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SUBMITTED ARTICLE

Local conditions and the economic feasibility of urban wastewater recycling in irrigated agriculture: Lessons from a stochastic regional analysis in California

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Abstract

Using treated wastewater for crop irrigation could help mitigate water scarcity. We examine the feasibility of this strategy focusing on the role of local conditions, such as the costs and benefits of alternative wastewater discharge options, and adaptability of agricultural production to water quantity and quality changes. Our approach accounts for uncertainties in the availability of natural water resources and regulatory constraints concerning wastewater discharge. Our analysis of a region in Southern California finds reuse for crop irrigation unwarranted; however, utilizing that practice to support agriculture in the region is economically inexpensive. A sensitivity analysis reveals that diversified agriculture and limitations on the safe and remote discharge of treated wastewater are strong incentives for reuse in agricultural irrigation.

KEYWORDS

agricultural irrigation, optimal allocation, treated wastewater reuse, uncertainty

JEL CLASSIFICATION

C61, Q15, Q25, Q56

Reuse of treated wastewater as a strategy to mitigate water scarcity is on the rise globally. Still, the common practice in many locations around the world is discharging both treated and untreated wastewater to natural bodies of water, burdening the economy with significant social costs associated with health risks, and environmental pollution (Hernandez-Sancho et al., 2015). Thus, the potential for further expansion of reuse practices is significant (Sato et al., 2013).

Arguments in favor of treated wastewater reuse in irrigated agriculture emphasize the relative stability of supply by that source compared to other natural water sources (Feinerman & Tsur, 2014). Additional benefits are attributed to its use as a substitute for fresh water in crop production (Finkelshtain et al., 2020), and consequently, the opportunity costs associated with water scarcity, as well as forgone investments in water supply augmentation and infrastructure projects for alternative discharge options (Reznik et al., 2017). Another supporting argument for reuse is the potential savings in fertilizer and energy costs due to the presence of plant nutrients and trace elements (Dawson & Hilton, 2011).

However, evidence connecting the accumulation of harmful contaminants (to plants, animals, humans, and the environment) in soils, plants, and fresh produce related to irrigation with treated wastewater has already been established (Hanjra et al., 2012; Lado et al., 2012; Li et al. 2009; Paltiel et al., 2016) and suggests caution in adopting such practices. Furthermore, Schwabe et al. (2020) demonstrated that drought-related events and associated policies devised to manage demands (e.g., conservation mandates, water pricing rates, and others) can decrease the quantity and quality of wastewater. This has ramifications for the costs of treatment and the reliability of treated wastewater as a source for various beneficial uses, and can, therefore, impact the level of its substitutability with freshwater.

Using a general description of a regional economy and a dynamic optimal control framework, Reznik et al. (2019) demonstrated that the reuse of treated wastewater in irrigated agriculture is the preferred alternative for the economy. The authors compared this strategy to a safe discharge option, and discharge to nearby locations (e.g., rivers and streams, spreading fields, and others) with associated environmental damages. Their analysis concluded that reuse in agriculture is the optimal alternative, yet local conditions might affect the economic welfare tradeoffs, resulting in preference toward different strategies. Such local conditions include the availability, quality, and costs of alternative water supply sources, the number of beneficial uses to which treated wastewater can be allocated (according to regulation), existing infrastructure, or the costs of developing new infrastructure needed to exploit this resource, and the value of water for different users.

This article tests whether the reuse of treated wastewater in irrigated agriculture is a sustainable and economically efficient strategy. To answer this question, we develop a regional modeling framework that accounts for interaction and interdependencies among producers and consumers of treated wastewater and the environment. We then examine the conditions under which agricultural reuse is a feasible and sustainable alternative for an actual region in Southern California as well as on a wider scale for a range of prevailing local conditions. With respect to previous work (e.g., Dinar & Yaron, 1986; Feinerman et al., 2001; Goldfarb & Kislev, 2007; Hussain et al., 2001; Kanyoka & Eshtawl, 2012; Winpenny et al. 2010), our analysis also accounts for stochastic exogenous conditions (e.g., weather, natural freshwater availability, water quality, and prices of agricultural outputs), endogenizes treated wastewater quantity, quality, and costs, and considers several discharge alternatives for treated wastewater, including agriculture.

The following section describes the potential of treated wastewater reuse in California, emphasizing the broadness of our analysis and the importance of accounting for local and larger-scale exogenous conditions in determining the feasibility of treated wastewater reuse.

Next, in Section 2, we present the analytical framework used in our analysis. The following Section 3 describes the characteristics of the Escondido region in California, as well as providing a short review of several other regions of California in which a similar analysis adapted to regional local conditions can contribute. The next section provides a description and discussion of the results. The final section concludes.

WASTEWATER REUSE POTENTIAL IN CALIFORNIA

Similar to most of the developed world, treated wastewater discharge in California is regulated, and quantities, qualities, and location of effluent disposal are all determined and monitored by state agencies. Reuse of treated wastewater has increased in California from 175,500 acre-feet (AF) in 1970 to 714,000 AF in 2015. Although, representing a steady increase, the total volume reused in 2015 accounts for only 13% of all treated wastewater volume in the state (Dinar et al., 2020), indicating that the future potential for treated wastewater reuse is substantial. As a partial estimate, Heal the Ocean (2018) reported that treated municipal wastewater discharged directly into California's coastal waters in 2015 was about 1,128,000 AF—an equivalent of almost 3% of total agricultural and urban water consumption in the state for an average year.

Examining historical trends in more detail reveals that the increase in the total volume of treated wastewater reuse in California comprises increased quantities used in public landscape irrigation, golf courses, industrial cooling, and groundwater recharge. The volume of treated wastewater used in irrigated agriculture remained almost unchanged over the last two decades (Dinar et al., 2020: Table 5.1). According to WateReuse-California (2019), water agencies across the state have planned projects for treated wastewater reuse that can increase the volume utilized for nonpotable purposes (e.g., industrial cooling and irrigation of landscapes, golf courses, and agricultural cropland) by 60%, and more than double the volume of treated wastewater used for all purposes (including drinking)—through augmentation of groundwater and surface water systems, primarily in Southern California.

Chappelle et al. (2019) indicated that the evolution of the wastewater sector in California is highly uncertain and rests upon future implemented policies. According to the authors, existing infrastructure and regulatory constraints concerning treated wastewater discharge are inadequate to meet the challenges created by the adaptation of water users to droughts and climate change. Consequently, the authors conclude that wide diffusion in the state of treated wastewater reuse in irrigated agriculture is not necessarily the optimal strategy.

Thus, an educated analysis should rely on a framework that explicitly includes both local and wider-scale exogenous conditions. The variables of interest to be included are capacity development of different alternatives for treated wastewater disposal, quantity allocated to the different use alternatives, quality of the allocated water, and the costs associated with each allocation—specifically water for agricultural irrigation.

A REGIONAL MODEL TO EVALUATE WASTEWATER RECYCLING FOR AGRICULTURAL IRRIGATION IN CALIFORNIA

For the purpose of our analysis, we develop a framework to facilitate the different interdependencies in the economy associated with the allocation of water resources and discharge of treated wastewater. Instead of developing a model from scratch, we adopt the conceptual framework in Reznik et al. (2019), and we modify it for our purposes. The framework herein assumes steady-state conditions and ignores groundwater dynamics.[1] A schematic of the regional allocation problem is depicted in Figure 1.

The problem depicted in Figure 1 is the regional allocation of a natural water source between the urban and agricultural sectors, and the preferred disposal method for treated wastewater produced by the urban sector. The agricultural sector includes several farmers that differ in their farming practices and cultivate heterogeneous lands (e.g., in soil characteristics). As a consequence, crop profitability and yield sensitivity to water quantity and quality are not homogeneous among farmers and are the source of heterogeneity in water demand in the agricultural sector. As initial conditions, treated wastewater can be released from the treatment plant to a nearby location bearing a social cost. Alternatively, it can be reused for beneficial purposes within the region or conveyed to a safe location—following regulatory constraints and preventing regional pollution. However, this necessitates the development of new infrastructure and associated capital investments.

As an expansion of the framework presented in Reznik et al. (2019), our model includes another alternative for treated wastewater reuse—the augmentation of a water source that supplies water for all purposes in the region. Accounting for water quality considerations, the

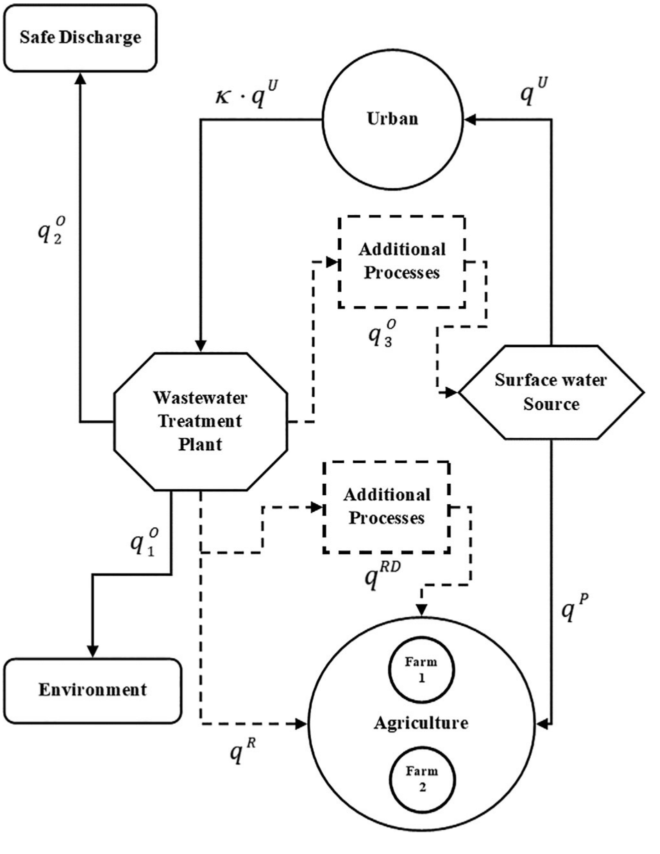

FIGURE 1 Schematic of regional optimization problem for water and treated wastewater allocation among competing demands

model endogenizes the decision of developing the infrastructure required to reduce harmful contaminants in treated wastewater prior to reuse. The model also accounts for uncertainty in water availability and quality. Thus, the model can be used to examine the feasibility of treated wastewater reuse under changing conditions in terms of potential discharge alternatives, exogenous constraints, and agricultural adaptability in any region analyzed. The detailed description of the adapted analytical framework, including the incorporation of uncertainty and the method of achieving a stochastic solution, can be found in Appendix A in Supporting Information.

THE CASE OF ESCONDIDO, AND A REVIEW OF SIMILAR REGIONS IN CALIFORNIA

The City of Escondido is located in San Diego County. The region relies primarily on surface water from imported (approximately 80%) and local sources (City of Escondido, 2017). Uncertainty of water supply availability and population growth trends are posing significant challenges to existing infrastructure and long-term efficient management of water resources in the region.

Avocado production, the main agricultural activity in this region, is one of the industries that are most susceptible to the negative impacts of water shortage in the region. Such negative outcomes have already manifested in recent drought years, in which the absence of alternative water sources for irrigation has resulted in growers paying significantly higher rates for potable water supplied by the city. In order to maintain production during drought years, growers have stumped trees on significant acreage, drilled deep wells to access water, and have used mobile desalters to avoid salinity damages from new groundwater sources.

The City of Escondido is required, by permit, to treat its sewage and dispose of the treated effluents into the ocean. Currently, only a fraction of the flow of sewage to the city's wastewater treatment facility, Hale Avenue Resource Recovery Facility, is recycled and reused for beneficial purposes. According to the city's projections, the range of wastewater generation in the future could be extended to the point at which the existing discharge and treatment capacities would no longer suffice. Such considerations create strong incentive to allocate recycled wastewater locally to avoid significant financial investments associated with the expansion of discharge capacity.

The following alternatives have been identified by the city as potential solutions to this problem. The first, referred to as nonpotable reuse for agriculture (NPR/Ag), relies on developing a supply system to allocate recycled treated wastewater to existing potable water consumers in the city, specifically avocado growers. The second option, indirect potable reuse (IPR), aims to develop a separate new system to desalinate treated wastewater and convey that water to augment the city's surface water supplies. According to that plan, desalinated effluents will be stored in Dixon Lake, one of 11 reservoirs owned and operated by the city. A detailed comparison between the two alternatives on the basis of infrastructural components and capital investment is presented in Table 1.

As presented in Table 1, the NPR/Ag system is smaller and cheaper, therefore, its development is more feasible in the short term. It also provides an alternative stable source of water for irrigating avocados, substituting fresh water, and reducing competition with the city for scarce and uncertain surface water supply. Although more expensive, the IPR system is larger and designed to treat water to a higher quality, enabling use of a larger share of the city's treated wastewater for various purposes—not limited to agricultural use only.

Both alternatives present uncertainty associated with their ability to defer the expansion of the ocean outfall capacity—a much larger project and investment level. For the IPR alternative,

TABLE 1 System components, capacities, and capital investment for NPR/Ag and IPR alternatives

System component	Capacity (TAF/year)	Capital investment (million $)	Description
NPR/Ag			
HARRF upgrade		15.9	Filter replacement to enhance treatment efficiency
Pumps and conveyance	12.9	34.8	101,600 feet of pipelines; 2 pump stations; 1 pressure-reduction station
Storage		2.6	Wet weather pond for storage during storm events
Desalination plant	2.2	19.9	Microfiltration (MF)/ultrafiltration (UF) process followed by reverse osmosis (RO) process to reduce salinity and chloride levels
IPR			
HARRF upgrade		101.1	Additional treatment capacity and inclusion of membrane bioreactor (MBR) technology
Pumps and conveyance	8.9	23.1	40,000 feet of pipelines; two pump stations
Desalination plant	4.5	79.7	MF/UF followed by RO and advanced oxidation disinfection process

Note: Capacity of each system component is determined by its most limiting infrastructure. We do not report capacity of system components for which data are unavailable.

the volume of effluent allocated through the system depends primarily on the unknown future of regulation in California concerning the use of recycled wastewater for beneficial purposes. If the city adopted the NPR/Ag system, the quantity of treated wastewater demanded by growers can vary with time, driven by profitability, and accounting for the price and quality of substitute water sources.

Review of similar regions in California

A growing number of regions in California (and in the world) face similar challenges as those of Escondido. We provide a short review of several such regions and highlight the differences and similarities to the studied region. All regions reviewed are similar in terms of population served by their regional wastewater treatment facilities and their capacities. Table 2 presents some descriptive information for these regions.

Table 2 shows the importance of proximity to the ocean when determining a safe discharge location for treated wastewater. In addition, when other bodies of water are in closer proximity to the ocean, these become natural candidates for safe discharge. However, in such cases, the share of treated wastewater volume discharged safely into the environment could be very small and highly susceptible to changes in exogenous conditions (e.g., the regions of Modesto and Santa Rosa). This is due to stringent regulation in California that limits quantity, quality, and timing of treated wastewater discharge to rivers and streams, and depending on river flow. As a

TABLE 2 Descriptive data for surveyed regions in California resembling Escondido

Region	Treatment level	Safe discharge location	Distance to ocean (miles)	Distance to safe discharge (miles)	Cultivated area (acres)	Crops grown	Reuse
Escondido	Tertiary	Ocean	14.00	15.70	330	1	Yes
San Juan Creek	Secondary	Ocean	0.35	2.00	425	3	No
Santa Cruz	Secondary	Ocean	0.34	2.32	922	5	No
Modesto	Tertiary	San Joaquin River	60.00	6.50	21,867	6	Yes
Santa Rosa	Tertiary	Laguna de Santa Rosa (tributary to the Russian River)	13.80	0.09	4132	4	Yes

Note: Distance to safe discharge for an ocean discharger includes additional piping system conveying effluent further into the ocean required by regulation; area cultivated and number of crops data for each region were gathered using identical data sources and methodology (see Appendices B and C in Supporting Information for further information); values for reuse of treated wastewater in each region relate to all beneficial purposes, not just agriculture.
Source: State Water Resources Control Board (SWRCB) National Pollutant Discharge Elimination System (NPDES) (n.d.).

result, the discharge of treated wastewater from an urban center to a specific river could be completely prohibited for a significant part of the year.

Table 2 also indicates that the level of wastewater treatment is higher in regions that reuse treated wastewater for beneficial purposes; however, beneficial purposes differ among the regions reviewed. In Escondido, approximately 3000 acre-feet per year (AFY) are diverted for cooling in a power plant. Santa Rosa is similar in that almost all treated wastewater is diverted to produce thermal power. In Modesto, which is located in the Central Valley, pastureland is irrigated with treated wastewater when discharge to the San Joaquin River is prohibited. The differences in the diversification of agricultural activity between Northern and Southern California are noteworthy among the reviewed regions.

RESULTS AND DISCUSSION

We start by describing the results from our base scenario, which mimics the existing actual conditions in Escondido. The calibration process of production and costs functions for the agricultural sector under this scenario relies on micro-level data surveyed from individual avocado growers (as described in Appendices B and C in Supporting Information). In addition, under this scenario, none of the alternatives for treated wastewater reuse are developed (i.e., the NPR/Ag and IPR systems), distinguishing it from other scenarios, in which we assume different initial conditions as will be described below. Other general assumptions, functional form choices, and data assignment for model parameters are described in detail in Appendix B in Supporting Information.

Base scenario

According to the results of the base scenario, the total volume of wastewater treated and allocated in the region is about 13,260 AFY. The optimal plan suggests that 77% of treated wastewater should be discharged to the ocean, about 17% is allocated to Lake Dixon to augment regional potable water supply, nearly 5.5% is discharged into the environment (with penalty), and less than 1% is allocated for irrigation of avocadoes. While only a very small share of total treated wastewater volume, effluent quantity allocated to agriculture amounts to almost 16% of total irrigation water in the region. The total volume of water diverted to avocado production is nearly 260 AFY, which is only a quarter of the actual water use by that sector in the region. Total freshwater use in the region is about 15,940 AFY. Compared to the observed water allocation and calibrated initial conditions, the allocation under the optimal plan for the base scenario implies a 5% reduction in water consumption for the urban sector, a 10% increase in average urban water prices, and about $2 million USD loss in consumer surplus.

Focusing on the base scenario results of the agricultural sector, the total land area cultivated by growers should shrink to a quarter of the existing area. Water use for that smaller farming land is also considerably lower than its observed level. Yield per cultivated acre is higher on average than the observed level, and this is mainly due to higher quality water allocated to agriculture. The efficient economic price (VMP = Value of Marginal Product) of water calculated based on these outcomes is $667 per AF, which is lower by 40% than the actual potable water price paid by farmers in the region. These outcomes, however, are not homogeneous for all farmers in the region. Table 3 presents farm-level agricultural indicators with respect to their observed levels.

According to the results presented in Table 3, some farmers (Farmer 2, 4, and 5) are significantly affected, and others (Farmer 1, 3, and 6) are more adaptive, and therefore, less impacted by changes suggested in the optimal plan. Specifically, the optimal plan indicates that Farmer 5 will stop production and exit the industry. Comparing our baseline results with the responses of growers to our survey, we find that Farmer 1, 3, and 6 reported the highest yields, with relatively low water application levels, and high concentrations of chloride and salinity in applied water.

Referring to the existing literature, which we reviewed earlier (e.g., Reznik et al., 2017; Reznik et al., 2019; Schwabe et al., 2020), we find that these outcomes require further discussion. We focus first on the role of treated wastewater reuse in the context of water supply reliability.

Treated wastewater reuse and supply reliability

Supply reliability can account for a substantive part of the value of a water resource, which is affected by the demand of water users (Tsur & Graham-Tomasi, 1991). It has been argued that treated wastewater could be a relatively reliable source of water supply for agricultural irrigation (Feinerman & Tsur, 2014), which can incentivize the adoption of this strategy. We examine this argument and the role of supply reliability on the feasibility of treated wastewater reuse by changing the level of uncertainty in available surface water supply within our model, and thus, the value of reliable supply.

Imported surface water supply to the region is a random variable in our analysis with an assumed discrete distribution (see Appendix B in Supporting Information), thus the exercise is separated into two parts. In one part, we change the mean value of the distribution, keeping its standard deviation fixed (at its observed level of 4000 AFY), and in the second part, we change the standard deviation while keeping the mean value fixed at an observed level of 24,000 AFY. In both parts of the exercise, we measure the uncertainty level using the coefficient of variation,

TABLE 3 Farm-level optimal water use, cultivated land, profit, yield per acre, and VMP as shares of their observed levels counterparts (in percent)

	Land cultivated	Total water use	Yield per acre	VMP	Total profit
Farmer 1	58	72	119	54	31
Farmer 2	11	11	97	50	−4
Farmer 3	66	76	136	66	46
Farmer 4	9	10	68	35	3
Farmer 5	—	—	—	—	—
Farmer 6	56	41	106	88	24
Total	26	25	119	62	21

Note: Values reported are the optimal levels of each variable as suggested by the base scenario results, divided by the observed level of that variable for each farm in our survey. For example, given conditions for the baseline scenario, the optimal water allocation plan for the region would have Farmer 1 reduce their land cultivated to 58%, and total water use to 72% of what is observed for Farmer 1. In terms of outcomes, under the optimal plan for the baseline scenario, yields would be 119% of the observed yield for Farmer 1, while VMP and profit would be down to 54%, and 31%, of observed VMP and profit, respectively, for Farmer 1.

which ranges from 10% to 30%. This is equivalent to incremental changes in the range of 40% reduction up to 45% increase, and 50% reduction up to 75% increase, in the mean, and standard deviation values, respectively, compared to their observed levels. Figure 2 depicts the outcomes of that exercise in terms of economic values for both the urban and agricultural sectors, as well as the level of treated wastewater allocated for all beneficial purposes in the region.

According to the results of our exercise, allocated quantities to both sectors decrease with higher uncertainty of available water supply. Consequently, as presented in Figure 2, economic benefits of both sectors also decrease when the uncertainty level of available water supply is higher (Panel [a] for agriculture and Panel [b] for the urban sector). However, the impact on the urban sector of higher uncertainty in available surface water supply to the region, induced by lower mean values, is clearly larger than the impact of higher uncertainty induced by higher standard deviation values. Specifically, reducing the mean value of available surface water supply to the region by about 40% (keeping standard deviation constant) results in a 20% decrease in urban water consumption, and an almost 8.5 times larger loss in consumer surplus with respect to the base scenario. However, increasing standard deviation by 75% only induces a 5% reduction in urban water consumption and twice the loss in consumer surplus with respect to the base scenario results. This mitigated effect is measured by almost $13 million USD in avoided consumer surplus loss.

Focusing on the results presented in Panel (c) of Figure 2 reveals that treated wastewater reuse plays a significant role in explaining these quantitative differences. Decreasing the mean value of water availability to the region (increasing uncertainty) decreases the volume of treated wastewater reused for all beneficial purposes. However, an opposite trend is presented with respect to the impact of higher uncertainty induced by higher standard deviation levels. Though not presented, it is important to note that for almost all scenarios examined, treated wastewater reuse in agriculture is found suboptimal or insignificant. Thus, the increase in treated wastewater allocated for beneficial purposes in the region resulting from elevated standard deviation levels, as well as the mitigated impact on the urban sector compared to the impact generated by lower mean values of available water supply, supports the argument of Feinerman and

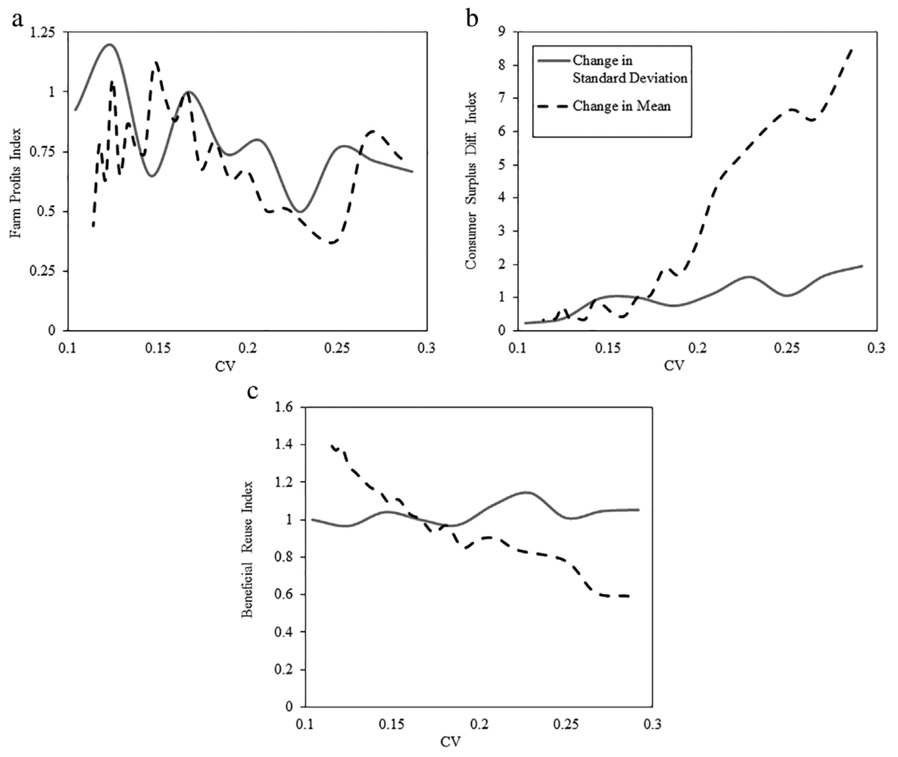

FIGURE 2 Regional indicators (base scenario result = 1) with respect to uncertainty level in water supply availability, measured as the coefficient of variation (CV). Panel (a): farm profits; Panel (b): difference in consumer surplus compared to calibrated value; Panel (c): treated wastewater allocated for all beneficial purposes in the region

Tsur (2014) with respect to using treated wastewater for stabilizing the water supply. However, due to local conditions of the region studied, this role is presented through the impact on the urban sector, rather than on agricultural activity. This latter conclusion is further elaborated in the following section.

Feasibility of treated wastewater reuse in agriculture and local conditions

Referring to our review of similar regions in California, we use a range of different scenarios in order to assess the sensitivity of our results from Escondido to local conditions observed elsewhere based on (i) location; (ii) baseline infrastructure for wastewater discharge; and (iii) agricultural diversification and productivity.

Similar to our base scenario, the parameterization of production and costs functions in agriculture, which mimics the actual conditions in the region of Escondido (primarily the specialization in avocado production), is termed *Escondido Agriculture*. We use additional parameterization, termed *California Agriculture*, which is hypothetical and is calibrated with respect to five different crops (leading at the state level in terms of cultivated land area). Such parameterization introduces flexibility in crop choice decisions at the farm level, providing an adaptation mechanism as potential response to changes in quantity and quality of irrigation water (see Appendix B in Supporting Information for a detailed description of both parameterizations).

We use the term *Ocean Discharger*, to describe the state of all scenarios in which the safe discharge alternative is already a sunk cost—similar to our region of interest in Escondido. Aligned with the conceptual framework of Reznik et al. (2019), in a second state, termed *Inland Discharger*, the initial capacity for the safe and remote discharge alternative is assumed to be zero, making that alternative a potential investment and an endogenous decision in the model.

Referring to potential reuse alternatives (Table 1) along with the base case, in which none of the reuse alternatives were developed, we constructed five other scenarios. Each assumes a different level of existing infrastructure developed as initial conditions (see Appendix D in Supporting Information for details). All six scenarios, including the base scenario, were run under both existing urban demand conditions (*Existing Demand*) and after recalibration (*Future Demand*). Consumed water quantity in the urban sector used in the recalibration is 50% larger than the original one, representing predicted higher demand due to population growth in the city of Escondido (Black and Veatch, 2014).

In total, the analysis includes 48 model runs based on different combinations of the regional characteristics we have just described. We calculated for each scenario the quantity of treated wastewater allocated to agricultural irrigation, both directly and after desalination, as shares of total wastewater discharge, and of total agricultural water consumption in the region. Following Reznik et al. (2017), we also calculated for each scenario the added value of treated wastewater reuse in agriculture as the economic welfare difference to a scenario in which this strategy is prohibited. Table 4 presents these calculated values averaged across the six scenarios of potential reuse alternatives for the different combinations of agricultural activity parameterizations, safe discharge infrastructure initial conditions, and urban demand assumptions.

According to Table 4, under the *Escondido Agriculture* parameterization, *Ocean Discharger* and *Existing Demand* conditions, the allocated amount of treated wastewater for avocado irrigation is almost insignificant compared to total wastewater discharged in the region. This result is exacerbated under *Future Demand* conditions suggesting that reuse of treated wastewater for agricultural irrigation is not a sustainable strategy for the region studied.

Comparing the outcomes under *Inland Discharger* conditions to the results under *Ocean Discharger* conditions, regardless of assumed agricultural productivity parameterization, reveals that the reuse of treated wastewater in irrigated agriculture accounts for a larger share of the total amount of treated wastewater produced in the region. This implies that the reuse of treated wastewater in irrigated agriculture is a more attractive strategy when remote and safe discharge infrastructure is not yet developed and requires large investment as initial conditions, which is in agreement with the general findings in Reznik et al. (2019).

It is also indicated in Table 4 that, on average, the share of treated wastewater produced in the region and allocated for agricultural irrigation is larger under the *California Agriculture* parameterization compared to the *Escondido Agriculture* parameterization. For the former, we also found that the desalination of treated wastewater prior to reuse in irrigated agriculture (in order to avoid yield loss due to salinity damages) is in most cases a suboptimal strategy, enriching the existing discussion in the literature around this topic (Reznik et al., 2017; Slater et al., 2020). These last two findings suggest that the feasibility of treated wastewater reuse in irrigated agriculture is strongly dependent on the agricultural sector's adaptability with respect to changes in water quantity and quality through land-use decisions, and given crops' sensitivity to water application level and salinity.

TABLE 4 Treated Wastewater (TWW) allocated to crop irrigation, directly and after desalination, shares of total TWW discharge, and total water use in agriculture; and regional economic welfare changes attributed to treated wastewater reuse in agriculture

	Direct TWW reuse		Desalinated effluent reuse		
	Share of total TWW	Share of Ag. Consump.	Share of Total TWW	Share of Ag. Consump.	Welfare changes
Escondido agriculture and existing demand					
Inland discharger	30.74	69.69	14.48	22.34	0.71
Ocean discharger	0.98	27.43	0.77	21.38	0.06
Escondido agriculture and future demand					
Inland discharger	26.05	60.86	17.59	33.42	3.73
Ocean discharger	0.00	0.02	0.00	0.00	4E-05
California agriculture and existing demand					
Inland discharger	40.62	68.92	0.00	0.00	3.53
Ocean discharger	15.81	86.48	0.08	0.31	0.14
California agriculture and future demand					
Inland discharger	22.88	85.38	8.65	24.50	87.68
Ocean discharger	9.85	67.97	0.74	14.79	0.02

Note: As an example of the outcomes presented, for an *Inland Discharger*, under the *Escondido Agriculture* and *Existing Demand* conditions, treated wastewater reuse in irrigated agriculture accounts for about 30% and 70%, of total wastewater produced and treated in the region, and total water use in agriculture, respectively, on average across the six scenarios representing different baseline infrastructure assumptions. Economic welfare changes are calculated as differences with respect to a scenario in which treated wastewater allocation for crop irrigation is prohibited. These values are presented as percentage of the annual expenditures of the Water and Wastewater Utilities of the city of Escondido.

The added value of treated wastewater reuse in irrigated agriculture, presented in Table 4, is higher for regions with limited safe discharge possibilities, compared to regions in which safe discharge disposal is not constrained. Furthermore, this added value increases for the former regions and decreases for the latter when urban water demand rises. These findings are independent of crop diversification in the agricultural sector. A second prominent conclusion is that treated wastewater reuse is significantly more valuable to the economy in regions that have an agricultural sector that is more diversified in its crop portfolio.

An important conclusion that emerged from the different comparisons suggests that specialization in a single crop, namely avocado—a highly sensitive crop to salinity and chloride—could have a significant role in determining the feasibility of treated wastewater reuse in the Escondido region. This conclusion is further examined and illustrated in Appendix D in Supporting Information.

Supportive agricultural policies

The strong tradeoffs observed between quantity and quality of applied irrigation water, efficient water prices, yields, and profits in the agricultural sector (see Appendix D in Supporting

Information) led us to examine the cost (in terms of regional economic welfare) of supportive policies for the avocado industry. We examined the impact of subsidizing the price and setting quality thresholds for allocated water to agriculture, as well as maintaining the avocado industry at the same size as observed in Escondido. For the first policy, we use a value of 700 $/AF for the desired price of water, and values of 0.7 dS/m and 2.25 meq/L for salinity and chloride maximal thresholds levels, respectively.[2] For the second policy, we imposed minimal land and water requirements for agriculture, set at their observed levels in the region. In addition, under that policy only treated wastewater (directly or after desalination) can be used to satisfy the minimal water allocation requirement for agriculture, above that minimal requirement, all water sources can be utilized. The two policies are applied individually or simultaneously.

We find that under the minimal water and land allocation requirement policy only treated wastewater is used for irrigation of avocados. That allocation translates into lower water quality, yields, and profits with respect to observed levels. We also find that when the two policies are applied simultaneously, more water is allocated to agriculture, and regional blending of water sources is found optimal. That allocation leads to higher water quality, yields, and profits in the agricultural sector with respect to the outcomes of the minimal land and water allocation requirement policy applied alone.

We calculate the economic welfare differences between the simultaneous use of both policies and when each policy is applied individually. That cost equals $1.75 and $2.6 million USD, for the price subsidy and maximal water quality thresholds policy, and the minimal size requirement policy, respectively. These monetary values translate to 1.3% and 1.93%, respectively, calculated as a percentage of the annual expenditures of the water and wastewater utilities by the City of Escondido. It is implied that supporting agricultural activity in the region using these policies is warranted if these costs are surpassed by the indirect added value of agriculture to the region (which we do not quantify in our analysis), for example, through job creation, value of supporting/service industries, environmental amenities, and others.

CONCLUDING REMARKS

The reuse of treated wastewater for beneficial purposes, and specifically for agricultural irrigation is a strategy that has been increasing in recent decades and can help mitigate water scarcity. However, that practice also raises concerns with respect to its long-term impact on human health and the environment. Considering the spatial variation that exists in the multiple factors that need to be accounted for when determining the feasibility of treated wastewater reuse, local conditions can make a significant difference. In this article, we have analyzed a stochastic water and wastewater allocation problem of the Escondido region in Southern California, as well as some hypothetical conditions for crop diversification in agriculture and potential alternatives for treated wastewater discharge.

Our analysis of the Escondido region reveals that treated wastewater reuse in agriculture is not a sustainable strategy. Instead, our results suggest that safely discharging most of the effluent into the ocean, using existing infrastructure, and augmenting regional surface water supplies with the remaining portion of that water after desalination is the preferred strategy. The farming sector is severely affected by this strategy, reducing the area cultivated and water used, and consequently producing lower economic value with respect to the observed avocado industry in the region. Specialization in a single crop, specifically avocados, which are highly sensitive to chloride and salinity levels, is found to be a strong determinant of this outcome. Finally, we find that implementing supportive policies through allocation of treated wastewater directly, and after desalination, while keeping agricultural water prices low and their quality high, are inexpensive in terms of social-economic welfare. In pure economic terms, such policies would only be warranted if one can demonstrate that the indirect benefits of agriculture to the region surpass the cost of implementing these policies, which we calculated to be in the range of $1.75 and $2.6 million USD annually.

On a larger scale, our analysis concluded that reuse of treated wastewater in irrigated agriculture is an attractive strategy for regions that are characterized by diversified agricultural activities, and becomes extremely valuable to areas that are limited in their alternatives to discharge treated wastewater safely and remotely. These characteristics apply to most of the urban centers in the Central Valley of California, but also to some areas that are closer to the ocean as we reviewed earlier (e.g., Santa Rosa). Our analysis also supports previous arguments favoring reuse of treated wastewater due to its stabilization value (Feinerman & Tsur, 2014).

The emerging conclusion is that the reuse of treated wastewater for beneficial purposes is indeed a first-best strategy for a regional economy. However, local conditions play an important role in determining the best beneficial use of that resource. With respect to the future evolution of treated wastewater reuse in California, we agree with Chappelle et al. (2019) that regulation and implemented policies will play a crucial role in determining the materialization of its potential.

In this article, we have taken a social planner perspective to confront the regional water allocation problem in Escondido. However, it is well known that different equilibria with respect to the decision variables analyzed could arise when strategic behavior of economic agents is accounted for. Such analyses will be explored in our future research. Finally, our empirical analysis of Escondido is tailored to the specific conditions in this region. Such conditions include the lack of intertemporal groundwater storage, altitude differences between storage reservoirs for surface water and planned facilities for treated wastewater supply, and distance to safe disposal of treated wastewater in the ocean. These conditions have direct implications on the nature of the analysis (i.e., steady-state versus dynamic), the feasibility of different disposal alternatives, and the costs associated with them, as well as other functional form and parametric assumptions in the model. Applying the regional framework presented herein to other regions across California and across the world would be another useful extension of our work.

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ENDNOTES

[1] Restructuring the analytical framework as a dynamic optimization problem is merely a technical procedure.

[2] These values were provided by the avocado growers in the region as the desirable levels of these parameters in their responses to our survey.

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