water

Article

Blending Irrigation Water Sources with Different Salinities and the Economic Damage of Salinity: The Case of Israel

Yehuda Slater [1], Ami Reznik [1], Israel Finkelshtain [1,2] and Iddo Kan [1,2,*]

[1] Department of Environmental Economics and Management, The Robert H. Smith Faculty of Agriculture, Food and Environment, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 761001, Israel; yehuda.slater@mail.huji.ac.il (Y.S.); ami.reznik@mail.huji.ac.il (A.R.); israel.finkelshtain@mail.huji.ac.il (I.F.)
[2] The Center for Agricultural Economics Research, P.O. Box 12, Rehovot 761001, Israel
* Correspondence: iddo.kan@mail.huji.ac.il

Abstract: Israel's water and vegetative agriculture sectors are interdependent, as the latter constitutes the solution for wastewater disposal. We employ a dynamic mathematical programming model that captures this interdependence for evaluating the economic damage of irrigation water salinity under two strategies of blending water sources with different salinities: field blending, which enables farmers to assign water with a specific salinity to each crop, and regional blending, under which all crops experience similar water salinity. Relative to field blending, the buildup rate of desalination under regional blending is slightly expedited; nevertheless, reallocations of water sources across sectors and crops increase the average irrigation water salinity, and the overall welfare decreases by USD 0.08 per cubic meter of irrigation water—about 20% of the water's average value of marginal product. Salinity-sensitive crops will face the largest per hectare production reduction if regional blending replaces field blending; however, the combined variations in the prices of irrigation water and agricultural outputs may motivate farmers to move irrigation water to these crops. Under equilibrium conditions in the two sectors, a 1% increase in the average salinity of the irrigation water supplied to a region reduces the value of the marginal product of that water by 2.4% and 1.6% under field and regional blending, respectively.

Keywords: irrigation; salinity; agriculture; policy; water; economics; model

Citation: Slater, Y.; Reznik, A.; Finkelshtain, I.; Kan, I. Blending Irrigation Water Sources with Different Salinities and the Economic Damage of Salinity: The Case of Israel. *Water* **2022**, *14*, 917. https://doi.org/10.3390/w14060917

Academic Editor: Guido D'Urso

Received: 10 February 2022
Accepted: 14 March 2022
Published: 15 March 2022

1. Introduction

For thousands of years, man has been coping with salinization processes in irrigated agriculture [1], which is the main consumer of water worldwide, accounting for nearly 70% of the total global water withdrawal [2]. This problem continues to worsen, and today, 25–30% of the world's irrigated lands in more than 100 countries are affected by salt [3,4]. Population growth, which increases the demand for both food and freshwater for domestic use, further contributes to this growing challenge, as it incentivizes the expansion of irrigated lands and the use of non-freshwater sources such as brackish water and treated wastewater (TWW) for irrigation [5]. These processes are further augmented by climate change, which increases irrigation needs due to higher vapor–pressure deficits [6] and reduces the natural enrichment of freshwater sources [7]. Moreover, the common agronomic solution to salinization is to apply excess amounts of irrigation water to leach the salts below the root zone [8]. However, that method gradually increases the salinity of groundwater bodies [9] and consequently counteracts its original purpose. The use of desalination, which is a remedy for both the growing water shortage and salinization, is steadily increasing [10], but it consumes a great deal of energy and entails high brine disposal costs [11].

The processes described above reflect a strong linkage between agricultural irrigation and the supply of water to different users—a link that should be accounted for in the design of sustainable and economically viable solutions to the problems of water shortages and salinization. This study focuses on irrigation practices in agricultural regions with access to several water sources of different salinities and evaluates the impact of these practices on water management in a multiregional water distribution network. Specifically, we evaluate the economic damage caused by salinity under different strategies for blending irrigation water sources with different salinities. We focus on the case of Israel—a country equipped with a complex water supply system and a large agricultural reliance on non-freshwater sources such as TWW and brackish water, which together, constitute about 60% of the country's total irrigation water. Our economic analysis accounts for the impact of blending options on agricultural cropping patterns, optimal long-term management policies, and the development of the Israeli water supply system.

Despite the vast agronomic literature on the production impacts of irrigation water mixtures (e.g., recent agronomic studies explore the impact of conjunctive use of water resources [12,13], employ GIS for assessing salinity impacts under different irrigation practices [14], and measure the impacts of water irrigation strategies on soil and plant properties [15]), economic analyses of that issue are scarce. Parkinson et al. [16] were probably the first to economically evaluate water blending options. Knapp and Dinar [17], Dinar et al. [18], Kan et al. [19], and Kan [20] employed field-level models to study the profitability of mixing water sources with different salinities for the irrigation of specific crops. Feinerman and Yaron [21] and Kan and Rapaport-Rom [22] incorporated blending options in regional-scale models, in which the land allocation across crops was endogenous. However, all of these studies assumed exogenous water supplies and therefore overlooked the implications of water management strategies within agricultural regions on the water economy as a whole. The contribution of this paper is the introduction of the nexus between the agricultural and water sectors into the economic analysis of water blending strategies.

The linkage between the intraregional management of irrigation water and the design of economy-wide water-supply systems is of particular importance in water economies that supply water to different users from multiple sources and/or where the recycling of domestic TWW in irrigated agriculture creates a strong interdependence between the two sectors. In such water economies, the optimal allocation of water across users depends on their demands for the various water sources, where the demand of any farming region for different water types depends on the irrigation practices in that region. This is the case in Israel, where the water distribution network connects almost all users and sources in the country. That connectivity implies that water usage at a particular place and time may have opportunity costs, as it cannot be used for other purposes at alternative locations and times [23].

Hydroeconomic models provide a powerful tool to analyze water management problems on different scales and under various spatiotemporal conditions (see [24–34]). However, to the best of our knowledge, the only hydroeconomic model that incorporates salinity considerations in the allocation of water to urban and agricultural users is the MYWAS-VALUE (Multi Year Water Allocation System-Vegetative Agricultural Land Use Economics) model, which was developed by Slater et al. [35] for the case of Israel. Slater et al. [35] employed MYWAS-VALUE to evaluate the societal deadweight loss entailed by overlooking the impact of salinity on agricultural production in the design of water infrastructures. However, the model presumes regional irrigation water blending; that is, all of the inflows of water sources into any agricultural region are mixed before they are applied to the irrigated crops. This assumption has two drawbacks: first, compared to field-level blending, regional water blending may increase the detrimental impact of salinity on agricultural production because it affects all of the irrigated crops in any given region, including both salinity-tolerant and salinity-sensitive ones. Consequently, the exaggerated salinity damage may motivate the faster-than-optimal expansion of desalination capacities. Second, it turns out that farmers in Israel rarely blend irrigation water from different sources (personal communication; Anat Levingert, Senior Manager of the Consulting and Professional Service of the Israeli Ministry of Agriculture (Shaham)). Thus, designing the long-term development of water infrastructures under the assumption of the regional blending of irrigation water sources may yield results that both inflate the agricultural damage incurred due to salinity and that are inconsistent with reality.

In this paper, we analyze two irrigation water mixing scenarios: field blending (FB) and regional blending (RB). The difference between the scenarios with respect to the intraregional water supply system is illustrated in Figure 1 for a hypothetical region, in which farmers grow five crops and have access to three water sources with different salinities: freshwater, TWW, and brackish water. Under FB, farmers can select a specific combination of the three sources for each crop, whereas the RB scenario implies one combination for all crops. Note that, while both scenarios do not preclude the non-blending option, avoiding blending in the RB case implies that only one water source is used in the entire region, whereas the FB scenario enables farmers to use all of the water sources that are available to them by assigning a single water source to each crop.

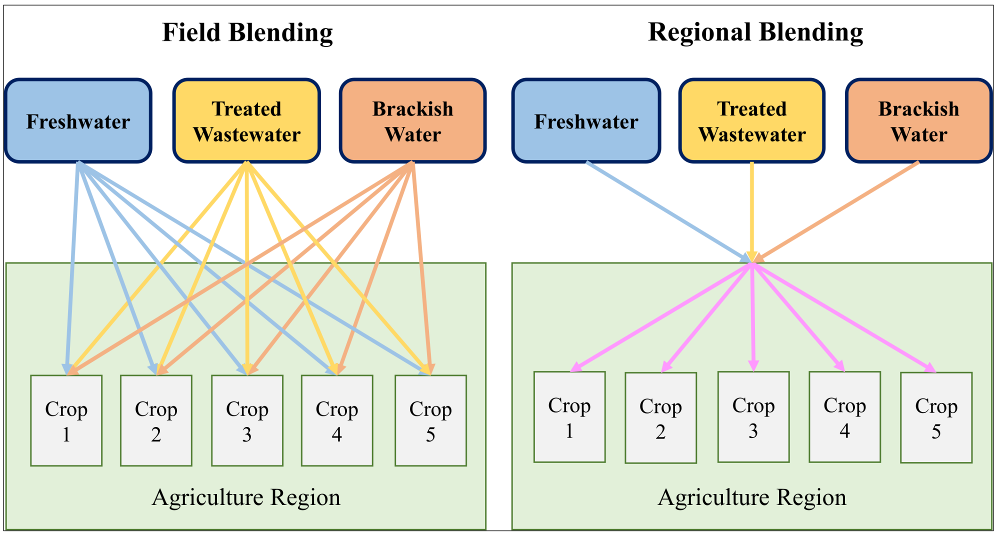

Figure 1. Schematic illustration of the field and regional blending scenarios in an agricultural region with five crops that can be irrigated by three water sources with different salinity levels: freshwater, treated wastewater, and brackish water.

Our analysis is based on the MYWAS-VALUE framework. We first calibrate the model under the FB assumption to reproduce the observed situation in a baseline year (2019). Then, we run the model under the FB and RB scenarios for a period of 30 years. We found that switching from FB to RB slightly expedites the development of desalination plants, but the average irrigation water salinity increased due to the reallocation of water sources across sectors and crops. Although salinity-sensitive crops face the largest reduction in per hectare production, the combined impact of changes in the (endogenously determined) prices of irrigation water and agricultural outputs motivates farmers to shift more water and land to the production of these crops.

We consider three measures of the economic damage caused by salinity under the two blending scenarios. The first measures the reductions in the agricultural production value caused by the design of water infrastructures that ignore the impact of irrigation-water salinity on agricultural production. This reduction amounts to USD 1195 and USD 1326 per hectare under the FB and RB scenarios, respectively (all monetary values are in terms of the 15th year of the 30-year planning horizon). The second measure is based on the negative relationship between the irrigation water value of the marginal product (VMP) in an agricultural region and the average salinity of the region's irrigation water; on average, the VMP decreased with the salinity by USD 0.39 and USD 0.30 per dS m^{-1} per cubic meter of irrigation water for the case of FB and RB, respectively, or by -2.4 and -1.6 in terms of elasticity (note that both VMP and salinity are endogenous in MYWAS-VALUE). The last measure computes the marginal damage caused by salinity based on the shadow values of the salt-balance constraints along the water delivery system; a salinity increase of 1 dS m^{-1} costs USD 525 and USD 534 million a year for the whole country under FB and RB, respectively. Per cubic meter of irrigation water, we achieved USD 0.42 per dS m^{-1}, with minor differences between the blending scenarios being observed.

The following section briefly describes the MYWAS-VALUE model; Section 3 compares the results under the two blending scenarios and discusses the three measures of the economic damage of irrigation water salinity; Section 4 concludes the paper, and Section 5 discusses the limitations of the analysis and avenues for future research.

2. Methods

The Israeli water supply system was designed to cope with challenges associated with temporal and spatial water distribution. Natural freshwater sources are enriched during the winter, whereas most of the consumption occurs in the summer; this pattern requires water storage. The water delivery system was originally designed to transfer water from the rainier northern parts of the country to the populated center and for irrigating the large agricultural lands in the south. Since 2005, with the installation of desalination plants on the Mediterranean coast, the supply has been gradually shifted to a west–east direction. As a public property, water is centrally managed by the government, which designs the supply and controls consumption through a set of prices, quotas, and pumping licenses [36]. These physical and legislational structures imply that the government is facing a water management optimization problem that integrates dynamic and spatial dimensions. The MYWAS-VALUE model was developed to solve such problems.

MYWAS is a dynamic model of the Israeli water system, and VALUE represents the activities in the vegetative agricultural regions as incorporated into MYWAS. MYWAS encompasses 21 urban regions that consume freshwater for domestic and industrial uses and 18 agricultural regions that can consume freshwater, TWW, and brackish water. The water sources are represented in the model by 19 naturally enriched freshwater stocks, 5 seawater desalination plants, 4 non-enriched brackish water aquifers, 19 wastewater treatment plants, 163 freshwater pipelines, and 74 pipelines for sewage, TWW, and brackish water. MYWAS determines the socially optimal allocation of water types to the demand regions during each period throughout a predetermined planning horizon while also accounting for the welfare of the water users in those regions, the variable supply costs, the constraints associated with water availability in the sources, and the infrastructural capacity constraints. In addition, the model determines the extent to which each infrastructural water element is extended during each period while weighing the investment costs versus the net benefits associated with the extended capacities in future periods.

VALUE is a positive mathematical programming (PMP) model of MYWAS's 18 agricultural regions. Each region incorporates 55 crops whose output prices constitute equilibrium in the statewide markets for industrial, export, and local fresh vegetative products that are assumed to be competitive. The crop production functions account for the salinity of the water supplied to each crop. The land allocations to the crops in the regions maximize social welfare subject to regional input constraints, where social welfare incorporates the surpluses of the consumers of agricultural products minus the production costs. The constrained inputs in each region include land, foreign workers (who are allocated to farmers based on cropping patterns), and the amounts of water delivered to the region from accessible sources; the latter is determined by MYWAS.

Population growth shifts the demand for water in urban zones and the country-wide demand for vegetative agricultural products to the right, thereby driving the dynamic expansion of water supply infrastructures. The model tracks the salinity concentrations along the water supply system and can control the salinity of the irrigation water in each agricultural region by increasing desalination capacities and/or changing the shares of allocated water from the different sources accessible to the region. The model reports the efficiency water prices at any node of the water distribution network, which are equal to the shadow price of the water at this node. In addition, it reports the irrigation water's

VMP, which depends on its salinity. Of course, for an optimal allocation, the efficiency water price and the VMP are equal. Based on the efficiency prices, the model reports the allocation of welfare among the urban and agricultural water users, the water suppliers, and the consumers of agricultural outputs (this presumes that prices are the exclusive water allocation instrument in the water economy; in practice, this is the case in Israel, although prices are higher than optimal because of cost recovery regulations [29]). Our scenarios span a 30-year period, which we divide into 10 equal sub-periods to reduce the computational burden; each period is referred to by its last year.

The version of MYWAS-VALUE that is employed in this study was calibrated based on 2019 data (the model is available as a Supplementary Material to this paper). A detailed description of the model is provided by Slater et al. [35]; the rest of this section describes the recalibration of the VALUE model under the FB assumption, which replaces the RB specification based on which the version of the model in Slater et al. [35] is calibrated.

Our challenge is to calibrate VALUE in the absence of field-level information regarding the actual allocation of water types to the crops in each region—an allocation that is assumed to be optimal in the prevailing situation. To that end, we employ a multistage calibration procedure that involves the optimal assignment of the water sources accessed by a region to the crops grown therein while accounting for the crops' relative salinity tolerance and profitability. Specifically, we introduce a preliminary stage to the commonly used two-stage procedure applied for the calibration of classical PMP models [37]. In this preliminary stage, water types are optimally allocated to each crop subject to their respective regional water availability constraints, where the land allocated to each crop is kept constant at its baseline level. Note that our production function for each crop is a nonlinear function that relates the per hectare yield to the per hectare annual water application and the salinity level of the applied water (as in Slater et al. [35], the per hectare annual amount of water applied to each crop is constant, and therefore only changes in the salinity of the water assigned to each crop affect its per hectare yield); thus, changes in the type of water applied to a crop vary its per hectare outputs. Therefore, the preliminary calibration stage optimally assigns the water sources to the crops and sets the production function parameters so as to reproduce the per hectare yield reported in crop budget reports (see Appendix A for a formal description of the preliminary calibration stage). Then, we apply the first stage of the PMP calibration procedure, which elicits the dual values of the perturbed crop-specific land constraints. Note that to obtain the correct dual values, one should also incorporate the water allocations to the crops as decision variables, which renders the optimization problem of that stage nonlinear (in contrast to the first-stage linear problem of the original PMP procedure). The rest of the calibration process follows the second stage of the PMP procedure as well as the calibration of the demand functions for agricultural products and urban water usage (see [35]).

The outcome of the preliminary calibration stage with respect to the optimal allocation of irrigation water types to crops involves minimal blending; that is, each crop is irrigated by only one water type, where mixtures are assigned to a few crops to meet the availability constraints associated with the regional water sources. While this qualitative result was already shown by Kan and Rapaport-Rom [22], here, the water allocation to crops is optimal rather than imposed by other criteria (e.g., Kan and Rapaport-Rom [22] employed a hierarchical procedure to assign water types to crops). Figure 2 presents the allocation of the irrigation water types—desalinated freshwater (EC = 0.25 dS m^{-1}), fresh groundwater (EC = 1 dS m^{-1}), TWW (EC = 1–1.77 dS m^{-1}), and brackish water (EC = 2.35–4.0 dS m^{-1})—to four groups of crops classified according to their sensitivity to salinity: sensitive, moderately sensitive, moderately tolerant, and tolerant [38]; as expected, the higher the salinity tolerance of the crops, the higher the salinity of the irrigation water allocated to them.

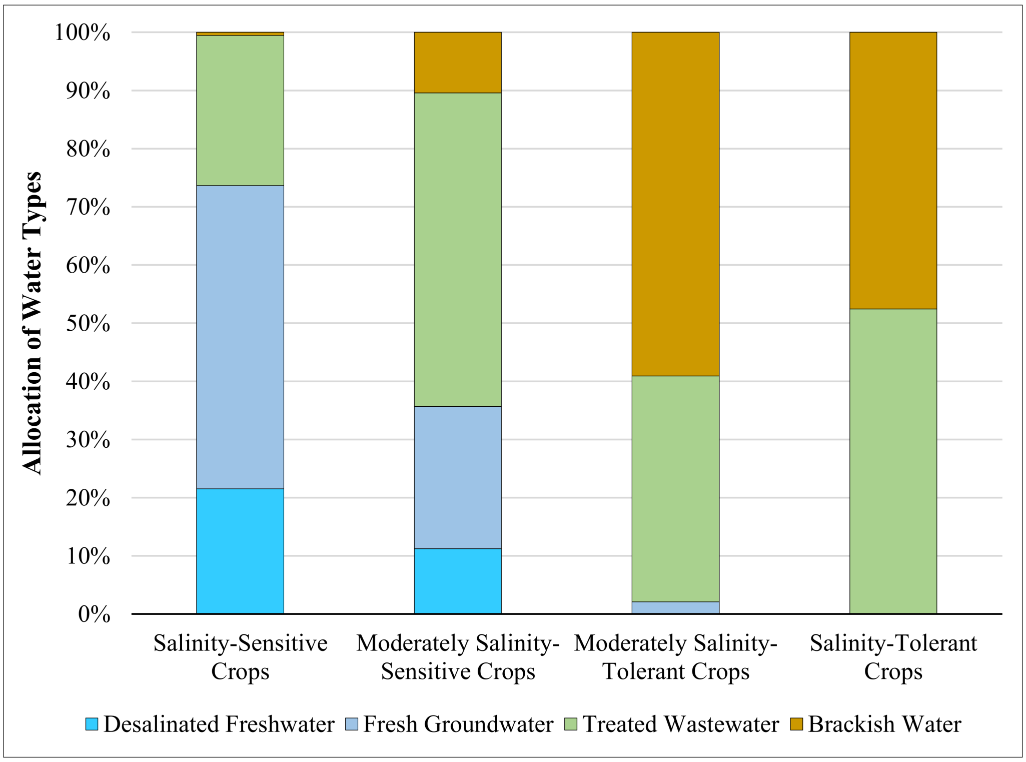

Figure 2. Optimal allocation of the four irrigation water types that differ in terms of their salinity levels to four groups of crops with different salinity tolerances.

3. Results

We used the calibrated MYWAS-VALUE model to evaluate the impact of RB versus FB on the optimal inter-regional water allocation policies, the development of water infrastructures, the agricultural activities of the farmers, and the economic welfare of the country. In the analysis, we refer to the role of adaptation by the farmers through the reallocation of their lands to the crops. We first describe the implications on the water supply patterns associated with the switch from FB to RB. Then, we present the allocation of welfare in the economy under the two scenarios and explain the welfare differences between the two scenarios by analyzing the farmers' adaptations through land and water allocations. Finally, we present three alternative measures to determine irrigation water salinity damage.

3.1. Water Supply

It turns out that the intraregional strategies with respect to irrigation water blending only have a minor impact on the water supply patterns in the country as a whole; the total amount of water supplied to all users varies by less than 1% between the FB and RB scenarios. While minor, these changes correspond to the hypothesis that the salinity impact under the RB assumption is exaggerated: the buildup of seawater desalination capacity under the RB scenario is expedited (Figure 3). Consequently, for a short period of time during the middle of the planning horizon, desalinated water replaced some of the natural freshwater and thereby reduced the salinity of the total supplied freshwater. In addition, the agricultural sector obtains slightly larger amounts of freshwater, whereas the freshwater quantities supplied to the urban sector decrease somewhat (not shown).

3.2. Welfare

The welfare implications of imposing RB instead of FB are summarized in Figure 4, which shows the associated average annual welfare changes (RB minus FB) expected for the various sectors (urban water consumers, consumers of agricultural products, farmers, water suppliers and the overall welfare; the welfare elements represent the annual discounted values, averaged over the planning horizon). In addition, to elicit the impact of agricultural adaptation, we compared the two blending alternatives while assuming that farmers do not adapt to changes over time by reallocating their land to different crops; these scenarios are termed as FBNA and RBNA (NA stands for "no adaptation") in the figure.

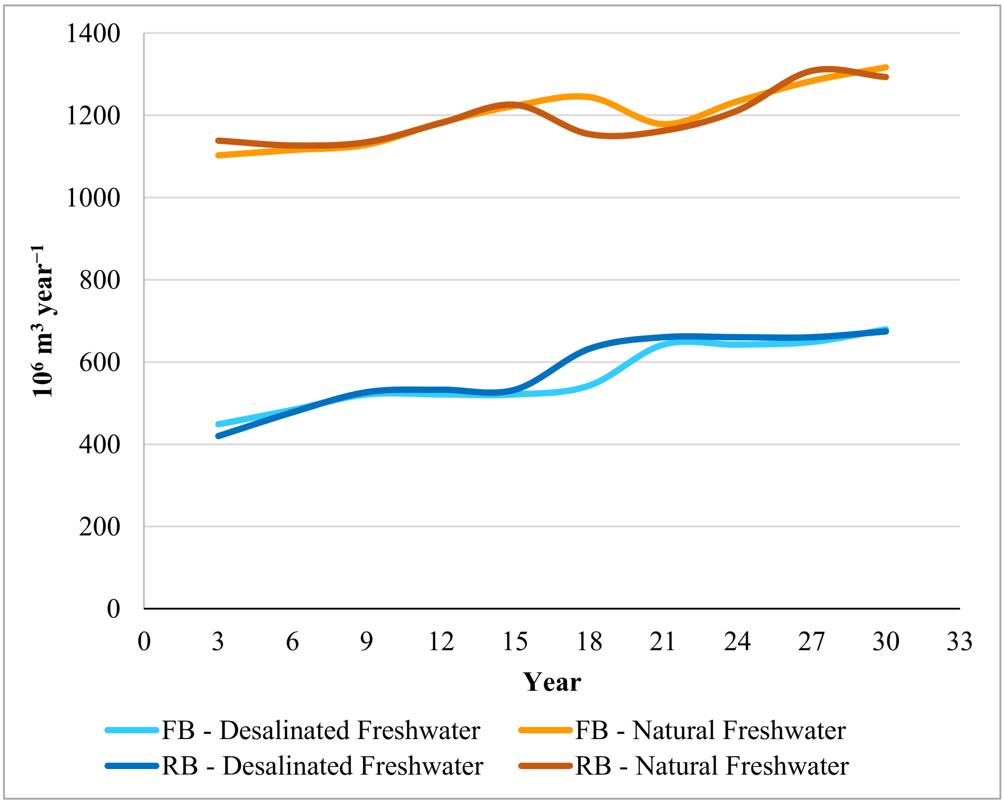

Figure 3. Trajectories of freshwater types supplied from desalination plants and natural sources throughout the simulated 30-year period under the FB and RB scenarios.

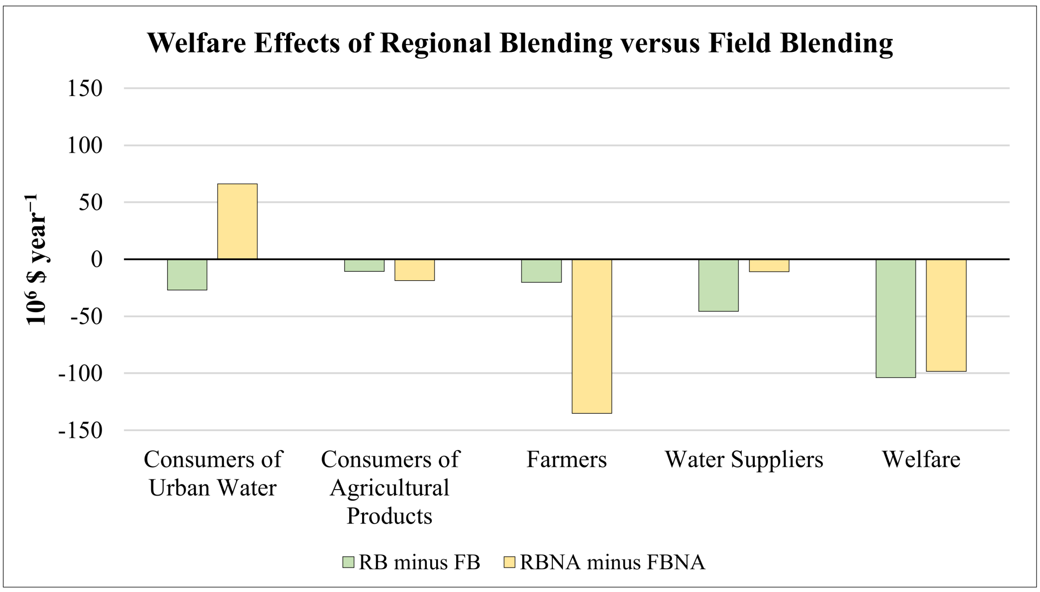

Figure 4. Differences in welfare elements computed under the field blending (FB) and regional blending (RB) scenarios when agricultural land adaptation is allowed (RB minus FB) and not allowed (RBNA minus FBNA).

The overall welfare change is nearly USD 100 million a year—about 5% of the total variable water supply costs. On average, the deadweight loss amounts to USD 0.08 per cubic meter of irrigation water. Most of the burden associated with imposing RB falls on the water suppliers; as it will be shown later, this loss is due to lower efficiency water prices, which stem from the higher salinity of the irrigation water and consequently, its lower VMP. With no adaptation (RBNA minus FBNA), most of the welfare loss caused by RB versus FB is experienced by the farming sector, whereas the consumers of urban water benefit from this situation. Thus, by reallocating agricultural land and irrigation water across crops, farmers manage to reduce their welfare loss by 85% (see Section 3.3).

3.3. Land and Water Management

To understand the welfare changes reported in Figure 4, it is important to study agricultural land and water management decisions with respect to the four salinity tolerance groups presented in Figure 2 as well as the group of rain-fed crops. Figure 5 shows the shares of these five groups in terms of the country's total agricultural land, irrigation water, production value, and profit. While 26% of the land is allocated to salinity-sensitive crops, this group consumes more than 50% of the irrigation water, and accounts for 40% of the total profit. In comparison, the moderately sensitive crops are also responsible for 40% of the profits but consume more land and less water. The other groups of crops produce about 20% of the profits, with relatively little water consumption.

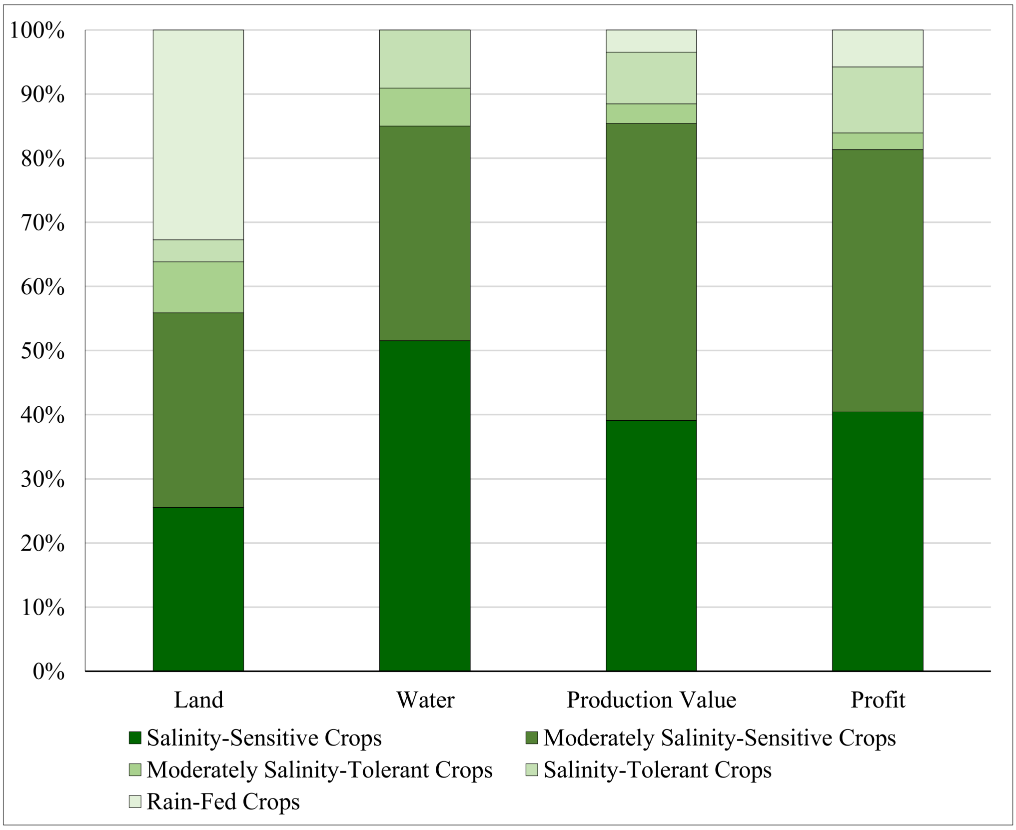

Figure 5. Shares of the groups of salinity-tolerant/sensitive crops and rain-fed crops in the state-wide total agricultural land, irrigation water use, production value, and profit at the calibration stage.

In essence, the shift from FB to RB increases the salinity of the irrigation water for salinity-sensitive crops and reduces that of irrigation water for salinity-tolerant ones. In Figure 6, we report changes (RB minus FB) for a range of measures associated with that shift in relation to the five groups under consideration. Figure 6a shows that the salinity-sensitive crops obtain larger amounts of TWW and less freshwater under RB, whereas all of the other groups face the opposite change. Consequently, the average salinity of the irrigation water applied to the salinity-sensitive crops under RB increases compared to FB, and that of the irrigation water for the other groups declines (Figure 6b); this is because the salinity-sensitive crops consume more than half of the irrigation water (Figure 5), and therefore, on average across all groups, the salinity of their irrigation water increases from 1.11 to 1.16 dS m^{-1}. Figure 6b also shows that the changes in the average VMPs of the irrigation water types are opposite to those of the salinity-sensitive crops (except for the moderately salinity-sensitive crops, in which the change in the average VMP is slightly negative). As previously mentioned, the VMP constitutes the efficiency price of the irrigation water in our model such that lower VMPs imply lower prices; because the salinity-sensitive crops consume most of the water, the average water price declines by 10% (from USD 0.42 to USD 0.38 per cubic meter), and the number of payments delivered to the water suppliers by the agricultural sector decrease. Although urban water consumers face a slight price increase—and therefore their total welfare diminishes (Figure 4)—the overall profit of the water suppliers declines (Figure 4).

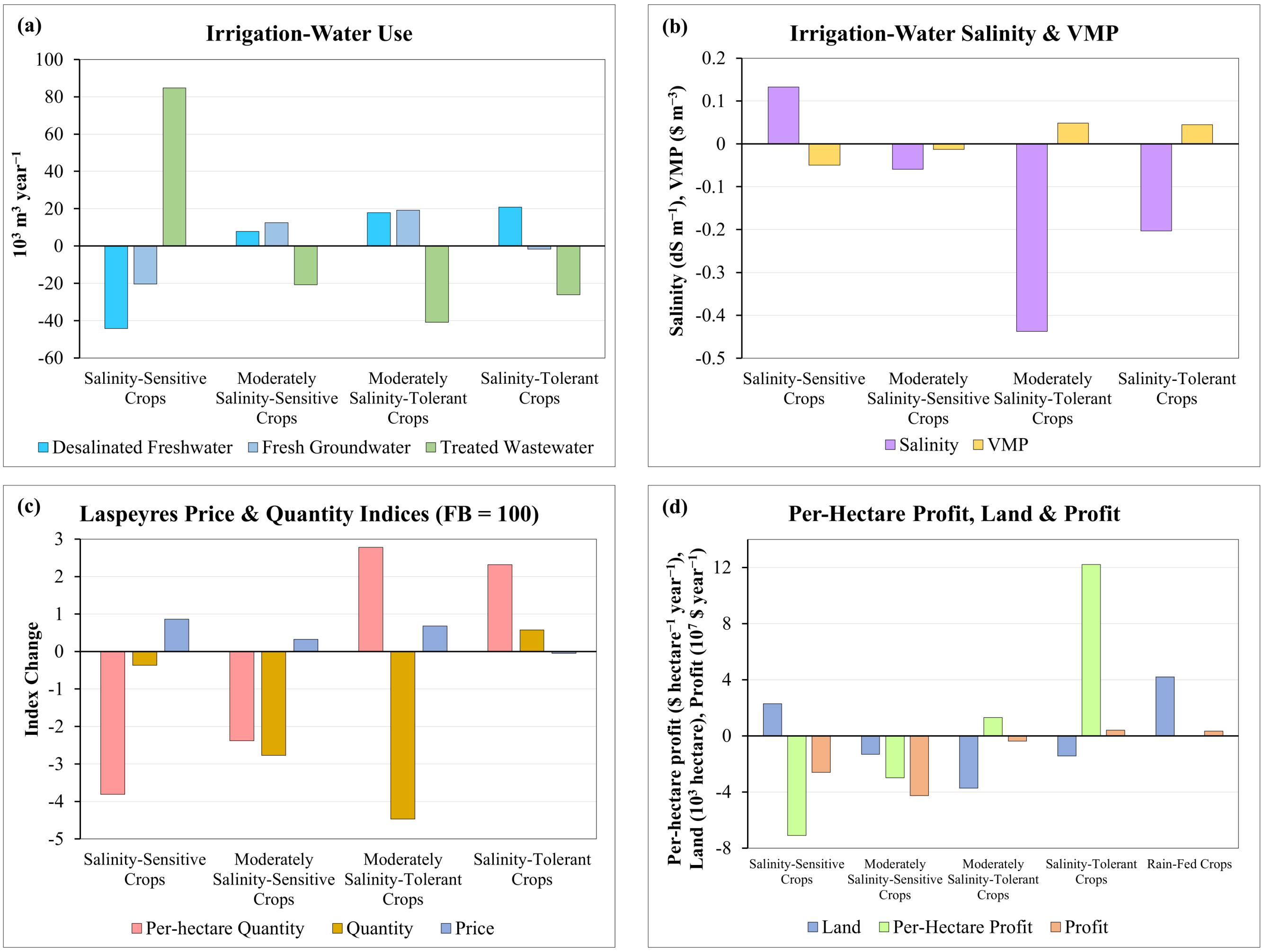

Figure 6. Differences between the RB and FB scenarios (RB minus FB) with respect to (**a**) irrigation water use, (**b**) salinity and VMP of irrigation water, (**c**) changes in Laspeyres quantity and price indices, and (**d**) land allocation, per hectare profit, and total profit—all reported for the groups of crops classified based on their salinity tolerance.

Figure 6c presents changes in the Laspeyres quantity and price indices (FB = 100), and Figure 6d reports the respective changes in land allocation and profits. The per hectare quantity index (computed by holding both the land allocated to the crops and their prices at their values under the FB scenario fixed) of the salinity-sensitive crops exhibits the largest reduction; however, because the land allocated to these crops increases (Figure 6d), the overall quantity of the salinity-sensitive crops' production declines only slightly. In turn, the output prices of these crops increase. Increasing the share of the salinity-sensitive crops in the total agricultural land entails less water for all of the other irrigated crops, and therefore, their share of the land shrinks, and they are replaced by rain-fed crops. Similarly, the combinations of changes in land and the per hectare productivity of the other groups dictate the overall quantity and price changes (Figure 6c), and, in turn, the per hectare profitability and total profit (Figure 6d).

In terms of per hectare profit, even after adaptation through a change in the crop portfolio, the growers of salinity-sensitive crops lose the most from the shift from FB to RB; farmers who grow moderately salinity-sensitive crops show a slight loss, and all other crops benefit. So why is more land allocated to salinity-sensitive crops? We explain this phenomenon using the differences across the crop groups with respect to the relationships between production and output prices, which affect the equilibrium in the markets for agricultural products. On average, the demand elasticity (computed here by dividing the change in the price index by that in the quantity index) of the salinity-sensitive crops is two orders of magnitude larger than that of the other groups; this is because the prices of most of the crops in that group are determined at equilibrium in the agricultural markets for fresh products, which are subjected to import tariffs. Thus, the lower per hectare production of the salinity-sensitive crops will increase the output prices of those crops, thereby increasing their per hectare profitability and motivating farmers to increase their land share; this, in turn, will moderate price changes until equilibrium is reached. As shown in Figure 4, for farmers, the land reallocation benefits amount to USD 115 million a year—about 7% of their profits under the FB scenario.

3.4. Salinity Damage

Here, we discuss three ways to measure irrigation water salinity damage. The first follows Slater et al. [35] and uses the MYWAS-VALUE to evaluate salinity damage in the context of water infrastructure development. In that work, two optimal infrastructural development scenarios were compared: one accounting for changes in irrigation water salinity throughout the planning horizon and the other considering fixed salinity; the difference between the two scenarios reflects the damage associated with salinity when it is ignored when designing water infrastructures. The assessment of that damage in terms of the value of agricultural produce in Slater et al. [35] was USD 1200 per hectare. By repeating the evaluation procedure under the FB and RB scenarios, we obtained per hectare damage of USD 1195 and USD 1326, respectively, i.e., an additional USD 131 per hectare due to RB.

Another way to express the economic damage caused by the salinity of irrigation water is to measure the relationship between salinity and the VMP of the irrigation water. To that end, we use the variability in the water VMPs and salinities across the agricultural regions that were incorporated into MYWAS-VALUE. In panels (a) and (b) of Figure 7, we plot the regional average VMP of the irrigation water versus the respective average salinity levels under the FB and RB scenarios (the data reported in Figure 7 exclude the most southern region, Arava, which is both detached from the country's main water distribution network and is characterized by extremely dry conditions). The regional irrigation water VMPs vary between USD 0.6 per cubic meter to almost zero across regions, with an average of USD 0.34 and USD 0.31 per cubic meter under FB and RB, respectively. Notice the larger variability in the regional average salinities under RB, which stems from the low usage of saline water in some regions with high shares of salinity-sensitive crops. The linear trendlines fitted to the data indicate a clear negative relationship between the water VMP and salinity, with a steeper slope under FB compared to under RB. On average, a salinity increase of 1 dS m^{-1} reduces the water VMP by USD 0.39 and USD 0.30 per cubic meter for the cases of FB and RB, respectively. In terms of elasticity, a 1% increase in the average salinity of the irrigation water supplied to a region reduces the value of marginal product of that water by 2.4% and 1.6% under field and regional blending, respectively (we obtained elasticities by estimating the equation $\ln(VMP_i) = \alpha + \beta \ln(salinity_i) + \varepsilon_i$, in which i is the region index, α is the intercept, and the slope coefficient β represents the elasticity).

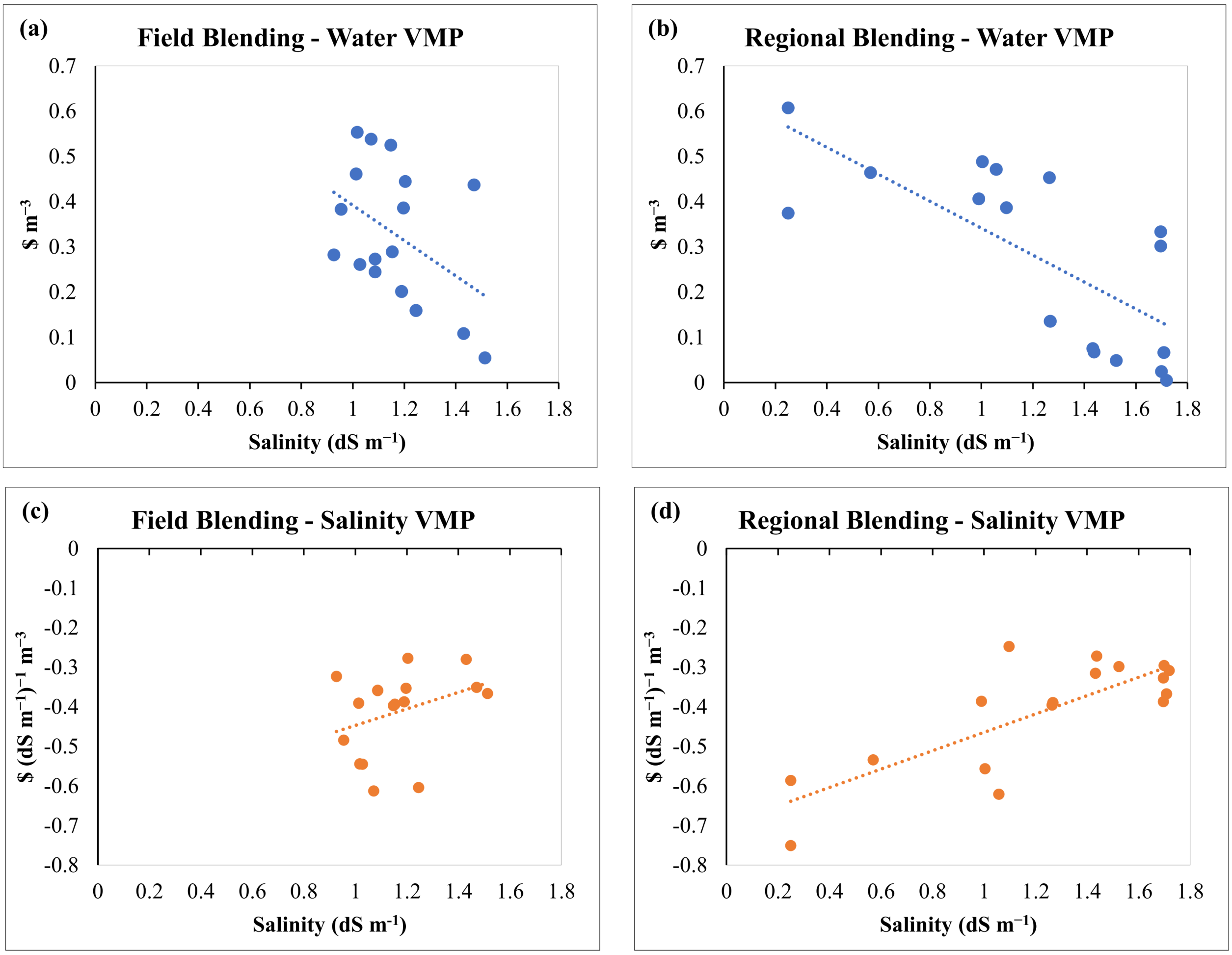

Figure 7. Regional VMPs of irrigation water and its salinity plotted against regional average salinities under the field blending and regional blending scenarios.

Recall that both the regional salinity and VMP of the water are endogenous in the model, and therefore, the curves depicted in Figure 7 represent the socially optimal relations between these measures rather than the marginal impact of salinity on the VMP. Our third measure of salinity damage is the VMP of the salinity itself; that is, the extent to which irrigation water with a higher salinity reduces the value of the agricultural production in a region. The VMP of the salinity is the shadow value of the salt balance constraint, which imposes equality between the amount of salt carried by the irrigation water supplied to a region and the salt content of the irrigation water applied to the crops. We obtained a welfare reduction of USD 525 and USD 534 million a year for a salinity increase of 1 dS m^{-1} under FB and RB, respectively. In panels (c) and (d) of Figure 7, we plotted the regional VMP of salinity divided by the regional amount of irrigation water (the units are USD (dS $m^{-1})^{-1}$ m^{-3}) against the regional average salinity. Per average cubic meter of irrigation water, the VMP of the salinity is similar under both scenarios, amounting to about USD -0.42 per dS m^{-1}. The trendlines fitted to the data indicate that the salinity is characterized by diminishing marginal damage, where a salinity increase of 1 dS m^{-1} reduces the marginal damage by USD 0.21 and USD 0.23 per dS m^{-1} per cubic meter of irrigation water under the FB and RB scenarios, respectively.

4. Conclusions

Based on the context of Israel, this paper shows that the management of irrigation water within the agricultural sector affects the optimal management of water in the water supply sector, and vice versa, and hence, the importance of accounting for the interrelationships between these sectors in the evaluation of economic damage due to irrigation water salinity. We used a mathematical programming model of the Israeli agriculture and water sectors to compare two intraregional irrigation water blending methods: blending at the field level, which enables a specific water salinity to be set for every crop, and regional blending, under which all crops obtain water with the same salinity. We found that enabling field-level blending reduces the land allocated to salinity-sensitive crops and increases welfare by USD 0.08 per cubic meter, which is about 20% of the average VMP for irrigation water. However, blending has been found to be suboptimal; this means that the welfare losses associated with regional blending could be avoided if regions were separated into sub-regions, each assigned to a different water type and a different set of crops. We evaluate the average salinity damage per cubic meter to be in the range of USD 0.30 to USD 0.42 per dS m^{-1} depending on the method employed to evaluate the damage and the irrigation water blending scenario.

5. Discussion

This study focuses on salinity as a single quality measure of irrigation water. However, in water-scarce areas, TWW has become a significant water source that renders salinity but one of many water quality measures. Compared to freshwater irrigation, the reuse of TWW in agricultural applications can harm agricultural production [39], degrade output qualities [40], and threaten the environment [41]. In response, TWW irrigation incentivizes stricter TWW quality standards [42] and attracts the development of new agricultural production technologies [43] and wastewater treatment methods [44]. Moreover, the supply of TWW is more stable than that of natural freshwater [45], and TWW contains nutritional elements that can partially replace fertilizers [46]. These processes have the potential to alter the use of irrigation water sources as well as the damage caused by salinity. To comprehend this, suppose that new regulations impose strict micropollutant standards that can only be met by the desalination of a large fraction of the generated TWW; in this case, the damage caused by salinity would become smaller and less sensitive to salinity changes. This implies that future economic studies of agricultural and water management should account for the interrelations across multiple water-quality measures.

Supplementary Materials: All the data used in this research have been incorporated into the MYWAS-VALUE model, which is available at: https://zenodo.org/record/3702053#.Xx1jpSgzZPZ (accessed on 3 January 2022).

Author Contributions: Conceptualization, Y.S., A.R., I.F. and I.K.; data curation, Y.S. and A.R.; funding acquisition, I.F. and I.K.; investigation, Y.S. and I.K.; methodology, Y.S., A.R., I.F. and I.K.; project administration, I.K.; software, Y.S. and A.R.; writing—original draft, Y.S.; writing—review and editing, A.R., I.F. and I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This study was partially funded by the Israeli Ministry of Agriculture and Rural Development (grant 12-09-0017), the Israeli Water Authority (grant 4501847408), the Israeli Ministry of Energy (grant 222-99-271), and the Center for Agricultural Economics Research at the Hebrew University of Jerusalem.

Data Availability Statement: Not applicable.

Acknowledgments: We thank the Editor and two anonymous reviewers for valuable comments. Thanks go to Yael Kachel from the Israeli Ministry of Agriculture and Rural Development for the data provisions.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

EC	Electrical Conductivity
FB	Field Blending
FBNA	Field Blending No Adaptation
MYWAS	Multi Year Water Allocation System
PMP	Positive Mathematical Programming
RB	Regional Blending
RBNA	Regional Blending No Adaptation
TWW	Treated Wastewater
VALUE	Vegetative Agricultural Land Use Economic
VMP	Value of Marginal Product

Appendix A. Preliminary Calibration Stage

Consider an agricultural region in which farmers grow O crops. The region has access to freshwater, TWW, and brackish water, the regional consumptions of which are limited to the amounts denoted Q^f, Q^h and Q^b, respectively, and their respective prices are p^f, p^h, and p^b, where $p^f > p^h > p^b$. Let q_o^f, q^h, and q_o^b denote the per hectare annual water applications of freshwater, TWW, and brackish water to crop o ($o = 1, \ldots, O$), respectively, where the sets $\mathbf{q}^f = \left(q_1^f, \ldots, q_O^f\right)$, $\mathbf{q}^h = \left(q_1^h, \ldots, q_O^h\right)$, and $\mathbf{q}^b = \left(q_1^b, \ldots, q_O^b\right)$ are defined accordingly. The total per hectare annual application to crop o, w_o, is considered constant. The production function is given by $\theta_o e_o\left(q_o^f, q_o^b, q^h\right)$, in which θ_o is a parameter for calibration, and $e_o(\bullet)$ is the evapotranspiration function of crop o, which is taken from Slater et al. [35]. The salinity of brackish water is higher than that of TWW, the salinity of which is higher than that of freshwater; therefore, $\frac{\partial e_o}{\partial q_o^f} > \frac{\partial e_o}{\partial q_o^h} > \frac{\partial e_o}{\partial q_o^b} > 0$. We denote by x_o, the land allocated to crop o, which is fixed at the preliminary stage. With the above setting, we first solve the nonlinear optimization problem

$$\max_{\mathbf{q}^f, \mathbf{q}^b,\ \mathbf{q}^h} \pi = \sum_{i=1}^{I} x_o \left[p_o \left(\theta_o e_o \left(q_o^f, q_o^h, q_o^b \right) \right) - p^f q_o^f - p^h q_o^h - p^b q_o^b \right] \tag{A1}$$

s.t.

$$q_o^f + q_o^h + q_o^b = w_o \ \ \forall \ \ o = 1, \ldots, O \tag{A2}$$

$$\sum_{o=1}^{O} x_o q_o^f \ \leq \ Q^f \tag{A3}$$

$$\sum_{o=1}^{O} x_o q_o^h \ \leq \ Q^h \tag{A4}$$

$$\sum_{o=1}^{O} x_o q_o^b \ \leq \ Q^b \tag{A5}$$

$$\mathbf{q}^f, \mathbf{q}^h, \mathbf{q}^b \geq 0 \tag{A6}$$

where the initial values of q_o^f, q_o^h, and q_o^b are set based on the shares of Q^f, Q^h, and Q^b in the total regional water $Q^f + Q^h + Q^b$, and the parameter θ_o is set so as to equate the computed yield to the observed one $\hat{Y}_o$:

$$\theta_o e_o \left(q_o^f, q_o^h, q_o^b \right) = \hat{Y}_o \ \ \forall \ \ o = 1, \ldots, O \tag{A7}$$

The resultant optimal water allocation sets $\mathbf{q}^{f*}$, $\mathbf{q}^{h*,}$ and $\mathbf{q}^{b*}$ are then used fto recalibrate θ_o based on Equation (A7).

References

1. Hillel, D. *Salinity Management for Sustainable Irrigation: Integrating Science, Environment, and Economics*; World Bank Publications: Washington, DC, USA, 2000.
2. *Water and Climate Change—The United Nations World Water Development Report*; The United Nations: New York, NY, USA, 2020. Available online: https://www.unwater.org/publications/world-water-development-report-2020/ (accessed on 6 November 2021).
3. Qadir, M.; Quillérou, E.; Nangia, V.; Murtaza, G.; Singh, M.; Thomas, R.J.; Drechsel, P.; Noble, A.D. Economics of salt-induced land degradation and restoration. *Nat. Resour. Forum* **2014**, *38*, 282–295. [CrossRef]
4. Zaman, M.; Shahid, S.A.; Heng, L. Soil salinity: Historical perspectives and a world overview of the problem. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer: Cham, Switzerland, 2018; pp. 43–53.
5. Vergine, P.; Salerno, C.; Libutti, A.; Beneduce, L.; Gatta, G.; Berardi, G.; Pollice, A. Closing the water cycle in the agro-industrial sector by reusing treated wastewater for irrigation. *J. Cleaner Prod.* **2017**, *164*, 587–596. [CrossRef]
6. Dai, A.; Zhao, T.; Chen, J. Climate change and drought: A precipitation and evaporation perspective. *Curr. Clim. Change Rep.* **2018**, *4*, 301–312. [CrossRef]
7. Rodell, M.; Famiglietti, J.S.; Wiese, D.N.; Reager, J.T.; Beaudoing, H.K.; Landerer, F.W.; Lo, M.H. Emerging trends in global freshwater availability. *Nature* **2018**, *557*, 651–659. [CrossRef] [PubMed]
8. Russo, D.; Laufer, A.; Bar-Tal, A. Improving water uptake by trees planted on a clayey soil and irrigated with low-quality water by various management means: A numerical study. *Agric. Water Manag.* **2020**, *229*, 105891. [CrossRef]
9. Hopmans, J.W.; Qureshi, A.S.; Kisekka, I.; Munns, R.; Grattan, S.R.; Rengasamy, P.; Ben-Gal, A.; Assouline, S.; Javaux, M.; Minhas, P.S.; et al. Critical knowledge gaps and research priorities in global soil salinity. *Adv. Agron.* **2021**, *169*, 1–191.
10. Darre, N.C.; Toor, G.S. Desalination of water: A review. *Curr. Pollut. Rep.* **2018**, *4*, 104–111. [CrossRef]
11. Jones, E.; Qadir, M.; van Vliet, M.T.; Smakhtin, V.; Kang, S.M. The state of desalination and brine production: A global outlook. *Sci. Tot. Environ.* **2019**, *657*, 1343–1356. [CrossRef]
12. Singh, A. Conjunctive use of water resources for sustainable irrigated agriculture. *J. Hydrol.* **2014**, *519*, 1688–1697. [CrossRef]
13. Gupta, S.K.; Singh, R.B.; Verma, A.K.; Chauhan, C.P.S. Conjunctive use of fresh and saline waters: Comparison of sequential, switching and blending modes. *J. Soil Salin. Water Qual.* **2015**, *7*, 79–89.
14. Peragón, J.M.; Pérez-Latorre, F.J.; Delgado, A.; Tóth, T. Best management irrigation practices assessed by a GIS-based decision tool for reducing salinization risks in olive orchards. *Agric. Water Manag.* **2018**, *202*, 33–41. [CrossRef]
15. Li, J.; Gao, Y.; Zhang, X.; Tian, P.; Li, J.; Tian, Y. Comprehensive comparison of different saline water irrigation strategies for tomato production: Soil properties, plant growth, fruit yield and fruit quality. *Agric. Water Manag.* **2019**, *213*, 521–533. [CrossRef]
16. Parkinson, H.L.; Maletic, J.T.; Wagner, J.P.; Sachs, M.S. Desalting saline ground water for irrigation: A case study, Buckeye Area, Arizona. *Water Resour. Res.* **1970**, *6*, 1496–1500. [CrossRef]
17. Knapp, K.C.; Dinar, A. Reuse of agricultural drainage waters: An economic analysis. *J. Am. Water Resour. Assoc.* **1984**, *20*, 521–525. [CrossRef]
18. Dinar, A.; Letey, J.; Vaux, H.J., Jr. Optimal ratios of saline and nonsaline irrigation waters for crop production. *Soil Sci. Soc. Am. J.* **1986**, *50*, 440–443. [CrossRef]
19. Kan, I.; Schwabe, K.A.; Knapp, K.C. Microeconomics of irrigation with saline water. *J. Agric. Resour. Econ.* **2002**, *27*, 16–39.
20. Kan, I. Yield quality and irrigation with saline water under environmental limitations: The case of processing tomatoes in California. *Agric. Econ.* **2008**, *38*, 57–66. [CrossRef]
21. Feinerman, E.; Yaron, D. Economics of irrigation water mixing within a farm framework. *Water Resour. Res.* **1983**, *19*, 337–345. [CrossRef]
22. Kan, I.; Rapaport-Rom, M. Regional blending of fresh and saline irrigation water: Is it efficient? *Water Resour. Res.* **2012**, *48*, W07517. [CrossRef]
23. Fisher, F.M.; Huber-Lee, A.T. *Liquid Assets: An Economic Approach for Water Management and Conflict Resolution in the Middle East and Beyond*; RFF Press: Washington, DC, USA, 2005.
24. Booker, J.F.; Howitt, R.E.; Michelsen, A.M.; Young, R.A. Economics and the modeling of water resource and policies. *Nat. Resour. Model.* **2012**, *25*, 168–218. [CrossRef]
25. Fisher, F.M.; Huber-Lee, A.T. The value of water: Optimizing models for sustainable management, infrastructure planning, and conflict resolution. *Desalin. Water Treat.* **2011**, *31*, 1–23. [CrossRef]
26. Harou, J.J.; Pulido-Velazquez, M.; Rosenberg, D.E.; Medellín-Azuara, J.; Lund, J.R.; Howitt, R.E. Hydro-economic models: Concepts, design, applications, and future prospects. *J. Hydrol.* **2009**, *375*, 627–643. [CrossRef]
27. Housh, M.; Ostfeld, A.; Shamir, U. Optimal multiyear management of a water supply system under uncertainty: Robust counterpart approach. *Water Resour. Res.* **2011**, *47*, W10515. [CrossRef]
28. Lavee, D.; Ritov, M.; Becker, N. Is desalination the most sustainable alternative for water-shortage mitigation in Israel? *Int. J. Sustain. Econ.* **2011**, *3*, 410–424. [CrossRef]
29. Reznik, A.; Feinerman, E.; Finkelshtain, I.; Kan, I.; Fisher, F.; Huber-Lee, A.; Joyce, B. The cost of covering costs: A nationwide model for water pricing. *Water Econ. Pol.* **2016**, *2*, 1650024. [CrossRef]
30. Reznik, A.; Feinerman, E.; Finkelshtain, I.; Fisher, F.; Huber-Lee, A.; Joyce, B.; Kan, I. Economic implications of agricultural reuse of treated wastewater in Israel: A statewide long-term perspective. *Ecol. Econ.* **2017**, *135*, 222–233. [CrossRef]

31. Saglam, Y. Welfare Implications of Water Shortages: Higher Prices of Desalination. Available at SSRN: https://ssrn.com/abstract=2271865 (accessed on 23 November 2021).
32. Tanaka, S.K.; Zhu, T.J.; Lund, J.R.; Howitt, R.E.; Jenkins, M.W.; Pulido, M.A.; Tauber, M.; Ritzema, R.S.; Ferreira, I.C. Climate warming and water management adaptation for California. *Clim. Change* **2006**, *76*, 361–387. [CrossRef]
33. Howitt, R.E.; MacEwan, D.; Medellín-Azuara, J.; Lund, J.R. *Economic Modeling of Agriculture and Water in California Using the Statewide Agricultural Production Model—Report for the California Department of Water Resources*; University of California: Davis, CA, USA, 2010.
34. Welle, P.D.; Medellín-Azuara, J.; Viers, J.H.; Mauter, M.S. Economic and policy drivers of agricultural water desalination in California's central valley. *Agric. Water Manag.* **2017**, *194*, 192–203. [CrossRef]
35. Slater, Y.; Finkelshtain, I.; Reznik, A.; Kan, I. Large-scale desalination and the external impact on irrigation—Water salinity: Economic analysis for the case of Israel. *Water Resour. Res.* **2020**, *56*, e2019WR025657. [CrossRef]
36. Kislev, Y. *The Water Economy of Israel—Policy Paper No. 2011.15*; Taub Center for Social Policy Studies in Israel: Jerusalem, Israel, 2011. Available online: http://taubcenter.org.il/wp-content/files_mf/thewatereconomyofisrael.pdf (accessed on 23 November 2021).
37. Howitt, R.E. Positive mathematical programming. *Am. J. Agric. Econ.* **1995**, *77*, 329–342. [CrossRef]
38. Maas, E.V.; Hoffman, G.J. Crop salt tolerance—Current assessment. *J. Irrig. Drain. Div. Am. Soc. Civil Eng.* **1977**, *103*, 115–134. [CrossRef]
39. Assouline, S.; Russo, D.; Silber, A.; Or, D. Balancing water scarcity and quality for sustainable irrigated agriculture. *Water Resour. Res.* **2015**, *51*, 3419–3436. [CrossRef]
40. Malchi, T.; Maor, Y.; Tadmor, G.; Shenker, M.; Chefetz, B. Irrigation of root vegetables with treated wastewater: Evaluating uptake of pharmaceuticals and the associated human health risks. *Environ. Sci. Technol.* **2014**, *48*, 9325–9333. [CrossRef] [PubMed]
41. Christou, A.; Agüera, A.; Bayona, J.M.; Cytryn, E.; Fotopoulos, V.; Lambropoulou, D.; Manaia, C.M.; Michael, C.; Revitt, M.; Schröder, P.; et al. The potential implications of reclaimed wastewater reuse for irrigation on the agricultural environment: The knowns and unknowns of the fate of antibiotics and antibiotic resistant bacteria and resistance genes—A review. *Water Res.* **2017**, *123*, 448–467. [CrossRef] [PubMed]
42. Miarov, O.; Tal, A.; Avisar, D. A critical evaluation of comparative regulatory strategies for monitoring pharmaceuticals in recycled wastewater. *J. Environ. Manag.* **2020**, *254*, 109794. [CrossRef] [PubMed]
43. Ogunmokun, F.A.; Wallach, R. Remediating the adverse effects of treated wastewater irrigation by repeated on-surface surfactant application. *Water Resour. Res.* **2021**, *57*, e2020WR029429. [CrossRef]
44. Grandclément, C.; Seyssiecq, I.; Piram, A.; Wong-Wah-Chung, P.; Vanot, G.; Tiliacos, N.; Roche, N.; Doumenq, P. From the conventional biological wastewater treatment to hybrid processes, the evaluation of organic micropollutant removal: A review. *Water Res.* **2017**, *111*, 297–317. [CrossRef]
45. Feinerman, E.; Tsur, Y. Perennial crops under stochastic water supply. *Agric. Econ.* **2014**, *45*, 757–766. [CrossRef]
46. Ofori, S.; Puškáčová, A.; Růžičková, I.; Wanner, J. Treated wastewater reuse for irrigation: Pros and cons. *Sci. Tot. Environ.* **2021**, *760*, 144026. [CrossRef]