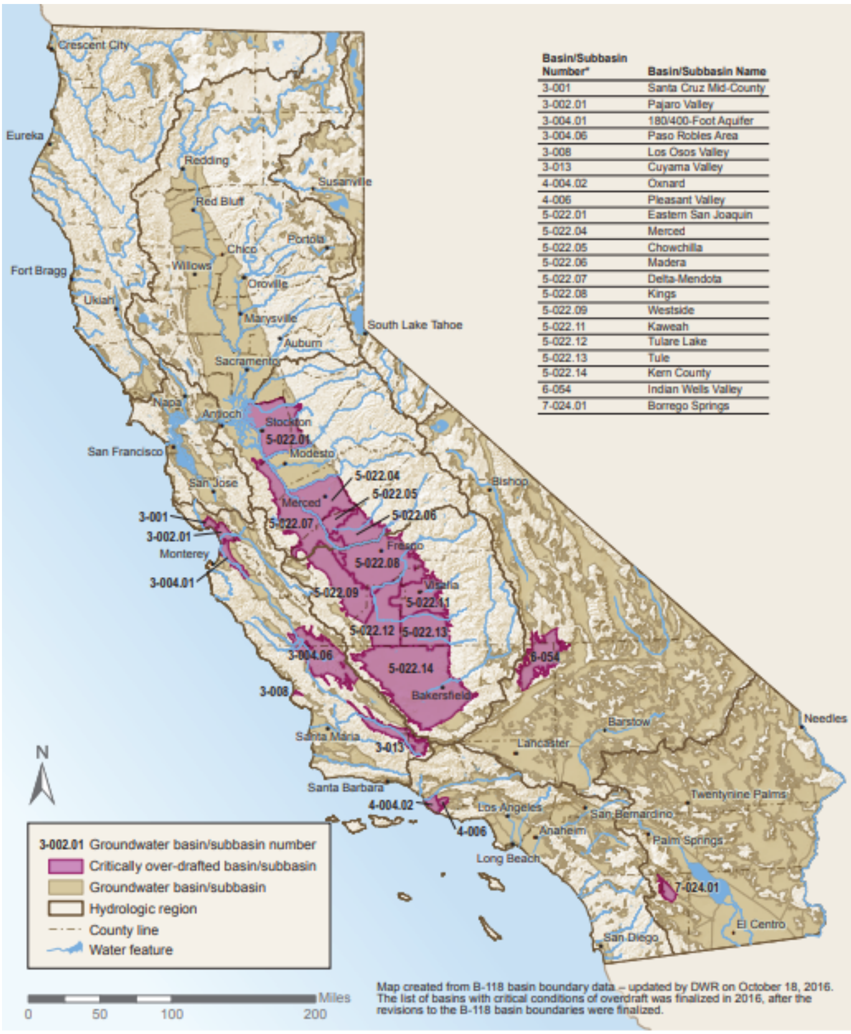


Figure 3: The two images above are from NASA's GRACE satellite. Water storage is drastically shrinking and the land is sinking, particularly in the Central Valley. (NASA JPL, n.d.)



Prepared by California Department of Water Resources for *Bulletin 118, Interim Update 2016.*

Figure 4: Critically overdrafted basins (colored in purple) are concentrated in the Central Valley. (DWR, 2016)

Over-extraction has also drastically affected the region's topography and has compacted nearby sub-surface soil. In some areas of the Central Valley, the land subsided by nine meters (roughly 27 feet) between the 1920s and 1980s, and continues to subside at rates close to three meters per year (Faunt et al, 2016). As land subsides and compacts, it also shrinks available groundwater storage (Marquez, 2017). The image below shows the areas of land subsidence in California, and according to the map, most of it is attributed to groundwater over-extraction.

This pattern of groundwater extraction in the Central Valley has depleted water from surface water bodies, like rivers and streams. Surface water bodies naturally reach equilibrium through discharge and recharge with groundwater aquifers. Pumping of groundwater disrupts these natural cycles. Consequently, pumping has depleted water from several Valley streams, rivers, ponds, and other surface water bodies as they attempt to return to equilibrium by draining into groundwater aquifers (Marquez, 2017). Coupled with natural discharge, groundwater pumping increases the risk of depleting aquifers, which eventually may cause riparian systems and springs to dry up. As climate change continues, studies have predicted that precipitation events may become less frequent, meaning recharge rates will further decrease (Thomas et al 2016).

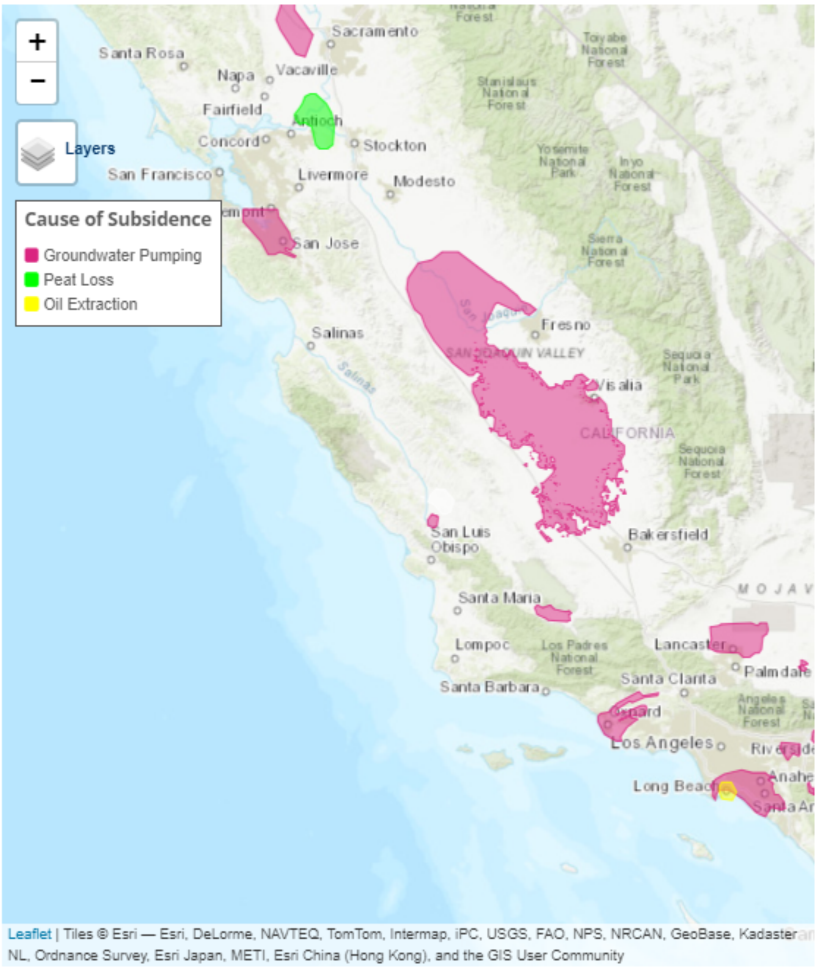


Figure 5: GIS map from the USGS showing land subsidence around California. Much of it is from groundwater pumping and is spatially concentrated in the Central Valley. (USGS, n.d.)

2.3 Groundwater Regulation – The Sustainable Groundwater Management Act (SGMA)

Despite countless studies proving over-extraction, groundwater pumping was not clearly regulated or even monitored by the state until 2014 with passage of, the Sustainable Groundwater Management Act (SGMA). SGMA sets a goal of maintaining sustainable groundwater levels in groundwater wells, and requires permitting, annual monitoring, and additional oversight in support of this effort (California Department of Water Resources, n.d.). Groundwater basins that are critically overdrafted must track any pumping activity and develop groundwater sustainability plans (GSPs).

By January 31, 2022, all GSPs must be in effect; by 2042 critically overdrafted basins, most of which are in the Central Valley (see Figure 4), must reach sustainable levels (California Department of Water Resources, n.d.). Although low priority basins are not subject to SGMA regulations, DWR encourages local groundwater sustainability agencies to develop a new management plan.

3. Literature Review of Irrigation Methods

1. *Large Scale vs Small Scale Irrigation and Delivery*

For this research paper, large scale irrigation is defined as supply from an irrigation district, or water delivered from a supplier (such as a district) to a water user (e.g., a farmer). Small scale irrigation is defined as the method of how a farmer distributes their water to on-site crops.

Large Scale Systems

Delivery Canals

Irrigation water in the Central Valley has historically been delivered via canals, which can bring large quantities of water to smaller distribution zones. An overwhelming majority of canal systems are unpressurized and use gravity to distribute the water to farms. These gravity-fed systems are often characterized by uncovered, unlined dirt channels, which allow water to interact with the atmosphere and to seep into the ground. From an efficiency perspective, evaporation and infiltration are considered water losses; however, infiltrated water can serve another purpose by recharging groundwater aquifers depending on local hydrology (DWR, 2015).

Irrigation canals can be lined with impermeable materials or left unlined as a dirt canal. At least one paper determined that seepage and evaporation from unlined canals wasted a substantial amount of water (Swamee, 2015). This is evident in semi-arid regions, like those in India, where unlined canals have caused severe waterlogging, or water saturation, and soil salinization. Evaporation and seepage may increase salt concentrations in delivered water by up to 85 percent, creating excessively saline on-farm soils (FAO, 2017). To avoid these problems, farms in semi-arid regions are encouraged to line channels with concrete, plastic, or clay (Singh, 2012). Lined canals increase flow-rates and decrease seepage into adjacent soils, saving 60 to 80 percent of the water lost in unlined canals (FAO, 2017).

Though lined canals are more efficient, they deteriorate and crack on the edges over time. Scientific literature is not consistent on how seepage from cracks and maintenance affects water loss, but some suggest that a “canal with cracked lining is likely to approach the quantity of seepage from an unlined canal.” (Swamee, 2015). However, others state that if cracks appear, the amount of water lost is dependent on the canal’s construction and maintenance practices. For example, lined systems typically prevent water losses by 43.5 to 66 percent, but because of cracked canals and improper maintenance, a project’s lining delivery system in Pakistan reduced losses by 22.4 percent (Arshad, 2009). In 2013, a system in Mexico reduced leakages by 26 percent with lined canals (World Bank, 2016). However, when the system installed the lining, it simultaneously installed advanced monitoring devices and improved operations management. Thus, it is difficult to determine whether water loss reduction was exclusively a result from the lining. More research is necessary to see if the two systems compound water savings or not.

Pressurized Distribution Systems

Equipped with pump stations and a network of pipelines, pressurized irrigation systems can deliver water to end users at varying flow rates. Flow rates can be adjusted to function at high or low flows depending on weather patterns and farms' on-farm irrigation technology demands. Pipe size, pressure intensity, and flow regulation vary depending on crop needs and geography. These systems are often more profitable to farmers than gravity-based systems, decreasing water consumption by almost 50 percent and increasing crop yield (Water Scarcity Regional Collaboration Platform, 2016). However, associated costs and risks like mismanagement or broken pipes are much higher than those of traditional, non-pressurized systems (Water Scarcity Regional Collaboration Platform, 2016).

Converting current infrastructure to pressurized systems in a piecemeal fashion is often preferred over replacing entire systems because it mitigates investment costs; however, there are drawbacks to this approach (Daccache, 2009). According to case studies in Italy, infrastructure designed for gravity-fed, fixed flow rates cannot adapt to pressurized deliveries because flow rates are variable for this type of infrastructure, meaning districts are obligated to retrofit their entire distribution network (Daccache, 2009). However, studies in Jordan, Morocco, and California (UC Davis) all confirm that the construction of an entire pressurized system has high risks of failure (e.g. hydraulic failure and breaking pipes), energy costs, and initial capital costs when upgraded from an unpressurized system (Daccache, 2009). Retrofitting a system already in place is less expensive, yet conversion to an entire pressurized system could compromise the former system's capacity to adapt to different delivery rates (Medellin-Azuara, 2012).

Pressurizing a system, however, does not always require installing pipes. Variable speed pumps, also known as variable frequency drive (VFD) pumps, can be installed by the end-user rather than system-wide to pressurize flow from a gravity-fed canal system onto an individual farm (Levisdow et al, 2014). VFDs are considerably more energy efficient than a system that is completely pressurized with pipes, as they draw water from a smaller reservoir and pump water over a shorter distance. These pumps not only allow irrigation districts to avoid costly modernization projects but help farmers transition from water-intensive irrigation practices to more sophisticated and efficient methods, like micro-drip irrigation (Levisdow et al, 2014). It should be noted that this technology still needs further testing and adjustments to fully exploit its efficiency potential (Levisdow et al, 2014). Furthermore, some irrigation districts utilize Supervisory Control and Data Acquisition (SCADA), which are computerized systems that allow users to remotely adjust water flow (Rijo, 2014). Although most SCADA systems are applied to pipeline systems, they can also be utilized to control water flow in open canal systems to open or close flood gates.[2]

Small Scale Systems

On Farm Irrigation Systems

Type of Irrigation System	Efficiency
Flood	
Basin	85%
Border	77.5%
Furrow	67.5%
Wild Flooding	60%
Gravity	75%
Average	**73%**
Sprinkler	
Hand Move or Portable	70%
Center Pivot and Linear Move	82.5%
Solid Set or Permanent	75%
Side Roll Sprinkler	70%
LEPA (Low Energy Precision Application)	90%
Average	**78%**
Drip /Micro irrigation	
Surface Drip	87.5%
Buried Drip	90%
Subirrigation	90%
Micro Sprinkler	87.5%
Average	**89%**

Note: Efficiency is defined here as the volume of irrigation water beneficially used (equal to evapotranspiration) divided by the volume of irrigation water applied minus change in storage of irrigation water.
Source: Salas et al. 2006

In the Central Valley, traditional irrigation methods include furrow and flood irrigation, which are fed by gravity-based delivery canals. Furrow irrigation involves diverting water through troughs, and thereby inundating nearby crop rows (Howell, 2003). Very little technology is required to utilize this irrigation method, and it is therefore relatively cheap, costing as little as $339 per acre, as opposed to $15,000 per acre for sophisticated irrigation technology (Amosson et al, 2011). However, in terms of water efficiency, only 67.5 percent (see Table 1, left) of water implemented by furrow irrigation is absorbed by plants, which is roughly 20 percent lower than many other methods (Howell, 2003; Salas et al, 2006). Flood irrigation is only slightly more efficient, with 73 percent of the water absorbed by crops (Salas et al, 2006). Because the water is exposed to the atmosphere in both of these methods, substantial water volumes are lost due to evaporation, thus lowering efficiencies of these irrigation methods. However, many farmers are willing to trade inefficiency for low irrigation costs. In fact, furrow and flood irrigation still account for roughly 43 percent[1] of the Central Valley's irrigated acres (Tindula et al, 2013).

[2] Personal Communication, Oakdale Irrigation District, April 2018.

Sprinkler irrigation forces pressurized water through a nozzle, which sprays out water to water plots of crops, which are sectioned based on how far a sprinkler can spray. The applied water is vulnerable to evaporation, and as a result, only 78 percent of it is used to irrigate crops (Salas et al, 2006). Micro-sprinklers are a more efficient type of sprinkler system. Rather than conventionally spraying large areas of land, micro-sprinkler applies low pressure water to a small area around the sprinkler head. Micro-sprinkler and surface drip are sometimes grouped together as micro-irrigation because they achieve similar efficiencies (Tindula et al, 2013).

Drip irrigation distributes low pressure water along rows of piping by dripping water via outlet holes to individual plants. This method can be used on or below the surface- subsurface drip uses the same technology as surface drip, but the delivery pipes run underground to apply water directly to the root zone (Tindula et al, 2013). Subsurface drip can irrigate crops without the influence of evaporation, making it more efficient than surface drip; a typical subsurface drip is around 90 percent efficient, which is roughly 2 percent more efficient than a surface drip system (Salas et al, 2006). By switching to pressurized on-farm irrigation systems, farmers could achieve considerable water savings. A study by the Pacific Institute concluded that converting 3.3 million acres of flood irrigated land to 2.2 million acres of sprinkler irrigation and 1.1 million acres to drip could conserve roughly 0.9 and 1.2 million acre-feet per year in a wet and dry year, respectively (Cooley, 2009).

Irrigation Management

Large Scale

Although technological advances play an important role in conservation efforts, they must be combined with efficient water management practices to achieve substantial water savings (Levidow et. al, 2014). Large scale management practices are determined by irrigation districts, who determine when and how to deliver water to farms. Unfortunately, there is often a disconnect between farmers' water demand and distribution schedules. (Playan et. al, 2006).

On-demand delivery schedules cater to a farmer's specific crop demand. Therefore, these deliveries result in higher crop yields than fixed, rotational delivery schedules, which distribute water regardless of demand (Playan, et. al, 2006). In fact, a 2002 study showed that farms under on-demand schedules performed better economically while decreasing seasonal water demand by up to 37 percent (Zaccaria et al., 2009). Additionally, because most crops are seasonal, farms that are dependent on rotational schedules are restricted to certain growing months, thus limiting what types of crops can be grown (Zaccaria et al., 2009). Additionally, crops growing on farms with rotational schedules are often overirrigated, which results in water loss – as much as 28 percent of the delivered water. To avoid this issue, many farmers on rotation schedules choose to additionally pump their own groundwater, which allows them to withdraw water only when needed; this essentially mimics the concept of on-demand deliveries.

Small Scale

Even on small scales, sophisticated technology has been developed to manage delivery. Sensors exist to detect water levels in the soil, plants, and atmosphere, and can be calibrated to a crop's water demand to ensure that it is watered at the proper time in the proper amount. These sensors operate on feedback loop, integrating real-time data on a crop's water consumption to determine the optimal delivery schedule. When paired with efficient irrigation technology, like micro-drip systems, water users can potentially reduce water consumption by up to 20% (Lorite et. al, 2015; McCready et. al, 2011).

An algorithm-based system can also be used to determine irrigation timing (Perea et. al, 2016). This technology relies on a self-evolving algorithm that automatically makes periodic adjustments to improve the efficiency of water delivery. For pressurized systems, the algorithm operates on variables based on energy consumption and water content in the soil, plants, and air. Because pressurized systems consume energy to power large pumps, lowering energy consumption often translates to increasing water efficiency. This methodology was applied to an irrigation district in Southern Spain, where it showed a 15% decrease in energy consumption without significant crop yield reductions (Perea et. al, 2016). Gravity-based irrigation systems are formulated by a different self-evolving algorithm, which depends on delivery times in each irrigation canal, water stress, and the overall network. (Belaqziz et. al, 2014). This methodology allows for scheduling before crops are dehydrated and has potential for 25% in water savings.

Deficit irrigation can also be used to manage irrigation timing. This method is based on dehydrating crops until it becomes critical to water them, thereby irrigating plants below their full water requirements. This theoretically reduces water usage while still maintaining crop yield, allowing farmers to potentially increase their profits (Fereres, 2007). Deficit irrigation has proven to work well with fruit and nut trees, but more research is necessary on other crops to make consistent claims. It is presumed to decrease water usage, but it is uncertain whether it actually does so. In 2006, two international studies declared that water losses due to evapotranspiration are comparable between deficit and conventional irrigation even though deficit irrigation is supposedly using less water (Fereres, 2007).

Deficit irrigation can reduce irrigation costs because farmers decrease water usage while increasing crop yield (Goncalves, 2010). However, this is not always the case. Studies across Spain and Portugal suggest that economic water productivity (EWP), a ratio of economic crop output to water price consumed, does not justify long-term deficit irrigation practices, particularly for farmers' profits (Rodrigues, 2009). Research also suggests that water prices play a role in overall financial and water savings.

4. Methodology

Before conducting an analysis of the water efficiency and potential savings achievable through use of different distribution system types, we established the following:

- Rotational deliveries are defined by a system where the supplier decides when water will be delivered to users.
- Districts on modified demand schedules integrate pressurized technology into a gravity-based system. Often, reservoir management is needed to maintain surface water supply.
- On-demand systems have a completely pressurized distribution network that allows them to adopt a flexible delivery schedule

1. *Potential Water Savings and Evapotranspiration Analysis*

The following analyses were conducted to determine the potential water savings that could be realized by modernizing distribution systems for a set of irrigation districts in the Central Valley. Our team reviewed roughly 60 Agricultural Water Management Plans (AWMPs), which are reports on efficient water management practices that agricultural water suppliers serving more than 25,000 irrigated acres are required to submit to the state. [3] However, most of the districts reviewed employ a combination of on-demand, modified, and/or rotation schedule delivery practices. Thus, if at least half of an irrigation district was characterized by one of the three systems, that district was qualified to be considered in this analysis. Four districts within each category were then chosen for full review because they were the most representative of the specified type of irrigation scheduling. These twelve districts are shown in Table 3.

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[3] California's irrigation districts prepare these plans in accordance with the requirements of the Water Conservation Act of 2009 (SBx7-7) and Executive Order B-29-15 (April 1, 2015). SBx7-7 requires agricultural water suppliers to prepare updates to their AWMP every five years and implement specified efficiency measures. AWMPs report on water supplies in district facilities and services areas.

Because modernization increases compatibility with efficient on-farm irrigation methods, such as subsurface drip and micro-irrigation (Zaccaria, 2018), the water savings from irrigation delivery system upgrades are calculated as an increase in that irrigation district's available water supply. "Water savings" represent the amount that would be retained for use, rather than lost to speepage and spillage. Water savings may result in water conservation, but may also be used for other purposes including groundwater recharge or expansion of irrigated land acreage and agricultural productivity. Therefore, with increased efficiency, farmers can expand the area of land they irrigate with the same total water consumption in a given year (Burt, 2011). The water savings from this analysis indicate the theoretical savings from modernization, but in practice, may not translate to an actual reduction in demand. The analyses of potential water savings do, however, suggest the ability to reduce water consumption if conservation is prioritized.

All water use and crop data were sourced from district AWMPs. The associated crop evapotranspiration (ET), cultural, and leaching values[4] were sourced from literature (ITRC et. al, 2003). The theoretical water needs of each crop type was calculated by adding ET, cultural, and leaching values. The breakdown of water sources (surface water, groundwater, and other) can be seen below in Section 6.1 (see Table 3).

Due to data scarcity and differences in reporting between AWMPs, the water savings analysis compared only the 12 districts identified, and then only throughout the period 2010-2014. Each district's AWMP further only contains water use data for one year within this period, and not all districts reported for the same year. Our dataset categorizes irrigation districts based on their delivery methods to show comparisons in water consumption between different delivery system types. First, we calculated the annual total water consumption (applied water) within a district by adding water consumed from private groundwater wells, surface water allocations, and other sources managed by the district (see Section 6.1, Table 3). This water volume was then divided by the total irrigated acreage in the district in a given year to create an applied water metric, in units of acre-feet per acre (equations shown below).

$$Total\ Consumed\ Water = surface\ water + groundwater + other\ sources$$

$$Applied\ water\ (AF/acre) = \frac{Total\ Water\ Consumed}{Total\ Irrigated\ Acreage}$$

[4] Cultural and leaching requirements include practices such as frost protection or reducing soil salinity.

Next, we used data on crop water demand – the amount of water needed for irrigation to meet the water loss through ET of different crops – to calculate a total theoretical water requirement for irrigated land and average theoretical water need (acre-feet per acre) for each district. This was calculated by summing the product of the crop water demand for different crop types and the percent breakdown of each crop present in a district (See ET Analysis Table in Appendix 2). An efficiency metric was then created using the formula shown below, comparing the theoretical crop water demand for a district against the actual applied water of that district:

$$Efficiency = \frac{Crop\ Water\ Demand\ (\frac{acre\ feet}{acre})}{Applied\ Water\ (\frac{acre\ feet}{acre})}$$

It should be noted some districts received an efficiency value greater than 1 due to the fact they applied *less* water than the projected theoretical volume needed based on evapotranspiration values listed in the literature. The applied water, crop water need, and the calculated efficiency metrics are displayed in Section 6.1 Table 3. A gross average for the selected districts is also displayed in the table.

Additional information, such as on-farm irrigation methods and water sources (private groundwater, district surface water, and other district sources) breakdowns within the district are displayed in Section 6.1 Table 4.

2. *GIS Map Analyses and Visuals*

ArcGIS (GIS) was used to spatially assess which geographic areas in the Central Valley may be most ideally situated for transitioning to a pressurized or lined canal irrigation system, based on three criteria:

- **Groundwater Basin Priority:** This model assumes that districts located over critically overdrafted basins will benefit more from a modernization project aimed at increasing surface water use efficiency relative to other districts.
- **Groundwater Infiltration Capacity:** A variety of physical factors influence the ability of surface water to infiltrate groundwater aquifers. For instance, the composition of the surface soil and local topography, among other factors, may prevent surface water from percolating and recharging groundwater. This model assumes districts with recharge-incompatible soil conditions may be more motivated to increase water use efficiency.

- **Crop Water Use:** Crops vary substantially in the amount of water required to obtain maximum yield. Therefore, the types of crops that a district grows affect the amount of water used. This model assumes that districts growing water-intensive crops, such as cotton and almonds, will benefit more from the water efficiency benefits of a modernization project than a district growing less water-intensive crops, such as carrots or lettuce. This assumption is based on research and observations that state switching to efficient irrigation methods will decrease water losses when growing water-intensive crops that employ conventional practices, like flood or furrow irrigation.

These criteria were selected following a review of available literature, meetings with community stakeholders, and conversations with experts in the fields of water use, irrigation, and groundwater modeling. This tool can serve as a guide for irrigation districts in determining whether and how their district may benefit from upgrading their water delivery infrastructure (e.g. from a traditional, gravity-fed system to a pressurized, piped distribution network).

To perform the GIS analysis, spatial data, which are stored in shapefiles, were obtained from publicly available online sources, such as the University of California, Davis (UC Davis) and the Department of Water Resources (DWR). Data relating to groundwater infiltration capacity was obtained from UC Davis's Soil Agricultural Groundwater Banking Index (SAGBI), which is a groundwater recharge suitability layer which accounts for five factors: deep percolation, root zone residency time, topography, chemical limitations, and soil surface condition. Crop type data was obtained from DWR's Land Use Viewer. Shapefiles containing information on groundwater basin priority were obtained from DWR's California Statewide Groundwater Elevation Monitoring (CASGEM) program. These three layers were combined in ArcGIS to create a benefit index, showing which areas have soil characteristics, crop type, and groundwater resources which are ideal for implementing a piped or lined canal water distribution system.

To create the benefit index, each of the three criteria described above were first reclassified to reflect the scoring system outlined in Table 2. The scoring for the groundwater basin priority layer was defined by the CASGEM layer itself, which was created by DWR and considers various factors, including total irrigated acreage, level of reliance on groundwater, and overdraft impacts (CADWR, 2018). Similarly, the scoring for the groundwater infiltration capacity was defined by the SAGBI layer itself, as described above. Once all layers were reclassified, they were converted to raster form and combined using the Raster Calculator tool.

Table 2: The scoring system for the benefit index is shown below.

Factor	Score	Definitions
Groundwater levels		
High	3	Defined by base layer
Medium	2	
Low	1	
Very Low	0	
Crop Water Use		**L/kg**
High Use	3	>3000
Moderate Use	2	1200-3000
Low Use	1	700-1200
Drought Survivors	0	<700
Groundwater Infiltration Capacity		**SAGBI Score**
Excellent	5	85-100
Good	4	69-85
Moderately Good	3	49-69
Moderately Poor	2	29-49
Poor	1	15-29
Very Poor	0	0-15
Benefit Level		
Very High	8-11	
High	6-8	
Moderate	4-6	
Low	2-4	
Very Low	0-2	

5. Results

1. Water Savings and Evapotranspiration Analysis

The districts selected suggested efficiency levels were greatest among the districts employing on-demand methods followed by modified demand and rotational methods. Based on Table 3 below, the irrigation districts employing on-demand delivery methods had a lower applied water value across crop types when compared to those with rotational or modified demand scheduling methods. The difference in water use efficiency is evident in the overall average district water use. In fact, there is almost a two acre-foot per acre difference in the average applied water between districts characterized by rotational and on-demand schedules. Overall, these values demonstrate that districts managed with on-demand schedules operate with higher water efficiencies than districts that operate on rotational or modified demand schedules.

Table 3 also shows a large range in water intensity and efficiency throughout districts that operate on modified demand schedules. Because modified demand districts are categorized based on their ability to schedule water deliveries within 48 hours, these districts can employ a variety of infrastructure to meet their scheduling requirements. Some modified districts rely on pressurization of part of their delivery system, whereas others can use regulating reservoirs to provide better scheduling. The differences in infrastructure employed likely contribute significantly to the wide range of efficiencies found in modified demand districts.

Differences in efficiency may apply even where the ultimate breakdown of on-farm irrigation techniques were approximately equivalent among districts utilizing the different distribution systems. For example, Lindmore Irrigation District (modified demand), Columbia Canal Company (modified demand), and Westlands Water District (on-demand) are all characterized by similar breakdowns of on-farm irrigation practices – 22 to 31 percent flood or furrow irrigation. While Lindmore averaged a theoretical water use efficiency of 1.04 for 2013-2014, and Columbia Canal 0.88 in 2011, Westlands, using on-demand distribution, averaged water efficiency close to 1.57 in 2010, though 1.09 in 2011 (See Table 3). Similarly, South Sutter ID and Pixley ID (both operating on modified demand), and all the rotational districts analyzed maintained a minimum of 78 percent flood or furrow irrigation for on-farm practices. However, South Sutter (0.94) and to a degree, Pixley (0.87) exhibited higher water use efficiency ratios than did any of the rotational districts analyzed, which ranged from 0.70 to 0.84. While several other factors, including whether during a wet or dry year, water supply source, or crop types, could influence the resulting efficiency, this comparison suggests that the distribution system itself was a potentially major factor in determining overall water use efficiency.

Overall, Table 3 indicates that there is potential for districts and farms to achieve substantial water savings by investing in modernization projects. Districts on a rotational schedule have, on average, the greatest potential for achieving water savings through upgrades to their delivery systems, which correspondingly would allow upgrades to farmers' individual irrigation systems. Some districts on modified demand could continue to raise efficiency by upgrading to on-demand distribution or by implementing automated SCADA systems to avoid spillage losses. Some variability in the amount of applied water and efficiency among individual districts, however, may be influenced by other district-specific factors.

Water Use and Efficiency					
District	**Year**	**Type**	**Crop Water Need (acre-ft/acre)**	**Applied Water (acre-ft/acre)**	**Efficiency**
On Demand					
Kern Tulare	2014	Critical	2.88	2.68	1.08
San Benito Co WD	2013	Critical	1.74	1.43	1.22
Westlands	2011	Wet	2.57	2.35	1.09
Westlands[5]	2010	AN	2.72	1.73	1.57
All Year Average			**2.48**	**2.15**	**1.24**
Modified Demand					
Lindmore	2013-2014 average	Critical	3.20	3.08	1.04
Riverdale	2012	Dry	3.12	3.23	0.96
South Sutter	2012	BN	3.85	4.08	0.94
Columbia Canal	2011	Wet	3.47	3.96	0.88
Pixley	2010	AN	2.94	3.39	0.87
All Year Average			**3.31**	**3.55**	**0.94**
Rotation					
South San Joaquin	2014	Critical	3.37	4.01	0.84
Fresno	2013	Critical	2.80	4.03	0.70
Orland	2012	BN	3.34	4.31	0.78
Oakdale	2005-2014 average	N/A	3.29	3.99	0.82
All Year Average			**3.20**	**4.09**	**0.78**

Table 3: The theoretical crop water need, actual applied water, and calculated efficiency for each district in specified years.

[5] Westlands total district water supply, including estimated groundwater use, for 2010 is identified by the district as 787,554 acre-feet. This total is well below historical average water supply for the district, which between 1994 and 2008 ranges between 1,184,492 acre-feet and 1,010,735 acre-feet per year. As a result, the efficiency ratio of 1.57 calculated for 2010 may not be indicative of usual practice, but, assuming accurate supply figures, does further indicate potential for savings with on-demand systems.

Water Sources and Irrigation Types								
District	**Year**	**Type**	**% Surface Water**	**% Private Groundwater**	**% Other Sources**	**% Gravity**	**% Drip/ Micro**	**% Sprinkler**
On Demand								
Kern Tulare	2014	Critical	33	53	14	0	100	0
San Benito Co WD	2013	Critical	69	31	0	1	43	56
Westlands	2011	Wet	94	6	0	23	65	12
Westlands	2010	AN	89	11	0	22	67	7
Modified Demand								
Lindmore	2014	Critical	0	97	3	31	69	0
Lindmore	2013	Critical	39	61	0	31	69	0
Riverdale	2012	Dry	22	78	0	No Data		
South Sutter	2012	BN	52	48	0	90	7	3
Columbia Canal	2011	Wet	97	3	0	26	74	0
Pixley	2010	AN	1	84	15	78	21	0
Rotation								
South San Joaquin	2014	Critical	68	31	1	93	7	0
Fresno	2013	Critical	60	32	8	80	1	19
Orland	2012	BN	38	62	0	93	6	1
Oakdale	2012	Dry	86	10	4	No Data		
Orland	2011	Wet	34	66	0	93	6	1
Oakdale	2011	Wet	No Data			No Data		
Orland	2010	BN	36	64	0	93	6	1
Oakdale	2010	AN	87	9	4	No Data		

Table 4: Breakdown of water sources and on-farm irrigation methods utilized in specified years for each district assessed in the efficiency analysis above.

Table 4, above, highlights differences in each district's irrigation water sources and the distribution of on-farm irrigation methods within the district. These factors may explain some values of the efficiency and applied water metrics. Rotational districts generally were characterized by low percentages of drip and microirrigation being employed due to incompatibilities with scheduling, consistent with personal communication from irrigation experts (Zaccaria, 2018).[6] Water year hydrologic classifications from DWR are provided for each district/year for reference.[7]

2. GIS

The site benefit map (Figure 6) was created by combining the three criteria layers described previously in the methodology section (Table 2). It displays the projected relative level of assessed benefit from a modernization project between different areas of the Central Valley, with scores ranging from 0-11. The numeric scores correspond to different relative levels of benefit, as follows:

- Very High: 8-11
- High: 6-8
- Moderate: 4-6
- Low: 2-4
- Very Low: 0-2

[6] Certain on-farm irrigation infrastructure (e.g. retaining ponds) can be engineered to allow rotation deliveries to serve drip and microirrigation.

[7] See DWR Chronological Reconstructed Sacramento and San Joaquin Valley – Water Year Hydrologic Classification Indices – available at http://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST. Water year hydrologic classifications are provided separately for both the Sacramento and San Joaquin Valleys, and are defined as either: W (Wet); AN (Above Normal); BN (Below Normal); D (Dry); or C (Critical).

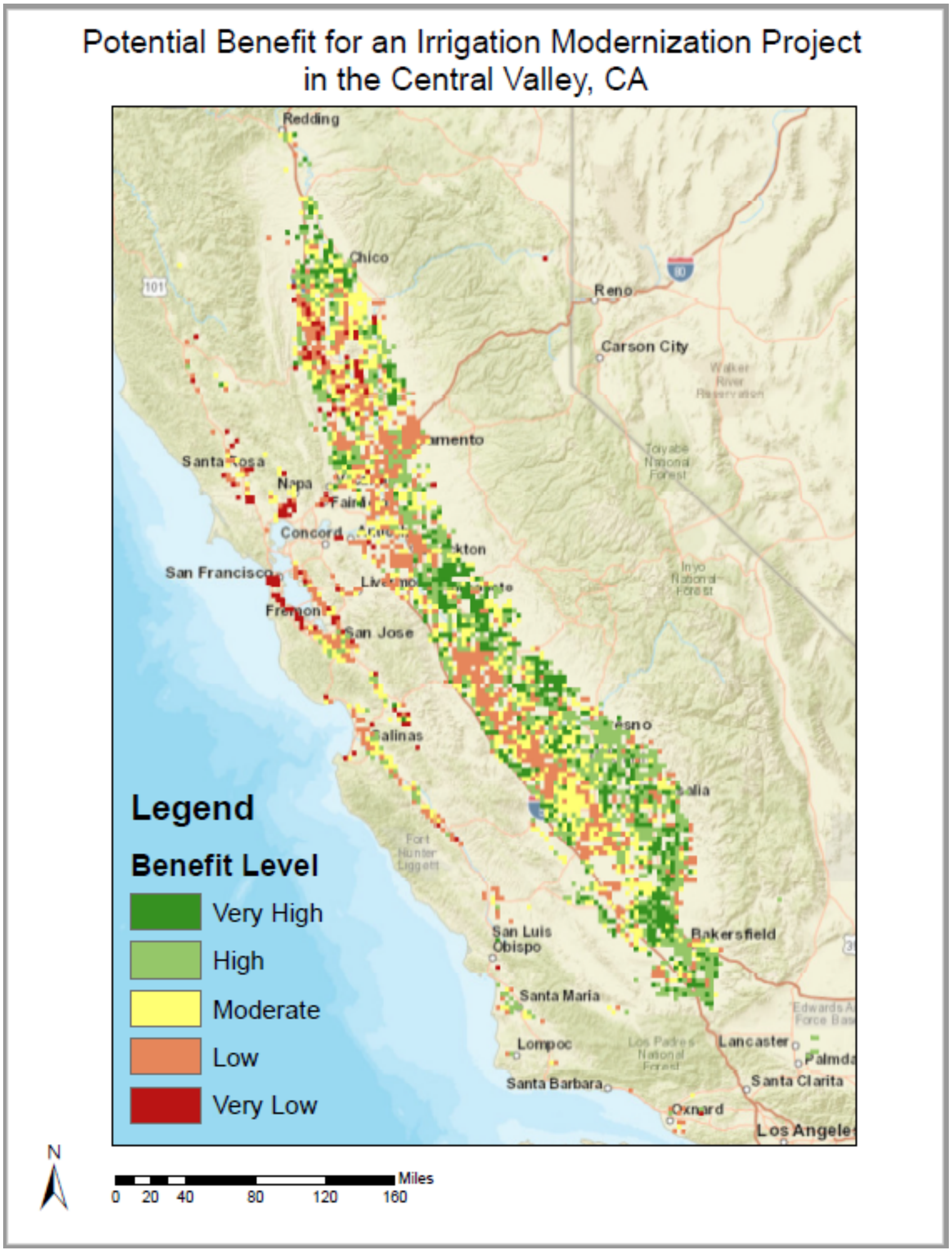

Figure 6: The potential relative level of water savings benefit of an irrigation modernization project in different areas across the Central Valley.

Dots on the map in Figure 7 below indicate the locations of different districts assessed in this analysis, which are the same districts considered in the quantitative analysis described in the previous section.

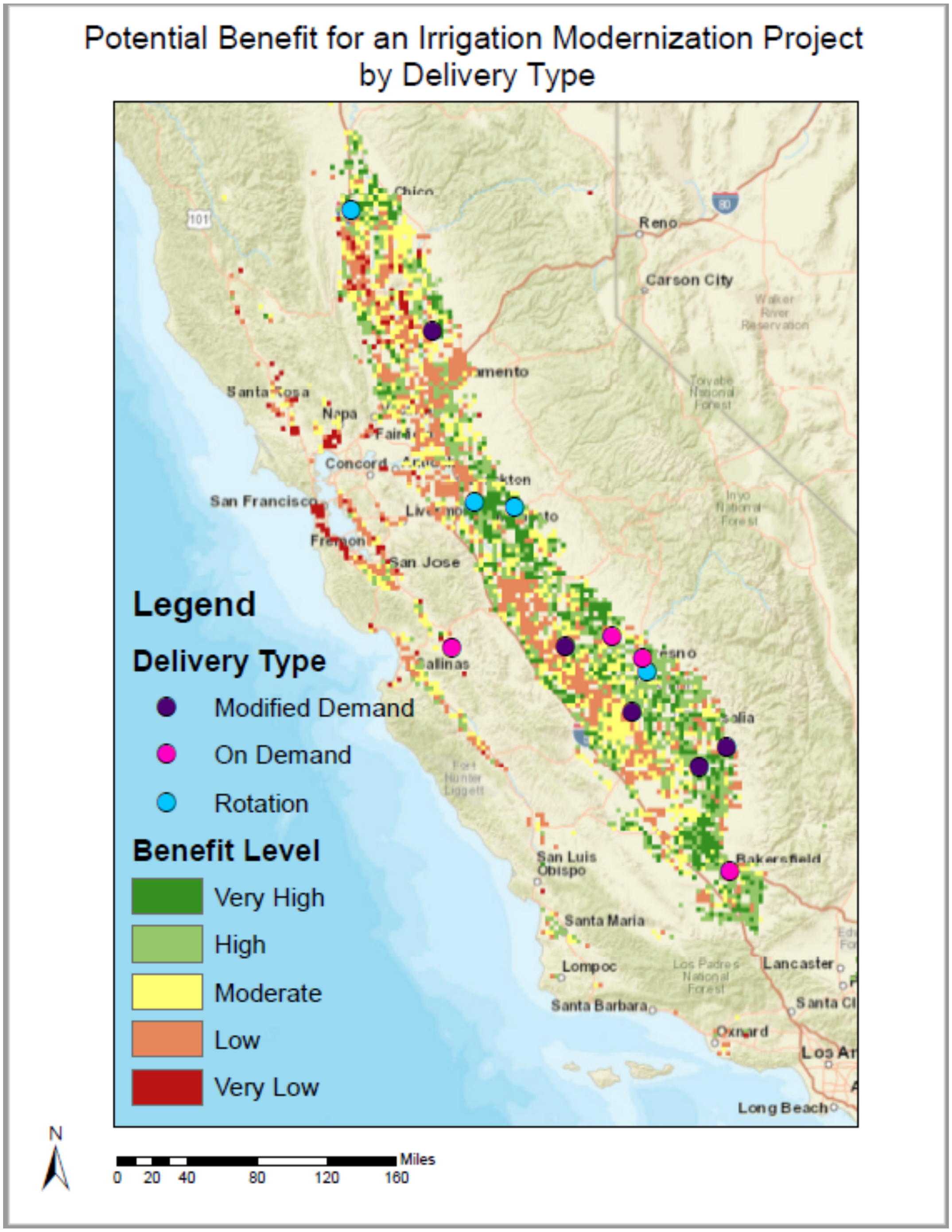

Figure 7: Location of districts assessed in this analysis.

The composite benefit analysis suggests that most of the Central Valley region can save water via an irrigation distribution system upgrade. Though there are some areas in the North and West that seem to have a lower potential to benefit from upgrades, most areas on the map could expect at least a moderate level of benefit from upgrading to a more water efficient system, and many areas anticipate a high or very high level of benefit. However, in some cases the criteria most directly influencing a lower benefit score may be related to the condition of the underlying groundwater supply aquifer or to the area being well-suited for groundwater recharge (meaning that less efficient irrigation practices may still result in water infiltrating to recharge groundwater); as a result, in these cases a lower score does not indicate that significant water savings is not achievable, but that there may be potential benefit to continue use of gravity fed distribution or to adjust irrigation practices to balance against benefits of improved efficiency.

Additionally, Figure 8 below displays a zoomed in portion of the benefit map. From this perspective, it appears that a larger proportion of districts analyzed using rotational or modified demand distribution fall in areas of high to very high benefit, relative to districts already using an on-demand system. This indicates, rather intuitively, that districts using more inefficient water delivery systems would benefit most from a modernization project.

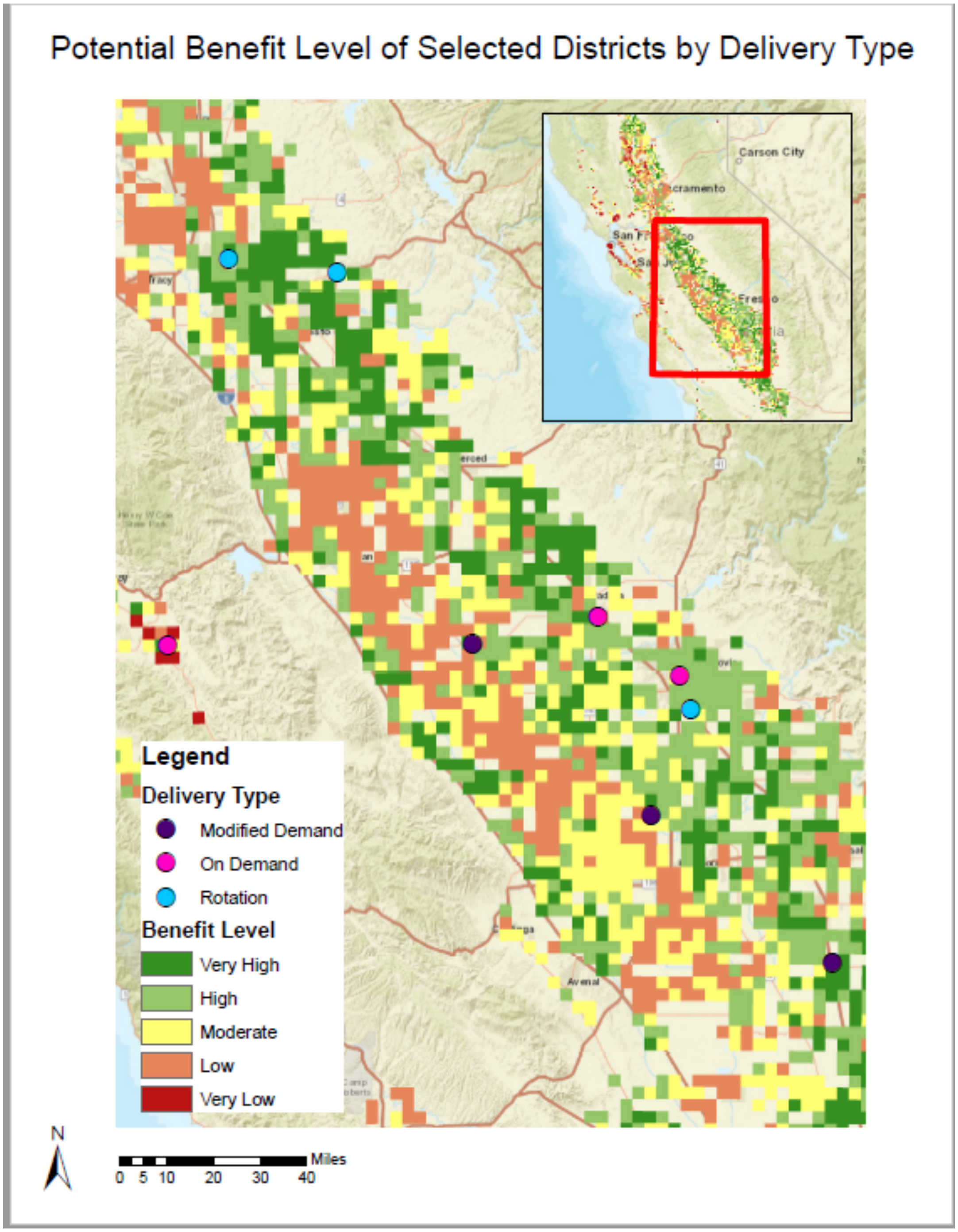

Figure 8: Magnified view of the Southern portion of the benefit map. Labels indicate the location and type of delivery system for the different districts considered in this analysis.

6. Discussion

1. Research Limitations

1.1 Data Access

Some of the data used in this analysis, including GIS layers and some AWMPS, are not available to the public. In these cases, much of it has been obtained from communications with engineers in select irrigation districts. Because some irrigation districts expressed privacy concerns regarding water usage, some data that was requested did not factor into the final analysis. Furthermore, the AWMPs for some years were only available for select districts, which made it difficult to get an overall picture of districts' water usage across a period of a few years. This could be a result of district submitting late reports, but in other cases, like those for 2012 and 2015, had to be requested[8] from DWR because they were not available on the State's website. Without enough data to show the different annual water use between districts, a comprehensive analysis was difficult to achieve. Some websites were also defunct, either because links to relevant data resulted in an error page or the website itself would not load. Useful shapefiles for GIS, for example, were not available for download on DWR's website. Additionally, due to lack of readily available data, the analysis did not spatially or quantitatively consider surface water rights. The analysis would have been stronger if it had considered them – even in dry years, senior water rights holders may receive enough surface water to obtain the benefits of efficient delivery infrastructure, whilst junior water rights holders may prioritize groundwater recharge to comply with SGMA regulation and to maintain enough supply to irrigate farmland. Lack of available or compatible data is a barrier to further analysis, and a potential area for improvement across the state.

1.2 Report Consistency

Analyzing AWMPs, even when available, was difficult because reports were inconsistent across districts, which further limited the data set that could be developed. Reports had informational discrepancies, with some districts providing more detail than others. Further, water supply and use figures for groundwater were often based on estimates by the district rather than on actual measurement of groundwater pumping (see, e.g., AWMPs for Westlands (2010, 2011) and Kern-Tulare (2014)), which creates a degree of uncertainty for calculation of water-use efficiency. In addition, DWR has not standardized its method for data submission and has not coordinated districts on reporting methods and requirements. As a result, many of the AWMPs are uniquely formatted and report water use in dissimilar metrics, which encumbers efforts to understand trends and patterns in water consumption across California. To fill in the data gaps, the research team called districts, including Orland ID, Kern-Tulare ID, Columbia Canal

[8] At the time of research, the 2012 and 2015 AWMPs were not available online and had to be requested. The 2015 AWMPs are now available on the DWR website.

Company, Lower Tule/Pixley ID, South San Joaquin ID, Byron-Bethany, and Turlock ID, to request their water use data directly. In addition, there may be a disconnect between the time farmers and irrigation districts begin implementing upgrades and the time that they are reported. Hence, a district could have changed its infrastructure significantly in comparison with what is indicated in the most recent AWMP.

2. Water Savings and Evapotranspiration Analysis

As shown in Table 3, there is strong evidence that transitioning irrigation management to operate using on-demand delivery schedules has the potential to result in significant water savings, as much as 2 acre-feet per acre of irrigated land, or roughly 650,000 gallons per acre. This is in part because modernizing delivery systems creates the potential to utilize more efficient on-farm irrigation methods that are compatible with on-demand delivery. Considering that agricultural districts can span up to several thousand acres, saving this amount of water can be crucial for maintaining a sustainable supply for California's urban, agricultural, and environmental uses. However, the analysis found that the most efficient districts that operate on an on-demand schedule are senior water rights holders, who are likely to have their full allocation distributed through sophisticated pressurized systems. Implementing these types of systems can be a financial challenge for junior water rights holders, who often employ gravity networks on rotational or modified scheduling mainly because of a lack of investment funds. However, if water use efficiency in the Central Valley is substantially improved, junior water rights holders may be able to upgrade their distribution infrastructure and rely less on pumping groundwater to meet crop needs.

3. GIS

Based on Figure 6, it is evident that most areas in the Central Valley have high or very high potentials to benefit from upgrading their water supply infrastructure. These regions, shown in Figure 6 in light and dark green, are particularly concentrated in the central and southern portions of the Central Valley, where most groundwater basins are critically overdrafted (See groundwater basin map in Figure 5 above). On the map shown in Figure 7, the selected districts that employ rotational delivery schedules are in areas that have strong potential for modernization projects. Though this analysis includes only a small number of the total irrigation districts in the Central Valley, it is apparent for those that were considered that rotational districts have the most potential for distribution system upgrades. Because funding for such projects is limited, upgrading infrastructure in rotational districts first would yield the most short-term benefits. That being said, there is also significant potential for many modified demand districts to benefit as well. Therefore, while we recommend prioritizing rotational districts, it is also important to recognize and capitalize on the substantial conservation gains that could be made by upgrades in modified demand districts.

4. Central Valley Field Visit

As part of the research project, a field visit was conducted in the Central Valley in April 2018 to observe irrigation district and farm operation. The research team visited four locations - three irrigation districts and a large farm – in Merced, Fresno, Tulare, and Kern Counties. Each location sourced and distributed its water differently, which was largely determined by the local geophysical and hydrologic characteristics of the area.

Some important qualitative conclusions were drawn from the trip, one being that surface water rights are a consequential factor in determining each district's distribution systems. The general trend from the field visit is that senior water rights holders are transitioning to pressurized systems more quickly than junior water rights holders.[9] California's drought in 2015-2016 was a wake-up call for senior water rights holders, who are often almost solely dependent on surface water as irrigation supply. The lack of available surface water supply during the drought appears to have changed attitudes towards modernization projects, and senior water rights holders have since been willing to pressurize their delivery infrastructure to prevent water losses. Based on the locations visited, senior water rights holders can more easily implement these projects because they are more financially capable, as system retrofits were entirely funded by the districts and their farmers. Junior water rights holders, on the other hand, appeared more hesitant to enact these infrastructure changes, mainly because most of the project funds would need to be supplied by external grants and scholarships, which may not be available, awarded to a district, or sufficient to cover the project investment. For just construction alone, infrastructure upgrades can range from $2 million to $150 million.[10] Thus, grant money is incredibly important for districts, particularly junior water rights holders, who have limited financial resources. Finally, junior water rights holders are not guaranteed a consistent surface water supply as compared with more senior right holders; as a result, a large surface water delivery project that might not see large water deliveries could be seen as an unproductive investment.

A second conclusion gathered from the field was that SGMA regulation is integral to managing water use, particularly for junior water rights holders, who are heavily dependent on groundwater. During the 2015-2016 drought, several junior water rights users did not receive

[9] Personal Communication, Bowles Farms and Pixley and Lower Tulare Irrigation Districts, April 2018.

[10] Personal Communication, Oakdale and South San Joaquin Irrigation Districts, spring 2018.

surface water allocations and therefore intensified their use of groundwater. In combination with the lack of funds and the effort to prioritize SGMA compliance, junior water rights holding districts have intentionally kept gravity-fed, dirt-lined networks in place.[11] Although gravity-fed, dirt-lined delivery systems are not as efficient, some water lost in conveyance is potentially recharged into groundwater basins. To comply with SGMA, some have built reservoirs on porous soils specifically to improve opportunities for groundwater recharge.[12]

An especially significant observation is a divide between how urban and agricultural sectors have approached water conservation. Both sectors realize that the main solution to a future water shortage is to maintain a reliable water supply. However, between a fear of losing water needed for food production, financial stability, and an increasing demand for drastic cuts in water usage, among other factors, there exists a polarizing gap when a holistic effort is needed to tackle conservation issues. The agricultural industry has urged for more dam storage, a request that has sparked controversy and criticism from the urban sector, environmental groups, and many water experts (Skelton, 2018). If progress towards better water conservation should continue, a plan to store or revitalize ecosystems with unused, conserved water must be discussed. This becomes particularly important if the effects of climate change vary the amount and times when snow melts in the Sierras, changing the time when farmers can rely on surface water to irrigate their crops.

7. Conclusions and Recommendations

This research project has assessed the Central Valley's methods of distributing irrigation water from an economic and regulatory perspective. According to the final results, the water intensity on rotational schedule is almost 2 acre-feet/acre more than that of an on-demand or a modified schedule. Additionally, the GIS analysis has shown that in consideration the local hydrology and geology, most of the Central Valley has strong potential for infrastructure upgrades, particularly districts in the Valley that we analyzed that employ rotational delivery schedules. Under the legal provisions of the State Water Code 1011b, there is more potential to implement modernization projects while also complying with SGMA. However, project feasibility is not the same for all irrigation districts. In addition to obtaining farmers' approval to modernize, financial challenges often discourage many districts from retrofitting their conveyance infrastructure. Although there are grants available by state agencies, like DWR and CDFA, strict vetting processes and application-specific requirements may hinder some districts from implementing these system upgrades. Besides the technical and financial challenges of water conservation, an urban and rural political divide has also fragmented California's water

[11] Personal Communication, Pixley Irrigation District, April 2018.
[12] Personal Communication, Kern-Tulare Irrigation District, April 2018.

conservation efforts. In light of the circumstances that may slow progress towards a water-secure future in California, we provide the following recommendations:

- Larger amounts of grant funding should be allocated for agricultural infrastructure improvement projects. Because these retrofits can easily cost tens of millions of dollars, many districts, particularly those who are junior water rights holders, are discouraged from implementing systems that would increase district-wide and on-farm water efficiency. Although there are already grant structures in place, they are not sufficient to cover project costs. Given that California's future climate is likely to decrease available surface water supply, providing the means to upgrade delivery systems can be crucial for maintaining a sustainable water supply.

- It is strongly recommended that more data be made easily accessible to the public, and that a more structured and standardized form of reporting (e.g. in AWMPs) be implemented. If data access had not been such an impediment, this research could have more thoroughly analyzed water usage among farms and districts, surface water rights in relation to groundwater basin levels, and the types of water delivery systems across California. However, due to inconsistent, unstandardized reporting and data access issues, the data set available was limited and the analysis could not reach its full potential.

- If a district should consider recharging groundwater to comply with SGMA, a method should be employed to ensure that all intended water is recharged to a groundwater basin. Although spreading water over porous soils is the easiest method to recharge groundwater, much of it is lost to evaporation. Considering that temperatures are likely to increase by the effects of climate change, artificial recharge methods that could minimize evaporation losses, like injection wells and aquifer storage recovery (ASR) wells, may be more effective in the future (Bouwer, 2002; Pyne, 1995). Direct recharge may allow opportunities for junior water rights holders to execute potential modernization projects, as they have mostly kept their unlined, gravity-fed networks to recharge any routed water that is lost to percolation. Direct recharge may also avoid nitrate contamination, a problem that continues to plague the safety of Central Valley's drinking water supply. With surface spreading methods, infiltrated water can carry nitrates and other contaminants from fertilizers and pesticides with it into groundwater basins (Harter and Lund, 2012).

- Because there is a political disconnect between different stakeholders, use of an unbiased third party is advised to mediate communications between the agricultural and urban sectors to secure effective water conservation strategies. There is one water supply that the entire state must share between growing food and supplying drinking water, among other critical uses. Thus, it is in public interest that a polarizing divide between cities and agricultural areas be arbitrated to move forward with conservation practices.

Implementing these recommendations will take time, but California cannot make substantial progress towards water security without considering these points. California's State Water Code has already opened a door for water conservation with Section 1011b, which protects users' surface water rights should they make efforts to decrease their water consumption. This is a small, but critical, step towards a larger effort; water policy makers, cities, and the agricultural industry must create and enforce a multi-faceted strategy towards salvaging a highly demanded water supply. One part of that strategy is modernizing water delivery systems in the Central Valley. This research, combined with work done by other universities across the state, can help California strengthen its water security for years to come.

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