Valuing Recycled Water for Irrigation: Direct and Indirect Benefits to Coastal Agriculture *

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Abstract

In the face of drought and climate change, many coastal agricultural regions are at risk of sea-level rise and the depletion of groundwater resources. When combined, these issues lead to seawater intrusion of the underlying groundwater storage, which is detrimental to agricultural production and difficult to combat. In a setting where alternative water resources are prized, one possible strategy to mitigate seawater intrusion is through the development of a municipal treated wastewater program. This paper is the first to empirically evaluate the benefits of recycled water in agriculture. I measure the direct effects of recycled water deliveries, evaluating crop choices and welfare gains for growers receiving water, using a panel mixed logit model. I then measure the indirect impacts, using event studies to measure how recycled water changes the salinity of the underlying water basin. I evaluate the effects for growers that receive recycled water, as well as those who do not have access to recycled water, but farm in the same region. In a high-value agricultural region, I find that growers receiving recycled water shift towards salt-sensitive, profitable crops, with welfare gains of $16 million dollars annually for 5500 acre-ft in delivered water. Salinity of the underlying aquifer, measured using total dissolved solids, improves near parcels receiving delivered water by up to 570 mg/L, and these changes occur in years where aquifer salinity levels are highest. Overall findings suggest that for delicate, profitable produce, recycled water is a promising strategy in mitigating damages from seawater intrusion and groundwater overdraft.
JEL: D62; Q15; Q24; Q51; Q54

Keywords: groundwater; climate change; recycled water; agriculture; salinity

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1 Introduction

The stability of water resources for agricultural production has always been an important topic, but the scale and urgency of the issue has dramatically increased in recent decades. Climate change has brought warmer temperatures, shifts in precipitation patterns, sea level rise, and an increase in extreme weather events to agricultural regions globally (Nicholls and Cazenave, 2010; Kunkel et al., 2013). Coastal regions are particularly at risk, since they often feature micro-climates conducive to the development of high-value crops that are difficult to grow in other locations. Rising temperatures and increased variability in precipitation can reduce the agricultural productivity of these delicate products, especially if the security of water resources is unknown. Water supply issues are magnified in coastal locations, as groundwater resources are subject to seawater intrusion, exacerbated by the overpumping of water (Wong et al., 2014).

If a region is reliant on groundwater that suffers from seawater intrusion, there are a limited number of strategies available to improve salinity conditions. Options hinge on actively reducing the amount of groundwater pumping or increasing the recharge of higher quality (lower salinity) water into the groundwater basin. [1] This may involve pricing groundwater or setting limits on extraction, building infrastructure that improves recharge, or finding additional sources of irrigation water. One emerging tool is to use treated municipal wastewater, or recycled water, to reduce the reliance on groundwater pumping and increase recharge to the underlying aquifer. As of yet, this is not a well-studied option, because there are limited micro-level water-use data available to credibly estimate individual grower impacts. In addition, recycled water itself is not typically of the highest quality, and is an expensive, "last-resort" solution that has not been implemented in many locations. However, in the uniquely profitable climates of coastal agricultural regions, recycled water has started to emerge as a potentially economically feasible adaptation strategy. Moreover, the possible benefits are expected to increase under climate change.

This paper rigorously investigates the viability of recycled water in a high-value coastal agricultural region as a mitigation strategy for drought and over-pumping of groundwater.

[1] In the case of soil salinity, a common mitigation strategy is to increase the application of irrigation water, in order to leach salts past the root zone in the soil. This is not as effective of an option when the irrigation water itself is saline, as is the case with seawater intrusion.

I use predicted crop choices to estimate welfare changes due to recycled water access, using a panel mixed logit choice model. The crop choice model is also used to estimate the damages associated with high salinity conditions. I then examine the impacts that recycled water has on improving the underlying water quality of the aquifer, using staggered difference-in-differences and event studies. I evaluate the effects for growers that receive recycled water, as well as those who do not have access to recycled water, but farm in the same region. I then discuss conditions under which recycled water may be economically viable. To my knowledge, this is the first economic study of a real-world implementation of recycled water in agriculture.

The Pajaro Valley, located on California's central coast, offers this critical opportunity to estimate the effectiveness of recycled water. Best known for its berries and vegetables, this region has documented seawater intrusion issues since the 1950s, due to its dependence on groundwater for irrigation and its proximity to the coast. With its foggy, temperate climate, growers in the highly productive valley are motivated to find solutions that allow them to continue growing high-value, salt-sensitive produce. The local water management agency developed a groundwater pricing scheme to fund a recycled water program, delivering municipal treated wastewater from the nearby town to growers along the coast experiencing high salinity. As part of their duties, the agency has been extensively monitoring groundwater quality, pumping, land use, and delivered water. This includes a rich network of monitoring wells, which enables the observation and interpolation of water quality across space and time. While their production of especially valuable crops means that Pajaro Valley is an early adopter in using recycled water, this analysis provides a useful template for other coastal agricultural regions likely to suffer from seawater intrusion in the coming decades.

I find that small quantities of recycled water provide substantial benefits to the Pajaro Valley. Growers who receive recycled water deliveries are able to grow higher-value, salt sensitive crops at increased yields. Their direct benefits, at $16 million annually, are higher than the management agency's annual program costs. In addition, the groundwater quality beneath parcels that receive recycled water deliveries substantially improves, primarily in years where groundwater salinity is otherwise much higher than average. Neighboring parcels that do not directly receive recycled water deliveries also see their groundwater quality improve in years of high basin-wide salinity, although the effects attenuate quickly. Conservatively, these water quality benefits add up to an additional $10.8 million in high salinity years. While all growers benefit from the recycled water program's prevention of future seawater intrusion, the current beneficiaries of the recycled water program are growers located nearest to the coast.

Overall, this paper has two major contributions: (i) the first quasi-experimental, empirical assessment of the welfare effects from the implementation of a recycled water program, and (ii) the first study to propose and analyze recycled water as a mitigation strategy for salinity or groundwater overdraft. While there is no current economic literature on the implementation of a recycled water program, Ziolkowska and Reyes (2016) discusses socio-economic factors that influence desalinization plant development. There are also several studies using survey methods to elicit a willingness to pay for recycled water or for products grown with recycled water. A few studies explore consumer concerns about the use of treated wastewater in agricultural production (Li et al., 2018; Savchenko et al., 2019). Menegaki et al. (2007) surveys agricultural producers on their willingness to pay for recycled water of various quality in Greece, when faced with no restrictions in freshwater supplies. More closely linked to our work, Iftekhar et al. (2021) use contingent valuation and contingent behavior methods to elicit willingness-to-pay estimates for recycled water in water-constrained Perth, Australia, finding that agricultural users and horticulturalists have the highest valuation at $91 AUD/acre-ft.

Seawater intrusion is a growing problem for coastal agriculture, affecting many regions globally (Lee and Song, 2007; Shammas and Jacks, 2007; Tuong et al., 2003; Milnes and Renard, 2004). There is a small but growing literature on the economic damages from saline irrigation water. Mukherjee and Schwabe (2014) conduct a hedonic analysis of farmland sales in California's Central Valley to estimate the marginal value of changes in groundwater salinity to irrigated agriculture. Rabbani et al. (2013) use survey methods in Bangladesh, examining severe damage to rice production due to a cyclone-induced seawater intrusion event. They find that average households lost 43-45% of their annual income, and salt-tolerant crops were not able to overcome the acute damage. Other research estimates salinity damages using structural approaches (Lee and Howitt, 1996; Schwabe et al., 2006; Connor et al., 2012; Roseta-Palma, 2002; Knapp and Baerenklau, 2006), since high-quality seawater intrusion data is limited. Currently, little research has been done to study ways to mitigate damages from salinity. There has been some work done to estimate the optimal groundwater extraction under seawater intrusion (Green and Sunding, 2000; Reinelt, 2020), as well as under saline soil conditions (Dinar and Knapp, 1986).

Direct damages from groundwater overdraft can be tricky to measure, since depletion of an aquifer typically occurs over a long time horizon. There is excellent work on the externalities associated with extraction and water supply reduction (Brozović et al., 2010; Pfeiffer and Lin, 2012; Edwards, 2016; Merrill and Guilfoos, 2017). Other research is focused on the economic damages from land subsidence, where the land surface sinks due to reduced groundwater tables. Wade et al. (2018) studies land subsidence in Virginia, finding that coastal pumping invokes the greatest externality, but inland rural communities experience the highest damages. Several policies have been proposed to overcome this market failure, including water prices and markets (Smith et al., 2017; Ayres et al., 2021; Bruno and Sexton, 2020) or restrictions on groundwater pumping (Drysdale and Hendricks, 2018). While often effective mechanisms, water prices and restrictions are politically unpopular. This work proposes a new policy mechanism to reduce groundwater overdraft: recycled water as an alternative water supply.

Results provide valuable insights for coastal regions experiencing seawater intrusion, but also for other locations affected by water quality or supply constraints. With sufficient treatment, recycled water programs can provide an additional clean source of water to also combat soil salinity, or other types of groundwater contamination. In fact, 20% to 50% of irrigated agriculture worldwide is already negatively impacted by salinity (Pitman and Läuchli, 2002; Assouline et al., 2015). Currently, there are recycled water facilities operating in California, Arizona, Texas, Florida, and Australia, and programs are being considered in water-stressed regions globally.

More broadly, this analysis has important policy implications for groundwater regulation. Many water basins around the world have already been stressed by persistent over-pumping of groundwater (Wada et al., 2010; Famiglietti et al., 2011). In California, groundwater issues are at the forefront of water policy debates, where on average groundwater accounts for 40% of the state's agricultural water supply. California's Sustainable Groundwater Management

Act (SGMA) of 2014 requires overdrafted basins throughout California to reach and maintain long-term stable groundwater levels and correct undesirable outcomes associated with pumping over the next 20 years. The legislation includes specific mandates to local groundwater agencies to address seawater intrusion. Evaluating the possible benefits of an alternative water supply is critical to informing optimal groundwater regulation.

The paper proceeds as follows. Section 2 describes the background and policy context, while Section 3 describes the data and descriptive statistics. Section 4 outlines the crop choice model and results for estimating the direct benefits of recycled water. Section 5 presents the specifications and results for the indirect benefits of recycled water. Section 6 evaluates Pajaro Valley's program and discusses the feasibility of recycled water in other contexts. Section 7 concludes.

2 Background

2.1 Seawater Intrusion, Recycled Water, and Management

In coastal regions, underground freshwater aquifers and seawater are not typically separated by an impermeable boundary. Instead, they coexist, with the seawater underlying the freshwater, since the salts in seawater give it a higher density. The seawater "toe" describes how far inland the saltwater layer extends below the freshwater aquifer. Seawater intrusion takes place when the saline seawater mixes with the freshwater aquifer. This frequently occurs when irrigation tubewells are drilled and users pump groundwater at a rate faster than the rate of recharge; i.e. more water leaves the aquifer than enters from rainfall or agricultural runoff. When groundwater is overpumped, the pressure causes cones of depression to form, and seawater starts to enter the freshwater zones. This issue is exacerbated with sea-level rise, because the increased ocean pressure extends the seawater toe further inland, putting more of the aquifer at risk of seawater intrusion.

In the Pajaro Valley, seawater intrusion has been documented since 1951, shortly after irrigation tubewells were introduced in the region. With little rainfall during the primary growing season, and surface water making up 1.6% of irrigation water sources, almost all irrigation water is from groundwater pumping. On average, 55,000 acre-ft of water is pumped annually. This is nearly twice the sustainable yield of the basin, meaning that only half of the extracted groundwater is replenished through rainfall or from irrigation runoff. These groundwater withdrawals, combined with the proximity to the coast, have resulted in severe seawater intrusion. The extent of the intruded region has increased seven-fold since it was first documented. Seawater intrusion in the Pajaro Valley, on average, moves inland approximately 200 ft/year, and renders 11,000 acre-feet of water unusable annually (Wallace and Lockwood, 2010).

The overpumping of groundwater and resulting seawater intrusion has led to salinity issues that currently impact crop production and threaten the stability of the basin's future water supplies. In 1980, the California Department of Water Resources listed Pajaro Valley as one of 11 water basins threatened by severe overdraft, out of 447 total basins (DWR, 1980). The severity of the overdraft led to the development of the Pajaro Valley Water Management Agency (PVWMA) in 1984, to develop conservation programs and manage water resources. Under the Sustainable Groundwater Management Act, PVWMA has been tasked with bringing the groundwater basin into "balance" by 2040, such that groundwater extraction does not exceed water recharge into the aquifer. [2] While the management agency is encouraging water conservation in the form of improved irrigation efficiency, their main projects are in the development of alternative sources of water and promoting its recharge into the basin.

The primary source of alternative water supplies to combat seawater intrusion comes from a treated municipal wastewater facility built in the town of Watsonville, along with limited runoff from nearby wetlands. Both of these projects are limited in scale, and are described in more detail below. In total, they have the capacity to provide approximately 7500 acre-feet of water annually (AFY), which is equivalent to 13% of the annual groundwater pumping in the region, although annual deliveries have not yet exceeded 5500 acre-ft. The total annual quantity of recycled water delivered can be found in Figure 1. Since the recycled water program can only provide a limited amount of the irrigation water requirements of the Pajaro Valley, as a means to allocate the limited recycled water supplies, the agency created a "Delivered Wa-

[2]PVWMA does have the authority to directly limit groundwater pumping, but that is not part of their current policy program. If the basin fails to come into balance by 2040, however, the Sustainable Groundwater Management Act will likely trigger pumping limits.

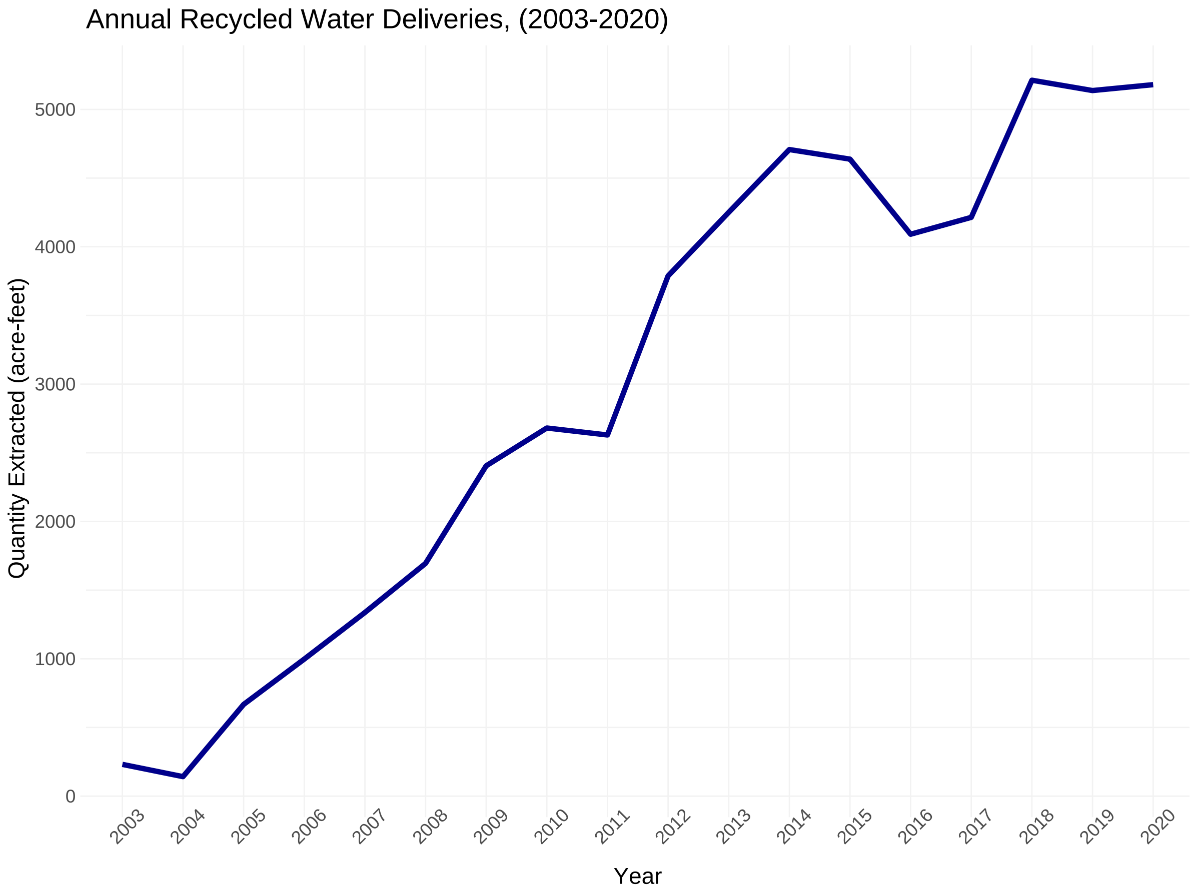


Figure 1: Annual Recycled Water Deliveries

ter Zone" (DWZ). The boundaries of the DWZ are shown in Figure 2. Only users within this zone have access to the alternative water supplies. This region was targeted because the negative externality that groundwater pumping imposes is larger for growers directly on the coast than for growers further inland. Moreover, underlying hydrologic characteristics of the aquifer mean that groundwater pumping in the southern part of the region has a greater externality than in the north. The eastern boundary of the DWZ is Highway 1, rather than a particular aquifer feature. The benefits that the recycled water has in the DWZ are threefold: the higher quality water allows growers with saline groundwater to improve their crop yields, the alternative water supply reduces pumping on the coast, and the runoff from the application of this water helps to recharge the aquifer.

For most of the groundwater irrigation in the Pajaro Valley, growers bore individual tubewells on their property, rather than using canals or a shared water conveyance system. With

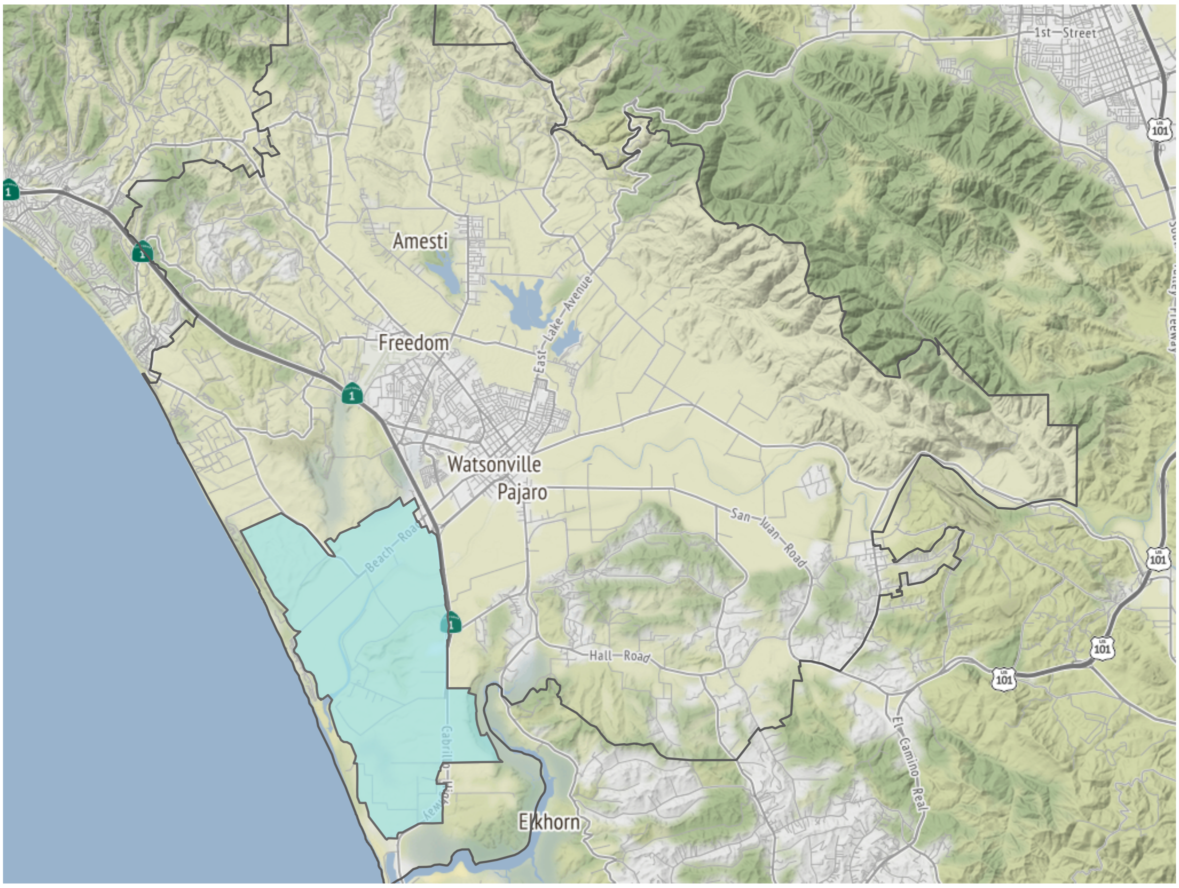


Figure 2: Pajaro Valley's Delivered Water Zone

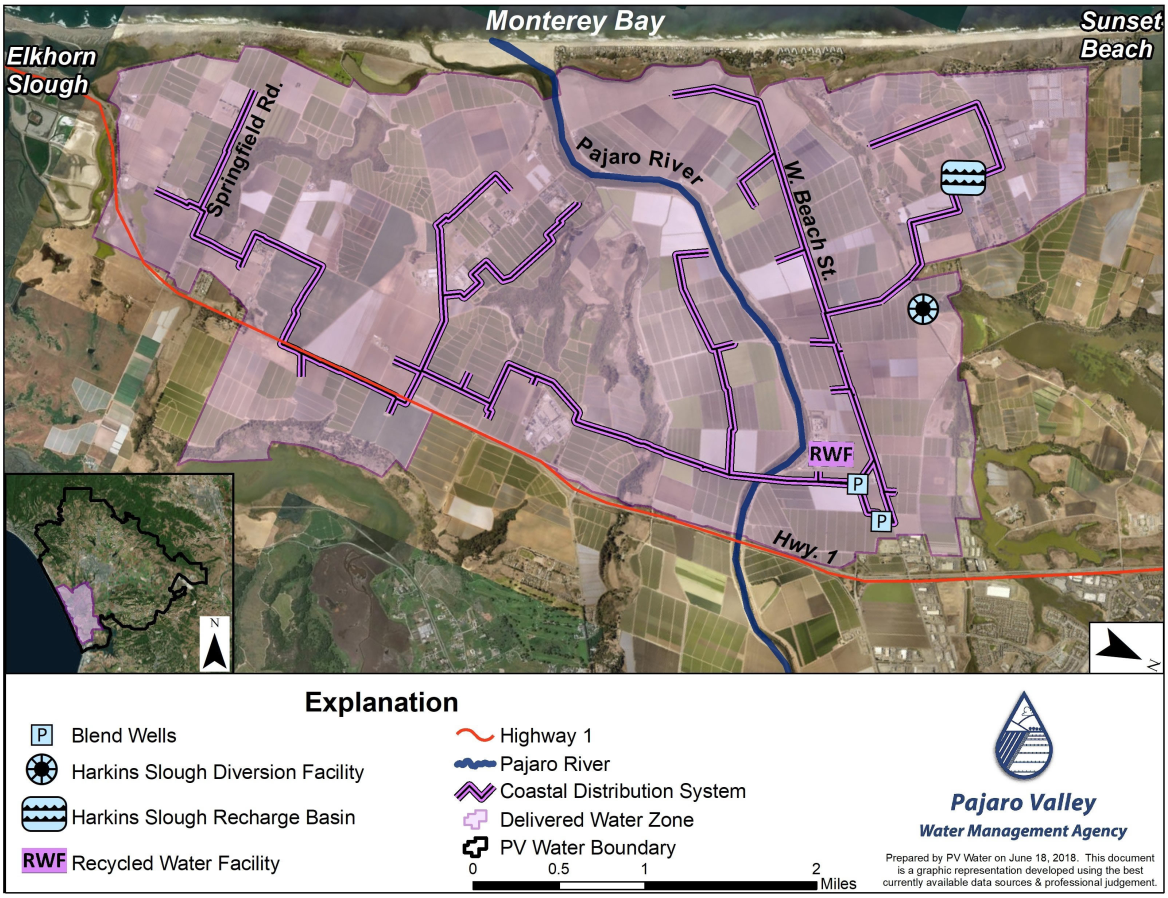


Figure 3: Pajaro Valley's Coastal Distribution System (Source: PVWMA)

the development of the recycled water program, the Delivered Water Zone needed a network of pipes, called the "Coastal Distribution System" (CDS) to move the recycled water to eligible growers. Construction began on the CDS in 2005, and has slowly increased over time. As of 2020, the CDS is approximately 20 miles long, and provides water to 5100 of the most severely affected agricultural acres. A map of the Coastal Delivery System can be found in Figure 3. Along the CDS, turnouts (essentially large water spigots), are installed in order to provide access to growers. In order for a grower in the DWZ to receive recycled water, the CDS needs to reach their parcel and have a turnout, the grower needs to submit an application, and there must be enough recycled water to meet both the needs of the current users and of the applicant.

Recycled water is sourced from the Watsonville Recycled Water Facility, which is a treated urban wastewater facility. It began operation in 2009. In the first full year of operation, the recycled water facility supplied 2700 acre-feet, but the facility has capacity for up to 6000 AFY, and plans have been approved to expand the facility further. While the recycled water is the main source of delivered water, there is some water available from the Harkins Slough Recharge and Recovery Facility. This facility intercepts some of the surface outflows from the Harkins Slough, which are wetlands just south of the Pajaro Valley. If not redirected for use in the valley, the outflow would have run into Monterey Bay, mixing with seawater. This storage facility has been in existence since 2002, and was the first groundwater recharge project constructed by the water management agency. While PVWMA has a permit to pump 2000 AFY from the Harkins Slough, the reality has been closer to 1000 AFY (with an actual delivered amount of approximately 160 AFY), due to a lack of flow through the Slough and the limited capacity in the recharge pond.

Since recycled water comes into contact with crops, proper treatment of the recycled water is paramount. In order to meet California's stringent recycled water standards, the water is tertiary treated, which means that all solids larger than 10 microns are removed, and the water is treated with UV light to kill pathogens. Some salts, nitrates, and phosphates may remain, but the quality is high enough to be directly applied to agricultural products, and safe enough to enter the aquifer for household use. [3] The average total dissolved solids (TDS) levels in recycled water is approximately 600 mg/L, which is high enough to cause some damage to salt-sensitive agricultural products, but much lower than TDS levels under drought conditions or in seawater-intruded wells. To ensure that salt contents are sufficiently low, the recycled water is also blended with water from inland wells.

2.2 Water Pricing and Metering

To generate revenue to support the program, PVWMA collects augmentation fees for delivered water and fees for groundwater pumping in the basin. [4] The pricing of both groundwater and recycled water began in 2002, and a tiered pricing system was established in 2010. A snapshot of 2016-2021 water prices, by category, are found in Table 1. The price of water varies

[3]Not removing nitrates and phosphates is beneficial to agricultural producers, who may be able to reduce their fertilizer applications of these nutrients.

[4]PVWMA has the ability to regulate and limit pumping directly, but has chosen to focus on the supplemental water projects and promotion of water conservation practices as alternatives to a command and control program.

Table 1: Water Prices in Pajaro Valley, Dollars/Acre-ft

Year	Recycled	GW Pumping (in DWZ)	GW Pumping (outside DWZ)	Residential
2016/17	359	258	203	97
2017/18	369	282	217	103
2018/19	381	309	231	109
2019/20	392	338	246	115
2020/21	392	338	246	115

in the Pajaro Valley depending on where the water is sourced (delivered or pumped), if the well is metered or unmetered (residential pumps are unmetered), and if the well is within the delivered water zone. While fees for recycled water are higher than the cost of groundwater pumping in the DWZ, the fees are structured specifically such that when one factors in the electricity costs of pumping groundwater, the recycled water is slightly cheaper.

To price groundwater, PVWMA meters all wells capable of extracting 10 AFY, as well smaller wells, if they serves 10 acres of orchard, 4 acres of berries or row crops, or 2.5 acres of greenhouse facilities. Municipal, agricultural, and industrial wells make up 87% of water use, while rural residential wells make up 2%, and the rest is consumed by delivered water users. Few residential wells have meters, so they are estimated to use 0.5 AFY, and are charged based on that estimate.

Pajaro Valley's water prices are high, relative to other groundwater charges. In most of the United States, groundwater pumping is not metered, and water prices are merely the electricity costs required to operate the pump. Even in locations where water prices have been implemented, they tend to be significantly lower than the prices in Pajaro Valley. In California's productive Central Valley, water prices are commonly between $70-150 per acre-foot, and the 2018 Farm and Ranch Irrigation Survey finds that California growers pay an average of $67 per acre-foot for "off-farm" water. However, there are some regions facing similar or much higher water prices, depending on water supply constraints. Growers in San Diego county, for example, pay $1700 an acre-foot, due to water scarcity. Moreover, in Pajaro Valley, the irrigation water costs are minor when compared to the revenue and profits for the crops grown in the region. On average, revenues are $34,000 an acre, and reach up to $68,000 per acre for strawberries. The combination of high revenues and low water requirements (around 2-3 acre-feet a year for most crops) leads me to believe that growers are not deficit irrigating in response to the water prices.

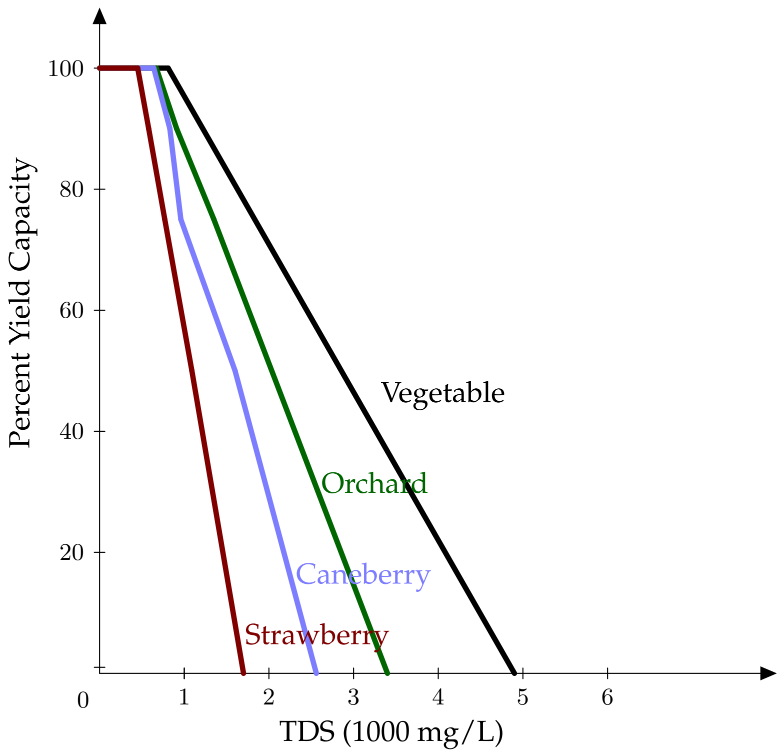
2.3 Agricultural Production

The Pajaro Valley is known for its production of delicate, high value produce, including strawberries, apples, raspberries, blackberries, artichokes, grapes, lettuce, and a variety of vegetables and herbs. As of 2019, total production value in the region was over $1 billion across 28,500 irrigated acres. The major California berry producer Driscoll's is headquartered in the region, as is the cider producer Martinelli's. The temperate, coastal climate is ideal for the production of these crops. Moderate temperatures year-round, sunny days, and foggy nights are excellent growing conditions for sensitive crops. However, the delicate nature of this produce means that they are also susceptible to other challenges, such as salinity damage.

Salinity damage impacts almost all stages of plant growth and development, including germination, vegetative growth, and reproduction (Hu and Schmidhalter, 2004). These effects lower crop yields and economic returns. For salinity in irrigation water, damages rarely occur until salinity reaches a crop-specific, critical "threshold". Then, crop yields decline linearly as salinity levels rise. The threshold at which salinity damages begin to occur varies significantly, depending on the crop. For example, strawberry yields begin to decline at TDS levels of around 450 mg/L, while zucchini may not decline in yields before TDS levels reach 2000 mg/L. Grattan (2002) estimates and compiles these thresholds and yield declines for a variety of crops grown in California. Figure 4 depicts the relationship between irrigation water salinity and yield for a subsample of crops in the Pajaro Valley.

Since crop revenues are so high for these products, even minor yield declines can lead to significant losses. In 2020, strawberry revenues were around $68,000 per acre, raspberries yielded around $59,000/acre, and apple revenues were $9,800 an acre. A yield loss of 10%, which would correspond to a TDS increase of 128 mg/L for strawberries, decreasing their

Figure 4: Decline in Crop Yields Due to Salinity



Source: Sears, Bruno, and Hanemann (2021).
"Caneberry" includes blackberries, raspberries, blueberries, and vine crops, while "orchard" refers to apples.

revenue by $6,800 an acre. Therefore, growers are motivated to find possible solutions to deal with salinity issues in their groundwater, although individual basin management is out of their control. An alternative water source, such as recycled water, with moderate salinity levels, can mitigate severe crop losses while also preventing further seawater intrusion.

3 Data and Descriptive Statistics

Data provided from Pajaro Valley Water Management Agency for this analysis consist of water quality measurements from the network of monitoring wells, quarterly pumping and recycled water deliveries, depth to groundwater contour maps, and annual land use data. The details on how these data are built into a parcel-level panel are below. Additionally, I bring in variables on temperature and precipitation, property boundaries and ownership, and crop prices and revenue. Summary statistics are presented in Table 2.

Table 2: Descriptive Statistics

	Mean	SD	Min	Max
Parcel Characteristics (parcel-year, 2003-2020)				
Total Dissolved Solids (mg/L)	598.620	710.170	268.762	17,103.720
Temperature (C)	13.047	0.930	10.813	15.781
Precipitation (mm)	140.192	85.720	7.768	419.035
Pumped Groundwater (AF)	29.164	56.977	0	1,106.819
Recycled Water Deliveries (AF)	8.961	23.692	0.000	229.119
Distance to Coast (meters)	28,029	4,174	24,411	31,249
Parcel size (ft^2)	1,476,116	3,305,805	94	51,618,600
Parcel Characteristics (parcel-year, 2009-2020)				
Depth to Groundwater (ft)	-2.309	6.679	-5	0
Fallow	0.13	0.34	0	1
Vegetable Row	0.31	0.46	0	1
Strawberry	0.25	0.43	0	1
Caneberry	0.17	0.38	0	1
Orchards	0.071	0.26	0	1
Nursery	0.064	0.24	0	1
Prices (region- and basin-year, 2009-2020)				
Groundwater Assessment Fee ($/AF)	201.04	55.98	80	338
Vegetable Row price ($/acre)	10,722	1,614	8,441	13,113
Strawberry price ($/acre)	67,164	7,697	54,029	78,387
Caneberry price ($/acre)	55,773	6,686	42,492	71,308
Orchard price ($/acre)	206,497	571,273	6,854	1,914,633
Nursery price ($/acre)	223,260	65,653	131,740	358,359

Note: This table reports summary statistics for parcel- and basin-level characteristics. Land use and depth to groundwater data are only available from 2009-2020, while the rest of the time-varying data are from 2003-2020. Reported TDS measurements are interpolated observations taken in the spring of each year (march-May). Precipitation is cumulative and temperature represents the average daily maximum, both from March-May of the growing year. Summary statistics for groundwater pumping and water deliveries reflect averages only for parcels that contain a well and/or a water turnout. Distance to the coast is calculated with CA's official boundary. Groundwater depth is measured in feet above mean sea level; negative values reflect feet below sea level. Land use is expressed with dummy variables equal to 1 if the majority of that parcel is planted in that crop. "Caneberries" include blackberries, raspberries, and blueberries and "orchards" include apples and vineyards.

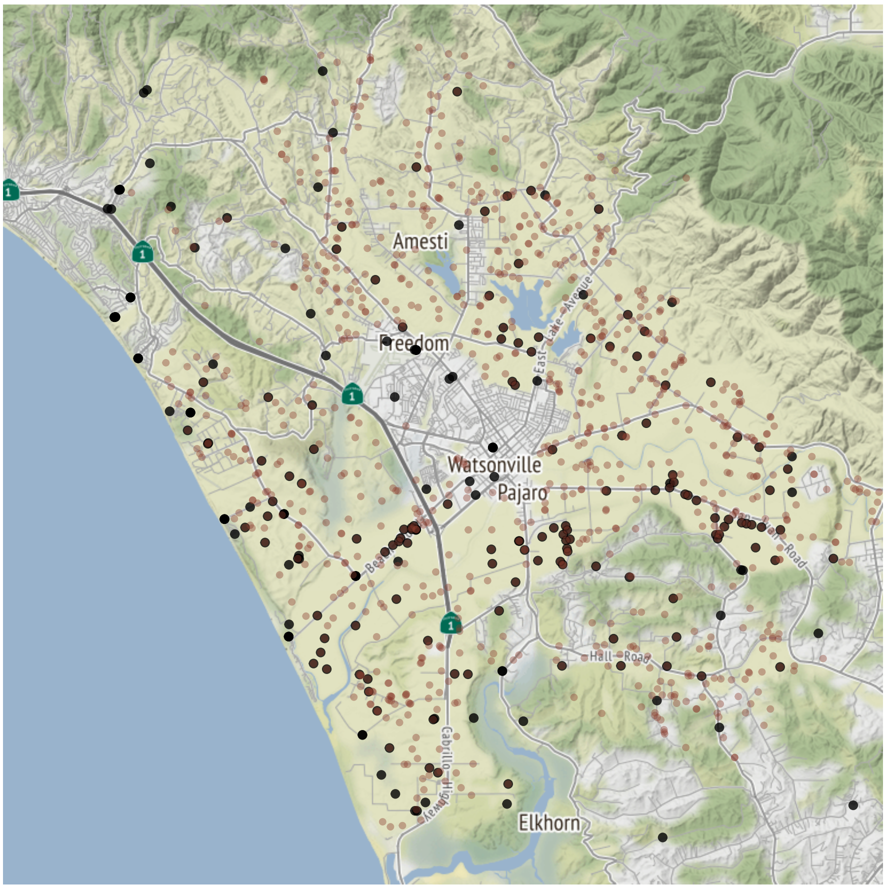
Pajaro Valley Water Management Agency has been collecting water quality data in the basin since 1957, and has built a network of 286 monitoring wells. The locations of these monitoring wells are depicted in Figure 5 as black dots, overlaid on top of all the metered wells in Pajaro Valley (shown as light brown dots). These monitoring wells are typically sampled twice annually, once in spring (March-May) and once in the fall (September-November). This sampling method captures water quality at two critical time periods: (i) spring is before the primary irrigation season, after winter rains and when water tables are the highest, and (ii) fall is after the main irrigation season, when water tables are the lowest. While PVWMA takes multiple salinity measurements, I use the total dissolved solids (TDS) measurement, as it is generally the most salient to growers. [5] For both fall and spring of each year, I take all water quality measurements of TDS and use an inverse distance weighting technique to interpolate a map of water quality for the entire Pajaro Valley. In the analysis, I focus on spring TDS, given that salinity before the growing season is considered to be the most important for agricultural water users, and is the most likely to predict summer basin conditions for growers.

Figure 6 shows the history of average spring TDS values spanning 2003-2020, highlighting seasonal salinity patterns in the basin. Averages for the delivered water zone and the rest of the Pajaro Valley are compared. For the full region, spring TDS levels averaged 645.9 mg/L and ranged from 272.4 mg/L to 17,103.7 mg/L. The dashed line at 600 mg/L represents the approximate average TDS level of the recycled water. As can be seen, average salinity levels in the basin are frequently lower than the TDS levels of the recycled water, except in years of very high salinity. The spikes in salinity, which are especially high within the delivered water zone, are largely caused by drought conditions: groundwater pumping stays relatively stable, but the lack of precipitation leads to less groundwater recharge. With less freshwater percolating through to the aquifer, TDS levels in the remaining water are higher, and seawater intrusion is more likely to occur.

As outlined above, there is significant variation in salinity across time. Importantly for our analysis, there is also spatial variation in salinity. This spatial variation is largely driven by inherent underlying characteristics of the aquifer, as well as distance to the coast and surface water sources. Parcel characteristics, such as soil properties, slope, and land elevation also play a role. Figure 7 shows average salinity levels across the Pajaro Valley basin from 2009-2020, plotted by decile. This figure indicates that inland regions, aside from those located near the Pajaro River, experience significantly lower levels of salinity, especially towards the

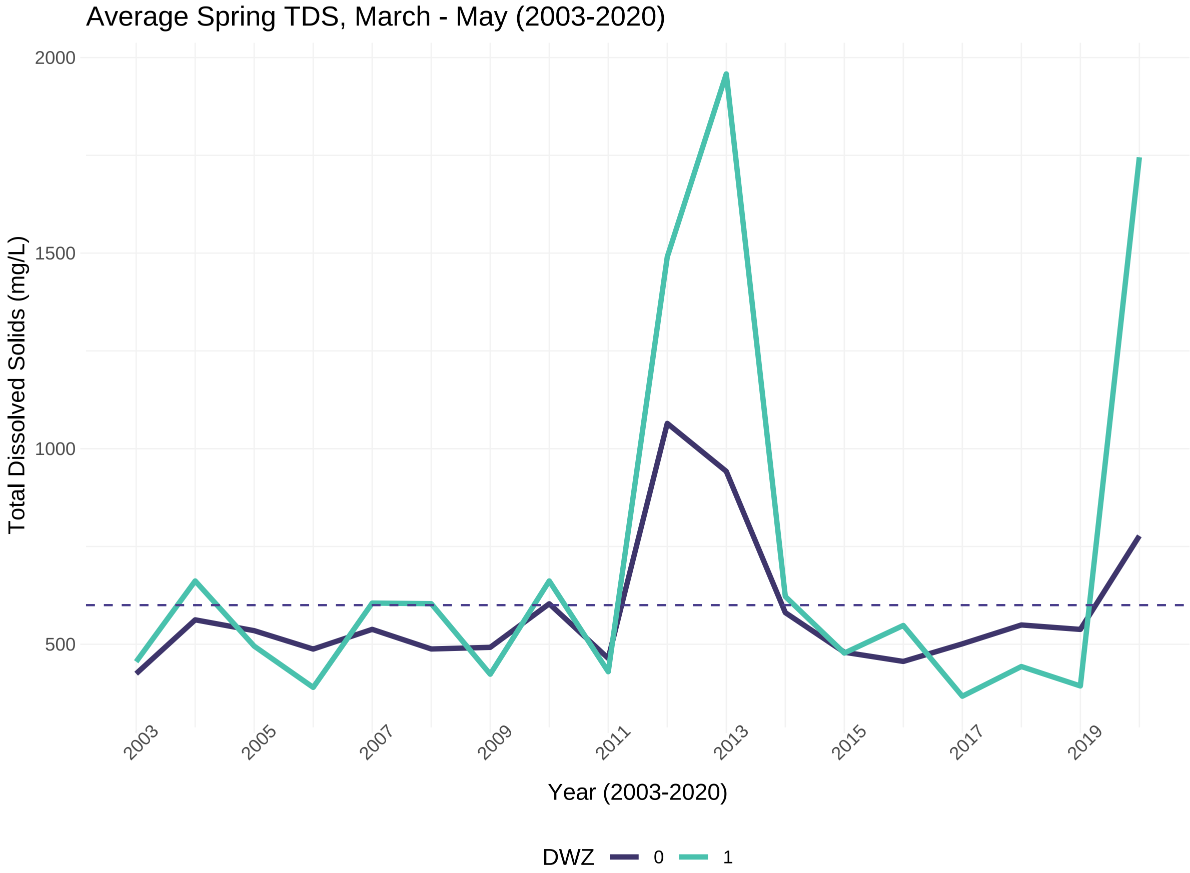
[5] Electrical Conductivity is highly correlated with total dissolved solids, and can typically be estimated from TDS using a simple conversion factor: 640 mg/L TDS = 1 ECw (dS/m), for ECw < 5 dS/m. Chloride is a salinity measure linked specifically to seawater, and is one component of the TDS measure. We chose TDS to look at total salinity (including chloride), since other salts, such as those found in recycled water, impact crop production in the same way. We perform robustness checks in a salinity damages mixed logit model with chloride in Sears, Bruno, and Hanemann (2021).

Figure 5: Metered and Monitoring Wells, Pajaro Valley, CA



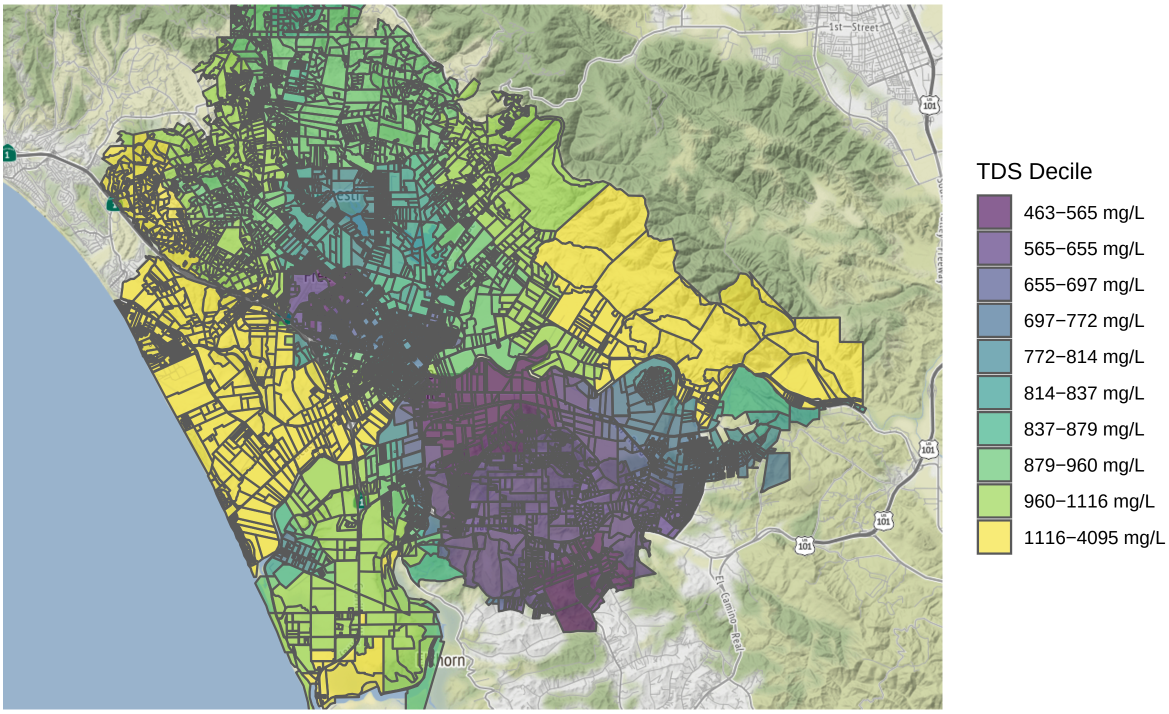
Note: Each light brown point depicts the location of a metered well in the Pajaro Valley, while each black dot represents monitoring wells used by PVWMA to determine water quality.

Figure 6: Average Spring Total Dissolved Solids (March-May), 2003-2020



Note: Figure shows average parcel-level spring TDS (mg/L) in groundwater from 2003 to 2020.

Figure 7: Spatial Variation in Total Dissolved Solids (TDS)



Note: The figure maps the average TDS (mg/L) from 2003-2020 for all parcels in the water agency service area. Values are interpolated from observations at monitoring wells and averaged across time. Each color represents a decile of average TDS.

south. Notably, the coastal region just north of the delivered water zone experiences some of the highest TDS levels, providing some initial evidence that recycled water may be having an impact within the delivered water zone.

An impressive feature of the data from Pajaro Valley are the data on annual land use, which covers the 2009 and 2011-2020 growing seasons. PVWMA visually inspects and records land use on an annual basis. PVWMA also engages in quality control practices, including randomly sampling parcels for additional checks. These ground-truthed land use data have key advantages over satellite data, which is known to have substantial error in measuring land use among California's unique crop set (Reitsma et al., 2016; Alix-Garcia and Millimet, 2020). Agricultural land use types include vegetable row crops, strawberries, blackberries and raspberries (caneberries), vine crops, artichokes, orchards, nursery crops, greenhouses, fallow ground, cover crops, and unknown agricultural use. Non-agricultural land use types include residential, industrial, natural habitat, and other. For the analysis, I join artichokes with vegetable row crops, blueberries and vine crops with caneberries, and cover crops and unknown agricultural land with fallow ground, given the limited number of parcels in each of these categories. [6]

These detailed land survey data are coupled with tax assessor ownership and parcel boundary data from the County Assessor offices to form appropriate decision units. These data delineate property boundaries and enable assignment of land use and groundwater quality to each farm at the land parcel level, designated by the Assessor's Parcel Number (APN) in the tax assessor data. The average size of a parcel is 33.94 acres. I also use ownership data from the County Tax Assessor to aggregate parcels to the ownership level.[7] This helps both with crop decision-making (such as capturing crop rotation if it occurs), and with water attribution. Since not every parcel has a well or recycled water turnout, but almost all parcels use groundwater or recycled water, I want to assign that parcel water from the most likely source, which would be a well or turnout on another parcel owned by the same person.

The definition of "agricultural land" is therefore a parcel with documented ownership information that has been designated by PVWMA at some point to have produced a crop, and has known access to water. To be classified as having known access to water, the parcel must contain a well or a recycled water turnout, or the owner of the parcel has a different parcel with well/turnout access. In order to provide a comparison point on how restrictive this definition is, we look at the tax assessor land use classifications. After filtering out land uses that involve residences, businesses, and industry, across Santa Cruz and Monterey counties there are 1653 parcels that could plausibly be in agriculture. After restricting the dataset to parcels that also

[6]In 2009, there was a large number of parcels labeled as "Unknown Agricultural Use" that may have corresponded to the time of sampling, which corresponds to a spike in "fallow" ground in that year. Robustness checks leaving 2009 out of the analysis lead to almost identical results.

[7]The data available on ownership vary slightly between Monterey and Santa Cruz counties. For Monterey, the owner's name(s) are listed, along with the share of the the parcel owned. For parcels with multiple owners, I use the parcel owner with the largest share as our "primary owner", and aggregate the parcels associated with their name. For Santa Cruz, owner names were not available, but mailing addresses were. Parcels are aggregated by their mailing addresses. Due to this limited information, if someone owns parcels in both Monterey and Santa Cruz counties, I am unable to link them together. Minor cleaning of names and addresses occurred to improve ownership matches.

have a clearly linked source of water, I'm left with 1048 parcels. Therefore, this is a relatively restrictive set of qualifications. While this could lead to an overestimation of water applied per acre for the parcels classified as being in agriculture, as described below, there is no evidence that this is biased in a particular direction for growers receiving delivered water. Moreover, the difference-in-differences analysis and event studies do not use quantities of recycled water delivered in their analysis.

There are 978 documented wells across Pajaro Valley and 102 recycled water turnouts in the DWZ, all with quarterly measurements of how much water was pumped or delivered. For all of the wells owned by the same owner, I pool the total water pumped and area-weight the water across all parcels planted in a crop during that year. I follow the same procedure for all turnouts owned by the same owner. This assumes that water needs across all crops are similar, which is largely the case for crops grown in the Pajaro Valley, which require between 2-3 acre-feet a year. I classify a parcel as using water if they are listed for an agricultural purpose that is not fallow. This includes "unknown agriculture". This does not include parcels that have no information on their agricultural status, making the assumption that PVWMA is capturing all agricultural fields.

I gather outside data to estimate crop prices and weather patterns. Data on temperature and precipitation are from PRISM Climate Data, which incorporates coastal weather patterns and land elevation into its projections. The data projections have approximately an 800 m resolution. I use the gridded data cell that lines up with the centroid of each of the parcels. I use averages of monthly mean temperatures and total precipitation in the spring of each year, at the parcel level. County Agriculture Commissioner Reports provide information on crop prices and revenue. Since several of the land use types include multiple crops, I take area-weighted averages of crop prices and revenue for each land use category, and average these across Santa Cruz and Monterey counties.

4 Direct Effects: Crop Choice Model

The following section evaluates the impact that recycled water has on growers that receive water deliveries using a discrete crop choice model. Growers receiving recycled water may see benefits of two forms: (i) their yields may improve with higher quality water, and (ii) they may be able to grow more salt-sensitive crops. To capture these benefits in tandem, I use a revealed preference, panel mixed logit model that evaluates the impacts of salinity and recycled water on crop choice, and calculates the willingness to pay for improvements in salinity. This framework also allows for a simulation to find the counterfactual crop choices without recycled water deliveries. The modeling framework, empirical strategy, and results of the model are detailed below.

4.1 Empirical Strategy

Spatially and time-varying data on groundwater quality, recycled water deliveries, and land use allow for the estimation of a panel mixed logit model to understand the impacts of salinity and recycled water on crop choices. The research design relies on observable changes in groundwater quality and recycled water deliveries, along with controls for observable and unobservable factors that may be correlated with both salinity, recycled water, and crop choice.

I take a similar approach to the working paper by Sears, Bruno, and Hanemann (2021) that estimates damages associated with groundwater salinity. Building on these methods, this approach differs in a few key ways. Most importantly, I consider only parcels that can be clearly linked to a source of water, since the analysis specifically accounts for recycled water deliveries. Additionally, part of the water assignment structure involves adding in tax assessor data to the model, and standard error clustering at the ownership level. This helps account for decision-making on crop rotations, allocation of water across parcels, and crop diversification that may occur. Finally, I allow for an unbalanced panel of parcels in agriculture: a parcel is able to leave agriculture and is still counted in the analysis up until the point of departure.

For each parcel i, a grower chooses a crop type j in year t. I assume the grower is profit maximizing and that each parcel produces a single crop (fallow ground, strawberries, vegetables, caneberries, orchards, or nursery crops). Profits for a given crop j depend on the output price p_{jt} and the crop yield Y_{ijt}. Crop yields are a function of groundwater quality s_{it}, recycled water deliveries w_{it}, and other factors to production Z_{it}. Production functions are assumed to be differentiable and exhibit diminishing marginal productivity to variable inputs, such that

$\frac{\partial f_j}{\partial s_i} < 0$ and $\frac{\partial f_j}{\partial w_i} < 0$ for all $j = 0, .., K$, and $\frac{\partial f_j}{\partial s_i} \neq \frac{\partial f_k}{\partial s_i}$ and $\frac{\partial f_j}{\partial w_i} \neq \frac{\partial f_k}{\partial w_i}$.

A grower chooses the crop that yields the greatest profit. Therefore, across crop choices $j = 0, 1, ..., K$, the optimal crop choice is the one that yields the highest profit for given levels of s_{it}, w_{it}, p_{it}, and Z_{it}. I set the outside option $j = 0$ to be fallow ground, and normalize its profits to zero. The choice problem is:

$$\Pi_{it} = \max_j \left\{ \Pi_1^*(s_{it}, w_{it}, Z_{it}, p_{jt}), \ldots, \Pi_j^*(s_{it}, w_{it}, Z_{it}, p_{jt}), \ldots, \Pi_K^*(s_{it}, w_{it}, Z_{it}, p_{jt}) \right\} \tag{1}$$

The probability of choosing crop j in year t is therefore:

$$\rho_{ijt} = Prob[\Pi_j^*(s_{it}, w_{it}, Z_{it}, p_{jt}) > \Pi_k^*(s_{it}, w_{it}, Z_{it}, p_{jt})], \forall j \neq k \tag{2}$$

Profits can be estimated by:

$$\pi_{ijt} = \theta_j s_{it} + \omega_j w_{it} + Z_{it}'\gamma + \alpha p_{jt} + D_{jt}'\beta_i + \delta_t + \chi_c + \epsilon_{ijt} \tag{3}$$

where θ_j and ω_j estimate crop-specific impacts from changes in groundwater salinity and recycled water deliveries. γ is a vector of coefficients that captures the effects of parcel-specific characteristics on crop choice, including: parcel size, distance to the coast, temperature and precipitation, depth to the groundwater table, lagged crop choice, and water prices. The impact of lagged crop prices are described by α and assumed to be valued in the same way across parcels. D_{jt} is an indicator for the crop grown. In the mixed logit model, its coefficient, β_i is allowed to vary randomly and with parcel-level characteristics Z_{it}, w_{it} and s_{it}. The time trend δ_t captures linear basin-wide trends over time, and χ_c captures county fixed effects.

If the unobserved component, ϵ_{ijt}, is assumed to be distributed i.i.d. extreme value, and if the profits of the outside option are set at 0, then the probability of choosing the jth crop can be written as:

$$\rho_{ijt} = \frac{e^{\pi_{ijt}}}{\sum_{j=0}^{K} e^{\pi_{ijt}}} = \frac{e^{\pi_{ijt}}}{1 + \sum_{j=1}^{K} e^{\pi_{ijt}}}, \tag{4}$$

where the parameters can be estimated by maximum likelihood. The panel mixed logit structure model avoids invoking the Independence of Irrelevant Alternatives (IIA) assumption that troubles multinomial and conditional logit models (McFadden and Train, 2000; Nevo, 2000), which is particularly important in a setting with perennial crops and repeated observations over time.

The mixed logit model provides the framework for the direct welfare estimates of the delivered program. Under this structure, a simulation is run that estimates growers' crop choices if they did not have access to recycled water, and estimates welfare with and without the water deliveries. In addition, the estimates from the mixed logit model provide willingness-to-pay (WTP) estimates for improved water quality by crop, by dividing the marginal utility of reducing salinity by the absolute value of the parameter estimate on crop price α. Identification of the WTP hinges on the assumption that, conditional on the suite of relevant spatial and time-varying parcel-level observables and an annual time trend, unobservable factors are not correlated with both salinity levels and crop prices.

4.2 Identification Concerns

One potential concern with this analysis is that groundwater salinity may be endogenous to crop choice, if salinity is controllable by an individual farmer. While soil salinity problems can often be managed by an individual grower, provided that they have enough freshwater to leach salts out of the root zone, groundwater salinity is harder to influence. Groundwater salinity is largely based on unobserved hydrological and transmissivity properties of the underlying aquifer, along with recharge rates from precipitation and runoff, distance to the coast, and aggregate basin-wide groundwater pumping. In the crop choice model, I explicitly control for groundwater pumping, depth to groundwater, temperature, and precipitation.

It is also possible that basin-wide groundwater pumping may be influenced by other unobserved economic factors that also impact crop choice. I control for the distance to the coastline, since this is an important determining factor of soil texture and the spatial distribution of salinity in the Valley, and because coastal micro-climates determine how well crops grow in certain areas. Features of the parcel, such as its size and crop history, are also likely to influence planting decisions and could be correlated with salinity. The inclusion of a linear time trend accounts for basin-wide unobservables that may trend linearly with both salinity and crop choice over time. Finally, the inclusion of county fixed effects and time and parcel random effects can combat regional effects that may be correlated with salinity.

To identify the impacts of recycled water on crop choice, there may also be concerns about how recycled water is allocated. Conditional on being in the delivered water zone, assignment of recycled water is somewhat random: parcels that lie on the currently constructed portion of the Coastal Delivery System are the only parcels able to receive water deliveries. Growers apply for their recycled water turnout to be turned on. Application acceptance is conditional on whether there is excess recycled water available to serve the needs of all current users, and on underlying groundwater salinity. Recycled water availability depends on facility capacity, which has slowly increased over time. Finally, while underlying groundwater salinity does impact application acceptance, a parcel's groundwater salinity is not highly correlated with its impact on the aquifer salinity: i.e. the positive or negative externality from recycled water deliveries or groundwater pumping to neighboring parcels is not well-linked to a parcel's own salinity levels. This is especially important for the identification of the DiD and event studies, since salinity is explicitly controlled for in the crop choice model.

Finally, it's important to note that the outside option in the choice model is fallow land, rather than land that leaves agriculture. I drop parcels from the sample after they leave agriculture permanently. This is standard in the crop choice modeling literature, largely because it is difficult to think about comparing annual profits to a lump sum payment received when exiting agriculture. However, it does limit the model to thinking about relatively short-run effects of salinity damages. It is plausible that a grower experiencing dramatic increases in groundwater salinity may not believe that water quality will improve or that they will receive recycled water on a fast-enough timeline to remain in business. In the appendix, I use linear probability models to test this hypothesis, finding that increases to salinity are not significantly linked to parcels leaving agriculture.

4.3 Results

Results from the crop choice model are presented in Table 3. Column 1 shows the basic conditional logit estimates and Column 2 presents the mixed logit results, which is the preferred specification and has a lower AIC. The table reports crop-specific estimates of the effect of groundwater salinity, where salinity is measured as the total dissolved solids (1000 mg/L) from March-May of the growing season. In the mixed logit, the coefficients on the crop indicator variables are treated as random variables and are allowed to vary across parcels. Their coefficients and estimated standard deviations are also reported in the table, while coefficients on additional independent variables are suppressed. Standard errors are clustered by owner. I control for parcel-specific factors that directly affect salinity, including the depth to the groundwater table, groundwater pumping, the cumulative precipitation from March-May of the growing year, and the average mean daily temperature from March-May of the growing year. Also included are factors related to the parcel that may affect crop choice, including the parcel size, recycled water deliveries, distance to the coastline, and additional aggregate controls for agency's water pumping fee and a linear annual trend. All reported coefficients are relative to fallow ground, which increases in response to an increase in salinity.

Results demonstrate that, compared to fallow ground, an increase in groundwater salinity decreases the probability that a farmer will grow a high-value, salt sensitive crop. We see the largest effects among vegetables, strawberries, and caneberries, the most profitable and some of the most salt-sensitive crops grown in the region.

Since not all crops in our choice set are grown in the delivered water zone, the clearest way to evaluate the impact that recycled water has on crop choice is to look at the marginal effects of changes in salinity on crop choice for parcels that do and do not receive recycled water deliveries. These results are presented in Figure 8. Results are presented for each of the major crops that are grown both inside and outside of the delivered water zone, for three levels of TDS: 500, 1000, and 1500 mg/L. These are all relatively moderate levels of salinity: enough to impact yields, but not enough to completely destroy a crop. We see that parcels receiving water deliveries are much more likely to plant strawberries or nursery crops at all levels of salinity, and are slightly less likely to plant vegetables.

Table 3: Crop Choice Model

	Cond. Logit	Mixed Logit
Ave Price$_{t-1}$	5.58e-07***	4.25e-07***
	6.96e-08	(1.74e-07)
Vegetable	7.13***	3.13*
	(1.14)	(1.67)
Strawberry	11.58***	9.29***
	(1.08)	(1.38)
Caneberry	-6.96***	-13.92***
	(1.74)	(2.97)
Orchard	-16.96***	-10.44*
	(2.72)	(5.72)
Nursery	4.86**	2.99
	(1.92)	(3.63)
Vegetable SD		1.48
		(0.13)
Strawberry SD		0.83
		(0.12)
Caneberry SD		2.95
		(0.19)
Orchard SD		6.02
		(0.59)
Nursery SD		4.55
		(0.47)
Vegetable TDS	-0.040	-0.093*
	(0.036)	(0.051)
Strawberry TDS	-0.085**	-0.065*
	(0.036)	(0.040)
Caneberry TDS	-1.38***	-0.55**
	(0.26)	(0.26)
Orchard TDS	-1.91	-0.38
	(-1.91)	(0.31)
Nursery TDS	-0.00061	0.046
	(0.037)	(0.050)
Num of Obs.	55278	55278
Log Likelihood	-12299.013	-9462.3503
AIC	24720.027	19066.701
Delivered Water$_{t-1}$	X	X
Pumped Water$_{t-1}$	X	X
Crop Choice$_{t-1}$	X	X
Depth to Water & Water Price	X	X
Temp & Precip	X	X
Parcel Size & Dist. to Coast	X	X
County FE	X	X
Year	X	X

Regressions are discrete choice models, looking at land use choice by parcel. The baseline land use choice is fallow ground, which increases in magnitude over the course of our sample period.
Robust (clustered by owner) standard errors in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

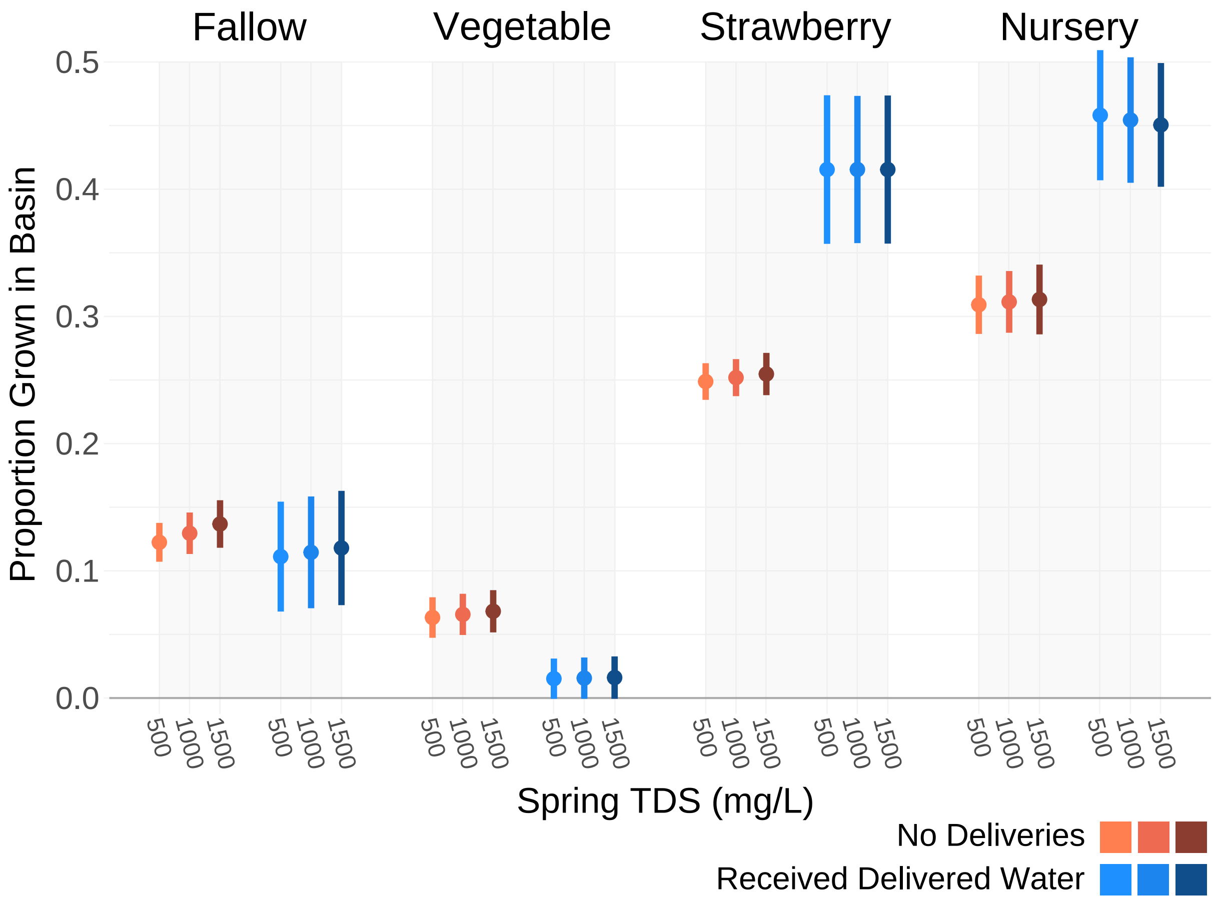


Figure 8: Marginal Effects of the Crop Choice Model, by Crop and by Water Source

Anecdotally, when talking with growers in the Pajaro Valley, they stated that the recycled water is allowing them to grow strawberries in locations where the water quality was previously too poor. While this anecdotal evidence is clearly encouraging, I test this using the panel mixed logit structure by running a simulation that looks at how crop choices change for the parcels receiving delivered water if those deliveries no longer existed. I simulate and compute the annual utility-maximizing crop choices for each parcel under a scenario where there are no direct recycled water deliveries. To do this, I keep the estimated marginal utilities for the attributes of crops, parcels, and climate variables the same as in the panel mixed logit model in Table 3. For each parcel that currently receives recycled water, I estimate the probability of choosing each crop type and use these to predict each parcel's baseline crop choice. Then, the simulation recalculates the probabilities of each crop being grown for these parcels after removing the water deliveries to reflect the no recycled water scenario.

The differences in the estimated crop choice distribution is plotted in Figure 9, depicting which crops are chosen in the face of an elimination of recycled water. There is a dramatic increase in the amount of fallow ground, and significant declines in strawberry acreage and vegetables. There is an increase in nursery crops, which are the most salt tolerant. Caneberries and orchards are not frequently planted in the delivered water zone, and experience virtually no change.

To put the losses from planting lower value crops (or no crops) into dollar terms, I estimate how welfare shifts for growers who no longer receive delivered water. Following the procedure outlined by Small and Rosen (1981), where a change in welfare corresponds to the compensating variation for the removal of the recycled water program, expected welfare is defined as:

$$E[W_i] = \frac{1}{|\alpha|} \ln \sum_j \exp(\pi_{ijt}) \tag{5}$$

I estimate the welfare under the current scenario, and then re-estimate welfare with respect to the new predicted choices made under the program removal. The difference in welfare is shown in Figure 10. Across the subset of parcels that have received recycled water, there is a significant decline in welfare when the program is removed. This is expected, as growers are now required to use their highly saline water to produce crops, and make crop choices that

Figure 9: Estimated and Simulated Changes in Crop Choice under Removal of Recycled Water Program

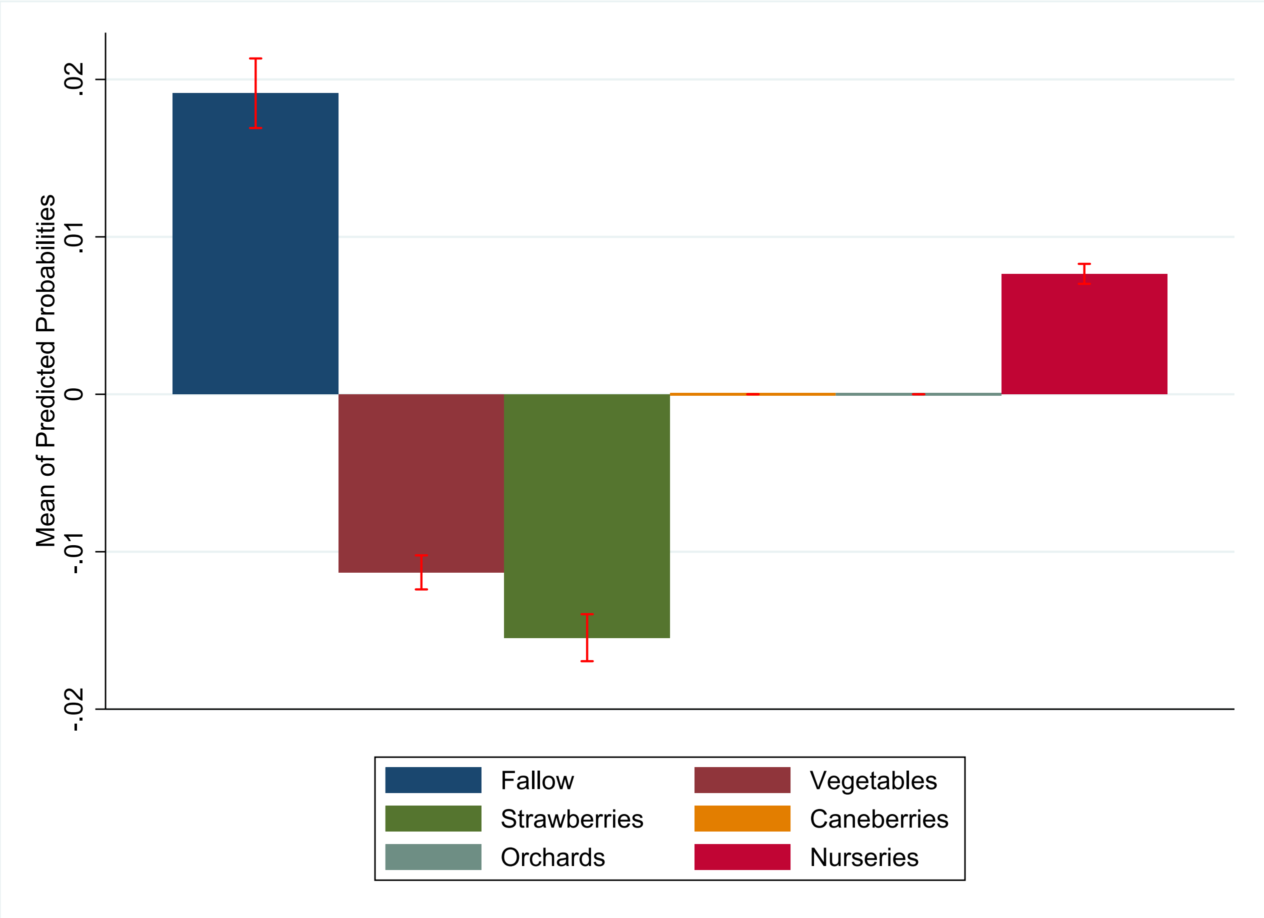
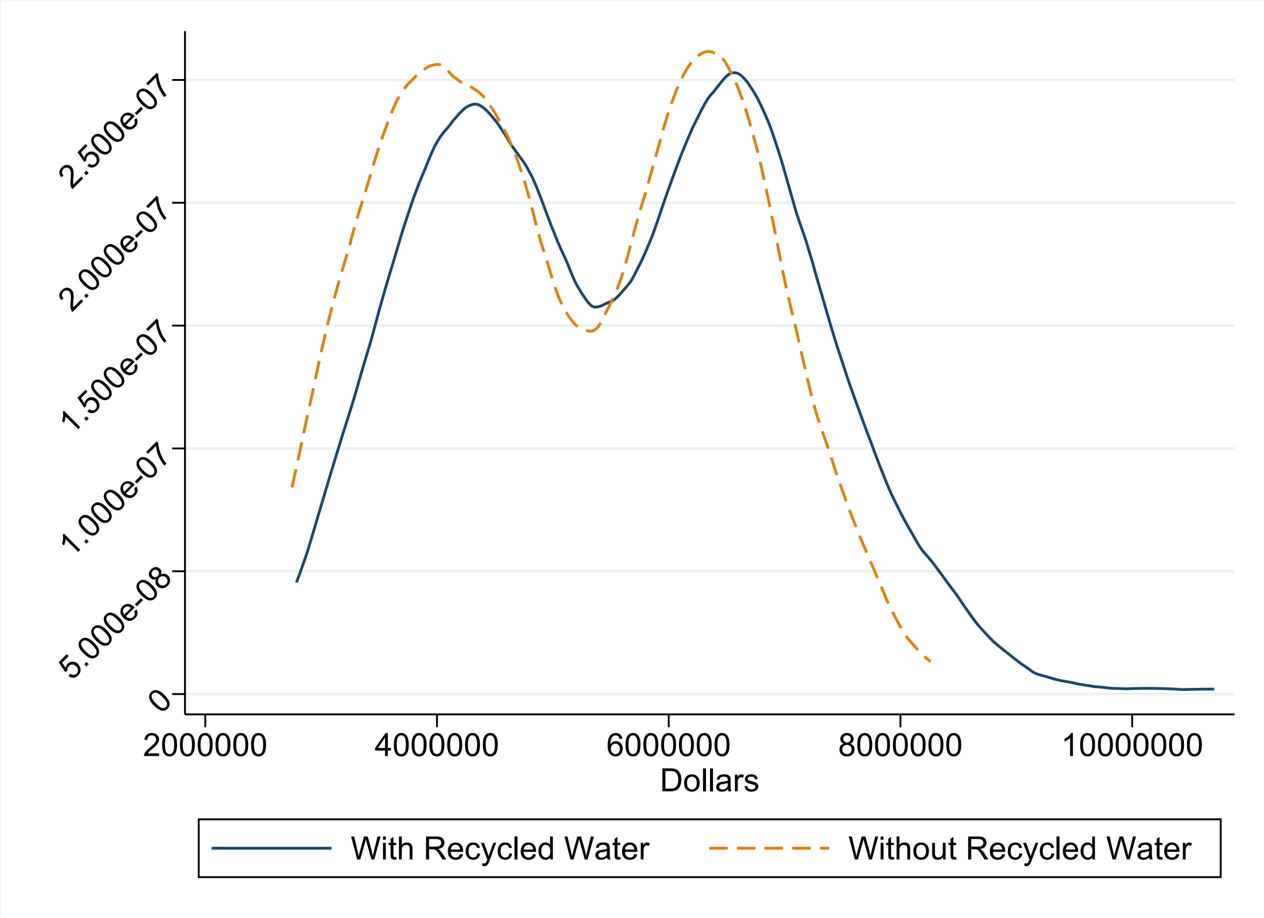


Figure 10: Kernel Density of Welfare with and without Recycled Water Program, for Parcels Receiving Delivered Water



are lower value but more robust to salinity, or choose to not grow a crop altogether. In total, I estimate that the direct welfare loss for growers no longer receiving recycled water amounts to \$176 million across 471 parcels. This translates to a welfare loss of approximately \$16 million annually.

Finally, the estimates from the crop choice model allow me to estimate growers' willingness to pay (WTP) for a reduction in groundwater salinity. I focus on crops whose estimates in Table 3 were significant at the 95% confidence level or greater, namely, vegetables, strawberries, and caneberries. The willingness to pay estimates for a reduction in groundwater salinity of 10 mg/L are reported in Table 4, on a dollar per acre basis, as well as the 95% confidence interval of the estimates. While these willingness-to-pay estimates are wide-ranging, the high dollar

Table 4: Willingness to Pay, for a 10 mg/L Reduction in TDS

	Willingness to Pay 10 mg/L reduction	Std. Error
Vegetables	$ 2475.88	$ 991.36
Strawberries	$ 1737.88	$ 850.60
Caneberries	$ 13136.92	$ 5564.39

Note: This table reports the estimated willingness to pay for a 10 mg/L reduction in TDS. Estimates are based on the panel mixed logit model presented in Table **??**. Units are in dollars per acre. The standard error is calculated using the delta method.

values suggested by strawberries and caneberries indicate that growers highly value water with low salinity levels. The magnitude of these willingness-to-pay estimates are relatively high. Using the (Grattan, 2002) estimates of crop responses to salinity, a 10 mg/L increase in salinity would be likely to decrease revenue for strawberries by approximately $446 dollars per acre, which is within the WTP range calculated here, but on the lower side.[8]

5 Indirect Effect Results: Impacts of Recycled Water to the Aquifer

The crop choice model above estimates the direct benefits to growers receiving recycled water deliveries, determining if growers are able to grow salt-sensitive, higher value crops. However, the model cannot capture the impacts of the recycled water on the underlying water quality. These impacts are paramount to understanding the effect recycled water has on mitigating seawater intrusion, and that benefits that may be gleaned by other users of the groundwater supply. I estimate these impacts in three ways. First, I conduct a simple, parcel-specific fixed effects regression, using the 2009-2020 data used in the same analysis as the crop choice model. Next, I use the extended water quality, recycled water, and water pumping data from 2003-2020 to estimate a staggered differences-in-differences model, where treated parcels are those that start receiving regular deliveries of recycled water. Finally, I implement an event study framework to evaluate how recycled water impacts water quality over time.

[8] This back-of-the-envelope calculation assumes that salinity levels are above the threshold (450 mg/L) where strawberry yields are negatively impacted.

5.1 Empirical Strategy

5.1.1 Fixed Effects Model

I start by considering a simple fixed effects model for two reasons. First, I want to look at how marginal increases in delivered water impact groundwater quality. Secondly, it is worth looking at a specification that matches as closely to the crop choice dataset as possible, even if the subsequent regressions have a longer time horizon. The structure of the fixed effects regression is:

$$\text{TDS}_{it} = \beta\text{Recycled}_{it-1} + \gamma\text{Well}_{it-1} + \rho\text{Temp}_{i,t-1} + \chi\text{Precip}_{it-1} + \delta\text{Crop}_{it-1} + \tau_i + \epsilon_{it} \quad (6)$$

where Recycled_{it-1} is the lagged annual quantity of delivered water to a parcel. As described in the data section, a parcel is assumed to have received delivered water if a turnout located within a parcel's boundaries receives delivered water, or another parcel owned by the same owner receives water from a turnout (which are designed to have the capacity to serve multiple parcels). All water that an owner receives is divided across all their parcels, area-weighted by the size of the parcel. I apply the same weighting methodology to Well_{it-1}, which is lagged pumped well water. We also lag spring average temperatures and precipitation (Temp_{it-1} and Precip_{it-1}, and include lagged crop choices and parcel fixed effects. Lagged crop choices are included since differences in management practices and crop characteristics may influence how water leaches through the groundwater system.

In an effort to construct a regression that is as similar as possible to the panel mixed logit model estimating damages from salinity, I estimate a regression without parcel fixed effects but including the same control variables implemented in the prior regressions:

$$\text{TDS}_{it} = \alpha + \beta\text{Recycled}_{it-1} + \gamma\text{Well}_{it-1} + \rho\text{Temp}_{it-1} + \chi\text{Precip}_{it-1} + \delta\text{Crop}_{it-1} + \omega\text{Coast}_i + \lambda\text{Size}_i + \epsilon_{it} \quad (7)$$

The basic fixed effects model provides a useful link to the crop choice model, and conveys important information about the impact of marginal changes in recycled water deliveries. However, this model does not take advantage of the full dataset or of the slow rollout of the recycled water deliveries. Therefore, I use staggered difference-in-differences and event studies to take a longer-term view of the recycled water impacts.

5.1.2 Staggered Difference-in-Differences Model

Water deliveries started in 2002, to three (of 102) turnouts, and slowly increased over time, as the recycled water facility was built and as storage capacity increased. The Coastal Delivery System broke ground in 2005, and has slowly expanded as funding becomes available. For example, an additional 700 acres were connected to the pipeline in 2020. Receiving recycled water deliveries is conditional on having a pipeline (and turnout), and enough system capacity to add a parcel's water needs to the system. Once a turnout starts delivering water, water deliveries continue to be delivered annually to the same parcel 96% of the time, effectively continuing to the treat the parcel over the course of the sample period. While recycled water deliveries have continued to increase over time, the majority of the turnouts were delivering some water by 2007. To determine the effect of recycled water deliveries on the underlying groundwater quality of the parcel, I begin by estimating the following difference-in-differences model under staggered adoption:

$$TDS = \beta Treated + \gamma Well_{i,t-1} + \rho Temp_{i,t-1} + \chi Precip_{i,t-1} + \delta Crop_{i,t-1} + \tau_i \qquad (8)$$

where $Treated$ is an indicator that takes the value of one after a parcels starts received delivered water in a quantity of greater than 1 acre-ft a year. [9] For reference, the median quantity of delivered water to a parcel is 21 acre-ft. The coefficient β measures the difference in the change in Spring TDS for parcels that have received recycled water relative to the change in TDS for parcels that had yet to receive or never implemented water deliveries, after controlling for owner and time-varying factors that also correlate with salinity. In this way, β provides an estimate of the average treatment effect for treated parcels (ATT). This empirical approach allows for identification of the relationship between recycled water deliveries and annual changes in

[9] There are twelve parcel-year observations that deliver greater than 0 acre-ft, but less than 1 acre-ft, which is (some percent) of the sample.

salinity, while also explicitly controlling for other confounding factors that are specific for each group of parcels owned, as well as for time-varying factors. Owner-by-year fixed effects are controlled for by τ_{it}.

The recycled water effect β is identified under the assumption that, after controlling for pre-trends, annual trends, and time-invariant owner characteristics, recycled water deliveries are as good as random. Equivalently, the annual salinity changes in parcels that had yet to receive recycled water are what the change in groundwater quality would have been for parcels who never receive delivered water.

5.2 Event Study

I next turn to an event study framework, as it can provide insight beyond staggered difference-in-differences, capturing the dynamic relationship between recycled water and groundwater salinity. Moreover, it has advantages in identification that staggered difference-in-differences methods may struggle with. Staggered DiD may not provide valid estimates of average treatment effects, since already treated units may effectively act as control units at later points in time. The estimated average treatment effect ends up as variance-weighted averages of several treatment effects (Goodman-Bacon, 2021). An event study framework can modify which units act as controls, so that parcels receiving recycled water are not compared to those receiving water in the past (Baker et al., 2021).

The setup of the event study is very similar to the staggered DiD, except that the difference-in-differences estimator is decomposed into $\bar{h} - \underline{h} - 1$ coefficients, as shown:

$$\text{TDS}_{ikt} = \sum_{h=\underline{h}}^{\bar{h}} \beta_h \text{Years Since}_{it}^{h} + \gamma \text{Well}_{it-1} + \rho \text{Temp}_{it-1} + \chi \text{Precip}_{it-1} + \delta \text{Crop}_{it-1} + \tau_{kt} + \epsilon_{ikt} \quad (9)$$

where

$$\text{Years Since}_{it}^{h} = \begin{cases} \mathbb{1}\{t \leq Treated_i + h\} \text{ if } h = \underline{h} \\ \mathbb{1}\{t = Treated_i + h\} \text{ if } \underline{h} < h < \bar{h} \\ \mathbb{1}\{t = Treated_i + h\} \text{ if } h = \bar{h} \end{cases} \quad (10)$$

The individual coefficients show the impact of being h years out, relative to the initial delivery of recycled water. The endpoints $\underline{h}$ and $\bar{h}$ are binned to include all dates before $\underline{h}$ and after $\bar{h}$, in order to make sure that the treatment effects are identified separately from time trends. The event-time effects are identified under identical conditions as the difference-in-differences model.

In addition, I am interested in how aquifer water quality is changed for parcels neighboring those that receive recycled water deliveries, but do not directly receive delivered water themselves. In this case, Treated_i is equal to 1 when a neighboring parcel first starts receiving delivered water in excess of 1 acre-ft a year. Otherwise, the structure remains the same as in Equation 9.

5.3 Results

5.3.1 Fixed Effects Model

To evaluate the indirect effects of the recycled water program, I see how recycled water deliveries impact the quality of the underlying groundwater aquifer. First, I look at an exploratory fixed effects model, using largely the same structure and data as the crop choice model. All estimates can be found in Table 5. Generally, the significance and coefficients on the control variables are in line with expectations. Of note, using more pumped groundwater does not have a significant impact on an individual parcel's groundwater quality, which is important for the identifying assumptions of the crop choice model: growers do not have a significant individual impact on their own water quality.

The coefficients on the lagged delivered water are highly similar, but the estimation with the parcel fixed effects have higher standard errors. I weakly find that a one acre-ft increase in recycled water lowers groundwater salinity by 0.7 mg/L. While the signs (and slight significance) on the delivered water coefficients are encouraging, this is unlikely to be enough to make any sort of sweeping claim on the effectiveness of recycled water, much less use these estimates in further analysis of the cost effectiveness of the recycled water program. Therefore, we turn towards staggered differences-in-differences and event study methods.

Table 5: Effects of Delivered Water on Groundwater Salinity, Fixed Effects Estimation

	Dependent variable:	
	Spring TDS (mg/L)	
	(1)	(2)
Well_{t-1}	0.032	0.399
	(0.216)	(0.369)
Recycled_{t-1}	-0.760^{*}	-0.709
	(0.409)	(0.455)
$\text{Spring Precip}_{t-1}$	1.217^{***}	1.760^{***}
	(0.222)	(0.161)
Spring Temp_{t-1}	-101.439^{***}	-46.785^{***}
	(10.088)	(8.748)
Depth_{t-1}	0.247	-17.056^{***}
	(1.551)	(1.658)
Area	0.00002^{**}	
	(0.00001)	
Distance to Coast	-0.041^{***}	
	(0.008)	
Water Price_{t-1}	-1.646^{***}	-1.315^{***}
	(0.481)	(0.235)
Vegetables_{t-1}	98.184^{**}	114.481^{***}
	(44.814)	(42.131)
$\text{Strawberries}_{t-1}$	78.934^{*}	113.162^{***}
	(47.459)	(42.703)
Caneberries_{t-1}	2.630	141.837^{***}
	(39.712)	(39.665)
Orchard_{t-1}	-216.297^{***}	89.778^{**}
	(53.580)	(42.004)
Nursery_{t-1}	183.451^{*}	272.837^{*}
	(100.302)	(165.255)
Constant	$3{,}259.140^{***}$	
	(265.128)	
Parcel FE		X
Observations	9,370	9,370
R^2	0.074	0.322
Adjusted R^2	0.073	0.226
Residual Std. Error	924.527 (df = 9356)	844.981 (df = 8207)

Note: Regressions evaluate how groundwater salinity (measured by Total Dissolved Solids) changes with increases in delivered, recycled water. The control variables and time horizon match the crop choice model presented in Table 3. *p<0.1; **p<0.05; ***p<0.01

5.3.2 Differences-In-Differences

The results from the difference-in-differences specification are presented in Table 6. Results suggest that a parcel that receives delivered water will see a 218.9 mg/L improvement in their water quality. This is a significant improvement, corresponding to approximately a 10% yield improvement in strawberries (if the salinity is higher than the 480 mg/L threshold), or a 5% yield improvement in orchard crops (if salinity is higher than the 640 mg/L threshold). This kind of improvement in water quality is both impressive and realistic, as salinity levels do vary that much from the beginning to the end of the growing season for many parcels.

While these results are encouraging, it is important to compare these results with the event study, to combat the concerns about the interpretation of staggered difference-in-differences methods. In addition, it allows us to see where the improvements are occurring in time, and whether or not they stay consistent.

5.3.3 Event Study

Results of the event study specification outlined in Equation 9 are shown in Figure 11. The overall treatment effect suggests that water quality improves by -239 mg/L after receiving recycled water deliveries. This is a similar magnitude as the DiD results, which had an overall treatment effect of -219 mg/L, and suggests that the staggered DiD results may not be overly biased. It is also useful to note the pre-trends in the event study, which are insignificant from zero, and are also an important identification requirement for the difference-in-differences estimates.

Perhaps the most striking results of the event study are the significantly negative spikes in years 7-9, as well as in year 15. On first glance, it is not immediately intuitive why treatment effects would be zero (or slightly positive) for the first six years, and then have a highly significant effect in improving water quality in year seven. However, when we look specifically at treatment timing and salinity levels in the region, the results fall into place. The median time in which an eventually treated parcel receives its first delivery is 2006. This means that on average, a parcel reaches treatment year seven in 2013, which corresponds to a massive increase in salinity in the delivered water zone, as shown in Figure 6.

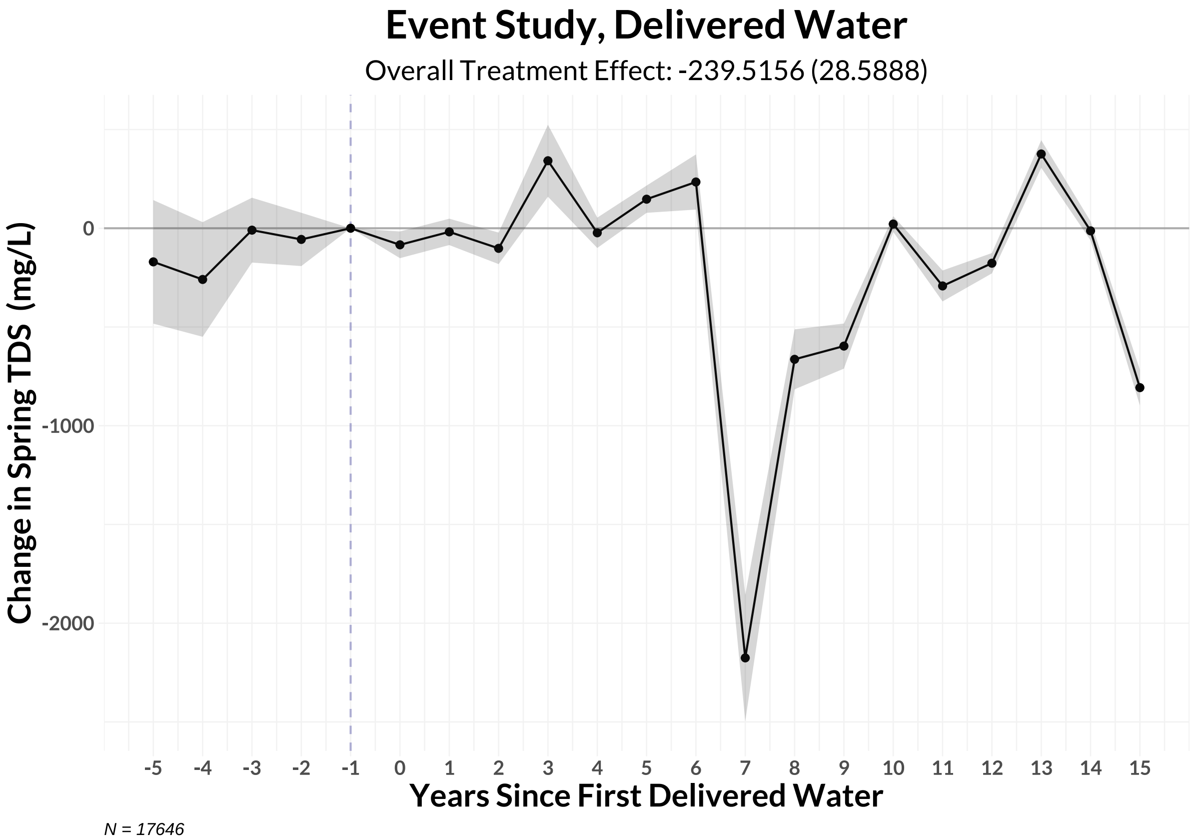
Table 6: Effect of Delivered Water on TDS

Dependent Variable:	SpringTDS
Model:	(1)
Variables	
Treated	-218.9***
	(38.97)
Well_{t-1}	0.0966
	(0.1549)
Temp_{t-1}	-41.59
	(74.04)
Precip_{t-1}	-0.0770
	(0.4248)
Fixed-effects	
Year×Owner	Yes
Fit statistics	
Observations	17,646
Adjusted R^2	0.71605

Two-way (County & Year) standard-errors in parentheses

Signif. Codes: ***: 0.01, **: 0.05, *: 0.1

Figure 11: Event Study Results



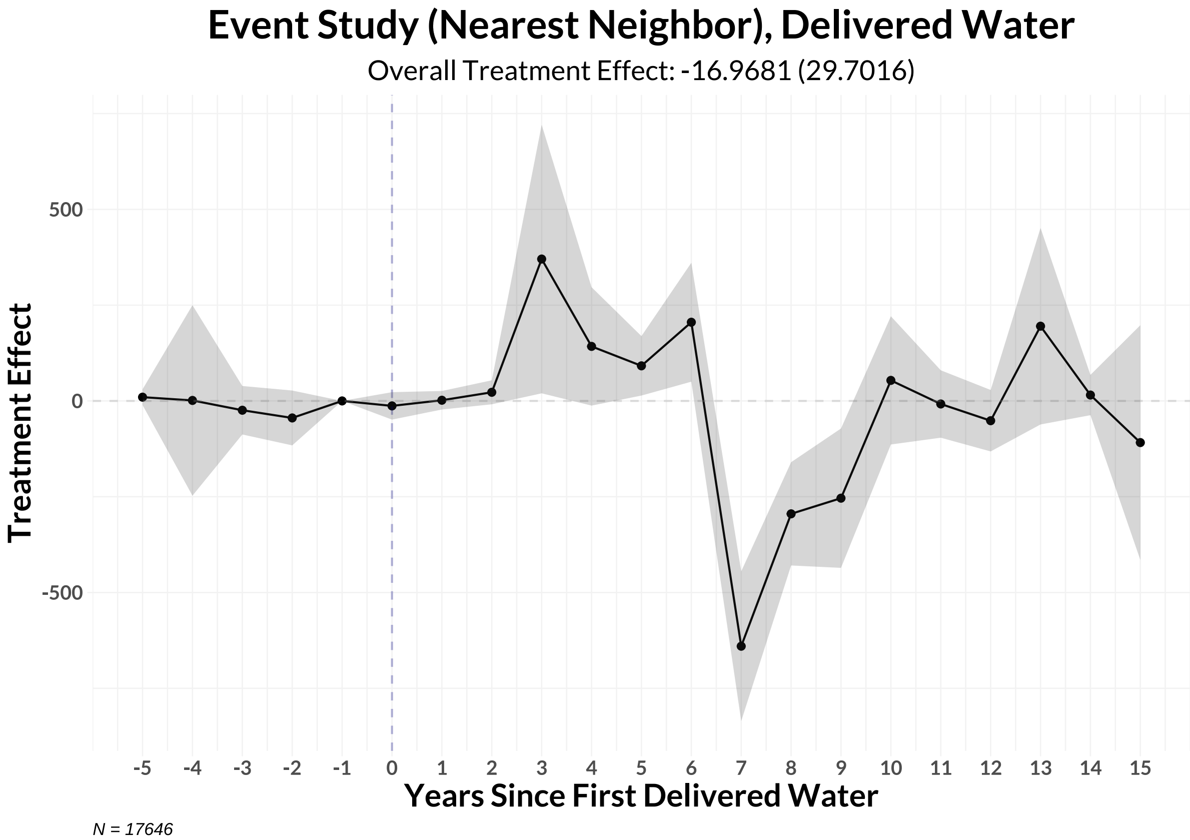
Scientifically, this makes sense: recycled water is going to have a bigger impact in improving water quality in years when the groundwater salinity is exceptionally high, especially when the quantity of recycled water is a much smaller fraction than the water in the groundwater basin. Moreover, the average TDS of the recycled water is frequently higher than the average TDS level in the delivered zone, as depicted by the dashed line in Figure 6. In fact, the only years in which recycled water quality is much higher than the average aquifer quality is in 2012-2013 and 2020. Therefore, we would expect that recycled water would significantly improve underlying water quality in those years, which is what is reflected in the event study figure.

The results for the neighboring parcels are presented in Figure 12. This figure reports similar, but attenuated, findings to the water quality results directly underneath treated parcels. Across the board, confidence intervals are a bit noisier, but pre-trends are still at zero. The overall treatment effect is no longer significant, but water quality improvements up to 570 mg/L are reported in years 7-9 after the first recycled water deliveries. These effects are arguably the most interesting when considering the indirect benefits of the recycled water program. Although growers that receive recycled water deliveries still use some water from the underlying aquifer, growers without delivered water are the ones truly reaping the benefits from increased aquifer water quality.

I use the event study results for the neighboring parcels to make a back of the envelope calculation of the benefits of recycled water on the aquifer. This allows for the most conservative estimate: there is no "double-counting" of the benefits for producers who receive recycled water, and who may not use as much groundwater as those without recycled water supplies.

In years of high salinity, we see TDS levels substantially improve for neighboring parcels, up to 570 mg/L. According to the (Grattan, 2002) estimates, a 500 mg/L reduction in TDS would translate to a 16% increase in vegetable yields or a 39% increase in strawberry yields. The WTP estimates calculated in the crop choice model say that this may have an impact of up to $123,000 per acre for vegetable producers and $86,850 per acre for strawberries. A more conservative approach would be to look only at changes in crop revenue for these crops. In crop revenue terms, a TDS improvement of 500 mg/L would have an impact of $14,345 on

Figure 12: Event study results: Parcels neighboring those receiving recycled water



strawberries and $1,125 for vegetables per acre. For these neighboring parcels, benefits would add up to additional $10.78 million in benefits for strawberries and $1.52 million for vegetables. Of note, these are benefits that only accrue in years of especially high salinity.

6 Conclusion

Coastal agricultural regions are facing several key issues under climate change: rising temperatures, increased precipitation variability, sea level rise, and a higher incidence of drought and extreme weather events. The interaction of these problems with limited groundwater supplies leads to the over-extraction of groundwater and seawater intrusion. Treated municipal wastewater is a promising strategy that can be used to prevent further groundwater overdraft and mitigate current damages from salinity. Through its use as an alternative water supply, growers can directly use this water on their fields, reducing their reliance on constrained groundwater resources and preventing further seawater intrusion. For growers facing highly saline groundwater, the recycled water can also serve as a higher quality water source, allowing for the production of more salt-sensitive crops and increasing yields.

While recycled municipal water is a promising concept, and programs are starting to be implemented in water-stressed regions, there is little economic research on the impacts of recycled water to growers. This study explores the value of recycled water in two ways: (i) the welfare gains for growers directly receiving water deliveries, through higher-value crop choices and improved yields; and (ii) changes in the underlying aquifer quality below the recycled water delivery area, to evaluate indirect impacts of recycled water. To study the direct effects of recycled water on crop choices and welfare, I use a panel mixed logit choice model. The structure of this approach allows for simulations of grower decisions in the absence of a recycled water program and estimates of the willingness to pay for changes in groundwater salinity, while capturing heterogeneity in crop choice decisions. To evaluate the impacts of recycled water on aquifer salinity, I use staggered difference-in-differences and event studies, given the slow ramp-up of water deliveries over time.

I find that growers receiving recycled water are less likely to leave their ground fallow, and are more likely to plant high-value, salt sensitive crops, such as strawberries. Welfare gains for producers directly receiving water deliveries add up to $16 million annually for 5500 acre-ft of delivered water. I also find that recycled water improves the water quality of the underlying aquifer. The effects are strongest directly underneath parcels receiving recycled water, and are driven by years where salinity levels are highest. Neighboring parcels that do not receive water deliveries only see improvements in water quality in high-salinity drought years. Since recycled water also has non-negligible salinity levels, improvements to water quality are negligible or non-existent in years of high rainfall.

Altogether, these welfare gains are a conservative estimate for benefits to agricultural producers. I look at immediate benefits to agricultural producers, as they make crop choice decisions in a saline, water-constrained environment. This study does not capture the full effects of the additional water supply in preventing longer-term seawater overdraft. For example, farmland further away from the delivered water zone may be able to avoid severe seawater intrusion in upcoming decades due to the recycled water program, although their current salinity levels may not change. However, the findings of improvements in water quality directly on the coast do serve as promising indicators that future seawater intrusion is being at least partially managed. While beyond the scope of this paper, if hydrologic models were used to estimate individual well-level externalities, a basin-wide model of improvements in water quality may be estimated.

The combination of Pajaro Valley's high value crops and temperate coastal climate means that they are willing to invest in expensive programs to maintain agricultural production in the region. However, the future of using municipal treated wastewater as an additional water source is expanding rapidly. There are 250 small-scale recycled water programs in California alone, with others in Arizona, Florida, and Texas. Moreover, there is a promising future for recycled water in locations such as in South Korea, where groundwater overdraft has led to seawater intrusion in 41-50% of coastal groundwater sources (Lee and Song, 2007). Recycled water has a three-fold benefit in our setting and in many other coastal regions, where it provides an additional water supply, improves water quality, and prevents seawater intrusion. However, in the face of future drought and limited freshwater availability, the benefits of an additional water supply may alone be enough to justify the costs of a recycled water facility in arid regions worldwide. Regardless, recycled water may play a major role in climate change mitigation strategies for coastal regions in the future.

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