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The Regional-Scale Dilemma of Blending Fresh And Saline Irrigation Water

by

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Abstract

Field-level economic analyses have indicated that blending fresh and saline water is suboptimal. This paper examines this issue on a regional scale, where both water sources and land are concurrently allocated to crops. We compare regional water-distribution networks that enable salinity adjustment at the field level to networks that allow controlling water salinity on a regional scale only, such that salt concentrations cannot differ per crop. We characterize the conditions for optimal blending under regional salinity-control networks, and show that these conditions can be met in empirical studies based on production models commonly used in the literature. Empirical analysis of 16 regions in Israel revealed optimal blending in six of them. The paper analyzes the relationship of shadow values of water and land constraints to the properties of distribution networks, and relative farming profitability under exogenous and endogenous water- and land-pricing schemes.

Keywords: irrigated agriculture; positive mathematical programming; salinity

JEL classification: Q15

The Regional-Scale Dilemma of Blending Fresh and Saline Irrigation Water

1. Introduction

Due to water scarcity, which an estimated 60% of the world's population is expected to be facing by the year 2025 (Qadir et al., 2007), there is increasing reliance on various higher-salinity water sources as substitutes for freshwater irrigation. One of these sources is aquifers containing brackish water, as utilized, for example, in Israel (Pasternak and De Malach, 1995), Texas (Mehta et al., 2000), and Argentina (Foster and Chilton, 2003). Another source is drainage emitted from subsurface tile lines, which are installed to lower the water table in waterlogged areas, for example, in Pakistan (Ghassemi et al., 1995), California (Oster and Grattan, 2002) and Australia (National Water Commission, 2006). Irrigation by wastewater, which carries salts added through domestic, industrial, and animal production uses of fresh water, constitutes both a reliable substitute for an unstable supply of (scarce) fresh water, and a way to avoid costly alternative disposal methods. Therefore, treated wastewater application in agriculture is on the rise in California (State Water Resources Control Board, 1999), Australia (Schaefer, 2001), Europe (Angelakis and Bontoux, 2001), the Middle East, and North Africa (FAO, 1997).

A regional blending dilemma arises whenever a few water sources with differing salinity levels are available for irrigation within a given region (a region is considered an area wherein multiple crops are grown — be it a farm, a district, etc. — whereas a field is assigned to a single crop). Irrigating all of the crops in a region with a mixture of all of the water sources is one option. Alternatively, each source can be applied unmixed to a specific group of crops; e.g., brackish water and fresh water to salinity-tolerant and salinity-sensitive crops respectively. Yet these are only two of numerous water-management alternatives, e.g., some sources may be blended, others applied unmixed, and the rest not consumed at all.

In fact, water blending has been used in many regions throughout the world, including the North China Plain (Sheng and Xiuling, 1997), the Broadview water district in California (Wichelns et al., 2002), Australia (Hamilton et al., 2007), Egypt (Tanji and Kielen, 2002), and Pakistan (Sharma and Minhas, 2005). Blending options have also been the subject of extensive agronomic studies examining their impacts on yield and soil properties [see Dudley et al. (2008) for review]. However, those studies do not tell us whether the widespread blending practice is an efficient strategy.

Perhaps the first to analyze the efficacy of mixing waters were Parkinson et al. (1970); however, they considered only predetermined blending combinations. In Feinerman and Yaron (1983) and Knapp and Dinar (1984), blending was endogenous and, depending on prices and crops’ salinity tolerance, could become optimal at the regional and field levels respectively. However, in both of those studies, salinity was the only factor affecting production.

Dinar et al. (1986) analyzed the blending issue at the field level, based on the crop-water-salinity production model developed by Letey et al. (1985), wherein larger quantities of water can compensate for yield reductions caused by higher salinity levels. Using the quadratic production functions estimated by Letey and Dinar (1986), Dinar et al. (1986) showed that field-level blending can be optimal in the case of salt-tolerant crops such as cotton. Kan et al. (2002) utilized the same production model (Letey et al., 1985) to estimate sigmoid production functions. They concluded that blending becomes optimal only when field-level water-application constraints are introduced. On the other hand, incorporating the positive impact of salinity on the quality of output in some crops may render field-level blending economically justifiable (Kan, 2008).

In a given region, the farmers' flexibility with respect to controlling the salinity of the water applied to each of their fields depends on the number of separate water types to which they have access. This accessibility, in turn, depends on both the farmers' direct access to water sources (e.g., to aquifers and on-farm drainage systems) and the properties of intra-regional water-supply networks; such networks may deliver wastewater from treatment plants, fresh water from snowmelt-runoff catchments, etc. As accessibility to a larger number of water sources entails higher water-distribution costs, to achieve efficiency, a regional planner should weigh the benefits derived from the flexibility provided by the distribution network against the associated water-distribution costs. This paper focuses on the benefits side of this cost-benefit equation.

Specifically, two kinds of water-distribution networks are considered: networks that provide every field in a region with access to all available water sources, thereby enabling field-level salinity control (FLSC) of water; and networks that supply a single type of water with uniform salinity level to all fields, thereby allowing only regional salinity control (RSC). While FLSC networks are expected to generate the highest farming profits, they may also carry the highest distribution costs, particularly in regions where, in order to enable separate conveyance of each water source to every field, parallel pipe systems need to be installed.

Regarding these two networks, our objectives are (1) to explore the basic links between efficient water management at the field and regional levels, particularly with respect to the blending dilemma, and (2) to evaluate the difference in farming profits between these networks under various water- and land-pricing schemes. These are essentially empirical issues, and as such, they are analyzed based on specifications:

The modeling approach developed by Kan et al. (2002) is adopted and applied to the case study of Israel.

We develop a regional-scale positive mathematical programming (PMP) model that allocates constrained land and water sources among 45 crops. The spatial units of the analysis are *ecological regions*, i.e., this partitioning of Israel into 21 zones is commonly used by the authorities for data collection and spatial analyses. Each ecological region is characterized by specific geological, topographical, demographic, and climatic attributes, which affect both the conditions for agricultural production and the availability of water sources. Our analysis focuses on the 16 regions that have access to at least two of the four potential sources of irrigation water: fresh water, brackish water, and secondary- and tertiary-treated wastewater. Table I reports the land and irrigation water available for agricultural production in the 16 ecological regions, ordered from north to south. Southern regions face drier climate conditions and have access to lower quantities of fresh water, yet a larger number of alternative sources.

Table I about here

All water sources in Israel are state property, and as such, the government controls their consumption by setting non-tradable user quotas, as well as administrative prices that are uniform nationwide. As in many other countries, prices in Israel do not reflect water scarcity (Kislev, 2006; Molle, 2009). The state also owns the vast majority of the agricultural land, and charges leasing fees based on cropping acreage and regions, regardless of land-market prices (Israel Land Authority, 2010). In our empirical analysis, we compare the FLSC and RSC networks' profitability under the observed administrative water and land prices, as well as under prices determined endogenously, i.e., prices that incorporate the shadow values of the regional water and land constraints.

The following section describes the regional water-management model and its versions vis-à-vis the structure of the distribution networks. In the third section, we analyze the link between efficient water management on the field and regional scales. The fourth section describes the specifications and data of the empirical analysis, the results of which are discussed in the fifth section. Section six concludes.

2. The Model

Consider a small region $j,\ j = 1,...,J$, in a small, open economy. Each of the region's farmers can potentially grow I crops. Farms in each region are assumed to be identical and to be acting in a competitive environment subject to regional conditions and constraints. Hence, our model skips the farm level and considers the regionally aggregated effects of various water-distribution networks in terms of land and water allocations among crops, and the associated regional crop-production profits.

The region has access to N types of water sources, which differ only in their salinities, prices, and regional-availability constraints. We denote by $\overline{W}_j^n$ (m^3 yr^{-1}) the regional quantity constraint of water source $n,\ n = 1,...,N$. We let c^n (in deci-Siemens per meter, dS m^{-1}) and p^n (\$ m^{-3}) be the salinity and price of source n, respectively; both are uniform across regions, and exogenous from the regional farmers' point of view.

A regional water-supply network enables provision of only $K,\ K \le N$, types of water, which are separately distributed to all fields in the region. Suppose that, of the N available water sources, the first $M = N - K + 1$ sources are restricted to being distributed only after they have been blended together, whereas each of the other

$N-M$ sources can be distributed separately. Let us index by *k*, $k=1,...,K$, a specific water type available for irrigation, such that $k=1$ stands for the mixture of the first M sources; $k=2$ is water source number $M+1$; and K is water source N. The salinity and price of the mixed water ($k=1$) are $c_j^1=\left(\sum_{n=1}^{M}W_j^n\right)^{-1}\sum_{n=1}^{M}c^nW_j^n$ and $p_j^1=\left(\sum_{n=1}^{M}W_j^n\right)^{-1}\sum_{n=1}^{M}p^nW_j^n$ respectively, where W_j^n (m^3 yr^{-1}) denotes the regional use of water source *n*.

Let w_{ij}^r (mm yr^{-1}) be the precipitation during crop *i*'s growing season in region *j*, the salinity of which is c^r (dS m^{-1}); and let w_{ij}^k (mm yr^{-1}) denote the application of water type *k* to crop *i*, $i=1,...,I$, in region *j*. Then, the quantity of water applied to crop *i* in region *j* is $w_{ij}=\sum_{k=1}^{K}w_{ij}^k$, and the salinity and price of this water are $c_{ij}=\left(w_{ij}+w_{ij}^r\right)^{-1}\left(\sum_{k=1}^{K}w_{ij}^kc_j^k+w_{ij}^rc^r\right)$ and $p_{ij}^w=w_{ij}^{-1}\sum_{k=1}^{K}w_{ij}^kp_j^k$ respectively.

Let p_i (\$ ton^{-1}) be crop *i*'s output price, which is similar across all regions in our small, open economy. Denote by π_{ij} (\$ ha^{-1} yr^{-1}) the annual per-hectare revenue minus water-purchasing costs associated with crop *i*:

$$\pi_{ij}=p_iy_{ij}\left(w_{ij},c_{ij}\right)-p_{ij}^ww_{ij} \tag{1}$$

where $y_{ij}\left(w_{ij},c_{ij}\right)$ (ton ha^{-1} yr^{-1}) is crop *i*'s production function specific to region *j*. The regional farming profits, Π_j (\$ yr^{-1}), are given by:

$$\Pi_j=\sum_{i=1}^{I}\left(x_{ij}\pi_{ij}-g_{ij}\left(\mathbf{x}_j\right)\right) \tag{2}$$

where x_{ij} (ha) is the land allocated to crop *i*; $\mathbf{x}_j = \left(x_{1j},...,x_{IJ}\right)$ is the vector of land allotments; and the function $g_{ij}\left(\mathbf{x}_j\right)$ (\$ yr^{-1}) represents the annual non-water production costs associated with crop *i*. The function $g_{ij}\left(\mathbf{x}_j\right)$ indirectly reflects the impact of various unobserved factors considered by farmers when contemplating land allocation among crops, including the spatial variability of the soil quality, marketing and agronomic risks, managerial limitations, etc. Under the PMP modeling approach, $g_{ij}\left(\mathbf{x}_j\right)$ is assumed to be continuous and strictly convex with respect to all $i = 1,...,I$, and therefore, when adequately calibrated to reproduce an observed land allocation in a base year, land changes smoothly in response to exogenous shocks that affect the relative per-hectare profitability of the crops (Howitt, 1995a).

From a regional planner's point of view, the optimization problem is:

$$\begin{aligned}
&\max_{\mathbf{x}_j,\mathbf{W}_j,\mathbf{w}_j} \Pi_j - C_j \\
&s.t. \quad \sum_{i=1}^{I} x_{ij} \le X_j, \\
&\qquad \sum_{i=1}^{I} x_{ij} w_{ij}^1 \le \sum_{n=1}^{M} \overline{W}_j^n \\
&\qquad W_j^n \le \overline{W}_j^n \qquad \forall\ n = 1,...,M \\
&\qquad \sum_{i=1}^{I} x_{ij} w_{ij}^k \le \overline{W}_j^k \quad \forall\ k = 2,...,K
\end{aligned} \tag{3}$$

where $\mathbf{W}_j = \left(W_j^1,...,W_j^M\right)$ is the vector of regional water utilizations of the *M* blended sources; $\mathbf{w}_j = \left(\left(w_{1j}^1,...,w_{1j}^K\right),...,\left(w_{Ij}^1,...,w_{Ij}^K\right)\right)$ is the set of vectors of per-hectare applications of the *K* water types to the *I* crops; C_j is the intra-regional water-distribution costs; and X_j (ha) is the regional land constraint.

The FLSC and RSC distribution networks constitute extreme cases of this model. Under FLSC, $K = N$, i.e., the regional distribution network enables access by all fields to all *N* water sources available to the region. The RSC scenario is obtained by setting $K = 1$, such that $M = N$, i.e., the network provides all fields with access to one water type only, be it one of the N sources or a mixture of all or part of them.

While we formulate and study the properties of the agricultural profits function Π_j, explicit analysis of the features of the intra-regional distribution-cost function C_j is beyond the scope of this work. We do, however, refer to options to reduce costs by changing the spatial distribution of water types, as well as to the impacts of the costs on the economic feasibility of switching between RSC and FLSC networks.

3. Interrelations of Water Management on Field and Regional Levels

Is it optimal to blend waters when the regional distribution network enables FLSC? And if not, then how does this outcome affect options for decreasing supply costs? Moreover, if indeed field-level blending is suboptimal, can blending under RSC networks ever become optimal? In other words, does the presence of an RSC network inevitably imply that only one of the sources available to a region should be utilized? To answer these questions, we conduct a micro-level analysis of optimal water management at the field level, and use the findings for inferences with respect to optimal strategies at the macro level, i.e., management on a regional scale.

For simplicity's sake, in this section we assume the availability of only two water sources ($N = 2$), one of which is fresh, the other saline, with availability constraints of $\overline{W}^f$ and $\overline{W}^s$; salinity levels of c^f and c^s; and prices of p^f and p^s respectively. The relationships $c^s > c^f > c^r$ and $p^f > p^s$ are assumed.

We begin with the FLSC scenario. Denote by w_i^f and w_i^s respectively the per-hectare quantities of fresh and saline water specifically applied to crop i (regional indices are omitted). Let us define η_i as the fraction of fresh water applied to crop i:

$\eta_i = w_i^f / w_i$, i.e., $\eta_i \in [0,1]$, where cases of $1 > \eta_i > 0$ represent blending; and $\eta_i = 0$ and $\eta_i = 1$ are the two non-blending options. If the economic problem in Equation (3) is formulated in terms of η_i and w_i, then the variable η_i constitutes a convenient instrument for analyzing the optimality of blending the fresh and saline waters specifically applied to crop *i*. These two decision variables determine both the salinity of the water applied to crop *i*,

$$c_i(w_i, \eta_i) = \frac{\left(c^f \eta_i + (1-\eta_i)c^s\right)w_i + c^r w_i^r}{w_i + w_i^r} \tag{4}$$

and its price — $p^w(\eta_i) = p^f \eta_i + (1-\eta_i)p^s$ — such that Equation (1) becomes

$$\pi_i(w_i, \eta_i) = R_i(w_i, \eta_i) - p^w(\eta_i)w_i \tag{5}$$

where $R_i(w_i, \eta_i) = p_i y_i(w_i, c_i(w_i, \eta_i))$ is crop *i*'s per-hectare annual revenue.

We set aside the supply cost C_j and assume for simplicity's sake that water constraints are not binding, i.e., under optimization, each water source's value of marginal production (VMP) is equal to the water's price. Under FLSC, the optimal per-hectare annual water application w_i^* and the blending variable η_i^* are set to maximize $\pi_i(w_i, \eta_i)$; we define this maximum as $\pi_i^* \equiv \pi_i(w_i^*, \eta_i^*)$.

The features of the function $y_i(w_i, c_i(w_i, \eta_i))$ are a key factor in the blending dilemma. Production functions are fitted to each of the crops incorporated in our empirical analysis based on the meta-modeling method used by Kan et al. (2002), as detailed in the next section. In this section, we make use of a function resulting from this procedure. To illustrate, we take the case of watermelon in the Beit She'an region, where the salinities of the fresh and saline water are 1 and 4 dS m^{-1} respectively. The discussion is based on the graphical exposition presented in Figure 1.

Figure 1 about here

In Figure 1a, isoquants of $\pi_i(w_i, \eta_i)$ are plotted in the $w_i^s : w_i^f$ plane (lighter shaded contours are associated with higher values) under the observed water prices in the Beit She'an region: $p^f = 7$ and $p^s = 5$¢ per cubic meter, i.e., a water-price ratio of $p^f / p^s = 1.4$. Under these specific conditions, $w_i^* = 700$ mm yr^{-1} and $\eta_i^* = 1$ (point *a*), i.e., optimality entails application of pure fresh water. In Figure 1b, we keep p^s, while p^f increases to p^s quadrupled, which yields the pair $w_i^* = 345$ mm yr^{-1} and $\eta_i^* = 1$ (point *b*)—this is another freshwater corner solution. Note, however, the emergence of a local maximum at $w_i = 1{,}182$ mm yr^{-1} and $\eta_i = 0$ (point *c*). In Figure 1c, where the freshwater price is further amplified to $p^f / p^s = 10$, this pure saline water local maximum becomes the global maximum (point *d*), i.e., $w_i^* = 1{,}182$ mm yr^{-1} and $\eta_i^* = 0$. Thus, as already shown by Kan et al. (2002), as long as the field-level water applications of both water sources are not constrained, field-level blending does not constitute an optimal strategy under any water-price ratio; i.e., cases of $1 > \eta_i^* > 0$ do not appear. This finding, which is shown here for watermelons, holds for all 45 crops across the 16 ecological regions in our study.

What are the implications of this field-level analysis for regional water management in general, and for saving on distribution costs in particular? Since field-level blending is suboptimal, the regional farming profits would be maximized by applying each water source separately to a different set of crops. This gives rise to the question: If water sources should be applied separately in any case, then why should every single field in a region have access to all water sources, when non-uniform spatial distribution of water types might reduce supply costs?

Suppose that a regional planner splits a region into N subregions, providing each with access to only one of the N water sources. If the area devoted to each subregion is set equal to the aggregated lands allocated to the crops corresponding to its water type under the FLSC optimal solution, then this regional splitting strategy could yield the same maximal farming profits as with the FLSC network; concomitantly, there may be a considerable savings in water-distribution costs, since parallel pipe systems need not be installed. However, farmers may resist the splitting option because of the income inequality that might be created among the water source-related subregions; hence, this option should be considered in view of the tradeoff between efficiency and inequity.

We turn now to the RSC scenario: The water-distribution network enables access of every field in the region to only one type of water, the salinity of which is set prior to distribution by a mixture of all available water sources. In our dual-water-source region, this constraint implies $\eta_i = \eta$ for all $i = 1,...,I$. Moreover, cases of $\eta = 0$ and $\eta = 1$ mean that the region completely waives utilization of one of the sources — fresh water or saline water — respectively; if such an outcome is optimal with respect to farming profits, it may also significantly reduce water-supply costs, since the expenses associated with extracting one of the sources and blending the two water types are avoided. The question is: Can solutions of $1 > \eta^* > 0$ emerge? In other words, does the suboptimality of field-level blending exclude the optimality of blending on a regional scale? Can we infer that installation of an RSC network will automatically render utilization of only one water source optimal? This is our next subject.

Setting aside the intra-regional supply costs C_j, the regional-scale optimization problem in Equation (3) becomes:

$$\max_{\mathbf{x},\mathbf{w},\eta} \Pi(\mathbf{x},\mathbf{w},\eta) = \sum_{i=1}^{I} \left(x_i \pi_i (w_i, \eta) - g_i(\mathbf{x}) \right)$$
$$s.t. \quad \sum_{i=1}^{I} x_i \le X, \quad \eta \sum_{i=1}^{I} x_i w_i \le \overline{W}^f, \quad (1-\eta) \sum_{i=1}^{I} x_i w_i \le \overline{W}^s \tag{6}$$

Suppose that this problem is solved in two stages: first, for any given level of η, the optimal land allocation $\mathbf{x}^*(\eta) = \left(x_1^*(\eta),\ldots,x_I^*(\eta)\right)$, and water applications $\mathbf{w}^*(\eta) = \left(w_1^*(\eta),\ldots,w_I^*(\eta)\right)$ are found. This yields the regional profit function $\Pi^*(\eta) = \Pi\left(\mathbf{x}^*(\eta),\mathbf{w}^*(\eta),\eta\right)$. Then, in the second stage, the optimal blending level, η^*, is computed so as to maximize $\Pi^*(\eta)$. This process may mimic an optimization procedure carried out by a regional planner who controls η: while searching for η^*, the planner takes into account that η is considered a given by farmers and affects their decisions regarding allocation of land and application of water to crops.

Thus, given η, and assuming an internal solution with respect to both variables $x_i^*(\eta)$ and $w_i^*(\eta)$ for all $i = 1,\ldots,I$, the maximization of $\Pi(\mathbf{w},\mathbf{x},\eta)$ with respect to **w** and **x** under the regional land and water constraints yields the first-order conditions (FOCs):

$$\frac{\partial R_i}{\partial w_i} + \frac{\partial R_i}{\partial c_i}\frac{\partial c_i}{\partial w_i} - \eta\left(p^f + \lambda^f\right) - (1-\eta)\left(p^s + \lambda^s\right) = 0 \quad \forall \; i = 1,\ldots,I \tag{7}$$

$$\pi_i^*(\eta) - \frac{\partial g_i\left(\mathbf{x}^*(\eta)\right)}{\partial x_i} - \lambda^x = 0 \quad \forall \; i = 1,\ldots,I \tag{8}$$

where $\lambda^f \ge 0$, $\lambda^s \ge 0$ (both in \$ m^{-3}) and $\lambda^x \ge 0$ (\$ ha^{-1}) are the shadow values of the regional freshwater, saline-water, and land constraints respectively; we define $\pi_i^*(\eta) \equiv \pi_i\left(w_i^*(\eta),\eta\right)$. To simplify the theoretical analysis, we suppose that the administrative prices p^f and p^s and the water availability constraints $\overline{W}^f$ and $\overline{W}^s$ are high enough to render both water constraints nonbinding, such that $\lambda^f = 0$ and

$\lambda^s = 0$. By substituting $\mathbf{x}^*(\eta)$ and $\mathbf{w}^*(\eta)$ into the objective function in Equation (6), we get $\Pi^*(\eta)$, which is the output of the first optimization stage. In the second stage, we search for η^*, which maximizes $\Pi^*(\eta)$. Using the envelope theorem, we obtain:

$$\frac{d\Pi^*(\eta)}{d\eta} = \sum_{i=1}^{I} x_i^*(\eta) \frac{d\pi_i^*(\eta)}{d\eta} \tag{9a}$$

$$\frac{d^2\Pi^*(\eta)}{d\eta^2} = \sum_{i=1}^{I} \left(x_i^*(\eta) \frac{d^2\pi_i^*(\eta)}{d\eta^2} + \frac{dx_i^*(\eta)}{d\eta} \frac{d\pi_i^*(\eta)}{d\eta} \right) \tag{9b}$$

A necessary condition for the optimality of blending is the existence of η^* such that $1 > \eta^* > 0$, for which both the FOC $\frac{d\Pi^*(\eta^*)}{d\eta} = 0$ and the second-order condition (SOC) $\frac{d^2\Pi^*(\eta^*)}{d\eta^2} < 0$ are met, and $\Pi^*(\eta^*) = \max_{\eta} \Pi^*(\eta)$, $\eta \in [0,1]$. In Appendix A, we prove that a necessary condition for the fulfillment of these internal optimal-solution requirements is strict concavity of the function $\pi_i^*(\eta)$ for at least one of the I crops. We now turn our attention back to Figure 1, wherein the achievement of this particular condition is analyzed empirically.

The dashed curves in Figures 1a, 1b, and 1c represent the function $\pi_i^*(\eta)$, plotted in the $w_i^s : w_i^f$ plane under the aforementioned p^f / p^s water-price ratios of 1.4, 4, and 10 respectively. Each of these curves is composed of the points at which the isoquants of the function $\pi_i(w_i, \eta_i)$ are tangent to the iso-salinity lines $w^s / w^f = (1-\eta)/\eta$, as illustrated in Figure 1a for the cases of $\eta = 0.4$ and $\eta = 0.8$. Our focus is on Figure 1d, wherein these three $\pi_i^*(\eta)$ functions are plotted versus η. The aforementioned absence of an internal field-level optimum with respect to watermelon ($1 > \eta_i^* > 0$) is evidenced by the optimal corner solutions indicated on

Figure 1d by points *a*, *b*, and *d* commensurate with the optima in Figures 1a, 1b, and 1c respectively. However, does the absence of optimal internal field-level solutions rule out the potential appearance of an optimal internal solution on the regional scale (i.e., $1 > \eta^* > 0$)? The answer is no: Under the p^f / p^s water-price ratio of 1.4, the function $\pi_i^*(\eta)$ for watermelon is strictly concave, as required for the optimality of regional blending.

Apparently, concavity emerges with $\frac{d\pi_i^*(\eta)}{d\eta} > 0$ only, and vanishes otherwise, i.e., the concavity disappears as the water-price ratio p^f / p^s increases; this phenomenon is valid for all crops analyzed in this study that do exhibit concavity (e.g., watermelon, potato, tomato, and celery). This is the fundamental feature eliminating the optimality of field-level blending, yet enabling blending to become optimal under the RSC scenario. Given this characteristic, the FOC for optimal regional blending, $\sum_{i=1}^{I} x_i^*(\eta) \frac{d\pi_i^*(\eta)}{d\eta} = 0$, can be satisfied provided that under the same water-price ratio, some crops exhibit $\frac{d\pi_i^*(\eta)}{d\eta} < 0$, and others $\frac{d\pi_i^*(\eta)}{d\eta} > 0$, where, as required by the SOC, the concavity associated with the latter group overcomes the convexity of the former. Thus, we conclude that the optimality of blending under RSC networks cannot be rejected a priori; empirical water-management analyses should allow for the appearance of blending options.

The optimality of blending under RSC depends on a range of factors, among them the shadow values of the water and land constraints. If a water source's usage is limited by a binding constraint, then under optimal conditions, the water's VMP is equal to the sum of the water-purchasing price and the constraint's shadow value (see

Equation 7). Another factor is the $g_i(\mathbf{x})$ functions: As shown in Appendix A, their convexity levels play a role in fulfilling the SOC for an internal optimal solution. This convexity depends on the land's shadow value λ^x (see Equation A3 in Appendix A). Thus, binding water and land constraints affect the appearance of blending as an optimal strategy through their respective shadow values.

4. Specifications, Calibration, and Data

Returning to the general optimization problem (Equation 3), an empirical, regional-scale PMP analysis based on any ecological region $j,\ j = 1,...,16$, requires parameterization, estimation, and calibration of the production function $y_{ij}(w_{ij}, c_{ij})$ and the non-water cost function $g_{ij}(\mathbf{x}_j)$ with respect to each crop $i,\ i = 1,...,45$.

Beginning with the production side, the production function represents yield responses to variations in water application and salinity, which should be based on solid agronomic theory and validated by well-designed field experiments. At the same time, it should have enough degrees of freedom to enable calibration based on microeconomic principles, so that the PMP model will reproduce water allocations observed in a base year. To achieve these two goals, we adopt the composite production function developed by Kan et al. (2002):

$$y_{ij}(w_{ij}, c_{ij}) = \phi_{ij} + \theta_{ij} e_{ij}(w_{ij}, c_{ij}) \tag{10}$$

where ϕ_{ij} (ton ha^{-1} yr^{-1}) and θ_{ij} (ton m^{-3}) are parameters, and $e_{ij}(w_{ij}, c_{ij})$ (m^3 ha^{-1} yr^{-1}) is a function relating evapotranspiration (ET) to water application and salinity:

$$e_{ij}(w_{ij}, c_{ij}) = \frac{E_{ij}}{1 + \alpha_{1ij}\left[\alpha_{2ij} c_{ij} + \alpha_{3ij}\left(w_{ij} + w_{ij}^{r}\right)^{\alpha_{4ij}}\right]^{\alpha_{5ij}}} \tag{11}$$

Here, E_{ij} (m^3 ha^{-1} yr^{-1}) is crop *i*'s potential ET in region *j*, and α_{1ij} through α_{5ij} are parameters. The production function's parameters are estimated and calibrated by a four-stage meta-analysis procedure, as described in Appendix B. At the heart of this analysis lies the plant-level agronomic model developed by Shani et al. (2007) as a refinement of Letey et al.'s (1985) model. While in the latter, additional water quantities can perfectly offset yield reductions caused by increases in salinity, under Shani et al. (2007) such perfect offsets are limited to low ranges of water application.

There are three noteworthy properties of the production function. First, while the function is calibrated to reproduce base-year water applications, the responses to variations in water and salinity are dominated by the experimentally-based estimates of their impacts on ET, formulated by Equation (11). Second, for a crop lacking such experimental information, the ET function can be borrowed from another crop of the same botanical family (e.g., from barley to wheat), while the conversion to yield is accomplished by calibration based on data of the specific crop under consideration. Finally, the functional form of ET transforms the yield function $y(w,c)$ into an increasing sigmoid function with respect to water. In contrast to the quadratic function (used, for instance, by Letey and Dinar, 1986), for each crop *i* there is some strictly positive water application, denoted $w_{ij}^{\min}$, under which the water's VMP equals the water's value of average production (VAP); if the corresponding VAP exceeds the water price, then $w_{ij}^{\min}$ constitutes a lower bound on the set of optimal per-hectare water applications. This property has a potential impact on regional-scale optimization under regional water-quantity constraints: A change in the salinity of the water applied to crops — either through blending or through assignment of crops to water types that differ from those to which they were assigned in the calibration stage —

shifts the crops' water-production function, and may cause the selection of $w_{ij}^{\min}$ for all $i,\ i = 1,...,45$, eventually resulting in land fallowing. Thus, land fallowing under our PMP model may be a result of both the sigmoid structure of the production function $y(w,c)$ and the convex non-water production cost function $g(\mathbf{x})$.

For the non-water cost function $g_{ij}(\mathbf{x}_j)$, we adopt the commonly used quadratic specification (e.g., Howitt, 1995b; Röhm and Dabbert, 2003):

$$g_{ij}(\mathbf{x}_j) = x_{ij}\left(\beta_{ij} + \tfrac{1}{2}\delta_{ij}x_{ij}\right) \tag{12}$$

where β_{ij} and δ_{ij} are parameters calibrated by the two-stage PMP calibration procedure developed by Howitt (1995a). Note that this simplified cost function, like other more general cost functions that require implementation of more sophisticated calibration procedures (e.g., Paris and Howitt, 1998; Heckelei and Wolff, 2003), has the convexity property that affects the emergence of optimality of blending waters on the regional scale (see Appendix A).

Data were collected from publicly available information sources. The base year for the analysis was 2002, and all monetary values are in US dollars for that year (the model and the entire dataset are available from the authors upon request). Base-year average per-hectare yield, output prices, and average per-hectare non-water costs were available only for the nationwide level, and were obtained from the Israel Central Bureau of Statistics (ICBS, 2004) and various production-instruction reports published by the Israel Ministry of Agriculture and Rural Development (IMARD, 2002). To calibrate a non-water cost function for the lowest profitable crop (see Howitt, 1995a), the associated maximum yield reduction below average yield was calculated, using nationwide yield levels for the period 1992-2002. Regional-scale base-year data included the cropping areas of 45 crops in each region, the price, and total consumption of water from each of the four sources; precipitation and potential ET levels during the growing season of each crop; and the Christiansen uniformity coefficient associated with each crop, all from the ICBS (2004) and IMARD (2002) reports. The salinities of the fresh and brackish waters were 1 and 4 dS m^{-1} respectively, and the salinity of both the secondary- and tertiary-treated wastewaters was 2 dS m^{-1}. The typical soil characteristics incorporated into the agronomic model (Shani et al., 2007) for each region were obtained from Ravikovitch (1992).

Our regionally aggregated data did not provide information on the type of water applied to each crop. Therefore, a hierarchical procedure was employed to allocate waters to crops. Given the current Israeli regulations prohibiting the blending of fresh water and treated wastewater [blending is expected to be permitted when proposed new regulations on wastewater treatment come into effect (Israel Ministry of Environmental Protection, 2003)], and the relative rarity of brackish-water applications, we assume that, in the base year, only one type of water source was used for irrigating each crop. Initially, the regional quantity of treated wastewater was allocated to crops meeting the regulations regarding agricultural use of wastewater (Israel Ministry of Health, 1999). Then, brackish water was allocated to the most saline-tolerant crops using the salinity-tolerance ranking suggested by Maas and Hofmann (1977). The remaining crops were assumed to be irrigated with fresh water. Then, the base-year per-hectare water applications were calculated for each crop based on factorization of the quantities indicated by IMARD’s (2002) production instructions so as to match the computed regional total water consumptions to the observed ones.

5. Empirical Analysis

The objectives of the empirical analysis were to compare the FLSC and RSC scenarios with respect to utilization of land and water resources and farming profitability under exogenous and endogenous pricing schemes of water sources and land.

As already noted, no cases of blending were found under the FLSC scenario, i.e., each crop is irrigated by only one type of water. Nevertheless, blending emerges in the case of RSC, as can be culled from the right-hand section of Table II, which presents the region-level use of land and water resources under the FLSC and RSC scenarios in terms of percentage of the regional constraints reported in Table I. Since under our RSC scenario, water of one quality only was delivered to all fields, any exploitation of more than one water source implies blending, which occurs in six of the 16 regions.

Table II about here

With respect to the water constraints, overall water use under FLSC amounts to 86%, compared to only 75% under RSC (Table II, last row). On the other hand, total utilization of fresh water under FLSC is 3% less, a difference attributed to the FLSC network's ability to separately irrigate salinity-tolerant crops with higher-salinity water sources. In contrast, in the RSC case, any utilization of saline water increases the salinity of the single-water type delivered to all crops. Therefore, to reduce the salinity of the supplied irrigation water, the application of fresh water is higher in regions where fresh water is blended with saline water (e.g., in the Jordan Valley and Ra'anana). Freshwater use is also higher in regions where irrigation by saline water is avoided altogether (e.g., in the Hula Basin and Western Galilee), due to the need to compensate therein for the associated reduction in the total quantity of water utilized for irrigation.

Land fallowing appears in four cases (see Table II): In the Rehovot and Jordan Valley regions under FLSC; and in the Jordan Valley and Jezreel Valley regions in the RSC scenario. Examination of the waters' VMP versus VAP reveals that for all irrigated crops, VAP > VMP, implying that the appearance of the uncultivated area is related to the quadratic non-water cost functions rather than to the sigmoid structure of the water's production function.

Under what conditions is switching from the RSC to FLSC network warranted? Our analysis reveals that the pricing methods of agricultural water and land play a crucial role in this issue. Table III presents the differences between the FLSC and RSC networks with respect to the shadow values of water and land constraints.

Table III about here

As aforementioned, the contribution of fresh water to production is greater under RSC; therefore, the FLSC-minus-RSC differences in freshwater's shadow values are negative in most regions. Positive differences in the shadow values of the other more saline sources reflect their relatively smaller contribution to production under RSC; exceptions are two cases related to tertiary wastewater usage: the Besor region, wherein application of tertiary wastewater only is optimal under RSC; and the Negev, wherein the constraint of brackish water is binding under FLSC, yet not under RSC. The overall difference in water scarcity can be evaluated by the average water shadow values weighted by their respective consumptions (Column 5, Table III). In most cases, the sign of the weighted average shadow values corresponds to that of fresh water; water is scarcer under RSC in nine of the 16 regions. Scarcity of land, on the other hand, is higher under FLSC in 11 regions. As pointed out by Schwabe et al.

(2006), water and land scarcities are both nonseparable, and are expected to exhibit opposite trends: As water availability decreases, crop production becomes less profitable; therefore, the VMP of the agricultural land diminishes. However, our analysis shows that when a few water types with differing salinities are utilized, the scarcities of both waters and land can be higher under FLSC; examples are the Western Galilee and Arava regions.

If water and land prices are set endogenously so as to incorporate resources' scarcities, the differences in shadow values affect the relative profitability of crop production under the FLSC and RSC networks. Table IV presents the differences in regional farming profits (FLSC minus RSC) under four schemes of water and land pricing: (1) both the water prices and land-lease fees are the base-year observed ones; (2) water prices only are set endogenously so as to incorporate the shadow values of the regional water constraints [e.g., in the two-water model (see Equation 6), the prices of fresh and saline water become $p^f + \lambda^f$ and $p^s + \lambda^s$, respectively]; (3) land prices only are set endogenously [i.e., the lease fees are increased by λ^x (see Equation 7)]; (4) both water and land prices are set endogenously. Switching from an RSC to an FLSC network is worthwhile only in regions where the difference in profits exceeds the (unknown) associated additional distribution costs (C_j).

Table IV about here

Running the calibrated PMP model under the base-year observed prices essentially improves the water allocation obtained through the aforedescribed hierarchical procedure employed to assign water types to crops in the base year; the land allocation is concomitantly ameliorated as per the changes in relative profitability of crops caused by the water-allocation adjustments. As expected, the FLSC version yields better improvements than the RSC one, i.e., the greater flexibility provided by

FLSC networks enables higher regional profits in all regions except the Harod Valley, wherein the solutions coincide. Setting water prices only endogenously increases the profit difference in the nine regions wherein the weighted average shadow values of water are lower under FLSC (Table III). In six of the other seven regions, the advantage of the FLSC network is reduced, and in one region—the Lower Galilee—the RSC network is even more profitable than is the FLSC; since FLSC distribution costs are expected to exceed those of RSC, RSC should be favored in this region under endogenous water prices. Following this rationale, if land prices only are set endogenously, RSC becomes the clear-cut preferred network in three of the aforementioned 11 regions wherein land shadow values are lower under RSC; obviously, FLSC becomes more appealing in the four regions exhibiting the opposite phenomenon. The overall effect of resource scarcity is obtained when both land and water prices are set endogenously; in this case, RSC is unquestionably the preferred scenario in three regions.

6. Concluding Remarks

By examining interrelations between field and regional levels of irrigation management, and performing an empirical analysis for the case of Israel, this paper derives the following main conclusions: (1) despite the suboptimality of blending water sources with differing salinity levels when water salinity can be controlled at the field level, the blending option should not be ruled out where a regional water-distribution network allows water salinity to be controlled solely on a regional scale; blending with such networks may be optimal; (2) due to the suboptimality of field-level blending, splitting regions into subregions, each assigned to irrigation by a different water source, may reduce water-distribution expenses without diminishing farming profits; (3) contrary to saline waters, freshwater consumption under RSC networks is frequently higher than under FLSC networks, which is attributed to the salinity increase associated with the use of saline water when blending is the optimal strategy; and to lower overall regional water utilization where optimality entails application of fresh water only; (4) when water sources of a few differing salinity levels are utilized, variations in land scarcity due to switching from RSC to FLSC may run in the same direction as that of the overall water scarcity, as measured by the average shadow values of the waters weighted by their respective consumptions; (5) only when prices of water and/or land are set endogenously so as to incorporate the scarcities of these resources might RSC networks become more profitable than FLSC networks, rendering RSC the preferred network without needing to account for the differences in intra-regional distribution costs.

These findings can serve as general guidelines for planners of water policy and intra-regional distribution networks. However, the design of networks in specific regions requires consideration of a range of factors overlooked by our analyses, e.g., the supply costs associated with various water-distribution options, region-specific feasibility constraints, scenarios involving intermediate salinity-control options (i.e., cases of $N > K > 1$), and efficiency versus inequity considerations. Furthermore, while our model may constitute a useful instrument for optimizing regional farming profits, it may also be extended along various avenues. Here we mention two potential subjects for future research.

First, the presence of contaminants in treated wastewater, such as pharmaceutical compounds and heavy metals, may give rise to regulations limiting the field-level application of wastewater; under such regulations, blending may become optimal under FLSC networks (Kan et al., 2002). For example, in our two-water analysis, if the application of saline water to watermelons had been restricted at the field level to a maximum of 160 mm yr^{-1}, blending the fresh and saline waters for watermelon irrigation would have become optimal in the Beit She'an region (see point *e* in Figure 1c). Such restrictions may also alter the relative profitability of both FLSC and RSC.

Second, the time unit of our model is one year, and therefore only the annual average salinity of the applied water is considered. For shorter time frames, Shani et al. (2009) developed a dynamic model for optimizing intra-growing-period distribution of field-level water applications; however, that model incorporates only one type of water. Extending their framework to the case of various water qualities may reveal the optimality of applying more than one water type throughout the growing season. In a longer time frame, irrigation by saline water may alter soil characteristics, thereby reducing productivity (e.g., Shani and Ben-Gal, 2005). Moreover, deep-percolation flows may gradually change the salinity of intra-regional water sources (Knapp and Baerenklau, 2006), and in turn the optimal solutions with respect to both blending and assignment of differing water types to crops.

Appendix A

Based on Equation (5) and employing the envelope theorem gives

$$\frac{d\pi_i^*(\eta)}{d\eta} = \frac{\partial R_i}{\partial c_i}\frac{\partial c_i}{\partial \eta} - \left(p^f - p^s\right)w_i^*(\eta) \qquad \text{(A1)}$$

The first right-hand-side element in Equation (A1) is positive, since $\frac{\partial R_i}{\partial c_i} < 0$ (outputs decline with higher salinities) and $\frac{\partial c_i}{\partial \eta} < 0$, which follows from Equation (4). Given $p^f > p^s$, the sign of $\frac{d\pi_i^*(\eta)}{d\eta}$ is indeterminate. Thus, there may be η, $1 > \eta > 0$, under which the linear combination $\frac{d\Pi^*(\eta)}{d\eta}=\sum_{i=1}^{I}x_i^*(\eta)\frac{d\pi_i^*(\eta)}{d\eta}$ (Equation 9a) is zeroed, i.e., the FOC can be met.

Turning to the SOC, using Equation (8), we obtain:

$$\frac{dx_i^*}{d\eta}=\left(\frac{d\pi_i^*(\eta)}{d\eta}-\frac{d\lambda^x}{d\eta}\right)\left(\frac{\partial^2 g_i\left(\mathbf{x}^*(\eta)\right)}{\partial x_i^2}\right)^{-1} \tag{A2}$$

$$\frac{d\lambda^x}{d\eta}=\frac{\sum_{i=1}^{I}\left[\frac{d\pi_i^*(\eta)}{d\eta}\prod_{L^{-i}}\frac{\partial^2 g_l\left(\mathbf{x}^*(\eta)\right)}{\partial x_l^2}\right]}{\sum_{i=1}^{I}\left[\prod_{L^{-i}}\frac{\partial^2 g_l\left(\mathbf{x}^*(\eta)\right)}{\partial x_l^2}\right]} \tag{A3}$$

where $l\neq i$ and L^{-i} is the set of $I-1$ crops, excluding crop *i*. Substituting into Equation (9b) and rearranging yields

$$\frac{d^2\Pi^*(\eta)}{d\eta^2}=\sum_{i=1}^{I}x_i^*(\eta)\frac{d^2\pi_i^*(\eta)}{d\eta^2}+\frac{\sum_{i=1}^{I-1}\sum_{u=i+1}^{I}\left[\left(\frac{d\pi_i^*(\eta)}{d\eta}-\frac{d\pi_u^*(\eta)}{d\eta}\right)^2\prod_{H^{-iu}}\frac{\partial^2 g_h\left(\mathbf{x}^*(\eta)\right)}{\partial x_h^2}\right]}{\sum_{i=1}^{I}\left[\prod_{L^{-i}}\frac{\partial^2 g_l\left(\mathbf{x}^*(\eta)\right)}{\partial x_l^2}\right]} \tag{A4}$$

where $h\neq i\neq u$ and H^{-iu} is the set of $I-2$ crops, excluding crops *i* and *u*.

Under the PMP assumption of $\frac{\partial^2 g_i\left(\mathbf{x}^*(\eta)\right)}{\partial x_i^2}>0$ for all $i=1,\ldots,I$, the right element in the right-hand side of (A4) is non-negative. Regarding the left element, Equation (A1) can be redifferentiated to obtain:

$$\frac{d^2\pi_i^*(\eta)}{d\eta^2}=\frac{\partial^2 R_i}{\partial c_i dw_i}\frac{dw_i^*}{d\eta}\frac{\partial c_i}{\partial\eta}+\frac{\partial^2 R_i}{\partial {c_i}^2}\left(\frac{\partial c_i}{\partial\eta}\right)^2-\left(p^f-p^s\right)\frac{dw_i^*(\eta)}{d\eta} \tag{A5}$$

the sign of which is undetermined due to the indeterminateness of $\frac{\partial^2 R_i}{\partial w_i \partial c_i}$ and $\frac{\partial^2 R_i}{\partial {c_i}^2}$ (Kan et al., 2002), as well as the indeterminateness of $\frac{dw_i^*(\eta)}{d\eta}$, which follows from the involvement of the two formerly mentioned elements, as well as others:

$$\frac{dw_i^*(\eta)}{d\eta} = -\frac{\left(\frac{\partial^2 R_i}{\partial w_i \partial c_i} + \frac{\partial^2 R_i}{\partial {c_i}^2}\frac{\partial c_i}{\partial w_i}\right)\frac{\partial c_i}{\partial \eta} + \frac{\partial R_i}{\partial c_i}\frac{\partial^2 c_i}{\partial w_i \partial \eta} - \left(p^f - p^s\right)}{\frac{\partial^2 R_i}{\partial {w_i}^2} + 2\frac{\partial^2 R_i}{\partial w_i \partial c_i}\frac{\partial c_i}{\partial w_i} + \frac{\partial^2 R_i}{\partial {c_i}^2}\left(\frac{\partial c_i}{\partial w_i}\right)^2 + \frac{\partial R_i}{\partial c_i}\frac{\partial^2 c_i}{\partial {w_i}^2}} \qquad \text{(A6)}$$

This implies that Equation (A4) may end up negative, i.e., the SOC, $\frac{d^2 \Pi^*(\eta)}{d\eta^2} < 0$, may also be satisfied. A necessary condition for this occurrence is the negativity of the element $\sum_{i=1}^{I} x_i^*(\eta)\frac{d^2 \pi_i^*(\eta)}{d\eta^2}$, which necessitates strict concavity of the function $\pi_i^*(\eta)$ for at least one crop i, $i = 1,...,I$.

Note that the convexity levels of the functions $g_i(\mathbf{x}^*)$ affect the value of the right element in the right-hand side of Equation (A4), and thereby influence the value of the sum $\sum_{i=1}^{I} x_i^*(\eta)\frac{d^2 \pi_i^*(\eta)}{d\eta^2}$ required for inducing the optimal internal solution.

Appendix B

In the first calibration stage, Shani et al.'s (2007) model is run to generate a dataset wherein ET values are calculated for various combinations of annual water applications and salinities. These plant-level data are translated into field-level quantities by assuming a log-normal spatial distribution of water infiltration, as suggested by Knapp (1992). The mean value of this distribution equals 1 for mass balance (Feinerman et al., 1983), and the standard deviation is calculated to fit

Christiansen's uniformity coefficient (see Knapp, 1992) of the irrigation system typically used for each crop. Then, in the second stage, the produced dataset is used to estimate the parameters α_{1ij} - α_{5ij} by nonlinear regression, subject to the feasibility constraint: $\frac{\partial e_{ij}\left(w_{ij}, c_{ij}\right)}{\partial w_{ij}} \leq 1$. In the third stage, the parameter θ_{ij} is calibrated based on the FOC with respect to water application: Let w_{ij}^{0}, c_{ij}^{0}, and p_{ij}^{0w} be the base-year-observed quantity; salinity; and price of the water applied to crop *i* in region *j* respectively. Then, optimality requires equality between the irrigation water's VMP and its price:

$$p_i \theta_{ij} \frac{\partial e_{ij}\left(w_{ij}^{0}, c_{ij}^{0}\right)}{\partial w_{ij}} = p_{ij}^{0w} \tag{B1}$$

Finally, in the fourth stage, the calibrated θ_{ij} parameter, the base-year yield, and y_i^0, as well as w_{ij}^{0} and c_{ij}^{0}, are substituted into Equation (10) for calibration of the parameter ϕ_{ij}.

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Table I. Regional land and water constraints

Region	Land (10^3 ha)	Fresh water (10^6 m^3)	Secondary wastewater (10^6 m^3)	Tertiary wastewater (10^6 m^3)	Brackish water (10^6 m^3)	Total water (10^6 m^3)
Hula Basin	17.8	59.8	3.6	-	-	63.4
Western Galilee	24.7	39.6	6.2	-	-	45.8
Beit She’an	12.3	53.3	0.1	-	10.6	64.0
Harod Valley	4.1	16.0	-	-	0.7	16.7
Jordan Valley	2.1	21.9	-	-	1.9	23.7
Lower Galilee	12.9	17.2	4.1	-	-	21.3
Jezreel Valley	25.0	16.3	39.4	-	0.4	56.0
Nazareth	10.4	4.1	3.2	-	-	7.4
Hadera	23.1	53.5	27.8	-	-	81.3
Ra’anana	16.3	65.2	11.3	-	0.5	77.0
Rehovot	34.3	56.9	29.1	-	3.9	89.9
Jerusalem	8.1	7.2	19.6	-	-	26.8
Lachish	37.6	27.8	17.8	7.4	3.4	56.5
Besor	22.9	10.3	-	55.0	5.3	70.7
Negev	63.5	17.8	20.2	77.1	5.5	120.5
Arava	7.1	6.8	-	-	48.7	55.6
All regions	322.2	473.7	182.4	139.5	81.0	876.6

Table II. Utilization of water and land under FLSC and RSC networks, expressed in terms of % of the constraints reported in Table I

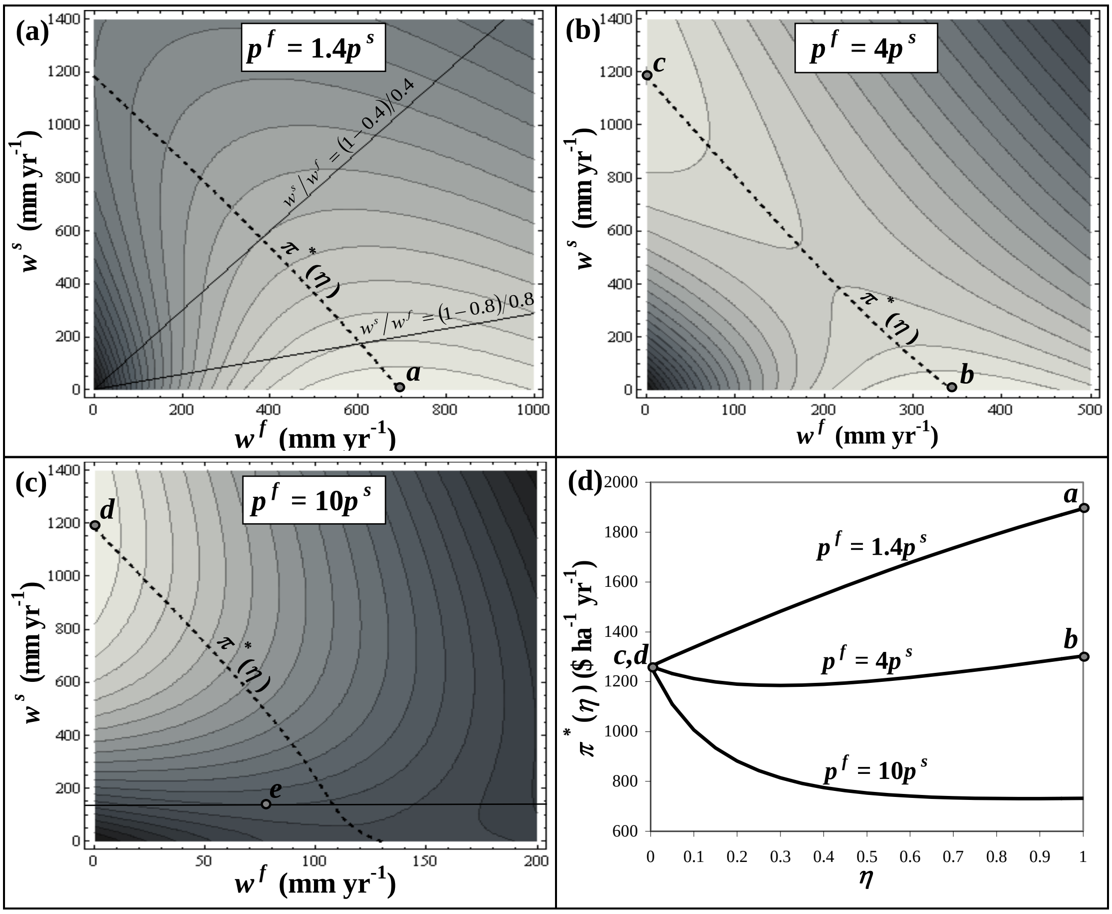
	Field-Level Salinity Control						Regional Salinity Control					
Region	**Fresh water**	**Secondary wastewater**	**Tertiary wastewater**	**Brackish water**	**Total water**	**Land**	**Fresh water**	**Secondary wastewater**	**Tertiary wastewater**	**Brackish water**	**Total water**	**Land**
Hula Basin	97	100	-	-	97	100	100	0	-	-	94	100
Western Galilee	90	100	-	-	92	100	100	0	-	-	87	100
Beit She’an	100	100	-	47	91	100	100	0	-	0	83	100
Harod Valley	100	-	-	0	96	100	100	-	-	0	96	100
Jordan Valley	91	-	-	100	92	99	94	-	-	100	95	99
Lower Galilee	100	39	-	-	88	100	100	0	-	-	81	100
Jezreel Valley	100	100	-	0	99	100	100	0	-	0	29	83
Nazareth	100	38	-	-	73	100	100	0	-	-	56	100
Hadera	100	100	-	-	100	100	100	0	-	-	66	100
Ra’anana	85	100	-	100	87	100	88	100	-	0	89	100
Rehovot	77	100	-	37	83	94	87	100	-	0	87	100
Jerusalem	100	75	-	-	82	100	100	0	-	-	27	100
Lachish	96	20	100	2	67	100	100	0	100	0	62	100
Besor	5	-	100	0	79	100	0	-	100	0	78	100
Negev	100	0	100	100	83	100	100	0	100	0	79	100
Arava	100	-	-	59	64	100	100	-	-	59	64	100
All regions	91	76	100	53	86	99	94	22	100	38	75	99

Table III. Differences (FLSC minus RSC) of water and land shadow values

Region	Fresh water (cent m^{-3})	Secondary wastewater (cent m^{-3})	Tertiary wastewater (cent m^{-3})	Brackish water (cent m^{-3})	All waters weighted average (cent m^{-3})	Land (\$ ha^{-1})
Hula Basin	-0.1	0.5	-	-	-0.1	0.2
Western Galilee	-0.3	4.2	-	-	0.3	0.5
Beit She’an	-0.4	1.8	-	0.0	-0.5	0.8
Harod Valley	0.0	-	-	0.0	0.0	0.0
Jordan Valley	0.0	-	-	1.9	0.2	0.0
Lower Galilee	9.3	0.0	-	-	8.0	-7.3
Jezreel Valley	-11.9	0.3	-	0.0	-18.2	2.6
Nazareth	0.1	0.0	-	-	-9.2	0.3
Hadera	-3.6	2.2	-	-	-3.4	6.2
Ra’anana	0.0	1.6	-	7.1	0.3	0.0
Rehovot	0.0	2.2	-	0.0	0.9	-1.5
Jerusalem	-15.5	0.0	-	-	-40.3	18.6
Lachish	-7.5	0.0	3.6	0.0	-5.2	32.2
Besor	0.0	-	-1.9	0.0	-1.9	2.8
Negev	-0.4	0.0	-2.1	1.6	-2.0	105.8
Arava	35.5	-	-	0.0	6.9	1.0

Table IV. Differences (FLSC minus RSC) of agricultural profits (10^6 \$ yr^{-1}) under observed and endogenous water and land prices

Region	Observed prices	Endogenous water prices	Endogenous land prices	Endogenous water & land prices
Hula Basin	0.04	0.08	0.02	0.06
Western Galilee	0.29	0.17	0.22	0.10
Beit She’an	0.05	0.27	-0.01	0.21
Harod Valley	0.00	0.00	0.00	0.00
Jordan Valley	0.04	0.00	0.04	0.00
Lower Galilee	0.78	-0.82	1.37	-0.23
Jezreel Valley	2.03	3.83	1.61	3.42
Nazareth	0.08	0.07	0.06	0.05
Hadera	1.52	2.85	0.63	1.96
Ra’anana	0.33	0.11	0.33	0.11
Rehovot	1.10	0.44	1.41	0.75
Jerusalem	1.29	2.40	0.34	1.45
Lachish	9.69	11.51	2.13	3.96
Besor	0.16	1.20	-0.24	0.80
Negev	1.10	2.73	-40.86	-39.23
Arava	2.62	0.19	2.58	0.15



Note: In (a), (b), and (c), lighter shaded contours are associated with higher values.

Figure 1. Graphic illustration of the relationships between the conditions for optimal blending under the FLSC and RSC scenarios, based on the case of watermelons in the Beit She'an region.

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