Structural Analysis of Irrigation-Water Substitutes to Freshwater

Abstract

While salt and pollutant contents of non-freshwater sources can reduce their agricultural productivity relative to freshwater, the supply of non-freshwater is frequently more stable than that of freshwater, and treated wastewater carry nutritious elements that may save fertilization expenses. Which of these counter attributes dominates becomes a question with water-management implications in areas where farmers have access to both non-fresh- and fresh-water sources. We develop a methodology for structural economic analysis of irrigation-water substitutes to freshwater. Specifically, we generalize the estimation of farmers' demand for a single water source under increasing block-rate tariffs (Bar-Shira et al. 2006) to the case of multiple water sources that differ in both their qualities and tiered prices. The methodology enables to identify the impact accessibility to different sets of water sources has on the features of the demand to each source. We apply the method to micro data on the agricultural sector in Israel, differentiating between freshwater and aggregated non-freshwater sources (brackish- and treated wastewater). We find non-freshwater to be not-less productive than freshwater, pointing at a balance between the positive and negative attributes of non-freshwater. Expectedly, we find lower freshwater-price elasticity in farms with access to both water sources compared to those accessible to freshwater only. We conduct simulations to examine the historical Israeli policy of replacing freshwater by non-freshwater quotas using a non-freshwater/freshwater exchange rate of 1.2, and find that an exchange rate of only 0.3 was required to retain farming profits unchanged. We simulate perfectly competitive markets for non-freshwater and freshwater, and find that, due to the interrelations of the demand functions of the two sources, simultaneous trade could increase farmers' profits by 50% compared to the non-trade baseline, whereas a trade in a single non-freshwater and freshwater market would yield a profit increase of only 22% and 12%, respectively.

Key words: Water quality, block-rate pricing, irrigation, water markets

JEL codes: Q15, Q18

Introduction

Processes of population growth and climate change steadily decrease the availability of freshwater for agricultural production, and enhance irrigation by non-freshwater sources such as brackish water and treated wastewater (TWW) (Qadir et al., 2007). On the one hand, the salt and pollutant contents of these alternative sources can reduce their agricultural productivity and applicability relative to freshwater (Dinar et al., 1986; Hanjra et al., 2012; Ratola et al., 2012); on the other hand, the supply of non-freshwater is frequently more stable than that of freshwater (Feinerman and Tsur, 2014), and TWW may also carry nutritious elements that save fertilization expenses (Dawson and Hilton, 2011). Which of these counter attributes dominates becomes a question with water-management implications in areas where farmers have access to both non-fresh- and fresh-water. This paper develops a methodology for structural economic analysis of irrigation-water substitutes to freshwater under increasing block-rate tariffs. The method enables estimation of demand functions for multiple irrigation water sources with different qualities. The methodology and its policy implications are illustrated using micro data from Israel.

According to Young (2005), estimations of irrigation-water demands were based on either the *deductive* or *inductive* approaches, each has its specific characters (Scheierling et al., 2006). Deductive-based studies use mathematical programming (MP) models to calculate residual scarcity rents of water sources (Booker et al., 2012). MP was widely employed to agricultural systems with access to a few water sources with various qualities, salinity in particular; studies by Parkinson et al. (1970), Feinerman and Yaron (1983), Knapp (1992), Schwabe et al. (2006), Kan and Rapaport-Rom (2012) and Connor et al. (2012) illustrate development of topics and methods along decades. Specific applications of the deductive approach to the derivation of water demands appear in Moore and Hedges (1963), Booker (1995) and Medellin-Azuara et al. (2009) with respect to the demand for freshwater, and by Kan et al. (2007) for multiple water sources with diversified qualities.

The inductive approach refers to the estimation of water demand functions based on applications of econometric procedures to sampled observations; see Lynne (1978), Nieswiadomy (1985), Moore et al. (1994), Schoengold et al. (2006) and Speelman et al. (2009). For the specific case of increasing block-rate tariffs, the literature presents structural discrete/continuous choice (DCC) and reduced-form instrumental variable models. Both methods were applied for estimating residential water demand in various regions (e.g., Nieswiadomy and Molina, 1989; Hewitt and Hanemann, 1995; Nauges and Blundell, 2002; Dahan and Nisan, 2007); using a Monte Carlo analysis, Olmstead (2009) conclude that there is no clear choice among the two methods in terms of estimation bias. The DCC model, originally introduced by Burtless and Hausman (1978) and generalized by Moffitt (1986), was first applied to irrigation water by Bar-Shira et al. (2006). However, to the best of our knowledge, as yet all the inductive-approach applications were limited to freshwater only. We propose a methodology that extends the Bar-Shira et al. (2006) DCC analysis so as to enable estimation of demand functions for multiple water sources that differ in their qualities.

Our methodology integrates into the DCC model the notion of water effectiveness proposed by Caswell and Zilberman (1986); it is used here to refer to all non-freshwater water sources in terms of their agricultural productivity relative to freshwater. We specify a linear freshwater-equivalents function, wherein each non-freshwater source is multiplied by a substitution-rate parameter that represents the source's productivity equivalence to freshwater. This linear specification implies that water sources are sequentially exhausted, where the sequence depends on the relations between the abovementioned substitution-rate parameters and the relative water prices. Essentially, this ordinal consumption pattern of water sources that differ in their qualities is a generalization of the consumption nature of a single water source under the presence of increasing block-rate prices: water in the second price-tier quota is consumed only once the (lowest) first-tier allotment is exhausted, and so forth. By integrating this structure into a DCC model, our methodology enables estimating the substitution rates between non-freshwaters and irrigation freshwater. Moreover, it also enables characterizing the impact accessibility to various water sources has on the properties of agricultural water demand.

We apply the methodology to the case of Israel, a semi-arid country with a steadily rising water scarcity. All Israel's water sources are public property (MNI, 1959), and both the supply and consumption are centrally managed by administrative extraction licenses, pumping fees, and consumption prices and quotas. Since the late 1980th, one of the governmental reactions to the growing water scarcity was to replace agricultural freshwater allotments by TWW quotas, using an exchange rate of 1.2 m^3 of TWW to a cut of 1 m^3 of freshwater quota (Kislev, 2011). Consequently, the share of TWW out of the total agricultural water consumption has increased from about 3% in 1985 to nearly 40% in 2010 (IWA, 2012); this makes Israel the country with the largest agricultural reliance on TWW.[1] Together with brackish-water use (about 15%), non-freshwater sources constitute today the majority of agricultural water consumption.

While other countries that face growing water scarcity are expected to increase their non-freshwater irrigation,[2] Israel is currently a unique source of information on the long-run patterns and implications of commercial farms' use of non-freshwater, TWW in particular. We obtained data on agricultural water consumers throughout Israel during 6 years in the 1990th and 2000th. This dataset enabled us to employ the methodology while differentiating between two water types: freshwater and an aggregation of non-freshwater sources (brackish water and TWW); about half of the sampled consumers have access to both sources, and the rest to freshwater only.

Our foremost intriguing estimation result reveals that non-freshwater is not less productive than freshwater; that is, from the farmers' perspective as manifested by our structural analysis, the aforementioned pros and cons of non-freshwater offset each other.[3]

Based on the estimation results we conduct simulations to explore the impacts of changes in exogenous variables. In line with the estimated high substitution between the two water sources, variations in non-freshwater quotas are found to have considerable impact on freshwater consumptions. With respect to water management, we study two policies, both represent reactions to increasing water scarcity. First, we examine the aforementioned exchange rate of 1.2 used to compensate farmers in Israel for freshwater-quota cuts, and find it to be extremely generous: given the estimated substitution rate and the large price difference between the two water sources, farmers' profits could be retained by an exchange rate of only 0.3. Second, we simulate the establishment of agricultural water markets in Israel. We consider markets for non-freshwater and freshwater, each as operating all along, and both simultaneously while accounting for the interrelations of the demand functions of the two sources. Assuming perfectly competitive markets, simultaneous trade expects to increase farmers' profits by 50% compared to the non-trade baseline, whereas a trade in a single non-freshwater and freshwater market would yield a profit increase of only 22% and 12%, respectively. Under simultaneous trade, on average, farms with access to both non-freshwater and freshwater sources are anticipated to purchase freshwater from the farms with access to freshwater only. We also identify a specialization trend: farmers with access to both water sources tend to further specialize in the use of the water source they mostly used in the baseline. We find that trade can considerably vary the spatial distribution of the composition of water-use throughout the country, such that consumers in southern Israel would exchange non-freshwater quotas with freshwater allotments, and northern consumers would do the opposite. Finally, we conclude that trade benefits are only slightly increased under forecasted climate-change-driven precipitation declines, implying that the establishment of water markets in Israel is warranted regardless of climate change.

The following sections present the structural model, estimation strategy, data and estimation results, sensitivity analysis, examination of policies, and some concluding remarks.

Structural Demand Equations

Consider a small open economy with *M* farmers. All farmers have access to freshwater sources, and a subgroup of farmers have access to additional non-freshwater sources – TWW and/or brackish water – where that accessibility is dictated by external factors such as the presence of a nearby wastewater treatment plant, a brackish-water aquifer, etc. That is, accessibility is exogenous from the farmers' standpoint. We denote by I and *J*, respectively, the number of farmers with access to both water sources and to freshwater only, where $I+J=M$.

Let w_i^s and w_i^f be, respectively, the amount of non-freshwater and freshwater consumed by farmer *i*, $i=1,...,I$, and $w_i = w_i^s + w_i^f$ denotes her total water consumption. We define

(1) $$w_i^e = w_i^f + \mu w_i^s$$

as the consumption of freshwater equivalents (Caswell and Zilberman, 1986), where μ is a parameter representing the technological marginal rate of substitution between non-freshwater and freshwater. Let $h_i\left(w_i^e\right)$ be the farm's production function, where $h_i\left(w_i^e\right)$ is twice differentiable with $h_i'\left(w_i^e\right)>0$ and $h_i''\left(w_i^e\right)<0$. Using Eq. (1), μ is the additional amount of freshwater needed to be consumed so as to offset a reduction in $h_i\left(w_i^e\right)$ due to a reduction in the consumption of one unit of non-freshwater:

(2) $$\left.\frac{dw_i^f}{dw_i^s}\right|_{h_i\left(w_i^e\right)=const.} = -\mu$$

Following the practice in our Israeli case study, non-freshwater is sold for a single price, p^s, subject to consumer-specific quotas, q_i^s, $i=1,...,I$, whereas freshwater is purchased based on a system of increasing block-rate tariffs with three price tiers. Let p^{fk} be the freshwater price at tier *k*, $k=\{1,2,3\}$, such that $p^{f3} > p^{f2} > p^{f1}$. Accordingly, denote by w_m^{fk} the amount of freshwater consumed by farmer *m*, $m=1,...,M$, at price *k*, such that the total freshwater consumption is $w_m^f = \sum_{k=1}^{3} w_m^{fk}$; the freshwater consumptions at tiers 1 and 2 are constrained by consumer-specific tier quotas such that $w_m^{f1} \le q_m^{f1}$ and $w_m^{f1} + w_m^{f2} \le q_m^{f2}$. There is also a quota for the total freshwater, q_m^f ; however, apparently, the constraint $w_m^f \le q_m^f$ was not enforced during our sample period.[4] Thus, for a relatively efficient farm who consumes freshwater at the third tier, the factor dictating the farm's total consumption is p^{f3} , and the existence of tier-prices 1 and 2 constitutes a subsidy. As indicated by Bar-Shira and Finkelshtain (2000), this subsidy enables the survival of less efficient farms who do not consume freshwater at the third tier; however, as shown by Schoengold and Zilberman (2014), increasing block-rate pricing is has a limited capacity to treat equity under a balanced budget.

The prices of agricultural outputs and inputs are fixed in our small open economy, and we therefore normalize $h_m\left(w_m^e\right)$ so as to represent the production value net of all non-water costs; then, the optimization problem faced by farmer *m* is

$$\begin{aligned} &\max_{w_m^s, w_m^f} \pi_m = h_m\left(w_m^f + \mu w_m^s\right) - p^s w_m^s - \sum_{k=1}^{3} p^{fk} w_m^{fk} \\ &s.t. \\ &w_m^s \le q_m^s;\ w_m^{f1} \le q_m^{f1};\ w_m^{f1} + w_m^{f2} \le q_m^{f2};\ w_m^s \ge 0;\ w_m^{fk} \ge 0\ \forall\ k = 1,2,3 \end{aligned} \tag{3}$$

Note that for any farmer *j*, $j = 1,...,J$, $w_j^s \equiv 0$; hence, $w_j^e \equiv w_j^f$, and the problem in Eq. (3) reduces to the specific case where farmers have access to freshwater only, which was the subject in Bar-Shira et al. (2006); in the followings we focus on the *I* farmers (with access to both water sources), and refer to the *J* farmers merely with respect to specific formulations and insights.

The non-freshwater's and freshwater's value of marginal production (VMP) are

$$v_i^s \equiv \partial h_i\left(w_i^e\right) / \partial w_i^s = \mu h'_i\left(w_i^e\right) \tag{4a}$$

$$v_i^f \equiv \partial h_i\left(w_i^e\right) / \partial w_i^f = h'_i\left(w_i^e\right) \tag{4b}$$

and the corresponding demand functions are

(5a) $$D_i^s\left(p^s, w_i^f\right) \equiv {v_i^s}^{-1}\left(p^s, w_i^f\right) = \left[{h'}_i^{-1}\left(p^s/\mu\right) - w_i^f\right]\Big/\mu$$

(5b) $$D_i^f\left(p^{fk}, w_i^s\right) \equiv {v_i^f}^{-1}\left(p^{fk}, w_i^s\right) = {h'}_i^{-1}\left(p^{fk}\right) - \mu w_i^s,\ k = \{1,2,3\}$$

Noteworthy is the role played by the transformation factor μ in translating non-freshwater consumptions and prices into freshwater equivalents, and vice versa.

Two issues arise. First, the demand functions in Eqs. (5a) and (5b) reflect price impacts on non-freshwater and freshwater consumptions, respectively, only in the case that their corresponding prices constitute the limiting factor; that is, when the quotas in the increasing block-rate price system are not effective. The factor that limits the consumption is dictated by the relation between the VMP functions in Eqs. (4a) and (4b) and the pricing schemes. Fig. 1 presents various possibilities of the down-sloped VMP functions v_i^s and v_i^f in relation to the corresponding increasing block-rate price schedules of the two water sources.

Figure 1 about here

Second, there is interdependence between the demand functions of the two water types. However, the linear specification in Eq. (1) implies that a profit-maximizing farmer *i* would consume water sequentially, from the lowest block price to the highest. In other words, only once water in the lowest tier have been exhausted, water in the next upper block price would be consumed, and so forth. Yet, again, comparison of non-freshwater and freshwater prices requires transforming non-freshwater prices into freshwater-price equivalents, using the transformation factor μ: p^s/μ versus p^{f1}, p^{f2} and p^{f3}. There are four possible relations between the transformation factor μ and the ratios of non-freshwater price to the freshwater tier prices:[5] (a) $\mu > p^s/p^{f1}$, (b) $p^s/p^{f1} > \mu > p^s/p^{f2}$, (c) $p^s/p^{f2} > \mu > p^s/p^{f3}$ and (d) $p^s/p^{f3} > \mu$. Each of these four options results in a different set of possible solutions to the optimization problem in Eq. (3), depending on the VMP functions v_i^s and v_i^f in relation to the increasing block-rate price schedules (Fig. 1). Appendix A summarizes the patterns of the various possible solutions under the four cases, as obtained based on the Karush-Kuhn-Tucker optimization conditions.[6] In Appendix B we detail how the Karush-Kuhn-Tucker conditions associated with Option (b) lead to the corresponding possible solutions reported in Appendix A. However, for the case of Israel, given the low price ratio of p^s / p^{f1}, we hypothesize (and later on verify statistically) that Option (a) prevails; therefore, our discussion proceeds based on this case.

Under Option (a), a profit-maximizing farmer *i* would consume freshwater merely after exhausting her non-freshwater quota q_i^s (see Appendix A). Thus

(6a) $$w_i^f = 0 \;\; if \;\; w_i^s < q_i^s$$

(6b) $$w_i^f \geq 0 \;\; if \;\; w_i^s = q_i^s$$

These two conditions imply that the consumption level of non-freshwater can be dependent on the non-freshwater price only in case that the freshwater price has no impact on the freshwater consumption (i.e., $w_i^s < q_i^s$, hence $w_i^f = 0$); and vice versa: the consumption of freshwater may depend on the freshwater prices merely when the non-freshwater price has no impact on the non-freshwater consumption ($w_i^f \geq 0$ if $w_i^s = q_i^s$). Based on these conditions, the demand functions in Eqs. (5a) and (5b) are no longer interdependent; they become

(7a) $$D_i^s\left(p^s\right) = h'^{-1}_i\left(p^s/\mu\right)/\mu$$

(7b) $$D_i^f\left(p^{fk}, q_i^s\right) = h'^{-1}_i\left(p^{fk}\right) - \mu q_i^s, \; k = \{1,2,3\}$$

and incorporate the transformation factor μ in an identifiable formulation.

As indicated in Appendix A for Option (a), under the v_i^{s1} and v_i^{s2} curves there is $w_i^s < q_i^s$, and therefore v_i^{f1} is the single option with respect to the freshwater's VMP, whereas v_i^{f2} through v_i^{f6} constitute valid options only in combination with v_i^{s3}; that is, when $w_i^s = q_i^s$. Thus, together with the combination of v_i^{s3} and v_i^{f1}, the total water consumed by farmer *i*, $w_i = w_i^s + w_i^f$, can be a result of the realization of eight potential combinations of the possible v_i^s and v_i^f curves presented in Fig. 1:

$$
(8) \qquad w_i = \begin{cases} 0 & if \;\; D_i^s\left(p^s\right) \le 0 \\ D_i^s\left(p^s\right) & if \;\; 0 < D_i^s\left(p^s\right) < q_i^s \\ q_i^s & if \;\; q_i^s \le D_i^s\left(p^s\right) \;\; \& \;\; D_i^f\left(p^{f1}, q_i^s\right) \le 0 \\ q_i^s + D_i^f\left(p^{f1}, q_i^s\right) & if \;\; 0 < D_i^f\left(p^{f1}, q_i^s\right) < q_i^{f1} \\ q_i^s + q_i^{f1} & if \;\; D_i^f\left(p^{f2}, q_i^s\right) \le q_i^{f1} \le D_i^f\left(p^{f1}, q_i^s\right) \\ q_i^s + D_i^f\left(p^{f1}, q_i^s\right) & if \;\; q_i^{f1} < D_i^f\left(p^{f2}, q_i^s\right) < q_i^{f2} \\ q_i^s + q_i^{f2} & if \;\; D_i^f\left(p^{f3}, q_i^s\right) \le q_i^{f2} \le D_i^f\left(p^{f2}, q_i^s\right) \\ q_i^s + D_i^f\left(p^{f3}, q_i^s\right) & if \;\; q_i^{f2} < D_i^f\left(p^{f3}, q_i^s\right) \end{cases}
$$

In four out of these eight combinations quotas are binding, wherein the demand functions in Eqs. (7a) and (7b) do not reflect consumption. The non-freshwater price affects consumption only under the v_i^{s2} option (which is combined with v_i^{f1}), and freshwater prices influence consumption only under the v_i^{f2}, v_i^{f4} and v_i^{f6} options (which are combined with v_i^{s3}). Noteworthy, the freshwater-price elasticity depends, not only on the freshwater price, but also on the consumption of non-freshwater: if $w_i^s < q_i^s$, the freshwater elasticity is zeroed; if $w_i^s = q_i^s$, and v_i^{f2}, v_i^{f4} or v_i^{f6} in Fig. 1 prevail, then, based on Eq. (7b), the freshwater consumption reduces with q_i^s such that larger levels of q_i^s yield larger freshwater elasticities.

In the next section we specify the production function and introduce random variables so as to formulate a likelihood function expressing the probabilities of the eight alternatives in Eq. (8).

Estimation Strategy

We specify a quadratic production function:

$$
(9) \qquad h_m\left(w_m^e\right) = A_m + a_m\left(w_m^f + \mu w_m^s\right) - \frac{b}{2}\left(w_m^f + \mu w_m^s\right)^2
$$

where A_m stands for the production effects of non-irrigation-water factors, and a_m and b are positive parameters. Accordingly, the demand functions in Eqs. (7a) and (7b) become

(10a) $$D_i^s\left(p^s\right)=\frac{a_i}{b\mu}-\frac{p^s}{b\mu^2}$$

(10b) $$D_i^f\left(p^{fk},q_i^s\right)=\frac{a_i}{b}-\mu q_i^s-\frac{p^{fk}}{b},\ k=\{1,2,3\}$$

Consider a panel data of *M* farmers over *T* periods. Let $\mathbf{x}_{mt}$ be a vector of observed variables on farm *m* and time *t*, $t=1,...,T$, and let d_{mt}^s be a dummy variable indicating access to non-freshwater sources (i.e., $d_{it}^s=1$ for all $i=1,...,I$ and $d_{jt}^s=0$ for all $j=1,...,J$). Using Eqs. (10a) and (10b), we specify the following periodical demand equations

(11a) $$D_{it}^s=\frac{\left(\boldsymbol{\eta}_1+\boldsymbol{\eta}_2\right)\mathbf{x}_{it}}{-\beta_1}+\frac{\beta_2+\beta_3}{\beta_1^2}p_t^s;\ i=1,...,I$$

(11b) $$D_{mt}^{fk}=\boldsymbol{\eta}_1\mathbf{x}_{mt}+\boldsymbol{\eta}_2\mathbf{x}_{mt}d_{mt}^s+\beta_1 q_{mt}^s+\beta_2 p_t^{fk}+\beta_3 p_t^{fk}d_{mt}^s;\ k=1,2,3;\ m=1,...,M$$

where $\boldsymbol{\eta}_1$, $\boldsymbol{\eta}_2$, β_1, β_2, and β_3 are parameters to be estimated. Except A_{mt}, all the structural elements of the optimization problem in Eq. (3) are identifiable, using the identities $\left(\boldsymbol{\eta}_1+\boldsymbol{\eta}_2\right)\mathbf{x}_{it}\equiv\frac{a_{it}}{b}$, $\beta_1\equiv-\mu$ and $\beta_2+\beta_3\equiv-\frac{1}{b}$ for the *I* farmers, and $\boldsymbol{\eta}_1\mathbf{x}_{jt}\equiv\frac{a_{jt}}{b}$, and $\beta_2\equiv-\frac{1}{b}$ for the *J* framers. This set of equations captures the structural linkage between the demands for the two water sources, represented by the identity $\beta_1\equiv-\mu$. In addition, taking advantage of the different accessibility of farmers to water sources, the equations enable identifying the impact of the accessibility to non-freshwater on the freshwater demand, represented by the parameters $\boldsymbol{\eta}_2$ and β_3.

Following Bar-Shira et al. (2006) and other DCC analyses, we consider two random variables that affect water demands. The first, α_{mt}, represents farming heterogeneity across the *M* farms and over time *t*; this random variable stands for technological and managerial features that are known to the farmer, but cannot be captured by variables observable to the econometrician; that is, $\mathbf{x}_{mt}$, d_{mt}^s, p_t^s and p_t^{fk}, $k=\{1,2,3\}$. The second random variable, ε_{mt}, represents errors associated with measurement, documentation, optimization and other factors that are all unknown to both the farmer and the econometrician. In line with Hauseman (1985), Moffitt (1986) and other DCC studies, we implement a linear additive formulation; using Eqs. (11a) and (11b), Eq. (8) becomes

$$
(12) \qquad w_{it} = \begin{cases}
\varepsilon_{it} & if \quad \alpha_{it} \le -D_{it}^{s} \\
D_{it}^{s} + \alpha_{it} + \varepsilon_{it} & if \quad -D_{it}^{s} < \alpha_{it} \le q_{it}^{s} - D_{it}^{s} \\
q_{it}^{s} + \varepsilon_{it} & if \quad q_{it}^{s} - D_{it}^{s} < \alpha_{it} \le -D_{it}^{f1} \\
q_{it}^{s} + D_{it}^{f1} + \alpha_{it} + \varepsilon_{it} & if \quad -D_{it}^{f1} < \alpha_{it} \le q_{it}^{f_1} - D_{it}^{f1} \\
q_{it}^{s} + q_{it}^{f_1} + \varepsilon_{it} & if \quad q_{it}^{f_1} - D_{it}^{f1} < \alpha_{it} \le q_{it}^{f_1} - D_{it}^{f2} \\
q_{it}^{s} + D_{it}^{f2} + \alpha_{it} + \varepsilon_{it} & if \quad q_{it}^{f_1} - D_{it}^{f2} < \alpha_{it} \le q_{it}^{f_2} - D_{it}^{f2} \\
q_{it}^{s} + q_{it}^{f_2} + \varepsilon_{it} & if \quad q_{it}^{f_2} - D_{it}^{f2} < \alpha_{it} \le q_{it}^{f_2} - D_{it}^{f3} \\
q_{it}^{s} + D_{it}^{f3} + \alpha_{it} + \varepsilon_{it} & if \quad q_{it}^{f_2} - D_{it}^{f3} < \alpha_{it}
\end{cases}
$$

Note that, whereas ε_{it} merely influences the demanded quantity, α_{it} affects both the demanded quantity and the pricing block that dictates the consumption, and therefore these two random effects are identifiable.

Eq. (12) is based on four assumptions. First, the distribution of α_{it} is similar for all the demand functions: D_{it}^{s}, D_{it}^{f1}, D_{it}^{f2} and D_{it}^{f3}. Second, while α_{it} captures heterogeneous random effects associated with the consumption of one water type (either w_{it}^{s} or w_{it}^{f}), ε_{it} captures the errors associated with the consumption of the sum of the two, w_{it}. Third, both distributions of α_{it} and ε_{it} are homoscedastic, and do not vary with the accessibility to non-freshwater. Finally, Eq. (12) is derived based on the assumption $1 > \mu > \frac{p^{s}}{p^{f1}}$. For example, consider the second possible solution $w_{it} = D_{it}^{s} + \alpha_{it} + \varepsilon_{it}$ subject to the condition $-D_{it}^{s} < \alpha_{it} \le q_{it}^{s} - D_{it}^{s}$, under which $q_{i}^{s} > w_{i}^{s} > 0$ and $w_{i}^{f} = 0$. The condition's left hand side, $-D_{it}^{s} < \alpha_{it}$, ensures $w_{i}^{s} > 0$; however, the right hand side, $\alpha_{it} \le q_{it}^{s} - D_{it}^{s}$, is more complex, since it involves two simultaneous conditions: $q_{i}^{s} \ge w_{i}^{s}$ and $w_{i}^{f} = 0$, which correspond respectively to $\alpha_{it} \le q_{it}^{s} - D_{it}^{s}$ and $\alpha_{it} \le -D_{it}^{f1}$.

Nevertheless, using Eqs. (10a) and (10b), and relying on $1 > \mu > \frac{p^s}{p^{f1}}$, the condition $\alpha_{it} \le q_{it}^s - D_{it}^s$ implies $\alpha_{it} \le -D_{it}^{f1}$.[7] Similar analyses yield the other 7 conditions in Eq. (12).

Regarding the *J* farmers with access to freshwater only, for them $q_{jt}^s = D_{jt}^s \equiv 0$, and therefore the second condition in Eq. (12) vanishes (one obtains $0 < \alpha_{jt} \le 0$, the probability of which is zero), and the first and third conditions are combined into one condition: $w_{jt} = \varepsilon_{jt}$ if $\alpha_{jt} \le -D_{jt}^{f1}$; thus, Eq. (12) incorporates only the 6 freshwater's VMP options depicted in Fig. 1.

The model's parameters are estimated by applying a maximum likelihood approach. Let $\Pr^{\psi}\left(w_{mt} \middle| \mathbf{x}_{mt}, d_{mt}^s, \mathbf{p}_{mt}, \boldsymbol{\theta}\right)$ be the probability of observing the water consumption w_{mt} by farmer *m* in year *t*, given the farm characteristics $\mathbf{x}_{mt}$ and d_{mt}^s, the price schedule $\mathbf{p}_{mt} = \left\{q_{mt}^s, q_{mt}^{f1}, q_{mt}^{f2}, p_t^s, p_t^{f1}, p_t^{f2}, p_t^{f3}\right\}$, and the parameter vector $\boldsymbol{\theta}$, which incorporates the parameters of the demand functions in Eqs. (11a) and (11b), and those of the distributions of α_{mt} and ε_{mt}. Note that we index the probability-function itself by the superscript ψ, $\psi = \{i, j\}$, which indicates the dependence on the accessibility to non-freshwater, as aforementioned. Based on Eq. (12), for some farmer *i* in year *t*,

$$
\begin{aligned}
&\Pr^{i}\left(w_{it} \middle| \mathbf{x}_{it}, d_{it}^s, \mathbf{p}_{it}, \boldsymbol{\theta}\right) = \\
&\quad \Pr\left[\varepsilon_{it} = w_{it}, \alpha_{it} \le -D_{it}^s\right] + \\
&\quad \Pr\left[\alpha_{it} + \varepsilon_{it} = w_{it} - D_{it}^s, -D_{it}^s < \alpha_{it} \le q_{it}^s - D_{it}^s\right] + \\
&\quad \Pr\left[\varepsilon_{it} = w_{it} - q_{it}^s, q_{it}^s - D_{it}^s < \alpha_{it} \le -D_{it}^{f1}\right] + \\
&\quad \Pr\left[\alpha_{it} + \varepsilon_{it} = w_{it} - q_{it}^s - D_{it}^{f1}, -D_{it}^{f1} < \alpha_{it} \le q_{it}^{f_1} - D_{it}^{f1}\right] + \\
&\quad \Pr\left[\varepsilon_{it} = w_{it} - q_{it}^s - q_{it}^{f_1}, q_{it}^{f_1} - D_{it}^{f1} < \alpha_{it} \le q_{it}^{f_1} - D_{it}^{f2}\right] + \\
&\quad \Pr\left[\alpha_{it} + \varepsilon_{it} = w_{it} - q_{it}^s - D_{it}^{f2}, q_{it}^{f_1} - D_{it}^{f2} < \alpha_{it} \le q_{it}^{f_2} - D_{it}^{f2}\right] + \\
&\quad \Pr\left[\varepsilon_{it} = w_{it} - q_{it}^s - q_{it}^{f_2}, q_{it}^{f_2} - D_{it}^{f2} < \alpha_{it} \le q_{it}^{f_2} - D_{it}^{f3}\right] + \\
&\quad \Pr\left[\alpha_{it} + \varepsilon_{it} = w_{it} - q_{it}^s - D_{it}^{f3}, q_{it}^{f_2} - D_{it}^{f3} < \alpha_{it}\right]
\end{aligned} \tag{13}
$$

To obtain the probability function for a *j* farmer, $\Pr^j\left(w_{jt}\left|\mathbf{x}_{jt},d^s_{jt},\mathbf{p}_{jt},\boldsymbol{\theta}\right.\right)$, one should replace the first three elements of Eq. (13) by the term $\Pr\left[\varepsilon_{jt}=w_{jt},\alpha_{jt}\le -D^{f1}_{jt}\right]$, and substitute $q^s_{jt}=d^s_{jt}=0$ in the relevant parts. Thus, for some farm *m*, the likelihood function can be generally written

(14) $$L_m=\prod_{t=1}^{T}\left[d^s_{mt}\Pr^i\left(w_{mt}\left|\mathbf{x}_{mt},d^s_{mt},\mathbf{p}_{mt},\boldsymbol{\theta}\right.\right)+\left(1-d^s_{mt}\right)\Pr^j\left(w_{mt}\left|\mathbf{x}_{mt},d^s_{mt},\mathbf{p}_{mt},\boldsymbol{\theta}\right.\right)\right]$$

and the sample likelihood function is

(15) $$L=\prod_{m=1}^{M}L_m$$

The errors α and ε are assumed to be statistically independent and normally distributed, $\alpha\sim N\left(0,\sigma_\alpha\right)$ and $\varepsilon\sim N\left(0,\sigma_\varepsilon\right)$, such that the likelihood in Eq. (15) can be formulated in terms of the standard normal density (Appendix C).

Data and Estimation Results

The administrative price schedules of irrigation water are usually updated every spring, in relation to the content of the groundwater storages at the end of the rainy season. While prices are common to all agricultural consumers, quotas are village specific. In 1989, the overall freshwater allotment, q^f, was set to every village based on its historical allocation from the early 1960th, and the block-rate pricing scheme was determined such that q^{f1} and q^{f2} equal 50% and 80% of q^f, respectively. These "1989 quotas" served as a reference for cuts in case of water shortage, where the reductions proceeded from the highest tier downward.[8]

Our analysis is based on an unbalanced panel of 1980 observations of village-level water consumptions, incorporating 369 cooperative (Kibbutzim) and semi-cooperative (Moshavim) villages in 6 years: 1996 through 1999, 2002 and 2008. During that period, all villages in the sample had access to freshwater, and part of them were connected also to at least one source of non-freshwater: brackish water, secondary- or tertiary-TWW; altogether, 1079 (54%) of the observations involve access to non-freshwater.[9] The consumptions and quotas were taken from official reports issued by the Israeli Water Authority. Rural communities purchase irrigation water from two types of suppliers: local water associations and the Mekorot company; the latter supplies about 60% of the water throughout the country. To ensure reliability of pricing data, we confine our analysis to villages who consume freshwater from Mekorot only. The prices of non-freshwater supplied by local entities are generally coincide with the Mekorot's regulated prices; hence, we include observations with non-freshwater consumption from both types of suppliers.

Figure 2 about here

To analyze relations between water consumption, pricing schemes and accessibility to non-freshwater sources, we present in Fig. 2 time trends of prices (all monetary values are in 2002 dollars) and per-village average annual quotas and consumptions. During the sample period, freshwater prices increased by about 75%, compared with only a 25% raise of the non-freshwater price (Fig. 2a). At the same time, freshwater quotas were cut (particularly q^{f2}), whereas non-freshwater quotas increased (Figs. 2b, 2c). These trends encouraged farmers with access to both water sources (Fig. 2b) to substitute freshwater use by non-freshwater, and in so doing they almost kept stable their overall water consumption at about 1.5 million m^3/year per village (not shown). In comparison, farmers with access to freshwater only were harmed twice: first, they had no alternative water sources, and second, the cut in their second-tier quota (q^{f2}) was relatively larger. Consequently, in 2008, these villages (on average) exhausted both quotas of the first and second tiers, whereas villages with access to both water sources did not.

Table 1 about here

Our explanatory variables (**x**) include geographical, climatologic and organizational data. Table 1 presents the variables' averages and standard deviations, separated according to villages with and without access to non-freshwater. The table reports statistically significant differences between the variable averages of the two village types; in the estimation we use the dummy variables d_{mt}^{s} to control for the potential different effects (see Eqs. (11a) and (11b)). To capture rural organizational effects, our variables include a dummy for semi-cooperatives that distinguishes them from the cooperative ones. Annual precipitation is expected to affect irrigation in case of drought periods during winter, which is the rainy season, and through soil moisture content afterwards; we also include a separate variable for precipitations in April to reflect potential needs in irrigation of winter crops before harvesting and of summer crops after sowing. Elevation above sea level indicates various climatologic and topographical characters. Agricultural area is included as an expected complementary production factor to water. Following Bar-Shira et al. (2006), the overall water allotment of a village, $q_{mt} = q_{mt}^{s} + q_{mt}^{f}$, is introduced as an instrument for long-run structural production design and heterogeneity in unobserved farm characteristics. In addition, we include a trend variable to control for changes along time in a wide range of factors (production technologies, preferences of agricultural-product consumers, etc.) and farm dummies to account for farm *fixed effects*.

Table 2 about here

The estimation results are summarized in Table 2. The first key element in our study is the estimated substitution coefficient $\beta_1 \; (\equiv -\mu)$, which equals -1.06 with a 95% confidence interval of $[-1.22, -0.90]$. Given that on average $\frac{p^s}{p^{f1}} = 0.747$, the fundamental hypotheses of our structural model, $\mu > \frac{p^s}{p^{f1}}$, prevails; that is, a profit maximizing farmer consumes freshwater only after exhausting her/his entire non-freshwater quota. The assumption $1 > \mu$, which is used for deriving Eq. (12) (see footnote 7), is not rejected. At the same time, we cannot statistically reject the possibility of $\mu \geq 1$, implying that non-freshwater may be perceived by farmers as more productive than freshwater. That is, the non-freshwater advantages (of having higher supply stability and nutrition content of TWW) may be viewed as overwhelming their disadvantages (of entailing irrigation limits and carrying higher salinity levels). From a policy perspective, in case that the government searches for an exchange rate between non-freshwater and freshwater quotas to retain unchanged the level of agricultural production, our results indicate that this exchange rate could be 1. More precisely, our estimated 95% confidence interval of β_1 $(=-\mu)$, $[-1.22,-0.90]$, implies the range $[0.82,1.11]$ for the non-freshwater-quota/freshwater-quota exchange rate $(=1/\mu)$; this range lays below the 1.2 rate employed in Israel during the 1990th.[10]

The second issue of interest is the impact accessibility to non-freshwater has on water-demand patterns. In other words, how farmers change their demand to freshwater when they get access to non-freshwater. Table 2 reports the coefficients corresponding to the two cases. Accessibility to non-freshwater was found making statistically significant difference in the coefficients of all the variables except “Annual precipitations” and “Agricultural land.” We now discuss the coefficients in details.

The trend variable is positive for both type of villages, but is significantly lower for those with access to non-freshwater sources; that is, accessibility to more stable and reliable water sources might enhance the adoption of water saving technologies, or, at the other hand, change cropping patterns in a way that limits opportunities of shifting production to more water-intensive-and-profitable crops. Semi-cooperative villages consume less than cooperatives – a phenomenon that can be attributed to historical differences in resource allocations that have led to a different agricultural production structure; the accessibility to non-freshwater alleviates this disparity. Increased annual precipitation reduces water consumption by both types of villages. The same holds for April rainfall, with a significantly lower impact on farms with non-freshwater utilization. Villages located in higher, and therefore more humid and steeped places, consume lower water amounts; yet, the effect on villages connected to non-freshwater sources is not statistically significant.

Apparently, larger agricultural area enlarges water consumption, but this effect is statistically significant only with respect to villages with accessibility to both water sources. Similarly, water consumption grows with the overall quota only in villages allotted with non-freshwater quotas. This finding corresponds the aforementioned non-imposition of the total freshwater water quotas, q^f, as well as our basic hypothesis that quotas affect the consumption of farmers with accessibility to non-freshwater; our results imply a consumption increase of 0.377 m^3 for a one cubic meter of quota augmentation. On the other hand, a village absent non-freshwater allotments is considerably more sensitive to water-price changes: if freshwater quotas are not effective, a price increase of one cent would reduce the village's annual freshwater consumption by 214,800 m^3, compared to only 50,240 m^3 in the case of a village accessible to non-freshwater. Examination of cropping patterns (not shown[11]) reveals that villages without connection to non-freshwater sources assign lower portions of their land to rain-fed crops, and larger shares to fruit trees; that is, their higher reliance on water-intensive farming may turn their production decisions more reactive to changes in water expenses. The σ_α and σ_ε estimates indicate that most of the estimation errors are attributed to the heterogeneity unexplained by our observable variables.

In Fig. 3 we present goodness-of-fit charts for the non-freshwater (Fig. 3a), and for the freshwater, separated into villages with access to both water sources (Fig. 3b) and to freshwater only (Fig. 3c); the predicted consumptions presented therein are the consumption expectations computed for every village at each year by applying a numerical integration based on the probability function in Eq. (13) and the estimated parameters. The predicted–versus–observed R^2 statistic of the entire data (all non-freshwater and freshwater observations) is 0.66.

Figure 3 about here

The consumption expectations presented in Fig. 3 incorporate the distribution of the VMP functions in relation to their intersections with the block-rate prices; we present the distribution in Fig. 4. In view of Fig. 1, these are the probabilities of $v^{s1} - v^{s3}$ for non-freshwater (Fig. 4a) and $v^{f1} - v^{f6}$ for freshwater (Fig. 4b); the latter probabilities are separated into villages with and without access to non-freshwater.

Figure 4 about here

Fig. 4a indicates that there is a probability of 0.91 that a village with access to non-freshwater exhausts its entire non-freshwater quota (v^{s3}), and 0.08 that the non-freshwater price dictates the village's water consumption (v^{s2}); the remaining, 0.01, is the probability of non-water-consumption at all. According to Fig. 4b, there is a probability of 0.21 that villages with access to non-freshwater do not consume freshwater; this, together with the aforementioned 0.91 probability of consuming the entire non-freshwater quota (Fig 4a), implies a probability of 0.12 (=0.91-0.79) that a village utilizes its entire non-freshwater quota, but does not consume freshwater at all. In comparison, there is only a 0.03 probability that a village without access to non-freshwater does not consume freshwater (Fig. 4b). Thus, accessibility to non-freshwater increases the probability of forgoing freshwater consumption. On the other hand, those farmers with access to non-freshwater who do consume freshwater have higher probability to consume at the third price tier (v^{f6}), whereas the consumption of most of the farmers with access to freshwater only is bounded by their second tier-price quota (v^{f5}).

Sensitivity Analyses

Variations in exogenous factors such as pricing schemes and climate conditions can change farmers' water consumption and profits. We study these effects by simulations. Table 3 reports the simulated impacts of changes in the prices and quotas composing the increasing block-rate price systems, and in the annual and April precipitations. We report the impacts of marginal changes in these variables on the consumption of fresh and non-freshwater, as well as their corresponding production values, profits, VMPs and the shadow value of the quotas in the increasing block-rate tariffs (see definitions in Appendix B);[12] all are expressed in terms of elasticities.

Table 3 about here

As expected, an increase in freshwater prices (quotas) reduces (increases) the consumption of freshwater. We obtain larger freshwater-price elasticities compared to Bar-Shira et al. (2006), and, as aforementioned, the freshwater price elasticity of villages with access to freshwater only is much higher than those with accessibility to non-freshwater. The changes in the freshwater's production values, VMPs and quota shadow values are all stemming from the responses of freshwater-consumption to the freshwater price (quota) changes; i.e., due to a movement along the freshwater demand function. However, also the production values, profits, VMPs and quota shadow values associated with non-freshwater consumption are affected, where the directions of the impacts are opposite to those on freshwater. This is due to the cross impact of freshwater on the non-freshwater's VMP; i.e., a shift of the non-freshwater demand function. Using Eq. (9) we get:

$$\frac{\partial^2 h_m\left(w_m^e\right)}{\partial w_m^s \partial w_m^f} = -b\mu \tag{16}$$

Note, however, that this cross impact occurs only in the case that the non-freshwater quota constraints are effective; that is, when v^{s3} in Fig. 1 prevails. If v^{s3} is combined with v^{f2}, v^{f4} or v^{f6}, then, a freshwater-price change would change freshwater consumption and thereby shift v^{s3}; if v^{s3} is combined with v^{f3} or v^{f5}, then, a freshwater-quota change would change freshwater consumption and thereby shift v^{s3}. In both cases the non-freshwater VMP is affected, but not the non-freshwater consumption, since it is bounded by the non-freshwater quota. In case that v^{s1} or v^{s2} prevail, both must be combined with v^{f1}, where freshwater consumption is zeroed, it does not react to variations in freshwater prices or quotas, and therefore it does not shift the non-freshwater VMPs v^{s1} or v^{s2}.

The cross impact of non-freshwater consumption also depends on the combinations of VMPs. A change in the non-freshwater price neither affects freshwater's consumption, nor freshwater VMP; this is because it affects non-freshwater consumption only when v^{s2} prevails, which implies zero freshwater consumption. Thus, non-freshwater price affects non-freshwater consumption only, and according to Table 3 the effect is minor, since the probability of v^{s2} is 0.08 only (Fig. 4a). A change in non-freshwater quota varies the consumption of non-freshwater when v^{s3} prevails, and thereby affects freshwater VMP for those cases in which v^{s3} is combined with $v^{f2} - v^{f6}$, the probability of which is 0.79 (Fig. 4b). This explains the considerable impact of non-freshwater quotas on the consumption and profitability of both water sources.

The effect of the climate variables on the demands for both water sources are generally low. It should be noted that our structural model identifies the production values associated with irrigation water only, indicating that larger annual or April precipitations reduce the production value attributed to irrigation water. However, larger precipitations may directly increase the production value through the A_{mt} parameter (Eq. (9)), which is unidentified by our model.

Policy Analyses

Increasing water scarcity attracts policies to enhance water-use efficiency (Thobanl, 1997). According to Molle (2009), Israel is but only one of many countries where agricultural water consumption is managed by a combination of charges and quotas. Thus, the Israeli experience is of particular interest to such regions in case that agricultural freshwater allotments are considered to be replaced by non-freshwater quotas. We employ our model to examine the implications of this policy on the agricultural sector in Israel.

Another policy that emerges under growing scarcity is the establishment of water markets. To date, water markets operated mainly in Australia (Young, 2014), western USA (Howitt and Sunding, 2003), Spain (Palomo-Hierro et al., 2015), Chile (Lobos, 1999), South Africa (Speelman et al., 2010), Mexico, India and Pakistan (Bjornlund and McKay, 2002). In Israel, water trade occurred informally for years (Kislev, 2001), and recently, following a subsequence of drought years, transfers of agricultural water quotas were limitedly permitted (Rofe, 2012).

We use our methodology to forecast the consequences of launching markets for fresh and non-fresh waters.

Non-freshwater/Freshwater Quota Exchange

As aforementioned, along with the development of wastewater treatment plants, the Israeli government has forced farmers to exchange their freshwater quotas with TWW allotments, employing an exchange rate of 1.2. This exchange rate was set based on agronomical considerations so as to compensate farmers for production losses due to irrigation with lower-quality water. That is, mainly the productivity drawbacks of non-freshwater use were taken into account, whereas factors that increase profitability, such as supply stabilization and savings in agricultural costs stemming from the TWW's nutrition content and lower price, were generally ignored. We use our model to study the impacts of exchange rates on farmers' profitability and production values.

Consider a village whose total freshwater quota, q_i^f, is enforced, and effectively binds the village's freshwater consumption. According to our modeling framework, this implies that the village's non-freshwater quota, q_i^s, is also exhausted. Suppose that q_i^f is cut by one unit, and the village is compensated by an increase in q_i^s based on some exchange rate, denoted r_i. By applying the complete differential to the profit function in Eq. (3), one obtains the exchange rate that keeps constant the village's profit, $r_i\left(d\pi_i = 0\right)$:

$$r_i\left(d\pi_i = 0\right) \equiv \left| \left. \frac{dq_i^s}{dq_i^f} \right|_{d\pi_i=0} \right| = \frac{a_i - bq_i^f - b\mu q_i^s - p^{f3}}{\mu\left(a_i - bq_i^f - b\mu q_i^s\right) - p^s} \tag{17}$$

Since $p^{f3} > p^s$, and our estimation result of $\mu > 1$ (although not statistically significant), we obtain $r_i\left(d\pi_i = 0\right) < 1$. An evidence to this finding is also provided by the quota-shadow values reported in Table 3: ¢11.5 per m^3 of non-freshwater quota compared with ¢3.4 per m^3 of freshwater quota.

It should also be noted that Eq. (17) represents the exchange rate $r_i\left(d\pi_i = 0\right)$ only when q_i^f is effective. In case that, indeed, a village consumes freshwater (i.e., q_i^s must be effective) , but q_i^f does not bind consumption (i.e., the village's freshwater consumption is dictated by one of the three tier prices, or bounded by the freshwater price-tier quotas q_i^{f1} or q_i^{f2}), a marginal cut in q_i^f would not affect the village's freshwater consumption. Then, in response to a marginal quota exchange, such a village will not reduce its freshwater consumption, but will increase its non-freshwater consumption corresponding to the increase in q_i^s . According to our estimations, 91% of the villages with access to both water sources exhaust their non-freshwater quotas (Fig. 4a), and most of these villages consume freshwater below q_i^f (Fig. 4b). Thus, most of the villages will benefit from any positive quota-exchange rate.

The same arguments hold with respect to exchange rates aiming at preserving production values. Using Eq. (9), one can obtain the exchange rate that retains the village's production value $r_i\left(dh\left(w_i^e\right) = 0\right) = \frac{1}{\mu}$, which may also be below 1 according to our estimates.

In Fig. 5 we present simulated per-village-average profits (Fig. 5a) and production values (Fig. 5b) under various exchange rates. In all cases we assume that the total freshwater quota q_i^f is enforced, and constitutes the basis for the freshwater cuts. The simulations incorporate the entire sample, implying that villages without access to non-freshwater sources also obtain non-freshwater allotments once their freshwater quotas are cut.

Figure 5 about here

Our results point out large gains to Israeli farmers derived through the quota exchange rate of 1.2. In the period 1985-2010 the share of non-freshwater out of the total irrigation water has increased from 12% to 53%, (IWA, 2012); based on the simulations in Fig. 5a, this implies an annual profit increase of about $37,000 per village, which amounts to nearly 17% profit rise. An exchange rate of about 0.3 would have eliminated these benefits. An exchange rate of about 0.6 would have retained production values unchanged (Fig. 5b).

Water Markets

Water markets are the subject of a vast economic literature (Chong and Sunding, 2006). The benefits and side effects of water trade were assessed under various conditions, particularly by the use of MP models; for instance, Vaux and Howitt (1984), Weinberg et al. (1993), Calatrava and Garrido (2005) and Hansen et al. (2008). On the other hand, econometric-based studies of water markets are rare (Hansen et al., 2014). We apply our structural model to evaluate the impact of the establishment of markets for fresh and non-fresh water sources on the Israeli agricultural sector.

Our analysis assumes perfectly competitive markets, ignores uncertainties and third party effects, disregards transaction and delivery costs, and neglects infrastructural, regulatory and other constraints that may restrict water transfers; that is, it is assumed that all the *M* (*I*) villages are allowed to trade their entire freshwater (and non-freshwater) quotas. We simulate trade under three scenarios, where trade is allowed (1) in non-freshwater only, (2) in freshwater only, and (3) simultaneously in both water sources.[13] Consider Scenario (1), under equilibrium in the non-freshwater market, for each village *i*, $i = 1,...,I$, the non-freshwater consumption is equal to the village's equilibrium non-freshwater quota q_i^{se}, and the non-freshwater VMPs of all the I villages are equal to the equilibrium non-freshwater-quota market price p^{se}; in addition, the following relations between the equilibrium aggregated non-freshwater quotas $Q^{se} = \sum_{i=1}^{I} q_i^{se}$, and the equilibrium non-freshwater market price p^{se}, prevail:

(18a) $$Q^s > Q^{se} \quad if \quad p^{se} = p^s$$

(18b) $$Q^{se} = Q^s \quad if \quad p^{se} > p^s$$

where $Q^s = \sum_{i=1}^{I} q_i^s$. Accordingly, equilibrium under Scenario (2) implies that for each village *m*, $m = 1,...,M$, the freshwater consumption equals the equilibrium freshwater quota q_m^{fe} ; the freshwater VMPs of all the *M* villages are equal to the equilibrium freshwater-quota market price p^{fe}; and the relations between the equilibrium aggregated freshwater quotas $Q^{fe} = \sum_{m=1}^{M} q_m^{fe}$, and the equilibrium freshwater market price p^{fe}, are:

(19a)	$Q^{f1} \geq Q^{fe} > 0$	$if \;\; p^{fe} = p^{f1}$
(19b)	$Q^{fe} = Q^{f1}$	$if \;\; p^{f2} > p^{fe} > p^{f1}$
(19c)	$Q^{f2} > Q^{fe} > Q^{f1}$	$if \;\; p^{fe} = p^{f2}$
(19d)	$Q^{fe} = Q^{f2}$	$if \;\; p^{f3} > p^{fe} > p^{f2}$
(19d)	$Q^{fe} > Q^{f2}$	$if \;\; p^{fe} = p^{f3}$

where $Q^{f1} = \sum_{m=1}^{M} q_m^{f1}$ and $Q^{f2} = \sum_{m=1}^{M} q_m^{f2}$. Simultaneous equilibrium in the two water markets under Scenario (3) integrates the conditions in Scenarios (1) and (2) such that:

(20a)	$Q^s > Q^{se} \;\; \& \;\; Q^{fe} = 0$	$if \;\; p^{se} = p^s$
(20b)	$Q^{se} = Q^s \;\; \& \;\; Q^{f1} \geq Q^{fe} > 0$	$if \;\; p^{se} > p^s \;\; \& \;\; p^{fe} = p^{f1}$
(20c)	$Q^{se} = Q^s \;\; \& \;\; Q^{fe} = Q^{f1}$	$if \;\; p^{se} > p^s \;\; \& \;\; p^{f2} > p^{fe} > p^{f1}$
(20d)	$Q^{se} = Q^s \;\; \& \;\; Q^{f2} > Q^{fe} > Q^{f1}$	$if \;\; p^{se} > p^s \;\; \& \;\; p^{fe} = p^{f2}$
(20e)	$Q^{se} = Q^s \;\; \& \;\; Q^{fe} = Q^{f2}$	$if \;\; p^{se} > p^s \;\; \& \;\; p^{f3} > p^{fe} > p^{f2}$
(20f)	$Q^{se} = Q^s \;\; \& \;\; Q^{fe} > Q^{f2}$	$if \;\; p^{se} > p^s \;\; \& \;\; p^{fe} = p^{f3}$

Note that when quota trade is allowed, farmers no longer consume water sequentially based on the exogenous tier-price quotas. This implies that the demand functions of the two water sources are interdependent, as in Eqs. (5a) and (5b). The simulations account for this interdependence by employing an iterative procedure.

Table 4 summarizes the simulation results. In view of the administrative prices (Table 1), the market equilibrium prices imply that Eqs. (18b), (19d) and (20e) hold for scenarios (1), (2) and (3), respectively. Consequently, compared to the baseline, allowing trade in non-freshwater

(freshwater) quotas would increase (decrease) the aggregated non-freshwater (freshwater) consumption from a per-village average of 913,000 (568,000) m^3/year to the aggregated administrative non-freshwater (second tier-price freshwater) quotas of 942,000 (543,000) m^3/year.[14] Thus, trade has almost no impact on the overall water consumption.

Table 4 about here

However, the impact of trade on farming profits is tremendous. Of particular interest is the impact of simultaneous trade in the two water sources in comparison to the trade in only one of them. Not surprisingly, the increase in farming profits[15] under Scenario (3) is the highest, being almost 50% higher compared to the baseline, followed by 22% and 12% profit increase under scenarios (2) and (1), respectively. Most of the profit increase under Scenario (3) is related to the group of *I* villages with access to both water sources – this group increases its freshwater consumption at the expense of the *J* villages.

Table 5 about here

Table 5 outlines the patterns of quota trades, indicating that the traded-quota volumes of both water sources are increased under Scenario (3). When freshwater-trade is allowed (Scenario 2), the group of *I* villages buys freshwater quotas from the *J* villages; this trend increases under Scenario (3), mostly because of the sharp increase in the per-village-quota volume purchased by the *I* villages, from an average of 549 to 1,254 thousand m^3/year. The transfer of quotas from the *J*- to the *I*-villages is explained by the differences in the demand elasticity and the distribution of consumption across the price blocks under the baseline: in view of Figure 4, 34% of the *I*-villages consume at the third price tier (v^{f6}) compared to only 10% of the *J*-villages; since the equilibrium price lays between the second and third tiers, more villages from the *J*-group face a price increase, and their consumption reduces more sharply due to their higher demand elasticity.

Table 6 about here

In Table 6 we farther analyze the trade patterns of the *I* villages accessible to both water sources under Scenario (3). Section (A) of the table points at a process of specialization in the use of water sources: 81% of the villages exchange water quotas of the two sources, most of them (52%) purchase freshwater quotas and sell non-freshwater, and 29% do the opposite; 17% reduce their quota holdings and only 3% extend both their non-fresh- and fresh-water quotas. In Section (B) of the table we split the *I* villages into four subgroups based on the combinations of two categories: the village's original aggregated quotas (non-freshwater plus freshwater) being above or below the per-village average total quotas, and the portion of the freshwater quota out of the aggregated allotments is larger or lower than the average. Villages endowed with relatively large total allotments tend to replace fresh- with non-fresh-water quotas, where this process is more prominent in villages with originally lower freshwater-quota share; that is, trade enhances specialization in water use.

We now turn to assess the impact of water trade on the spatial distribution of irrigation water. For decades Israel invests in infrastructures to deliver water throughout the whole country; therefore, the possibility that some regions will dry out others through the water markets is of concern to regulators (Rofe, 2012). Fig. 6 depicts the regionally aggregated variations in water consumptions under the three trade scenarios. A clear picture emerges: in most cases where non-freshwater trade is allowed, the three most southern regions (Besor, Negev and Arava) exchange non-freshwater with freshwater consumption, while all other regions exhibit an opposite trend. The total regional consumptions of the two water sources (Fig. 6c) vary from nearly -60% up to about + 30%, implying that trade can considerably affect water-use spatial distribution, but not to the extent of complete cease of irrigation at the regional level.

Figure 6 about here

Our final issue is the effect of climate on freshwater availability. As aforementioned, water markets have been generally considered in periods of growing water scarcity, when the benefits associated with trade are expected to be larger. Climate-change studies predict up to 20% precipitation reductions in Israel during the 21st century (Chenoweth et al., 2011; Givati and Rosenfeld, 2013). We simulated 20% reductions in the freshwater quotas and in the annual and April precipitations, and got an increase of only 4% in the farming profits associated with trade; that is, at least in Israel, droughts should not be a significant motivation for the establishment of water markets, as most of the trade benefits are obtainable regardless of precipitation declines.

Concluding Remarks

This paper develops a structural economic DCC model of water use by farmers that have access to multiple water sources with diversified qualities, and face increasing block-rate tariffs. An advantage of the methodology stems from its reliance on the inductive approach: it represents farmers' perceptions with respect to the productivity attributes of the different water sources, as manifested from real-world consumption patterns. The vulnerability of the methodology, as of any inductive analysis, is the need for detailed datasets; richer farming datasets, including inputs, outputs and profits, would enable validating and extending the scope.

Our methodology fits to cases where the accessibility to water sources is determined exogenously, and so are the constraints and prices (or costs) associated with the resource utilizations. In case of interdependence between the water use and the availability and/or extraction costs of water sources (e.g., water consumptions may affect drainage discharges (Kan, 2003) and deep percolations into groundwater bodies, which in turn influence pumping costs (Knapp and Baerenklau, 2006)), the analysis should control for such endogeneity effects. Future research may examine the impact of various functional-form specifications and differentiate between long- and short-run demands (see Bar-Shira et al., 2006). Finally, our analyses of water-management policies focus merely on their impacts on farming profits and production values; To capture the policies' influence on the water economy as a whole, the demand functions estimated by the methodology can be integrated into hydro-economic models such as CALVIN (Draper et al., 2003) and MYWAS (Fisher and Huber-Lee, 2011).

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Appendix A

		Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8
Option (a)		$\mu > p^s / p^{f_1}$							
Water use		$w_i^s = 0$ $w_i^{f_1} = 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$q_i^s > w_i^s > 0$ $w_i^{f_1} = 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^s = q_i^s$ $w_i^{f_1} = 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^s = q_i^s$ $q_i^{f_1} > w_i^{f_1} > 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^s = q_i^s$ $w_i^{f_1} = q_i^{f_1}$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^s = q_i^s$ $w_i^{f_1} = q_i^{f_1}$ $q_i^{f_2} - q_i^{f_1} > w_i^{f_2} > 0$ $w_i^{f_3} = 0$	$w_i^s = q_i^s$ $w_i^{f_1} = q_i^{f_1}$ $w_i^{f_2} = q_i^{f_2} - q_i^{f_1}$ $w_i^{f_3} = 0$	$w_i^s = q_i^s$ $w_i^{f_1} = q_i^{f_1}$ $w_i^{f_2} = q_i^{f_2} - q_i^{f_1}$ $w_i^{f_3} > 0$
v^s & v^f combinations		v_i^{s1} & v_i^{f1}	v_i^{s2} & v_i^{f1}	v_i^{s3} & v_i^{f1}	v_i^{s3} & v_i^{f2}	v_i^{s3} & v_i^{f3}	v_i^{s3} & v_i^{f4}	v_i^{s3} & v_i^{f5}	v_i^{s3} & v_i^{f6}
Quota shadow values	λ_i^s	0	0	$\mu h_i'\left(\mu q_i^s\right) - p^s$	$\mu p^{f_1} - p^s$	$\mu h_i'\left(q_i^{f_1} + \mu q_i^s\right) - p^s$	$\mu p^{f_2} - p^s$	$\mu h_i'\left(q_i^{f_2} + \mu q_i^s\right) - p^s$	$\mu p^{f_3} - p^s$
	$\lambda_i^{f_1}$	0	0	0	0	$h_i'\left(q_i^{f_1} + \mu q_i^s\right) - p^{f_1}$	$p^{f_2} - p^{f_1}$	$p^{f_2} - p^{f_1}$	$p^{f_2} - p^{f_1}$
	$\lambda_i^{f_2}$	0	0	0	0	0	0	$h_i'\left(q_i^{f_2} + \mu q_i^s\right) - p^{f_2}$	$p^{f_3} - p^{f_2}$
Option (b)		$p^s / p^{f_1} > \mu > p^s / p^{f_2}$							
Water use		$w_i^{f_1} = 0$ $w_i^s = 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$q_i^{f_1} > w_i^{f_1} > 0$ $w_i^s = 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^{f_1} = q_i^{f_1}$ $w_i^s = 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^{f_1} = q_i^{f_1}$ $q_i^s > w_i^s > 0$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^{f_1} = q_i^{f_1}$ $w_i^s = q_i^s$ $w_i^{f_2} = 0$ $w_i^{f_3} = 0$	$w_i^{f_1} = q_i^{f_1}$ $w_i^s = q_i^s$ $q_i^{f_2} - q_i^{f_1} > w_i^{f_2} > 0$ $w_i^{f_3} = 0$	$w_i^{f_1} = q_i^{f_1}$ $w_i^s = q_i^s$ $w_i^{f_2} = q_i^{f_2} - q_i^{f_1}$ $w_i^{f_3} = 0$	$w_i^{f_1} = q_i^{f_1}$ $w_i^s = q_i^s$ $w_i^{f_2} = q_i^{f_2} - q_i^{f_1}$ $w_i^{f_3} > 0$
Combinations of v^s & v^f		v_i^{s1} & v_i^{f1}	v_i^{s1} & v_i^{f2}	v_i^{s1} & v_i^{f3}	v_i^{s2} & v_i^{f3}	v_i^{s3} & v_i^{f3}	v_i^{s3} & v_i^{f4}	v_i^{s3} & v_i^{f5}	v_i^{s3} & v_i^{f6}
Quota shadow values	$\lambda_i^{f_1}$	0	0	$h_i'\left(q_i^{f_1}\right) - p^{f_1}$	$\frac{p^s}{\mu} - p^{f_1}$	$h_i'\left(q_i^{f_1} + \mu q_i^s\right) - p^{f_1}$	$p^{f_2} - p^{f_1}$	$p^{f_2} - p^{f_1}$	$p^{f_2} - p^{f_1}$
	λ_i^s	0	0	0	0	$\mu h_i'\left(q_i^{f_1} + \mu q_i^s\right) - p^s$	$\mu p^{f_2} - p^s$	$\mu h_i'\left(q_i^{f_2} + \mu q_i^s\right) - p^s$	$\mu p^{f_3} - p^s$
	$\lambda_i^{f_2}$	0	0	0	0	0	0	$h_i'\left(q_i^{f_2} + \mu q_i^s\right) - p^{f_2}$	$p^{f_3} - p^{f_2}$

		Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8
Option (c)		$p^s/p^{f_2} > \mu > p^s/p^{f_3}$							
Water use		$w_i^{f_1}=0$ $w_i^{f_2}=0$ $w_i^{s}=0$ $w_i^{f_3}=0$	$q_i^{f_1}>w_i^{f_1}>0$ $w_i^{f_2}=0$ $w_i^{s}=0$ $w_i^{f_3}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=0$ $w_i^{s}=0$ $w_i^{f_3}=0$	$w_i^{f_1}=q_i^{f_1}$ $q_i^{f_2}-q_i^{f_1}>w_i^{f_2}>0$ $w_i^{s}=0$ $w_i^{f_3}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=q_i^{f_2}-q_i^{f_1}$ $w_i^{s}=0$ $w_i^{f_3}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=q_i^{f_2}-q_i^{f_1}$ $q_i^{s}>w_i^{s}>0$ $w_i^{f_3}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=q_i^{f_2}-q_i^{f_1}$ $w_i^{s}=q_i^{s}$ $w_i^{f_3}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=q_i^{f_2}-q_i^{f_1}$ $w_i^{s}=q_i^{s}$ $w_i^{f_3}>0$
Combinations of v^s & v^f		v_i^{s1} & v_i^{f1}	v_i^{s1} & v_i^{f2}	v_i^{s1} & v_i^{f3}	v_i^{s1} & v_i^{f4}	v_i^{s1} & v_i^{f5}	v_i^{s2} & v_i^{f5}	v_i^{s3} & v_i^{f5}	v_i^{s3} & v_i^{f6}
Quota shadow values	$\lambda_i^{f_1}$	0	0	$h_i'(q_i^{f_1})-p^{f_1}$	$p^{f_2}-p^{f_1}$	$p^{f_2}-p^{f_1}$	$p^{f_2}-p^{f_1}$	$p^{f_2}-p^{f_1}$	$p^{f_2}-p^{f_1}$
	$\lambda_i^{f_2}$	0	0	0	0	$h_i'(q_i^{f_2})-p^{f_2}$	$\frac{p^s}{\mu}-p^{f_2}$	$h_i'(q_i^{f_2}+\mu q_i^s)-p^{f_2}$	$p^{f_3}-p^{f_2}$
	λ_i^{s}	0	0	0	0	0	0	$\mu h_i'(q_i^{f_2}+\mu q_i^s)-p^s$	$\mu p^{f_3}-p^s$
Option (d)		$p^s/p^{f_3} > \mu$[a]							
Water use		$w_i^{f_1}=0$ $w_i^{f_2}=0$ $w_i^{f_3}=0$ $w_i^{s}=0$	$q_i^{f_1}>w_i^{f_1}>0$ $w_i^{f_2}=0$ $w_i^{f_3}=0$ $w_i^{s}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=0$ $w_i^{f_3}=0$ $w_i^{s}=0$	$w_i^{f_1}=q_i^{f_1}$ $q_i^{f_2}-q_i^{f_1}>w_i^{f_2}>0$ $w_i^{f_3}=0$ $w_i^{s}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=q_i^{f_2}-q_i^{f_1}$ $w_i^{f_3}=0$ $w_i^{s}=0$	$w_i^{f_1}=q_i^{f_1}$ $w_i^{f_2}=q_i^{f_2}-q_i^{f_1}$ $w_i^{f_3}>0$ $w_i^{s}=0$	Not available	Not available
Combinations of v^s & v^f		v_i^{s1} & v_i^{f1}	v_i^{s1} & v_i^{f2}	v_i^{s1} & v_i^{f3}	v_i^{s1} & v_i^{f4}	v_i^{s1} & v_i^{f5}	v_i^{s1} & v_i^{f6}		
Quota shadow values	$\lambda_i^{f_1}$	0	0	$h_i'(q_i^{f_1})-p^{f_1}$	$p^{f_2}-p^{f_1}$	$p^{f_2}-p^{f_1}$	$p^{f_2}-p^{f_1}$		
	$\lambda_i^{f_2}$	0	0	0	0	$h_i'(q_i^{f_2})-p^{f_2}$	$p^{f_3}-p^{f_2}$		
	λ_i^{s}	0	0	0	0	0	0		

a. μ indicates an extremely low non-freshwater quality; for instance, very saline water sources. Since $w_i^{f_3}$ is not constraint by a quota, solutions 7 and 8 vanish.

Appendix B

We define the Lagrange function associated with Eq. (3):

(B1)
$$\begin{aligned} L_i &= h_i\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^s w_i^s - \sum_{k=1}^{3} p^{fk} w_i^{fk} \\ &+ \lambda_i^s\left(q_i^s - w_i^s\right) + \lambda_i^{f1}\left(q_i^{f1} - w_i^{f1}\right) + \lambda_i^{f2}\left(q_i^{f2} - w_i^{f1} - w_i^{f2}\right) \end{aligned}$$

where λ_i^s, λ_i^{f1} and λ_i^{f2} denote the shadow values of the respective quota constraints. The Carush-Kuhn-Tucker conditions are:

(B2) $$\mu h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^s - \lambda_i^s \le 0;\ w_i^s \ge 0;\ \left(\mu h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^s - \lambda_i^s\right) w_i^s = 0$$

(B3) $$h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^{f1} - \lambda_i^{f1} - \lambda_i^{f2} \le 0;\ w_i^{f1} \ge 0;\ \left(h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^{f1} - \lambda_i^{f1} - \lambda_i^{f2}\right) w_i^{f1} = 0$$

(B4) $$h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^{f2} - \lambda_i^{f2} \le 0;\ w_i^{f2} \ge 0;\ \left(h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^{f2} - \lambda_i^{f2}\right) w_i^{f2} = 0$$

(B5) $$h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^{f3} \le 0;\ w_i^{f3} \ge 0;\ \left(h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) - p^{f3}\right) w_i^{f3} = 0$$

(B6) $$\left(q_i^s - w_i^s\right) \ge 0;\ \lambda_i^s \ge 0;\ \lambda_i^s\left(q_i^s - w_i^s\right) = 0$$

(B7) $$\left(q_i^{f1} - w_i^{f1}\right) \ge 0;\ \lambda_i^{f1} \ge 0;\ \lambda_i^{f1}\left(q_i^{f1} - w_i^{f1}\right) = 0$$

(B8) $$\left(q_i^{f2} - w_i^{f1} - w_i^{f2}\right) \ge 0;\ \lambda_i^{f2} \ge 0;\ \lambda_i^{f2}\left(q_i^{f2} - w_i^{f1} - w_i^{f2}\right) = 0$$

Under the case of $p^s / p^{f1} > \mu > p^s / p^{f2}$ (Option (b)), we obtain eight sets of water consumptions that comply with conditions (B2) through (B8):

<u>Solution 1</u>: $w_i^s = w_i^{f1} = w_i^{f2} = w_i^{f3} = 0$

This solution is associated with the combination v^{s1} and v^{f1} in Fig. 1. The complementary slackness conditions in (B2) through (B5) are met by the definition of $w_i^s = w_i^{f1} = w_i^{f2} = w_i^{f3} = 0$, and (B6) through (B8) imply $\lambda_i^s = \lambda_i^{f1} = \lambda_i^{f2} = 0$.

<u>Solution 2</u>: $q_i^{f1} > w_i^{f1} > 0$ and $w_i^s = w_i^{f2} = w_i^{f3} = 0$

This solution combines v^{s1} with v^{f2} in Fig. 1. Conditions (B6) to (B8) imply $\lambda_i^s = \lambda_i^{f1} = \lambda_i^{f2} = 0$; conditions (B2), (B4) and (B5) are met by defining $w_i^s = w_i^{f2} = w_i^{f3} = 0$, and (B3) implies:

(B9)
$$h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) = p^{f1}$$

Note that $q_i^s > w_i^s > 0$ cannot hold, since then we get $\mu h_i'\left(\sum_{k=1}^{3} w_i^{fk} + \mu w_i^s\right) = p^s$ from (B2), which, together with (B9), violates the assumption $p^s / p^{f1} > \mu$. Similarly, $w_i^{f2} > 0$ and $w_i^{f3} > 0$ contradict this assumption.

<u>Solution 3</u>: $w_i^{f1} = q_i^{f1}$ and $w_i^s = w_i^{f2} = w_i^{f3} = 0$

The combination v^{s1} and v^{f3} in Fig. 1 prevails. From conditions (B6) and (B8) there is $\lambda_i^s = \lambda_i^{f2} = 0$, conditions (B2), (B4) and (B5) prevail by the definition $w_i^s = w_i^{f2} = w_i^{f3} = 0$, (B7) implies $\lambda_i^{f1} > 0$, and from (B3) we get $\lambda_i^{f1} = h_i'\left(q_i^{f1}\right) - p^{f1}$.

<u>Solution 4</u>: $w_i^{f1} = q_i^{f1}$, $q_i^s > w_i^s > 0$ and $w_i^{f2} = w_i^{f3} = 0$

In Fig. 1, the combination v^{s2} and v^{f3} exists. From conditions (B6) and (B8) there is $\lambda_i^s = \lambda_i^{f2} = 0$, conditions (B4) and (B5) prevail by $w_i^{f2} = w_i^{f3} = 0$, (B7) implies $\lambda_i^{f1} > 0$, and from (B2) and (B3) we get $h_i'\left(\mu w_i^s + q_i^{f1}\right) = p^s$ and $\lambda_i^{f1} = p^s / \mu - p^{f1}$, respectively; the latter is the cost reduction derived from a marginal increase in q_i^{f1}, which marginally reduces the consumption of non-freshwater; that is, of the more expensive water source in terms of freshwater equivalents.

<u>Solution 5</u>: $w_i^{f1} = q_i^{f1}$, $w_i^s = q_i^s$ and $w_i^{f2} = w_i^{f3} = 0$

The relevant combination in Fig. 1 is that of v^{s3} with v^{f3}. Condition (B8) implies $\lambda_i^{f2} = 0$, conditions (B4) and (B5) prevail by by $w_i^{f2} = w_i^{f3} = 0$, (B6) and (B7) imply $\lambda_i^s > 0$ and $\lambda_i^{f1} > 0$, and using (B2) and (B3) we get $\lambda_i^s = \mu h_i'\left(q_i^{f1} + \mu q_i^s\right) - p^s$ and $\lambda_i^{f1} = h_i'\left(q_i^{f1} + \mu q_i^s\right) - p^{f1}$.

Solution 6: $w_i^{f1} = q_i^{f1}$, $w_i^s = q_i^s$, $q_i^{f2} - q_i^{f1} > w_i^{f2} > 0$ and $w_i^{f3} = 0$

Combination v^{s3} and v^{f4} in Fig. 1 exists. Condition (B8) implies $\lambda_i^{f2} = 0$, condition (B5) holds due to $w_i^{f3} = 0$, conditions (B6) and (B7) imply $\lambda_i^s > 0$ and $\lambda_i^{f1} > 0$; using (B2), (B3) and (B4) there is $h_i'\left(\mu q_i^s + q_i^{f1} + w_i^{f2}\right) = p^{f2}$, $\lambda_i^s = \mu p_i^{f2} - p^s$ and $\lambda_i^{f1} = p^{f2} - p^{f1}$; that is, an increase in the non-freshwater quota saves consumption of freshwater at the second block price, and so does an increase in the freshwater quota at the first tier price.

Solution 7: $w_i^{f1} = q_i^{f1}$, $w_i^s = q_i^s$, $w_i^{f2} = q_i^{f2} - q_i^{f1}$ and $w_i^{f3} = 0$

In Fig. 1 v^{s3} and v^{f5} constitute the relevant combination. Conditions (B5) prevails through $w_i^{f3} = 0$, conditions (B6), (B7) and (B8) imply $\lambda_i^s > 0$, $\lambda_i^{f1} > 0$ and $\lambda_i^{f2} > 0$; using (B2), (B3) and (B4) we get $\lambda_i^s = \mu h_i'\left(q_i^{f2} + \mu q_i^s\right) - p^s$, $\lambda_i^{f1} = p^{f2} - p^{f1}$ and $\lambda_i^{f2} = h_i'\left(q_i^{f2} + \mu q_i^s\right) - p^{f2}$.

Solution 8: $w_i^{f1} = q_i^{f1}$, $w_i^s = q_i^s$, $w_i^{f2} = q_i^{f2} - q_i^{f1}$ and $w_i^{f3} > 0$

Fig. 1 implies the combination of v^{s3} with v^{f6}. From condition (B5) we get $h_i'\left(\mu q_i^s + q_i^{f2} + w_i^{f3}\right) = p^{f3}$. Conditions (B6), (B7) and (B8) imply $\lambda_i^s > 0$, $\lambda_i^{f1} > 0$ and $\lambda_i^{f2} > 0$, and using (B2), (B3) and (B4) we get $\lambda_i^s = \mu p^{f3} - p^s$, $\lambda_i^{f1} = p^{f2} - p^{f1}$ and $\lambda_i^{f2} = p^{f3} - p^{f2}$.

Appendix C

Let g_α and g_ε be, respectively, the normal distributions of α and ε, and define $g_{\alpha\varepsilon}$ as the joint distribution of α and ε, where, due to independence, there is $g_{\alpha\varepsilon} = g_\alpha g_\varepsilon$. Define $\varphi = \alpha + \varepsilon$ and denote by $g_{\varphi\alpha}(\varphi, \alpha)$ the joint normal distribution of φ and ε, where $\sigma_\varphi^2 = \sigma_\alpha^2 + \sigma_\varepsilon^2$ and $\rho \equiv \dfrac{Cov(\alpha, \alpha+\varepsilon)}{\sigma_\varphi \sigma_\alpha} = \dfrac{\sigma_\alpha^2}{\sqrt{(\sigma_\alpha^2 + \sigma_\varepsilon^2)\sigma_\alpha^2}} = \dfrac{\sigma_\alpha}{\sigma_\varphi}$. The distribution of α contingent on φ is given by $g_{\varphi\alpha}(\varphi,\alpha) = g_{\alpha|\varphi}(\alpha|\varphi) g_\varphi(\varphi)$. Then, with the omission of indices, the probability of observing water consumption by some farmer *I* is

$$
\begin{aligned}
\Pr^i(\cdot) = {} & g_\varepsilon(w) \int_{-\infty}^{-D^s} g_\alpha(\alpha) d\alpha + g_\varphi\left(w - D^s\right) \int_{-D^s}^{q^s - D^s} g_{\alpha|\varphi}(\alpha) d\alpha + \\
& g_\varepsilon\left(w - q^s\right) \int_{q^s - D^s}^{-D^{f1}} g_\alpha(\alpha) d\alpha + g_\varphi\left(w - q^s - D^{f1}\right) \int_{-D^{f1}}^{q^{f1} - D^{f1}} g_{\alpha|\varphi}(\alpha) d\alpha + \\
& g_\varepsilon\left(w - q^s - q^{f1}\right) \int_{q^{f1} - D^{f1}}^{q^{f1} - D^{f2}} g_\alpha(\alpha) d\alpha + g_\varphi\left(w - q^s - D^{f2}\right) \int_{q^{f1} - D^{f2}}^{q^{f2} - D^{f2}} g_{\alpha|\varphi}(\alpha) d\alpha + \\
& g_\varepsilon\left(w - q^s - q^{f2}\right) \int_{q^{f2} - D^{f2}}^{q^{f2} - D^{f3}} g_\alpha(\alpha) d\alpha + g_\varphi\left(w - q^s - D^{f3}\right) \int_{q^{f2} - D^{f3}}^{\infty} g_{\alpha|\varphi}(\alpha) d\alpha
\end{aligned}
\tag{C1}
$$

where for some farmer *j* one should replace the first three terms by $g_\varepsilon(w) \int_{-\infty}^{-D^{f1}} g_\alpha(\alpha) d\alpha$, and substitute $q^s = d^s = 0$.

Assume that $g_{\varphi\alpha}$ is a bivariate normal distribution, then, the $g_{\alpha|\varphi}(\alpha|\varphi)$ distribution is $N\left(\rho^2\varphi, \sigma_\alpha^2\left(1-\rho^2\right)\right)$. Denote by ϕ and Φ the standard-normal and cumulative-standard-normal distributions, respectively; then:

$$
\begin{aligned}
&\Pr^{i}\left(\cdot\right)=\frac{1}{\sigma_{\varepsilon}}\phi\left(\frac{w}{\sigma_{\varepsilon}}\right)\Phi\left(\frac{-D^{s}}{\sigma_{\alpha}}\right)\\
&\frac{1}{\sigma_{\varphi}}\phi\left(\frac{w-D^{s}}{\sigma_{\varphi}}\right)\left[\Phi\left(\frac{q^{s}-D^{s}-\rho^{2}\left(w-D^{s}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)-\Phi\left(\frac{-D^{s}-\rho^{2}\left(w-D^{s}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)\right]+\\
&\frac{1}{\sigma_{\varepsilon}}\phi\left(\frac{w-q^{s}}{\sigma_{\varepsilon}}\right)\left[\Phi\left(\frac{-D^{f1}}{\sigma_{\alpha}}\right)-\Phi\left(\frac{q^{s}-D^{s}}{\sigma_{\alpha}}\right)\right]+\\
&\frac{1}{\sigma_{\varphi}}\phi\left(\frac{w-q^{s}-D^{f1}}{\sigma_{\varphi}}\right)\left[\Phi\left(\frac{q^{f1}-D^{f1}-\rho^{2}\left(w-q^{s}-D^{f1}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)-\right.\\
&\left.\Phi\left(\frac{-D^{f1}-\rho^{2}\left(w-q^{s}-D^{f1}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)\right]+\\
&\frac{1}{\sigma_{\varepsilon}}\phi\left(\frac{w-q^{s}-q^{f1}}{\sigma_{\varepsilon}}\right)\left[\Phi\left(\frac{q^{f1}-D^{f2}}{\sigma_{\alpha}}\right)-\Phi\left(\frac{q^{f1}-D^{f1}}{\sigma_{\alpha}}\right)\right]+\\
&\frac{1}{\sigma_{\varphi}}\phi\left(\frac{w-q^{s}-D^{f2}}{\sigma_{\varphi}}\right)\left[\Phi\left(\frac{q^{f2}-D^{f2}-\rho^{2}\left(w-q^{s}-D^{f2}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)-\right.\\
&\left.\Phi\left(\frac{q^{f1}-D^{f2}-\rho^{2}\left(w-q^{s}-D^{f2}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)\right]+\\
&\frac{1}{\sigma_{\varepsilon}}\phi\left(\frac{w-q^{s}-q^{f2}}{\sigma_{\varepsilon}}\right)\left[\Phi\left(\frac{q^{f2}-D^{f3}}{\sigma_{\alpha}}\right)-\Phi\left(\frac{q^{f2}-D^{f2}}{\sigma_{\alpha}}\right)\right]+\\
&\frac{1}{\sigma_{\varphi}}\phi\left(\frac{w-q^{s}-D^{f3}}{\sigma_{\varphi}}\right)\left[1-\Phi\left(\frac{q^{f2}-D^{f3}-\rho^{2}\left(w-q^{s}-D^{f3}\right)}{\sigma_{\alpha}\left(\sqrt{1-\rho^{2}}\right)}\right)\right]
\end{aligned}
\tag{C2}
$$

where for the J farmers replace the first three elements by $\frac{1}{\sigma_{\varepsilon}}\phi\left(\frac{w}{\sigma_{\varepsilon}}\right)\Phi\left(\frac{-D^{f1}}{\sigma_{\alpha}}\right)$, and

substitute $q^{s}=d^{s}=0$.

Table 1 – Variables

Variable	Villages with access to freshwater only Average (std) (1)	Villages with access to both water sources Average (std) (2)	Difference (3) = (1) – (2)
Water consumption (w, 10^3×m^3/yr, dependent variable)	589 (352)	1,467 (1,126)	-878***
Semi-cooperative village (dummy)	0.89 (0.31)	0.52 (0.5)	0.37***
Annual precipitation (mm/yr)	494 (223)	431 (200)	62.9***
April precipitation (mm/yr)	20.3 (18.7)	18.4 (17.1)	1.87**
Height above sea level (m)	192 (231)	142 (178)	49.2***
Agricultural land (hectare)	191 (150)	448 (378)	-256***
Total quota (q, 10^3×m^3/yr)	707 (348)	1,496 (962)	-788***
Non-freshwater price (p^s, ¢/m^3)	-	14.4 (2.9)	-
Freshwater price – tier 1 (p^{f1}, ¢/m^3)	18.1 (4)	17.2 (3.3)	0.9***
Freshwater price – tier 2 (p^{f2}, ¢/m^3)	21.6 (4.5)	20.6 (3.8)	1.0***
Freshwater price – tier 3 (p^{f3}, ¢/m^3)	28.8 (5.7)	27.5 (4.7)	1.3***

*, ** and *** indicate statistical significance at 10%, 5% and 1%, respectively.

Table 2 – Estimation results

Variable	Villages with access to freshwater only	Villages with access to both water sources	Difference
Trend	187.6***	54.9***	-132.7***
Semi-cooperative	-1238*	-408.3	829.6***
Annual precipitation	-0.172	-0.312***	-0.14
April precipitation	-7.774***	-2.944***	4.83**
Height above sea level	-2.137**	-0.924	1.213**
Agricultural land	0.517	0.41**	-0.106
Quota	-0.204	0.377***	0.581***
Price	($\beta_2 =$) -214.8***	($\beta_2 + \beta_3 =$) -50.24***	($\beta_3 =$) 164.5***
Constant	8,032***	3,029***	-5,003***
Substitution (β_1)	-1.061***		-
σ_α	436.1***		-
σ_ε	87.52***		-
Log likelihood	-13,349		-
Wald $\chi^2(381)$	3,170		-

*, ** and *** indicate statistical significance at 10%, 5% and 1%, respectively.

Table 3 – Sensitivity analyses

	Value	Elasticity					
		Fresh-water Prices	Fresh-water Quotas	Non-fresh-water Price	Non-fresh-water Quota	Annual Precip.	April Precip.
Non-Freshwater							
Consumption (10^3×m^3)	899	0.00	0.00	-0.05	0.89	-0.01	0.00
Production Value (10^3×$)	380	0.23	-0.02	0.00	1.00	-0.04	-0.02
Profit (10^3×$)	251	0.35	-0.03	-0.50	1.06	-0.06	-0.02
VMP (¢/m^3)	24.9	0.40	-0.07	0.07	-0.25	-0.06	-0.02
Quota shadow value (¢/m^3)	11.5	0.86	-0.15	-1.01	-0.54	-0.12	-0.05
Freshwater							
<u>Villages with access to both water sources</u>							
Consumption (10^3×m^3)	559	-0.84	0.15	0.00	-0.93	-0.10	-0.04
Production Value (10^3×$)	232	-0.52	0.08	0.00	-1.01	-0.11	-0.04
Profit (10^3×$)	111	-0.99	0.22	0.00	-0.92	-0.12	-0.05
VMP (¢/m^3)	23.6	0.42	-0.08	0.00	-0.28	-0.06	-0.02
Quota shadow value (¢/m^3)	2.8	-1.36	0.30	0.00	-0.42	-0.23	-0.10
<u>Villages with access to freshwater only</u>							
Consumption (10^3×m^3)	580	-1.76	0.65	0.00	0.00	-0.03	-0.06
Production Value (10^3×$)	145	-1.61	0.60	0.00	0.00	-0.04	-0.08
Profit (10^3×$)	38	-2.69	0.72	0.00	0.00	-0.06	-0.11
VMP (¢/m^3)	22.4	0.22	-0.08	0.00	0.00	-0.01	-0.03
Quota shadow value (¢/m^3)	4.1	-1.85	-0.16	0.00	0.00	-0.05	-0.09
<u>All villages</u>							
Consumption (10^3×m^3)	568	-1.27	0.38	0.00	-0.50	-0.07	-0.05
Production Value (10^3×$)	192	-0.89	0.26	0.00	-0.66	-0.09	-0.06
Profit (10^3×$)	78	-1.37	0.33	0.00	-0.71	-0.10	-0.06
VMP (¢/m^3)	23.1	0.33	-0.08	0.00	-0.16	-0.04	-0.02
Quota shadow value (¢/m^3)	3.4	-1.63	0.05	0.00	-0.19	-0.13	-0.09

Table 4 – Water consumptions, production values and profits under the three simulated trade scenarios.

	Baseline	Scenario (1) Trade in non-freshwater only	Scenario (2) Trade in freshwater only	Scenario (3) Simultaneous trade in both water sources
A. Water market equilibrium price (¢/m^3)				
Non-freshwater (p^{se})	-	24.3	-	23.2
Freshwater (p^{fe})	-	-	22.1	22.6
B. Non-freshwater consumption (10^3×m^3/village-year)				
Villages with access to both water sources	913	942	913	942
C. Freshwater consumption (10^3×m^3/village-year)				
Villages with access to both water sources	551	563	548	604
Villages with access to freshwater only	588	588	535	470
All villages	568	574	543	543
D. Total non-fresh- and fresh-water consumption (10^3×m^3/village-year)				
Villages with access to both water sources	1,464	1404	1,461	1,546
Villages with access to freshwater only	588	588	535	470
All villages	1,065	1087	1,041	1,056
E. Production value (10^3×$/village-year)				
Villages with access to both water sources	613	658	611	694
Villages with access to freshwater only	145	145	139	123
All villages	400	425	397	435
F. Farming profit (10^3×$/village-year)				
Villages with access to both water sources	366	415	419	535
Villages with access to freshwater only	38	38	81	70
All villages	217	244	266	323

Table 5 – Sellers and buyers of non-freshwater and freshwater under the three simulated trade scenarios

	Non-freshwater		Freshwater					
	Villages accessible to both water sources		Villages accessible to both water sources		Villages accessible to freshwater-only		All Villages	
	Sellers	Buyers	Sellers	Buyers	Sellers	Buyers	Sellers	Buyers
	(1) Trade in non-freshwater only		(2) Trade in freshwater only					
Per village average trade (10^3×m^3/year)	-633	567	-246	549	-455	549	-344	549
Number of villages	510	569	644	432	571	330	1215	762
Total sample trade volume (10^6×m^3/year)	-322	322	-159	237	-260	181	-418	418
	(3) Simultaneous trade in both water sources							
Per village average trade (10^3×m^3/year)	-857	711	-388	1,254	-457	524	-420	924
Number of villages	489	590	739	338	621	280	1360	618
Total sample trade volume (10^6×m^3/year)	-419	419	-287	424	-284	147	-571	571

Table 6 – Trade impacts on changes in the quotas of the *I* villages with access to both water sources under simultaneous trade in both water sources (Scenario 3), for (A) all villages, and (B) for four subgroups of villages, allocated based on the villages' original total quotas being below/above the per-village average and their original freshwater-quota share being below/above the per-village average.

Non-freshwater quota		**Freshwater quota** Reduced	Increased	Reduced	Increased
	(A) All villages				
	Reduced	17%	52%		
	Increased	29%	3%		
	(B) Below-average original total quotas	& below-average freshwater-quota share		& above-average freshwater-quota share	
	Reduced	28%	49%	11%	75%
	Increased	20%	3%	11%	2%
	Above-average original total quotas	& below-average freshwater-quota share		& above-average freshwater-quota share	
	Reduced	12%	32%	19%	29%
	Increased	55%	1%	43%	9%

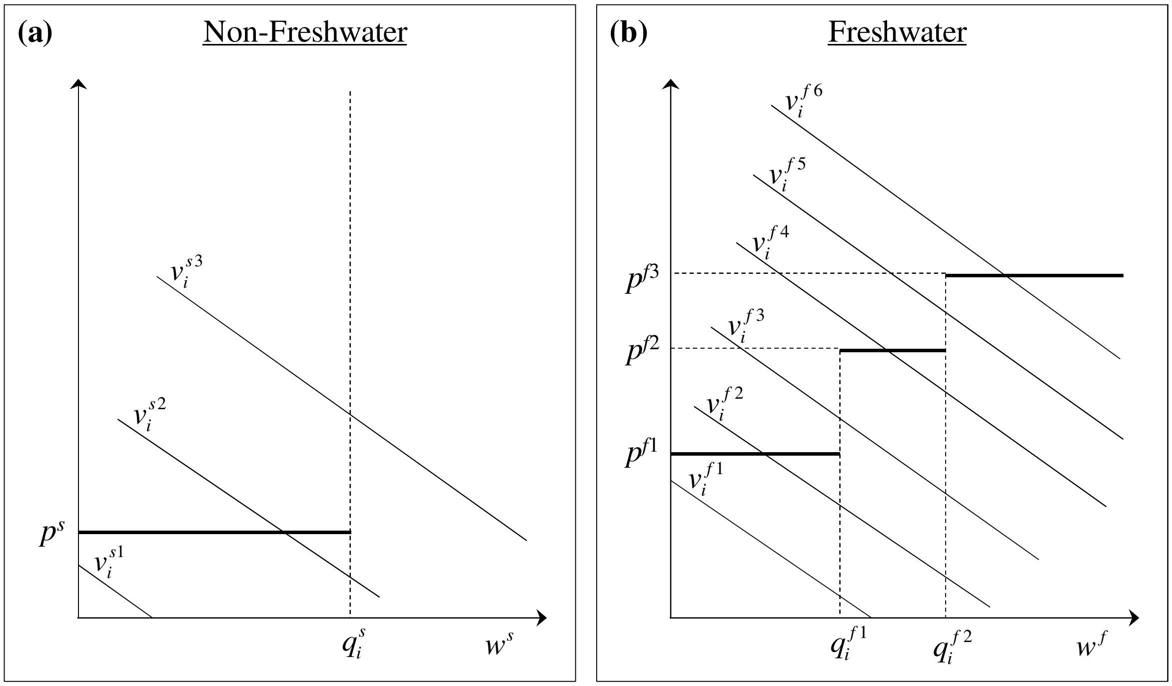

Figure 1 – Non-freshwater's and freshwater's VMPs in relations to price schedules

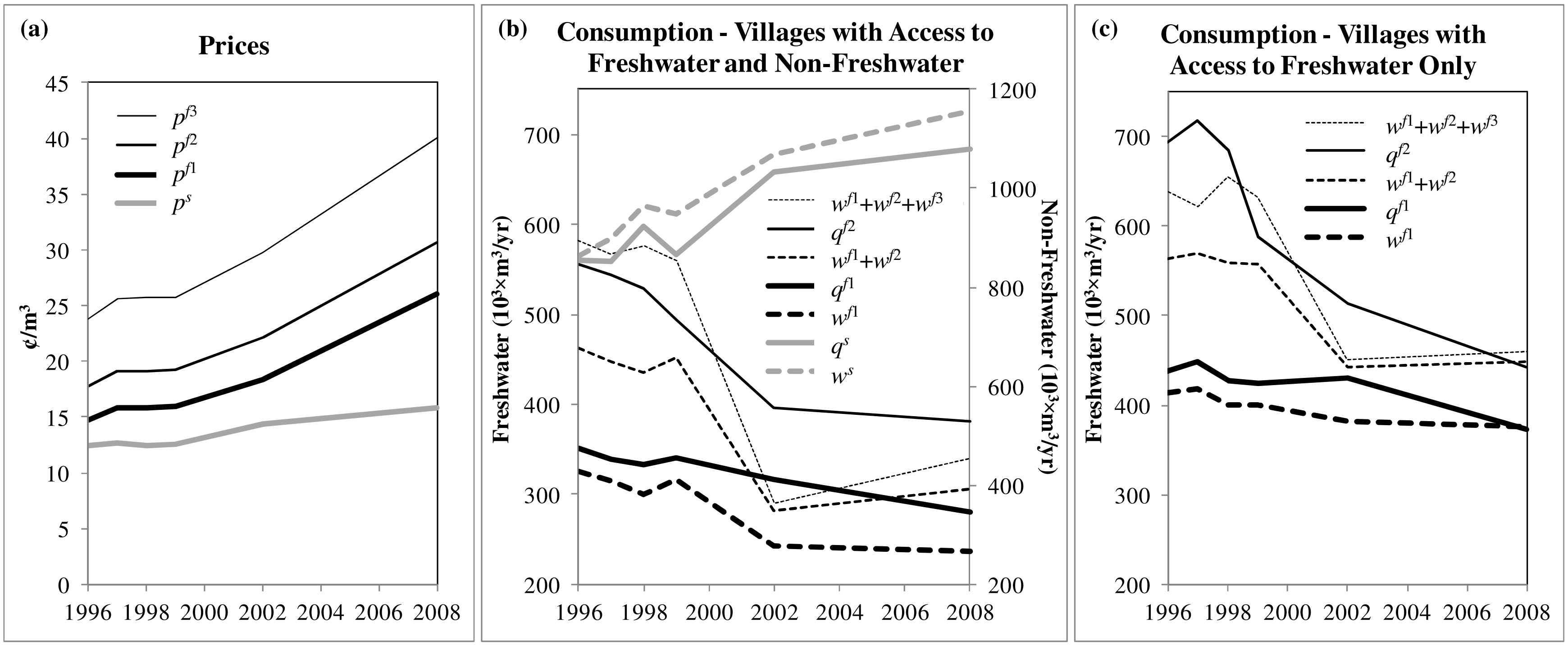

Figure 2 – Prices and per-village average annual quotas and consumptions

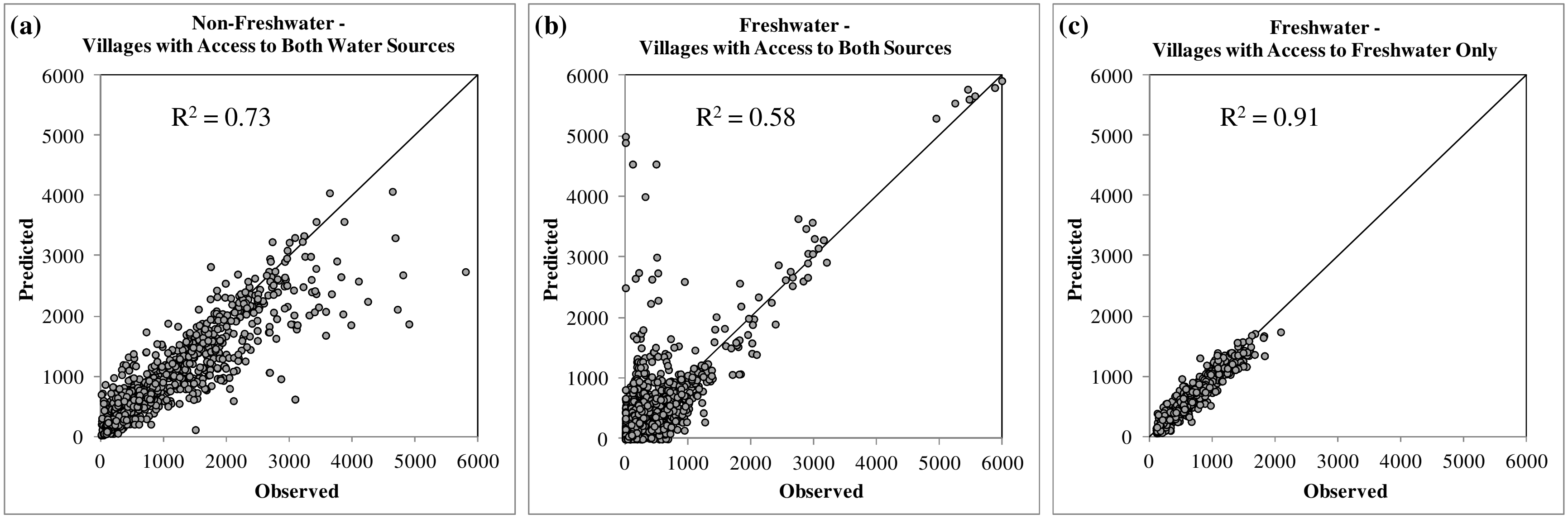

Figure 3 – Goodness of fit

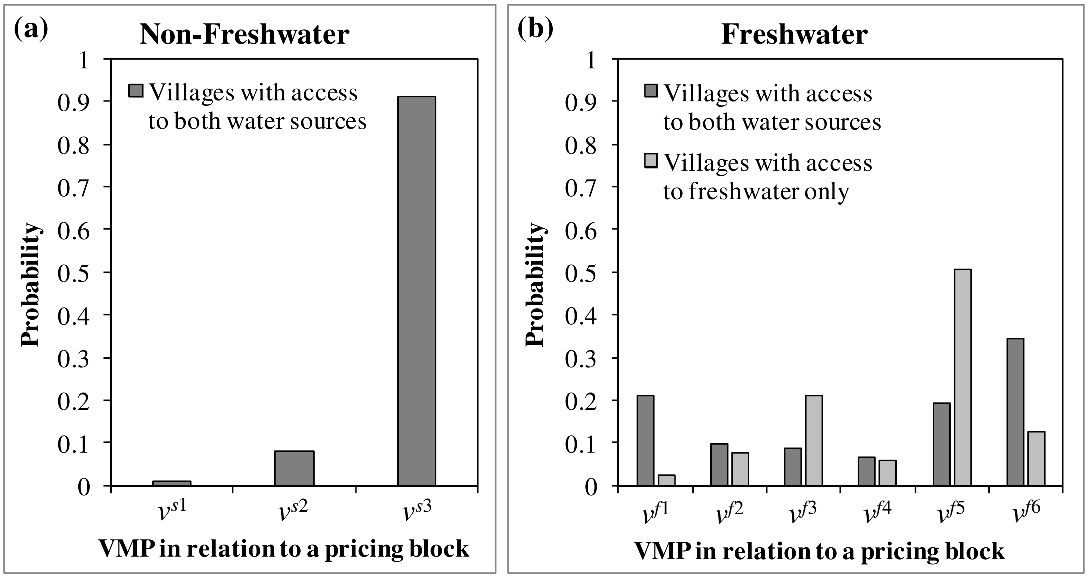

Figure 4 – Probability distributions of VMP functions in relation to intersection with pricing blocks (see Fig. 1)

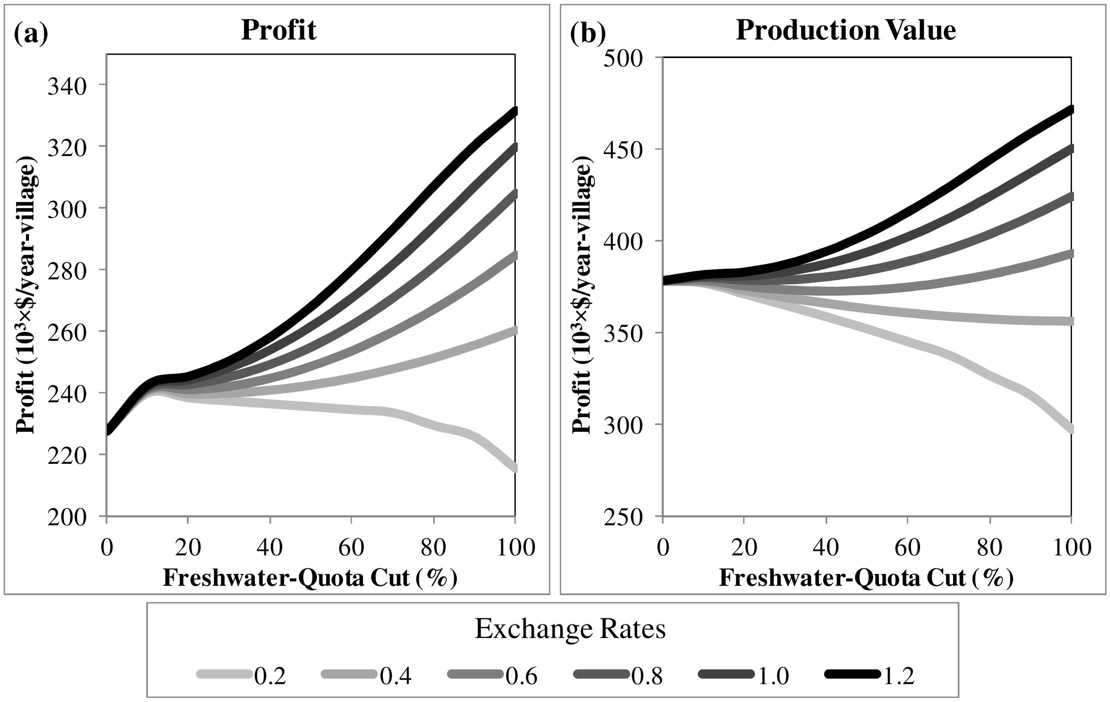

Figure 5 – Variations in per-village average (a) profit and (b) production value in response to cuts in freshwater quotas and increase in non-freshwater quotas based on different exchange rates

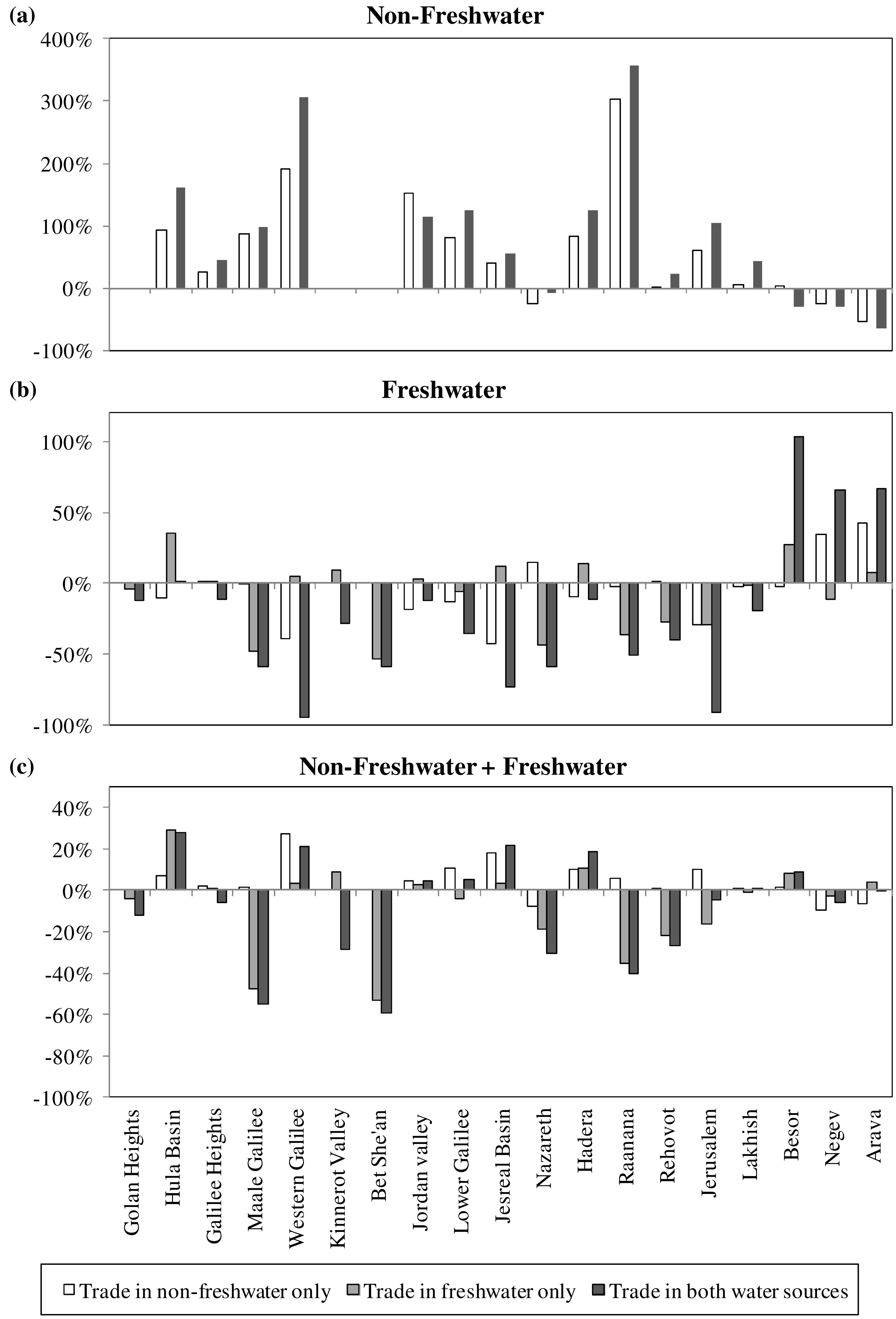

Figure 6 – Regional changes in (a) non-freshwater, (b) freshwater and (c) non-freshwater + freshwater consumptions under the three trade scenarios (regions are sorted from north (left) to south (right)).

Notes

[1] In comparison, TWW makes up 17% and 6% of the total irrigation water in Spain and California, respectively (Goldstein et al., 2014).

[2] In California, for instance, agricultural reuse of municipal wastewater has more than doubled in the period 1989 to 2009, and reuse was recently classified as a means for water districts to meet a legislative requirement to reduce water use by 20% by 2020 (NWRI, 2012).

[3] Despite the change in the composition of irrigation-water qualities along the years, the total vegetative agricultural production has increased (Kislev et al., 2013); this coincides our finding, but may also be attributed to technological improvements.

[4] Yet, we refer to the total freshwater quotas in the estimation and simulations.

[5] In the case of equality between μ and one of the three price ratios, non-freshwater becomes a perfect substitute to the freshwater in the corresponding block price such that both are considered as a single source, and the problem is reduced to the case of three blocks. For brevity we don't discuss these cases.

[6] In practice, farmers are charged based on their total consumption, starting from the lowest to the highest tier prices. Our analysis of the Karush-Kuhn-Tucker conditions does not impose this sequence; instead, it shows that this is the optimal one from farmers' perspective.

[7] Using Eq. (10a), $\alpha_{it} \le q_{it}^s - D_{it}^s$ is equivalent to $p_t^s \ge a_{it}\mu + b\mu^2\alpha_{it} - b\mu^2 q_{it}^s$, and from Eq. (10b) the condition $\alpha_{it} \le -D_{it}^{f1}$ is equivalent to $p_t^f \ge a_{it} + b\alpha_{it} - b\mu q_{it}^s$; hence, the condition $p^{f1} > \frac{p^s}{\mu}$ is met as long as $1 > \mu$. Later on we test the assumption $1 > \mu > \frac{p^s}{p^{f1}}$; we find the relation $\mu > \frac{p^s}{p^{f1}}$ being statistically significant, and the hypothesis $1 > \mu$ is not rejected.

[8] As aforementioned, the total freshwater allocation q^f was not enforced, and therefore quota cuts implied only reductions in the discounts associated with the first and second tiers.

[9] In general, the model can be extended so as to estimate a separate demand function for each of the three non-freshwater sources. However, this requires extending the likelihood function (Eq. 15) so as to distinguish between eight combinations of accessibility to the three non-freshwater sources. Due to data limitation, we treat here all three sources as a single aggregated one.

[10] Recall however, that in most cases these exchange rates were used only for allocating non-freshwater to farmers, without enforcing cuts in their overall freshwater allotments.

[11] Based on per-village acreage data provided by MOAG for the year 2002.

[12] Consumptions, production values, profits, VMPs and shadow values are all expressed in terms of expected values, computed based on numerical approximations of the normal distribution functions incorporated in the likelihood function. Production values and profits are computed while substituting $A_{mt} = 0$ for all observations.

[13] Regulations may restrict trade in non-freshwater to avoid negative impacts on groundwater; trade in freshwater may be politically unacceptable because prices of water for agricultural use are lower compared to those of water for domestic and industrial uses.

[14] While the trade in non-freshwater only under Scenario (1) affects the freshwater consumption of the *I* villages with access to both water sources, the trade in freshwater only under Scenario (2) does not alter the non-freshwater consumption of these villages; the latter character is because those villages that do not consume their non-freshwater quotas do not consume freshwater at all, since their freshwater VMP is below p^{f1}; hence, if freshwater trade is allowed, these villages would sell their entire freshwater quotas without affecting their freshwater consumption; that is, without affecting their non-freshwater VMP, and therefore without altering their non-freshwater consumption.

[15] Farming profits are computed based on the administrative prices. Note that profits that are computed based on the market equilibrium prices incorporate also income transfers between the consumers within the agricultural sector.