Ecological Economics 170 (2020) 106429

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Optimal water pricing: Accounting for environmental externalities☆

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ARTICLE INFO

Keywords:
Water economy
Regulation
Pricing
Ecosystem services

JEL classification:
C61
D62
H23
H41
Q25
Q28

ABSTRACT

A pricing-based mechanism that implements the optimal water policy while accounting for environmental externalities is developed. The analysis is presented in the context of a comprehensive water economy, stressing the tradeoffs between water use in the provision of ecosystem services vs. other uses. A distinction is made between *conveyed* and *instream* environmental water, which turns out to have important policy implications. It is shown that the allocation of instream water can be implemented by properly incorporating the (marginal) instream value of water within the shadow (in situ) price of natural water. The regulation of conveyed environmental water requires a quota-price combination. An example based on Israel's water economy is presented.

1. Introduction

In this work I study optimal water allocation while paying special attention to the role of water in supporting ecosystems. The analysis is carried out in the context of a comprehensive water economy that can accommodate a wide variety of real world situations. Such a framework allows evaluating the tradeoffs between the roles of natural water in the provision of material vs. nonmaterial services. As water becomes scarcer in many regions, due mainly to population growth, ecosystems are often the first to suffer. The present effort develops a framework to evaluate criteria for allocating water between private and environmental uses.

The analysis falls in the overlap of two literature strands: water economics (see the assortment compiled in Dinar and Schwabe, 2015), and economics of ecosystem services (see National Research Council, 2005; Milennium Ecosystem Assessment, 2005 and references they cite). It contributes to the former by proposing a pricing mechanism that implements the optimal water policy in the context of a comprehensive water economy. It contributes to the latter by including in the regulation mechanism the environmental externalities associated with the ecosystems provided or supported by the water allocation policy. There is a growing literature on the economic value of ecosystem services provided by water, which is mostly on a case-study base (see e.g., Weber et al., 2016; Jack and Jayachandran, 2019; Grant and Langpap, 2019). Accounting for the alternative cost of environmental water allocation induced by competition with water allocations for other uses, requires a comprehensive water economy framework, such as the one presented here.

The term water economy refers to a hydro-socio-economic arrangement consisting of water sources, users, the physical infrastructure connecting sources and users, and the institutions governing water allocation (property rights, allocation rules and norms). Within a given institutional setting, a water policy determines the allocation of water from each source to any sector and the investment in capital infrastructure needed to carry out the water allocation at each point of time. Such a water economy was formulated by Tsur (2009), who characterized the optimal steady state policy. Tsur and Zemel (2018) extended the analysis by characterizing the full dynamics of the optimal policy and showed that it evolves along two stages: a short infrastructure construction stage followed by a turnpike stage that converges to a steady state (the same steady state considered by Tsur, 2009).[1] The present effort focuses on implementation of the optimal policy via

☆ Helpful comments by the editor and two anonymous reviewers are gratefully acknowledged.

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[1] The term “turnpike” was coined by Dorfman et al. (1958) to represent a common economic situation: “…if origin and destination are far enough apart, it will always pay to get on to the turnpike and cover distance at the best rate of travel, even if this means adding a little mileage at either end. The best intermediate capital configuration is one which will grow most rapidly, even if it is not the desired one, it is temporarily optimal” (p. 311). See also Spence and Starrett (1975).

https://doi.org/10.1016/j.ecolecon.2019.106429
Received 20 March 2019; Received in revised form 23 July 2019; Accepted 2 August 2019
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water pricing, paying special attention to ecosystem services.

The analysis distinguishes between *conveyed* and *instream* environmental water. The former originates from the water sources and is conveyed to various sites to support ecosystem services (e.g., restoring a stream flow or an estuary). Instream water refers to natural water that could have been diverted or extracted but instead is left in its natural state (stream flows, aquifers, lakes) to support ecosystems, particularly aquatic (lakes, streams, estuaries) but also other terrestrial ecosystems (grassland, woodland) supported by natural water (surface and groundwater). Environmental water differs from water allocated to other sectors in that it (or the services provided thereof) is in essence a public good and this feature bears pronounced implications regarding regulation. For example, it implies that individual users cannot be identified and priced directly. I find that implementing the optimal allocation of conveyed environmental water requires a combination of quotas and prices. In contrast, the optimal allocation of instream water can be implemented based on pricing only, by properly incorporating the marginal instream value within the shadow (in situ) price of natural water.[2] The pricing-based regulation mechanism developed herein accounts for these properties.

To allow a sharp focus on implementation, attention is confined to the steady state allocation, to which the optimal policy converges in the long run. The optimal steady state formulation is the outcome of the full dynamic analysis and the latter, adopted to the current setting, is summarized in the attached (online) supplemental material.

The next section summarizes the water economy and the optimal steady state policy. The pricing mechanism that implements the optimal allocation is derived in Section 3 and shown to admit cost recovery (i.e., the proceeds it raises cover the variable and capital supply costs). Section 4 illustrates the analysis in the context of Israel's water economy and Section 5 concludes. Technical discussions are relegated to the appendix.

2. Optimal policy

As shown by Tsur and Zemel (2018) and Tsur (2019), the optimal policy begins with a short infrastructure construction stage, followed by a turnpike stage that converges to a steady state (the online appendix succinctly summarizes the dynamic analysis and derives the steady state). In this section I summarize the optimal steady state policy, which the regulation mechanism aims to implement. The discussion is terse, as it follows closely (including notations) the above cited works.

2.1. The water economy

A typical water economy consists of four user sectors and three water sources. The user sectors are domestic (households, offices, hospitals, schools, commercial), industry, agriculture and environment, indexed $j = D,I,A,E$, respectively. They receive water from three main water sources: natural, recycling and desalination, indexed $i = n,r,d$, respectively. Natural water occurs as stocks (aquifers, lakes, reservoirs) and flows (streams, rivers). The aggregate water stock is denoted Q. The water flows are included in the natural recharge $R(Q)$ representing the net addition of water during a time period (a year, say), i.e., inflow (mostly from precipitation) minus outflow (including evaporation). Recycled water is the outcome of treating domestic and industrial effluent and its supply is limited by the sewage generated by these two sectors and by the available infrastructure (treatment plants and conveyance facility). The supply of desalinated water is limited only by the existing desalination infrastructure (desalination plants and conveyance capacity).

Annual water allocation from source i to sector j is denoted q_{ij} and

$$q_{i\circ} = \sum_{j=D,I,A,E} q_{ij},\ \ i = n, r, d, \quad \text{and} \quad q_{\circ j} = \sum_{i=i,r,d} q_{ij},\ \ j = D, I, A, E, \tag{2.1}$$

indicate total annual allocation from source i and total annual allocation to sector j, respectively. A share β of the domestic and industrial allocations is discharged as sewage, which must be collected and treated due to environmental regulations, disregarding whether it is reused later on. The treated sewage, denoted $q_{s\circ}$, is the source of the recycled water. Thus,

$$q_{s\circ} = \beta(q_{\circ D} + q_{\circ I}) \tag{2.2}$$

and

$$q_{r\circ} \le q_{s\circ}. \tag{2.3}$$

Fig. 1 presents a schematic view of a water economy.

2.1.1. Water infrastructure

Water allocation requires two types of capital stocks: source-specific and distributional. The former is specific to a source, e.g., capital needed to extract or divert water from natural stocks ($i = n$), treatment plants that convert raw sewage into recycled water suitable for reuse ($i = r$ or s), or desalination plants ($i = d$). Distributional capital is used to allocate (distribute) water from each source to any sector. Source-specific capital stocks are denoted K_i, $i = n,r,d,s$, and the distributional capital stocks are denoted K_{ij}, $i = n,r,d,j = D,I,A,E$.[3] The entire capital stocks are represented by $K = \{K_i, i = n,r,d,s, K_{ij}, i = n,r,d, j = D,I,A,E\}$ and referred to as water infrastructure. As the capital stocks are expressed in monetary terms, they can be added to form the (monetary value of the) outstanding total water capital (infrastructure)

$$\mathbf{K} = \sum_{i=n,r,d,s} K_i + \sum_{i=n,r,d} \ \sum_{j=D,I,A,E} K_{ij}. \tag{2.4}$$

The water infrastructure imposes the following water allocation restrictions:

$$\begin{cases} q_{i\circ} \le \gamma_i K_i, & i = n, r, d, s \\ q_{ij} \le \gamma_{ij} K_{ij}, & i = n, r, d, j = D, I, A, E' \end{cases} \tag{2.5}$$

where $\gamma_i, i = n,r,d$, are coefficients indicating the maximal annual water flow that can be supplied from source i by one K_i unit, γ_s indicates the maximal sewage flow that can be collected and treated by one K_s unit, and the coefficients γ_{ij} represent the maximal annual water flow that can be distributed from source i to sector j by one K_{ij} unit. In light of Eq. (2.5), the minimal capital stocks needed to implement the water allocation $q = \{q_{ij}, i = n,r,d, j = D,I,A,E\}$ satisfy

$$\begin{cases} K_i = q_{i\circ}/\gamma_i, & i = n, r, d, s \\ K_{ij} = q_{ij}/\gamma_{ij}, & i = n, r, d, \ j = D, I, A, E^{\cdot} \end{cases} \tag{2.6}$$

2.2. Benefits

The annual (inverse) demands for water of the domestic, industry and agriculture sectors are denoted $D_j(q_{\circ j})$, $j = D,A,I$.[4] These downward

[2] The shadow price of natural water measures the benefit of not exploiting (extracting, diverting) the last unit of natural water, but instead leaving it in its natural state. It comprised three terms, representing scarcity, extraction costs and marginal instream value. The scarcity and extraction cost terms are common; the marginal instream value term is novel.

[3] It is convenient to include s (sewage) in the list of sources. However, because sewage is the source only of recycled water, s is not included in the distribution (ij) list.

[4] Literature on urban and industrial water demand includes Baerenklau et al. (2014), Baumann et al. (1997), House-Peters and Chang (2011), Olmstead et al. (2007), Renzetti (2002, 2015), Smith and Zhao (2015); literature on agricultural demand includes Howitt (1995), Just et al. (1983), Moore et al. (1994), Mundlak (2001), Scheierling et al. (2006), Schoengold et al. (2006), Tsur et al.

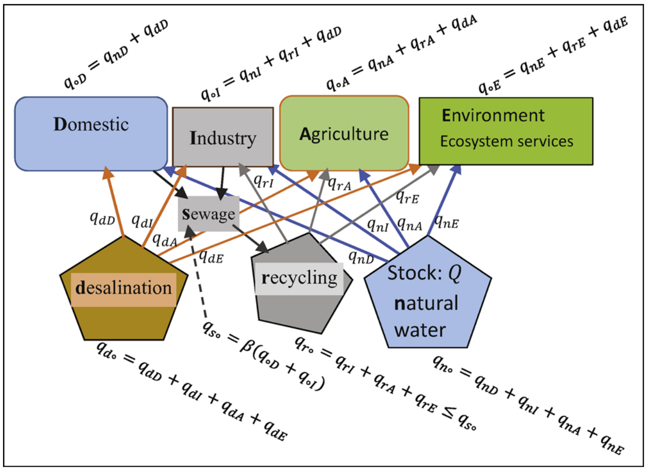

Fig. 1. A water economy scheme with the water allocations.

sloping curves measure the price sector j's users are willing to pay (WTP) for an additional (marginal) unit of water when they already consume $q_{\circ j}$. The (gross) surplus sector j's users derive from $q_{\circ j}$ is evaluated by the area underneath the (inverse) demand curves to the left of $q_{\circ j}$, $j = D,I,A$. These surpluses are denoted $B_j(q_{\circ j})$, $j = D,I,A$ (see Fig. 2).

Environmental benefits stem from the services provided by freshwater ecosystems (lakes, streams, rivers, estuaries, wetlands) and from terrestrial ecosystems supported by natural water (surface and groundwater). Ecosystem services are categorized into regulating services (filtering, pest control, pollination), material services (food and fiber production, drinking, cooking and hygiene), and nonmaterial services (aesthetic landscape, recreation, cultural). The benefits generated by the material services of freshwater (associated with the natural water allocations) are captured by the benefits of the domestic, industry and agriculture sectors (see Fig. 2). The environmental benefits are generated by regulating and nonmaterial services.[5] These benefits are of a public good nature, hence are hard to regulate.

The state of the ecosystems, hence the intensity and quality of their services, is affected by the natural water stock Q and by the conveyed environmental water allocation $q_{\circ E} = q_{nE} + q_{rE} + q_{dE}$. Examples of the former effect are when larger Q increases spring flows or improves the vegetation of terrestrial ecosystems overlaying an aquifer; examples of the latter include the use of recycled, natural or desalinated water to restor stream flows or to reduce diversions and extraction from natural sources.

Consequently, let $B_E^{is}(Q)$ and $B_E(q_{\circ E})$ denote the benefits generated by the ecosystem services affected by Q and $q_{\circ E}$, respectively.[6] The corresponding marginal benefits, denoted $D_E^{is}(Q) \equiv B_E^{is\prime}(Q)$ and $D_E(q_{\circ E}) \equiv B_E^{\prime}(q_{\circ E})$, constitute the demands for instream and conveyed environmental water, respectively. Conceptually, these demands (of the regulating and nonmaterial services embedded in B_E and B_E^{is}) are similar to the other sectors' demands (for the material services), in that $D_E^{is}(Q)$ represents the WTP for a marginal increase in Q and $D_E(q_{\circ E})$ represents the WTP for a marginal increase in $q_{\circ E}$. The main difference is that, while the material services provided by $q_{\circ j}$, $j = D,I,A$, are private goods, the (regulating and nonmaterial) services provided by Q and $q_{\circ E}$ are public goods. As a result, users of $q_{\circ j}$, $j = D,I,A$, can be identified and the demands $D_j(q_{\circ j})$, $j = D,I,A$, can be estimated from price-quantity data. In contrast, the public good nature of the ecosystem services does not allow identifying individual users of environmental water. As a result, estimation of the demands $D_E^{is}(\cdot)$ and $D_E(\cdot)$ must resort to non-market valuation methods (see e.g., Carson and Mitchell, 1993; Bateman et al., 2011; Koundouri and Davila, 2015; Weber et al., 2016). This feature bears profound implications regarding the regulation of environmental water via pricing and requires active participation of government institutions or non-government (NGO) organizations such as payment for environmental services (PES) groups (see Grant and Langpap, 2019; Jack and Jayachandran, 2019). These issues will be addressed in the regulation section below.

2.3. Supply costs

Annual water allocation entails variable and capital costs. The former consists of costs related directly to the water flows, such as energy, temporary labor and materials. The latter consists mainly of the interest and depreciation costs of the water infrastructure and is unrelated to the water allocation flows.[7] For both types, I distinguish between source-specific and distribution costs.

The variable cost incurred at source i is denoted $C_i(q_{i\circ})$, $i = n,r,d,s$, where $C_n(\cdot)$ may also depend on Q (larger natural water stocks entail lower extraction costs).[8] The variable cost of distributing water from source i to sector j is denoted $C_{ij}(q_{ij})$, $i = n,r,d$, $j = D,I,A,E$. The total variable costs associated with the annual allocation $q = \{q_{ij}, i = n,r,d, j = D,I,A,E\}$ at natural water stock Q is therefore

$$C(Q, q) = C_n(Q, q_{n\circ}) + \sum_{i=r,d,s} C_i(q_{i\circ}) + \sum_{i=n,r,d} \sum_{j=D,I,A,E} C_{ij}(q_{ij}). \tag{2.7}$$

At an interest rate ρ and capital depreciation rate δ, the (annual) capital cost incurred by the water infrastructure $K = \{K_i, i = n,r,d,s, K_{ij}, i = n,r,d, j = D,I,A,E\}$ is $(\rho + \delta)\mathbf{K}$, where $\mathbf{K}$ is the total water capital defined in Eq. (2.4). The total (annual) cost of allocating $q = \{q_{ij}, i = n,r,d, j = D,I,A,E\}$ at natural water stock Q is therefore

$$C(Q, q) + (\rho + \delta)\mathbf{K}, \tag{2.8}$$

where the water capital stocks K_i and K_{ij} that are summed up to form $\mathbf{K}$ (in Eq. (2.4)) satisfy Eq. (2.6). The unit supply costs are the change in the above cost associated with a marginal (one unit) change in $q_{ij}, i = n,r,d, j = D,I,A,E$. These unit costs consist of marginal costs, unit capital costs, and two shadow prices. I discuss each term in turn.

2.3.1. Marginal costs

The marginal costs, denoted m_{ij}, are the change in $C(Q,q)$ incurred by a small (marginal) change in q_{ij}. Noting Eqs. (2.1), (2.2) and (2.7), the marginal costs are expressed as

$$m_{ij} \equiv \frac{\partial C(Q, q)}{\partial q_{ij}} = \begin{cases} c_i(q_{i\circ}) + c_{ij}(q_{ij}) + \beta c_s(q_{s\circ}), & i = n, r, d, \; j = D, I \\ c_i(q_{i\circ}) + c_{ij}(q_{ij}), & i = n, r, d, \; j = A, E \end{cases}, \tag{2.9}$$

where $c_i(q_{i\circ}) \equiv C_i^{\prime}(q_{i\circ})$, $i = n, r, d, s$, $c_{ij}(q_{ij}) \equiv C_{ij}^{\prime}(q_{ij})$, $i = n, r, d$, $j = D, I, A, E$ ($c_n(q_{n\circ})$ and $c_n(Q,q_{n\circ})$ are used interchangeably). Notice that the marginal cost of sewage collection and treatment associated with q_{ij}, i.e., $\beta c_s(q_{s\circ})$, is included in the marginal costs of

(footnote continued)
(2004).

[5] It should be noted that the agriculture sector itself is an ecosystem that provides, in addition to material services (food and fiber), also regulating (micro-climate, flood, soil erosion) and nonmaterial (recreation, aesthetic landscape, heritage preservation) services (see Fleischer and Tsur, 2000, 2009; Tielbörger et al., 2010; Thiene and Tsur, 2013). The benefit of the agriculture sector, $B_A(q_{\circ A})$, captures only the material services of agriculture (food and fiber production).

[6] The "*is*," superscript stands for "instream". Instream water refers to natural water that could have been diverted or extracted but instead is left in its natural state to support ecosystem services.

[7] Constructing the infrastructure requires taking a loan whose service gives rise to the interest payments. Replacing the worn-out infrastructure constitutes the depreciation cost.

[8] As above (see footnote 3), it is convenient to include sewage ($i = s$) in the list of sources.

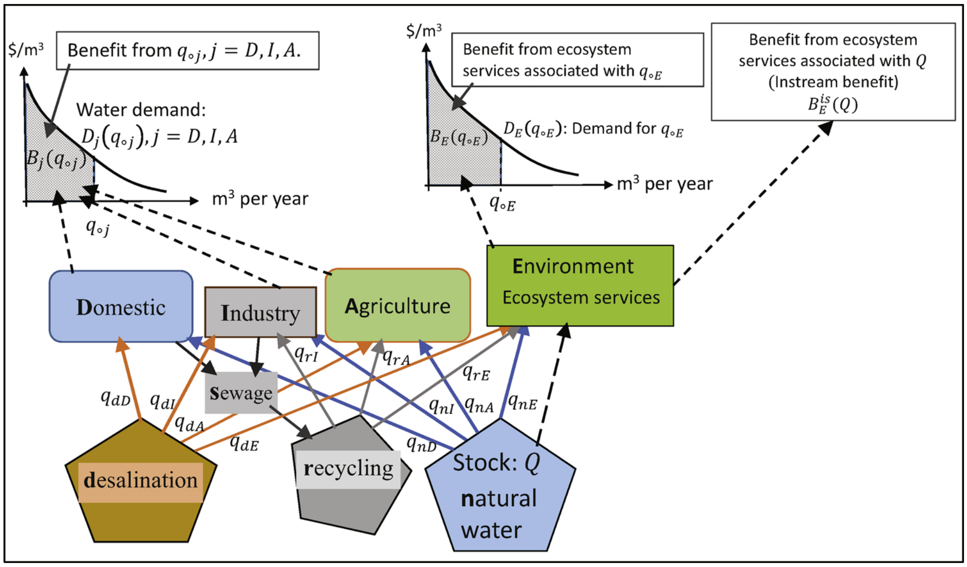

Fig. 2. Water benefits. The environment benefits $B_E(q_{\circ E})$ and $B_E^{is}(Q)$ are derived from ecosystem services supported by $q_{\circ E}$ and Q, respectively.

domestic and industrial users ($j = D,I$), as sewage is generated by these users.

2.3.2. Unit capital costs

The unit capital costs are the change in the capital cost $(\rho + \delta)\mathbf{K}$ incurred by a marginal (one unit) change in q_{ij}. Noting Eq. (2.6), increasing q_{ij} by one unit requires adding $1/\gamma_i$ units of K_i and $1/\gamma_{ij}$ units of K_{ij}. Moreover, for domestic or industrial users ($j = D,I$), the additional q_{ij} unit generates β units of sewage (cf. Eq. (2.2)) and this added sewage requires β/γ_s units of sewage capital K_s. At an annual capital price $\rho + \delta$, the capital cost associated with the unit increase in q_{ij} is therefore $(\rho + \delta)/\gamma_i + (\rho + \delta)/\gamma_{ij}$ plus $\beta(\rho + \delta)/\gamma_s$ for $j = D,I$. With $\mu_i \equiv (\rho + \delta)/\gamma_i$, $i = n,r,d,s$, and $\mu_{ij} \equiv (\rho + \delta)/\gamma_{ij}$, $i = n,r,d$, $j = D,I,A,E$, representing, respectively, the change in the cost of K_i and K_{ij} associated with a marginal change in q_{ij}, the unit capital costs associated with q_{ij}, denoted κ_{ij}, assumes the form

$$\kappa_{ij} = \begin{cases} \mu_i + \mu_{ij} + \beta\mu_s, & i = n, r, d, \ j = D, I \\ \mu_i + \mu_{ij}, & i = n, r, d, \ j = A, E \end{cases}. \tag{2.10}$$

2.3.3. Shadow prices

Two shadow prices affect the unit supply costs: the shadow price of natural water, denoted θ, and the shadow price of recycled water, denoted ξ. The shadow price of natural water (also called in situ value or price) measures the value of a unit of natural water left in its natural state Q. Understanding θ, thus, requires identifying the effects of a marginal (one unit) increase in Q. There are three possible effects. First, a small increase in Q increases the instream benefit by $B_E^{is\,\prime}(Q)$ (see Fig. 2). Second, it reduces the extraction (or diversion) costs of natural water. Third, it can alleviate the scarcity of natural water if Q has reached its lower bound, in which case Q cannot be further reduced and $q_{n\circ}$ cannot exceed the natural recharge. The shadow price θ assumes the form (see the online supplemental material)

$$\theta = \frac{B_E^{is\,\prime}(Q) - c_n{}'(Q)R(Q) + \vartheta}{\rho - R'(Q)}. \tag{2.11}$$

The numerator on the right-hand side of Eq. (2.11) contains the three terms discussed above: $B_E^{is\,\prime}(Q)$ is the marginal instream value; $-c_n{}'(Q)R(Q)$ is the marginal extraction cost;[9] and $\vartheta \geq 0$ represents the scarcity effect, which vanishes if Q exceeds its lower bound. The division by $\rho - R'(Q)$ translates these annual benefits into present values (of an indefinite benefit stream). The extraction cost and scarcity terms are common in dynamic water management models. The marginal instream value term $B_E^{is\,\prime}(Q)$, representing benefit from ecosystem services supported by natural water, is novel. As it increases θ, the marginal instream value renders natural water more expensive, implying that the optimal extraction or diversion of water from natural sources should be reduced. The pricing mechanism, formulated in the next section, accounts for this effect.

The shadow price of recycled water is denoted ξ and represents the implicit cost of the $q_{r\circ} \leq q_{s\circ}$ constraint (cf. Eq. (2.3)) when q_{ij} is increased by a one (marginal) unit. If the constraint is not binding, i.e., when the sewage flow $q_{s\circ}$ (cf. Eq. (2.2)) exceeds the demand for recycled water, then the constraint has no effect and $\xi = 0$. Otherwise (when the constraint is binding), $\xi > 0$ measures the effect of a small increase in q_{rj} (i.e., in the allocation of recycled water), which exacerbates the constraint, and $\beta\xi$ measures the effect of a small increase in the allocation of domestic or industrial water (q_{iD} or q_{iI}), which generate sewage and relaxes the constraint.

2.3.4. Unit supply costs

Accounting for the marginal costs (Eq. (2.9)), the unit capital costs (Eq. (2.10)) and the two shadow prices give the following unit supply costs associated with q_{ij}, denoted p_{ij}:

$$p_{nj} = \begin{cases} m_{nj} + \kappa_{nj} + \theta - \beta\xi, & j = D, I \\ m_{nj} + \kappa_{nj} + \theta, & j = A, E \end{cases}, \tag{2.12a}$$

$$p_{rj} = \begin{cases} m_{rj} + \kappa_{rj} + \xi - \beta\xi, & j = D, I \\ m_{rj} + \kappa_{rj} + \xi, & j = A, E \end{cases}, \tag{2.12b}$$

$$p_{dj} = \begin{cases} m_{dj} + \kappa_{dj} - \beta\xi, & j = D, I \\ m_{dj} + \kappa_{dj}, & j = A, E \end{cases}. \tag{2.12c}$$

[9] It is assumed that $C_n(Q,q_{n\circ}) = c_n(Q)q_{n\circ}$ and $c_n{}'(Q) \leq 0$. Thus, the reduction

(footnote continued)
in the supply cost of natural water is $-\partial C_n(Q,q_{n\circ})/\partial Q = -c_n{}'(Q)q_{n\circ}$, which at a steady state equals $-c_n{}'(Q)R(Q)$.

2.4. Optimal steady-state allocation

As noted above, the optimal water policy converges eventually to a steady state, in which all stocks (natural water and capital) and allocation flows are constant. I summarize below the steady state, to be implemented by the pricing mechanism developed in the next section. The derivation (based on Tsur and Zemel, 2014, 2018; Tsur, 2019) is outlined in the online supplemental material.

Given Q and θ, the optimal allocation satisfies the demand-equal-supply conditions

$$D_j(q_{\circ j}) \le p_{ij} \text{ equality holding if } q_{ij} > 0,\ \ i = n, r, d,\ \ j = D, I, A, E, \tag{2.13}$$

where ξ satisfies

$$\xi(q_{s\circ} - q_{r\circ}) = 0, \tag{2.14}$$

so $\xi = 0$ if constraint (2.3) is not binding and $\xi > 0$ otherwise. The optimal Q and θ satisfy

$$R(Q) = q_{n\circ} \tag{2.15}$$

and

$$\vartheta(Q - \underline{Q}) = 0. \tag{2.16}$$

Condition (2.15) requires that total natural water withdrawal equals natural recharge, which holds in a steady state where Q remains constant. In Eq. (2.16), $\underline{Q}$ is a lower bound of Q, which could be zero or some positive threshold below which undesirable events (e.g., seawater intrusion) may happen, and ϑ is the scarcity term in the shadow price θ (cf. Eq. (2.11)), which vanishes if $Q > \underline{Q}$ and otherwise is positive.

Denoting optimal steady state variables with a hat " ^ " superscript, e.g., $\hat{Q}$, $\hat{\theta}$, $\hat{q}$, $\hat{\xi}$ and $\hat{p}$, the above discussion is summarized in (see derivation in the online supplemental material):

Property 1. *Eqs.* (2.11) and (2.13)–(2.16) *provide 16 conditions to solve for* $\hat{Q}$, $\hat{\theta}$, $\hat{\xi}$, $\hat{\vartheta}$ *and* $\hat{q} = \{\hat{q}_{ij},\ i = n, r, d,\ j = D, I, A, E\}$. *In view of* Eq. (2.6)*, the steady-state capital stocks are*

$$\begin{cases} \hat{K}_i = \hat{q}_{i\circ}/\gamma_i, & i = n, r, d, s \\ \hat{K}_{ij} = \hat{q}_{ij}/\gamma_{ij}, & i = n, r, d,\ j = D, I, A, E \end{cases}. \tag{2.17}$$

The unit supply costs, specified in Eqs. (2.12), evaluated at the optimal steady-state policy are denoted $\hat{p} = \{\hat{p}_{ij},\ i = n, r, d, j = D, I, A, E\}$. I turn now to the task of implementing the optimal steady-state policy by means of water pricing.

3. Regulation

In addition to the environmental externalities (associated with the ecosystem services), which are the focus of this work, water economies are rife with market failures, e.g., common pool externality (when pumping/diverting water from shared aquifers, reservoirs or stream flows), returns to scale of water infrastructure (which constitutes a considerable share of the cost of water supply), and dependence on water ownership rights, allocation rules and norms. Water allocation, thus, must be regulated and such regulation is based in one way or another on water prices. I offer a regulation scheme, based on volumetric pricing, that implements the optimal allocation.[10]

The situation perceived is of a water economy consisting of users, suppliers and a regulator. The regulator is fully informed (natural recharge, variable costs, capital costs, demands, value of ecosystem services), thus can calculate the optimal $\hat{Q}$, $\hat{q} = \{\hat{q}_{ij},\ i = n, r, d, j = D, I, A, E\}$, $\hat{\theta}$ and $\hat{\xi}$ and the ensuing unit costs $\hat{p} = \{\hat{p}_{ij},\ i = n, r, d, j = D, I, A, E\}$, specified in Eqs. (2.12). The regulator seeks to implement the optimal allocation $\hat{q}$ by appropriately pricing the water facing consumers and suppliers.

To that end, the regulator uses the pricing mechanism based on (P,θ,ξ), defined as follows: (*i*) $P = (P_D,P_I,P_A,P_E)$ represents the user prices, where $P_j, j = D,I,A$, are the water prices imposed on domestic, industrial and agricultural users, respectively, and P_E is a price the regulator pays for each unit of conveyed environmental water (allocated from one of the sources for environmental purposes) up to the annual flow $q_{\circ E}$ satisfying $D_E(q_{\circ E}) = P_E$; (*ii*) θ is an extraction/diversion charge imposed on suppliers of natural water; and (*iii*) ξ is a charge imposed on suppliers of recycled water. The price P_E allows treating the allocations q_{iE}, $i = n,r,d$, in a way similar to the allocation of water to the other sectors, in spite of the public good nature of the former. After the regulator announces the policy (P,θ,ξ), suppliers decide how much to allocate from each source to each sector and users decide how much to consume.

When exists, denote by $q(P,\theta,\xi) = \{q_{ij}(P,\theta,\xi), i = n,r,d, j = D,I,A,E\}$ the water allocation induced by the pricing policy (P,θ,ξ) and let $p(P,\theta,\xi) = \{p_{ij}(P,\theta,\xi), i = n,r,d, j = D,I,A,E\}$ denote the corresponding unit costs, defined in Eqs. (2.12), evaluated at $q(P,\theta,\xi)$, θ and ξ.[11] The water economy is in equilibrium, i.e., $q(P,\theta,\xi)$ is an equilibrium allocation, if:

$$D_j(q_{\circ j}(P, \theta, \xi)) \le P_j \text{ equality holding if } q_{\circ j}(P, \theta, \xi) > 0,\ \ j = D, I, A, E, \tag{3.1a}$$

(recall that $q_{\circ j}(P,\theta,\xi) = \Sigma_{\,i=n,r,d}\, q_{ij}(P,\theta,\xi)$) and

$$q_{ij}(P, \theta, \xi) > 0 \text{ implies } p_{ij}(P, \theta, \xi) \le P_j,\ \ i = n, r, d,\ \ j = D, I, A, E. \tag{3.1b}$$

Conditions (3.1a) merely state that all sectors consume water along their demand curve. Conditions (3.1b) state that source *i*'s suppliers will supply water to sector *j* only if the unit supply cost $p_{ij}(P,\theta,\xi)$ does not exceed the price P_j they receive. If there exists a unique allocation $q(P,\theta,\xi)$ satisfying Eqs. (3.1), we say that the pricing policy (P,θ,ξ) implements the allocation $q(P,\theta,\xi)$. We seek the pricing policy that implements the optimal allocation $\hat{q} = \{\hat{q}_{ij},\ i = n, r, d, j = D, I, A, E\}$.

To that end, define

$$\hat{P}_j = \min_{i \in \{n,r,d\}} \hat{p}_{ij},\ \ j = D, I, A, E, \tag{3.2}$$

where it is recalled that the $\hat{p}_{ij}$'s are the p_{ij}'s defined in Eqs. (2.12) evaluated at $\hat{Q}$, $\hat{\theta}$, $\hat{q}$ and $\hat{\xi}$.[12] Then,

Property 2. *The pricing policy* $(\hat{P}, \hat{\theta}, \hat{\xi})$ *implements the optimal water allocation* $\hat{q}$.

The proof is presented in the appendix.

It is seen from Eqs. (3.1b) and (3.2) that

$$\hat{q}_{ij} > 0 \text{ implies } \hat{p}_{ij} = \hat{P}_j,\ \ i = n, r, d,\ \ j = D, I, A, E. \tag{3.3}$$

Thus, under the optimal policy, the unit costs of allocating water to sector j (the $\hat{p}_{ij}$, $i = n, r, d$) are the same for all sources that supply water to sector j and these unit costs are minimal. In particular, if the unit cost of some source i exceeds this minimum, i.e., $\hat{p}_{ij} > \hat{P}_j$, then no water is allocated to sector j from source i, i.e., $\hat{q}_{ij} = 0$. To sum:

Property 3. *The unit costs* $\hat{p}_{ij}$ *of all sources i that supply water to sector j are the same and equal* $\hat{P}_j$.

[10] On the various approaches commonly used in the water regulation see Johansson et al. (2002), Tsur and Dinar (1997), Tsur et al. (2004) and references they cite.

[11] Notice that suppliers, like the regulator, are fully informed of the marginal and unit capital costs, thus can calculate the unit costs p_{ij}'s associated with $q(P,\theta,\xi)$ upon observing the shadow prices θ and ξ (announced by the regulator).

[12] If allocating recycled water to households is not allowed, i.e., $\hat{q}_{rD} = 0$ is imposed, then $\hat{P}_D = \min_{i\in\{n,d\}}\hat{p}_{iD}$.

3.1. Environmental water pricing

As discussed above, the ecosystem services provided by $q_{\circ E}$ are public goods, hence the consumption of individual users cannot be identified and users cannot be priced directly. However, the optimal allocations $\hat{q}_{iE}$ and the associated unit costs $\hat{p}_{iE}$, $i = n, r, d$, can be calculated, together with those of the other sectors, based on the demands and unit supply costs, as described in Subsection 2.4. The regulator, thus, can calculate the associated $\hat{P}_E$, defined in Eq. (3.2) and use it when announcing the pricing policy $(\hat{P}, \hat{\theta}, \hat{\xi})$. Suppliers will then increase their environmental water allocations q_{iE} until their unit supply cost equals$\hat{P}_E$ (the price they receive from the regulator), which occurs at $\hat{q}_{\circ E}$. The cost to the regulator (i.e., what he pays the environmental water suppliers) is $\hat{q}_{\circ E}\hat{P}_E$. I discuss how to finance this cost in Subsection 3.2 below.

Instream water allocation entails no cost and the demand for the ecosystem services it provides is represented by the marginal instream value $D_E^{is}(\hat{Q}) = B_E^{is\prime}(\hat{Q})$, embedded in $\hat{\theta}$ (cf. Eq. (2.11)). Noting Eq. (2.12a), the shadow price $\hat{\theta}$ is included in $\hat{p}_{nj}$, $j = D, I, A, E$, hence also in the user prices $\hat{P}_j$, $j = D, I, A, E$, defined in Eq. (3.2). Thus, if the marginal instream value $B_E^{is\prime}(\hat{Q})$ is properly incorporated into the shadow price $\hat{\theta}$, it affects the water prices $\hat{P}_j$, $j = D, I, A, E$, and the ensuing optimal allocation properly accounts for the instream value of natural water.

3.2. Water proceeds and costs allocation

The policy $(\hat{P}, \hat{\theta}, \hat{\xi})$ implements the optimal allocation $\hat{q}$ (Property 2) and induces the unit costs $\hat{p}$ (see Claim 1 in the appendix). The ensuing capital infrastructure is $\hat{K}$, defined in Eq. (2.17) at the optimal $\hat{q}$. The annual supply costs equal (cf. Eq. (2.8))

$$C(\hat{Q}, \hat{q}) + (\rho + \delta)\hat{\mathbf{K}}, \tag{3.4}$$

where $\hat{\mathbf{K}}$ is total capital value of $\hat{K}$. The optimal pricing policy raises the annual proceeds $\sum_j \hat{q}_{\circ j}\hat{P}_j$. If the proceeds cover the supply costs we say that the policy is *self-sustained*. A self-sustained policy does not require external financial intervention (such as subsidizing water suppliers), which greatly facilitates the regulation. It turns out that the optimal pricing policy is self-sustained, as stated in:

Property 4. *The annual proceeds $\sum_{j=D,I,A,E} \hat{q}_{\circ j}\hat{P}_j$, raised under the optimal pricing policy $(\hat{P}, \hat{\theta}, \hat{\xi})$, exceed the annual supply costs (3.4) by the amount $\hat{q}_{n\circ}\hat{\theta}$.*

The proof is presented in the appendix.

Property 4 ensures that the total proceeds suffice to cover all the supply costs (variable and capital). How the different costs are remunerated varies across water economies depending on the institutional structure. As an example, consider the following situation. The regulator sets the users' prices $\hat{P}_j$, $j = D, I, A$, and the shadow prices $\hat{\theta}$ and $\hat{\xi}$. The proceeds $\sum_{j=D,I,A} \hat{q}_{\circ j}\hat{P}_j$, paid by domestic, industrial and agricultural users, are collected by water utilities (for domestic and industrial users) or water users associations (for agricultural users), which use these proceeds to pay suppliers of $\hat{q}_{ij}$, $i = n, r, d$, $j = D, I, A$. The proceeds $\hat{q}_{n\circ}\hat{\theta}$ and $\hat{q}_{r\circ}\hat{\xi}$ are collected by the regulator from natural and recycled water suppliers, respectively. The recycled water proceeds, $\hat{q}_{r\circ}\hat{\xi}$, are used to finance the subsidy $\hat{\xi}\beta(\hat{q}_{\circ D} + \hat{q}_{\circ I}) = \hat{\xi}\hat{q}_{s\circ}$, embedded in the water prices of domestic and industrial users (see Eqs. (2.12) and (3.2)). The natural water proceeds, $\hat{q}_{n\circ}\hat{\theta}$, have no cost counterpart and can be used to finance the supply cost $\hat{q}_{\circ E}\hat{P}_E$, which the regulator pays suppliers of $\hat{q}_{iE}$. If $\hat{q}_{n\circ}\hat{\theta} \geq \hat{q}_{\circ E}\hat{P}_E$, then the surplus should be returned to households (as lump sum payments). Otherwise, the difference $\hat{q}_{\circ E}\hat{P}_E - \hat{q}_{n\circ}\hat{\theta}$ should be raised independently (e.g., via taxes).

3.3. More on the shadow prices $\hat{\theta}$ and $\hat{\xi}$

As noted above, the shadow (in situ) price $\hat{\theta}$ accounts for the instream value as well as the extraction cost and scarcity of natural water (see discussion below Eq. (2.11)). It operates in two ways: first, by increasing the unit costs of natural water (cf. Eq. (2.12a)); second, by affecting the water prices $\hat{P}_j$ of all sectors (cf. Eqs. (2.12a) and (3.2)). The regulator can do away with the $\hat{\theta}$ charge on natural water suppliers by imposing instead a quota that restricts abstractions from natural sources to the desired level $\hat{q}_{n\circ}$. Such a quota can be administered, e.g., via permits assigned to natural water suppliers. However, to ensure that demand meets supply and the instream value of natural water is properly accounted for, the water prices $\hat{P}_j$ should remain unchanged. Thus, under abstraction quota on natural water (that replaces the charge $\hat{\theta}$), the supply costs of natural water are lower than those under the abstraction charge $\hat{\theta}$ by the (annual) amount $\hat{\theta}\hat{q}_{n\circ}$, yet the prices $\hat{P}_j$ and $\hat{q}_{nj}$, $j = D, I, A, E$, are the same in both cases, hence the proceeds are the same as well.[13] As a result, the profit of natural water suppliers under quota is higher than the profit under the charge $\hat{\theta}$ by the amount $\hat{\theta}\hat{q}_{n\circ}$. This is exactly the surplus proceeds to which no cost counterpart exists (see Property 4), hence should be seized by the regulator and returned to water users (as lump sum payments) or used to finance environmental water allocation (i.e., replacing all or part of the conveyed environmental water proceeds $\hat{q}_{\circ E}\hat{P}_E$). Under the charge $\hat{\theta}$, the regulator collects this sum directly from suppliers of natural water.

The purpose of $\hat{\xi}$ is to steer water allocations according to the recycled water constraint $\hat{q}_{r\circ} \leq \hat{q}_{s\circ}$, requiring that the supply of recycled water (which in equilibrium meets the demand for recycled water) does not exceed the domestic and industrial effluent. The shadow price of this constraint is $\hat{\xi}$, which affects in two ways: first, by increasing the unit cost of recycled water $\hat{p}_{rj}$ by $\hat{\xi}$ (cf. Eq. (2.12b)), which is transmitted to the water prices $\hat{P}_j$ of all sectors (cf. Eq. (3.2)); second, by subsidizing suppliers that allocate water to domestic and industrial users by the (per unit) subsidy $\beta\hat{\xi}$ (cf. Eqs. (2.12)), which is transmitted to the water prices $\hat{P}_D$ and $\hat{P}_I$ of domestic and industrial users (cf. Eqs. (2.12) and (3.2)). The rationale of $\hat{\xi}$ as a charge on suppliers is to equate supply and demand of recycled water (via the effect of the charge on the unit cost of recycled water and on the consumer prices $\hat{P}_j$). The rationale of $\beta\hat{\xi}$ as a subsidy stems from the sewage generation role of domestic and industrial users, recalling that $\hat{q}_{s\circ} = \beta(\hat{q}_{\circ D} + \hat{q}_{\circ I})$, so increasing the domestic and industrial allocations increases sewage discharge and thereby relaxes the recycled water constraint.

If the demand for recycled water, which in equilibrium equals the supply $\hat{q}_{r\circ}$, falls short of the available (treated) sewage even when $\hat{\xi} = 0$, then recycled water is not scarce (the constraint is not binding) and $\hat{\xi} = 0$. Otherwise, $\hat{\xi} \geq 0$ is chosen in order to equate the demand and supply of recycled water, i.e., $\hat{q}_{r\circ} = \hat{q}_{s\circ} = \beta(\hat{q}_{\circ D} + \hat{q}_{\circ I})$. In either case $\hat{\xi}(\hat{q}_{s\circ} - \hat{q}_{r\circ}) = 0$. Now, the charge $\hat{\xi}$ implies that recycled water suppliers pay the regulator the total (annual) amount $\hat{\xi}\hat{q}_{r\circ}$. On the other hand, the (per unit) subsidy $\beta\hat{\xi}$ the regulator pays to suppliers that allocate water to domestic and industrial (cf. (2.12)) entails the total (annual) subsidy payment $\hat{\xi}\beta(\hat{q}_{\circ D} + \hat{q}_{\circ I})$, which equals$\hat{\xi}\hat{q}_{s\circ}$ (recalling that $\hat{q}_{s\circ} = \beta(\hat{q}_{\circ D} + \hat{q}_{\circ I})$). Thus, the payments associated with $\hat{\xi}$ are budget neutral, i.e., neither require an external infusion of money nor leave any surplus.

Fig. 3 presents the regulation mechanism and specifies the decisions and actions taken by each player (regulator, suppliers and consumers). It begins with the regulator setting (announcing) the water prices $\hat{P}_j$, $j = D, I, A, E$, each sector faces, letting the suppliers decide how

[13] To see this, note that the supply of natural water under the abstraction charge $\hat{\theta}$ and under quota are the same, but when $\hat{\theta}$ is imposed the natural water suppliers pay the regulator the amount $\hat{\theta}\hat{q}_{n\circ}$ whereas under quota no such payments are made.

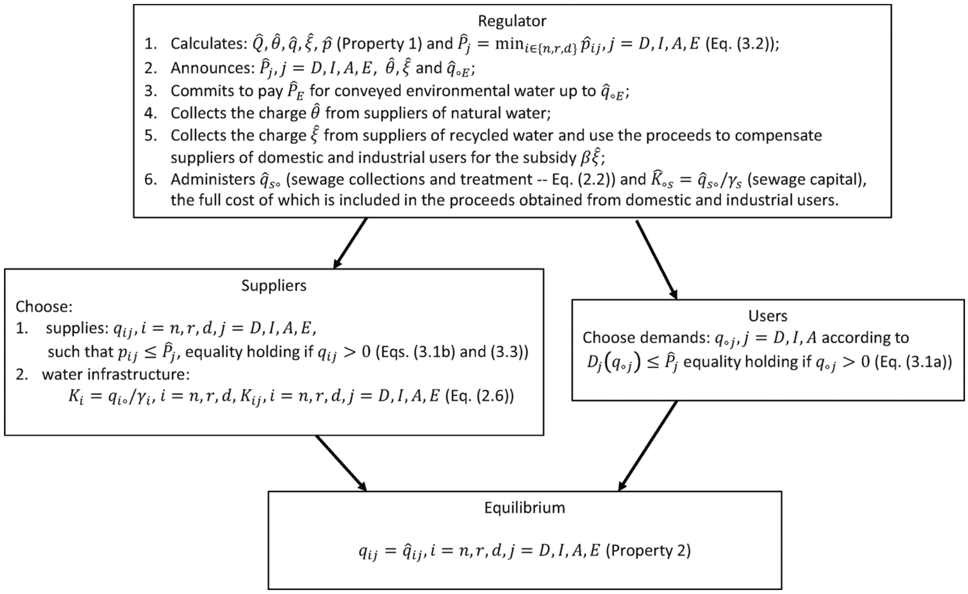

Fig. 3. A flowchart of the regulation mechanism.

much to allocate from each source to each sector and the consumers choose their own consumption rates. In addition, the regulator (*i*) sets a cap $\hat{q}_{\circ E}$ on the flow of conveyed environmental water up to which $\hat{P}_E$ is paid, (*ii*) charge suppliers of natural water the rate $\hat{\theta}$, (*iii*) charge suppliers of recycled water the rate $\hat{\xi}$ and use the proceeds to reimburse suppliers of domestic and industrial water for the subsidy $\beta\hat{\xi}$ embedded in $\hat{P}_D$ and $\hat{P}_I$ (cf. Eqs. (2.12) and (3.2)), and (*iv*) assigns responsibility for sewage collection and treatment (e.g., by subcontracting and reimbursing utilities), the full cost of which is included in the proceeds collected from domestic and industrial users. Note from (*i*) that the regulation of conveyed environmental water uses a price-quota combination. In contrast, the allocation of instream water is implemented by the natural water charge $\hat{\theta}$ via the marginal instream value $B_E^{is\,\prime}(\hat{Q})$ it contains (cf. Eq. (2.11)) and does not require a quota intervention.

3.4. Desalination

Desalination is often more capital intensive than the supply of natural or recycled water, in which case $\gamma_d \ll \gamma_i$, $i = n,r$.[14] Thus, $\mu_d = (\rho + \delta)/\gamma_d \gg (\rho + \delta)\gamma_i = \mu_i$, $i = n,r$, implying that the capital cost component of desalination is larger than that of natural and recycled water. If desalinated water is demanded by sector j, i.e., $\hat{q}_{dj} > 0$, then Condition (3.3) implies that $\hat{p}_{dj} = \hat{p}_{ij}$ for all sources i from which sector j receives water.

Suppose that natural water is supplied to all sectors, i.e., $\hat{q}_{nj} > 0$, $j = D, I, A, E$ – a common situation. Then, according to Property 3, desalinated water is supplied to households only if $\hat{p}_{dD} = \hat{p}_{nD}$. Noting Eqs. (2.12a) and (2.12c), assuming (for simplicity) linear variable costs, this condition implies

$$c_n(\hat{Q}) + \mu_n + c_{nD} + \mu_{nD} + \hat{\theta} = c_d + \mu_d + c_{dD} + \mu_{dD}.$$

Suppose that the distribution of natural and desalinated water to domestic users shares the same infrastructure, so $c_{nD} = c_{dD}$ and $\mu_{nD} = \mu_{dD}$. In this case, the above condition becomes

$$c_n(\hat{Q}) + \mu_n + \hat{\theta} = c_d + \mu_d. \quad (3.5)$$

The left-hand side of Eq. (3.5) is the unit cost of natural water (before distribution to the various sectors) and the right-hand side is the unit cost of desalination at the plant's gate. The former depends on the natural water stock $\hat{Q}$ and the associated shadow price $\hat{\theta}$ while the latter is constant (given by the desalination technology). Because $\hat{Q}$ and $\hat{\theta}$ represent long-run outcomes, condition (3.5) is necessary for desalination to be economically viable in the long run.

4. An example based on Israel's water economy

A description of Israel's water economy (sources, sectors, institutions) can be found in Kislev (2012). More up-to-date accounts of recycling and desalination, as well as allocation policies and prices, are discussed in Tsur (2015). A popular account, together with a historical overview, can be found in Siegel (2015).

Israel's water law states that (translated from Hebrew): "The country's water resources are public property, controlled by the state and are designated for the needs of its residents and the development of the country. For the purpose of this law, water resources include: springs, streams, rivers, lakes, reservoirs, either surface or groundwater, natural or artificial, standing or flowing, including drainage water and sewage."[15] The responsibility for enforcing this law falls on the Water Authority (WA) and its various agencies. This responsibility includes: long run planning of the water economy, setting annual permits for extraction and diversion from natural sources, coordinating the construction of recycling facilities, managing tenders for desalination plants, and regulating water allocation to all sectors via an elaborate system of quotas (for agricultural users and environmental sites) and cost-based tariffs for all sectors (see discussion in Kislev, 2012). All these tasks are addressed by the water economy model presented above.

I calculate the prices ($\hat{P}$, $\hat{\theta}$, $\hat{\xi}$) that implement the optimal allocation $\hat{q} = \{\hat{q}_{ij}, i = n, r, d, j = D, I, A\}$ and the ensuing infrastructure $\hat{K} = \{\hat{K}_i, i = n, r, d, s;\ \hat{K}_{ij}, i = n, r, d, j = D, I, A\}$, specified in Eq. (2.17).

Table 1 presents the parameters and functions used in the calculation of the optimal allocation and prices. The 6.5% discount rate and the 3% depreciation rate are the return on capital and depreciation set by the Water Authority (Belinkov, 2014). The unit variable and capital costs, presented in Table 2, were calculated based on documented

[14] Noting $q_{i\circ} \le \gamma_i K_i$, if desalination is more capital intensive it requires more capital to supply one unit of water, implying that γ_d is smaller than both γ_n and γ_r.

[15] Israel's Water Law, 1959, Chapter 1 (http://water.gov.il/Hebrew/about-reshut-hamaim/Pages/Legislation.aspx).

Table 1
Parameters and functions.

Parameter/function	Value	Description
ρ	0.065	Discount rate
δ	0.03	Depreciation rate
c_i, c_{ij}, μ_i, μ_{ij}	Table 2	Unit supply costs (shekel per m^3)
β	0.6	Sewage share from domestic and industrial sectors
$D_j^{-1}(P_j) = a_j - b_j P_j$	Table 3	Demand coefficients
$B_E^{is\prime}(Q)$	0.01	Marginal instream value (assumed)
$R(Q)$	1,000	Natural water recharge (MCM/y)
$\underline{Q}$	0	Lower bound on Q

Table 2
Unit supply cost data in shekel per m^3 (the exchange rate at the time of writing is $ 1 = 3.7 Israeli shekel).

	(c_{ij}, μ_{ij})				(c_i, μ_i)
	Domestic	Industry	Ag	Env	
Natural	2.21, 1.63	2.10, 1.50	0.30, 0.50	0.30, 0.30	1.20, 1.00
Recycled		2.15, 1.50	0.40, 0.45	0.20, 0.45	0.30, 0.80
Desalinated	2.10, 1.74	2.10, 1.50	0.30, 0.80	0.30, 0.80	1.50, 1.30
Sewage					1.47, 1.16

data.[16] The $\beta = 0.6$ share of sewage from the domestic and industrial allocations is taken from Tsur (2015).[17] The linear demands, $D_j^{-1}(P_j) = a_j - b_j P_j$, are assumed for convenience[18] and the $a_j, b_j, j = D, I, A$ parameters presented in Table 3 were calibrated based on consumption-price data reported by the Water Authority.[19] A summary of Israel's ecosystems, can be found in Lotan et al. (2017). Values of ecosystem services provided by different types of open space can be found in Fleischer et al. (2018), Fleischer and Tsur (2003). However, economic valuation of the ecosystem services provided by conveyed and instream water is not yet available. The environmental demand parameters and the marginal instream value $B_E^{is\prime}(Q)$ are therefore assumed.

The annual natural recharge of 1000 million m^3 (MCM/y) is based on the 1125 MCM/y average annual recharge during the period 1993–2009, reported in Weinberger et al. (2012, Table 7, p. 13). This figure excludes Gaza and the Eastern and Northeastern aquifers (underlying the West Bank). Subtracting the 100 MCM/y allocated to Jordan (under current agreements), leaves (after rounding) 1000 MCM/y. The zero lower bound $\underline{Q} = 0$ is a harmless normalization.

Table 3
Demand coefficients.

	Domestic	Industry	Agriculture	Environment
a	1200	130	1200	500
b	35	5	130	40

Table 4
Steady state allocation (MCM/y) and water prices (shekel/m^3).

	$\hat{q}_{ij}$ (MCM/y)				$\hat{q}_{i\circ}$
	Domestic	Industry	Agriculture	Environment	
Natural (n)	509.45	1.66	171.97	316.92	1000
Recycled (r)	0	18.67	559.49	47.08	625.23
Desalinated (d)	437.54	74.73	0	0	512.28
$\hat{q}_{\circ j}$	946.99	95.06	731.46	364.00	
Sewage (s)	622.20	57.03			625.23
$\hat{P}_j$ (shekel per m^3)	7.23	6.99	3.60	3.40	
$\hat{\theta}$ (shekel per m^3)	0.60	(natural water shadow price)			
$\hat{\xi}$ (shekel per m^3)	1.65	(recycled water shadow price)			

The steady state allocation $\hat{q} = \{\hat{q}_{ij}, i = n, r, d, j = D, I, A, E\}$ and prices $\hat{P}_j$, $j = D, I, A, E$, are reported in Table 4. The desirable desalination capacity is 512 MCM/y, allocated to households (437 MCM/y) and industry (75 MCM/y). The current desalination capacity in Israel is 600 MCM/y. The larger capacity could be justified by expected increase in demand due to population growth. The table indicates that agricultural users should receive water mostly from recycling plants (559 MCM/y) and some from natural sources (172 MCM/y). In actual practice the allocation of natural water to agriculture is larger (see Tsur, 2015). The reason could be insufficient infrastructure to convey recycled water from the densely populated center (where most recycling plants are located) to the cultivated areas the north and south. Indeed, the agricultural water allocation trends in the past two decades, shown in Fig. 4, reveal that the water economy evolves towards an allocation in which agriculture relies mostly on recycled water.

Table 4 reveals a substantial environmental water allocation of 364 MCM/y, supplied mostly from natural sources (317 MCM/y) and some from recycled sources (47 MCM/y). This allocation is at odds with the actual, much smaller, allocation. The reason might be because the assumed environmental water demand does not reflect the true demand or because the infrastructure needed to convey environmental water (natural and recycled) to environmental sites is underdeveloped.

Table 4 also presents the optimal prices ($\hat{P}$, $\hat{\theta}$, $\hat{\xi}$). The shadow price $\hat{\theta} = 0.6$ shekel/m^3 has a pronounced effect on the desalination scale of 512 MCM/y (above 50% of domestic water consumption). This substantial desalination alleviates the water scarcity in two ways: first it increases water supply by augmenting nature as an external water source; second, each m^3 of desalinated water allocated to households or industrial users contributes an additional $\beta = 0.6$ m^3 of recycled water (via the sewage these users generate). Thus, the shadow price $\hat{\theta}$ encourages desalination and the latter, in turn, alleviates water scarcity and reduces $\hat{\theta}$.[20]

I reiterate that the purpose of the example is illustrative. A thorough application, based on which policy recommendations can be drawn, requires elaborate water demand estimation of all sectors as well as up-to-date supply costs data.

[16] These data were derived from the cost breakdown underlying the water charges determined by the Water Authority (see http://www.water.gov.il/Hebrew/Rates/Pages/Rates.aspx), from Belinkov (2014) and from conversations with Amir Shakarov of the Water Authority (whose help is gratefully acknowledged).

[17] Rules for recycled water use vary from country to country. In Israel, arguably the world leader in this respect, the rules are still evolving as new information is accumulated (see discussion of crop irrigation rules in Chen and Tarchitzky, 2018). The current health regulation rules can be found (in Hebrew) in http://www.sviva.gov.il/subjectsEnv/Streams/SewageStandards/Pages/Milestones.aspx.

[18] The linear demand specification is made for illustration purpose. An empirical application, with detailed data and elaborate estimation of nonlinear demand specifications, is beyond the current scope.

[19] Water consumption data for the period 1998-2016 can be found in http://www.water.gov.il/Hebrew/ProfessionalInfoAndData/Allocation-Consumption-and-production/20173/intro.pdf. Water tariffs for this period can be found in http://www.water.gov.il/Hebrew/Rates/Pages/prices-archive.aspx. The linear demand coefficients were calibrated as follows. First, consumptions are regressed on an intercept and prices (with a time trend if needed): $q_{\circ j} = a_j - b_j P_j$, $j = D, I, A$. The inverse demand functions are then $D_j = a_j / b_j - (1/b_j) q_{\circ j}$.

[20] Indeed, calculating the steady state allocations and prices without desalination, i.e., assuming that no desalination plants were constructed, gives $\hat{\theta} = 3.28$ shekel/m^3.

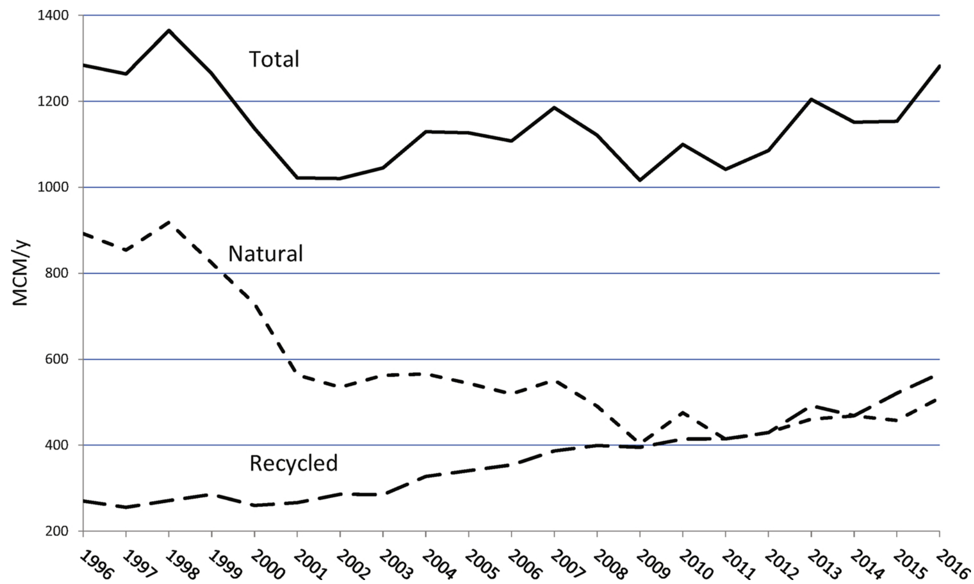

Fig. 4. Natural and recycled water allocation for agriculture: 1996–2016. (Source: Israel Water Authority: http://www.water.gov.il/Hebrew/ProfessionalInfoAndData/Allocation-Consumption-and-production/20173/intro.pdf.) .

5. Concluding comments

A pricing mechanism that implements the optimal water policy is derived, paying special attention to environmental water allocation. The analysis distinguishes between two types of environmental water: conveyed and instream. The former refers to water conveyed from water sources to various environmental sites; the latter refers to natural water that could have been diverted or extracted but instead is left in its natural state (aquifers, lakes, streams, rivers, estuaries) to enhance ecosystem services. I show that the regulation of these two types of environmental water differs considerably. In particular, the allocation of conveyed environmental water requires a quota-price combination; in contrast, the optimal allocation of instream water can be implemented solely by water pricing. The latter is accomplished by properly incorporating the marginal instream value within the shadow (in situ) price of natural water and properly incorporating the latter within the water prices facing users and suppliers.

The optimal prices depend on the unit supply costs and the latter include two shadow prices: one representing the in situ value of natural water and the other representing scarcity of recycled water. The former accounts for scarcity, extraction/diversion costs and instream value of natural water and has a pronounce effect on the desirability and extent of desalination. The latter reflects the scarcity of recycled water associated with its dependance on the flow of domestic and industrial effluent. The pricing policy is self-sustained, in that the proceeds it generates cover the total supply costs – a property that facilitates regulation.

The analysis stresses the importance of setting water policy within a comprehensive framework that incorporates all water sources and uses. The reason is that the optimal policy depends on all water demands and supply costs. Thus, for example, it is impossible to derive the optimal shadow price of natural water, which, inter alia, determines the allocation of instream water, without the consideration of recycled and desalinated water and the demands of all sectors.

The analysis focuses on the long run by considering the steady state, to which the optimal policy eventually converges. Extending the analysis to the transition (turnpike) stage requires adjustments that account for the dynamics of the natural water stock, which affects also the shadow price of natural water and thereby all other variables. These dynamic analysis, underlying these adjustments, is summarized in the online supplemental material.

Appendix A

A.1 Proof of property 2

Noting Eq. (2.12), under $\hat{\theta}$ and $\hat{\xi}$, the $p_{ij}(\hat{P}, \hat{\theta}, \hat{\xi})$ can differ from $\hat{p}_{ij}$ only if the $q_{ij}(\hat{P}, \hat{\theta}, \hat{\xi})$ differ from their respective $\hat{q}_{ij}$. Thus,

Claim 1. $q(\hat{P}, \hat{\theta}, \hat{\xi}) = \hat{q}$ *implies* $p(\hat{P}, \hat{\theta}, \hat{\xi}) = \hat{p}$.

It follows from Claim 1 that:

Claim 2. *If* $q(\hat{P}, \hat{\theta}, \hat{\xi}) = \hat{q}$*, then* $q(\hat{P}, \hat{\theta}, \hat{\xi})$ *satisfies Eqs.* (2.13) *and* (3.1).

Proof. That $q(\hat{P}, \hat{\theta}, \hat{\xi}) = \hat{q}$ satisfies Eq. (2.13) follows directly from Claim 1, recalling that $\hat{q}$ satisfies Eqs. (2.13) given $\hat{p}$. That $q(\hat{P}, \hat{\theta}, \hat{\xi}) = \hat{q}$ satisfies Eq. (3.1) is easily verified using Eqs. (2.13), (3.2) and Claim 1. In view of Claim 1, we need to show that $\hat{q}$ and $\hat{p}$ satisfy Eqs. (3.1). Suppose $\hat{q}_{ij} > 0$. Then Eqs. (2.13) imply $D_j(\hat{q}_{\circ j}) = \hat{p}_{ij}$. Suppose $\hat{p}_{ij} > \hat{P}_j$, where $\hat{P}_j$ is defined in Eq. (3.2). Then, from Eqs. (2.13), there exists a source $i' \neq i$ with $q_{i'j} > 0$ and $\hat{p}_{i'j} = \hat{P}_j$ satisfying $D_j(\hat{q}_{\circ j}) = p_{i'j} < \hat{p}_{ij}$, contradicting $D_j(\hat{q}_{\circ j}) = \hat{p}_{ij}$. Thus, $\hat{q}_{ij} > 0$ implies $\hat{p}_{ij} = \hat{P}_j$, verifying Eq. (3.1b). That $\hat{q}$ and $\hat{p}$ satisfy Eq. (3.1a) follows directly from Eqs. (3.1b) and (2.13).

We conclude that if the optimal allocation is unique, the pricing policy $(\hat{P}, \hat{\theta}, \hat{\xi})$ implements it, i.e., $q(\hat{P}, \hat{\theta}, \hat{\xi}) = \hat{q}$. The uniqueness of the optimal policy holds under mild conditions (see discussion in Tsur and Zemel, 2018). This completes the proof of Property 2.

A.2 Proof of Property 4

It is convenient to consider the case of linear variable cost functions

$$\begin{cases} C_n(Q, q_{n\circ}) = c_n(Q)q_{n\circ}, \ \ C_i(q_{i\circ}) = c_i q_{i\circ}, & i = r, d, s, \\ C_{ij}(q_{ij}) = c_{ij}q_{ij}, & i = n, r, d, \ j = D, I, A, E \end{cases} \tag{A.1}$$

with $c_n(Q)$ non-increasing in Q and $c_i, i = r,d,s$, $c_{ij}, i = n,r,d, j = D,I,A,E$, nonnegative parameters. If a policy is self-sustained in the linear case, it is also self-sustained for convex variable cost functions. Under Eq. (A.1), the unit supply costs, specified in Eq. (2.12), evaluated at the optimal allocation are

$$\hat{p}_{nj} = \begin{cases} c_n(\hat{Q}) + c_{nj} + \mu_n + \mu_{nj} + \beta c_s + \beta\mu_s + \hat{\theta} - \beta\hat{\xi}, & j = D, I \\ c_n(\hat{Q}) + c_{nj} + \mu_n + \mu_{nj} + \hat{\theta}, & j = A, E \end{cases}, \tag{A.2a}$$

$$\hat{p}_{rj} = \begin{cases} c_r + c_{rj} + \mu_r + \mu_{rj} + \beta c_s + \beta\mu_s + \hat{\xi} - \beta\hat{\xi}, & j = D, I \\ c_r + c_{rj} + \mu_r + \mu_{rj} + \hat{\xi}, & j = A, E \end{cases}, \tag{A.2b}$$

$$\hat{p}_{dj} = \begin{cases} c_d + c_{dj} + \mu_d + \mu_{dj} + \beta c_s + \beta\mu_s - \beta\hat{\xi}, & j = D, I \\ c_d + c_{dj} + \mu_d + \mu_{dj}, & j = A, E \end{cases}. \tag{A.2c}$$

The pricing policy $\hat{P}$ raises the annual proceeds $\sum_{j=D,I,A,E} \hat{q}_{\circ j}\hat{P}_j$, which using $\hat{q}_{\circ j} = \sum_{i=n,r,d} \hat{q}_{ij}$, can be expressed as

$$\sum_{j=D,I,A,E} \sum_{i=n,r,d} \hat{q}_{ij}\hat{P}_j.$$

Invoking Eq. (3.3), the annual proceeds (i.e., the above sum) can be expressed as

$$\sum_{j=D,I,A,E} \sum_{i=n,r,d} \hat{q}_{ij}\hat{p}_{ij}. \tag{A.3}$$

We now use Eq. (A.2) to evaluate Eq. (A.3).

The domestic and industrial sectors ($j = D,I$) raise the proceeds

$$\sum_{j=D,I} \sum_{i=n,r,d} \hat{q}_{ij}\hat{p}_{ij} = \sum_{j=D,I} \sum_{i=n,r,d} \hat{q}_{ij}[c_i + c_{ij} + \mu_i + \mu_{ij} + \beta(c_s + \mu_s - \hat{\xi})] + \sum_{j=D,I} \hat{q}_{nj}\hat{\theta} + \sum_{j=D,I} \hat{q}_{rj}\hat{\xi}.$$

Using $\hat{q}_{\circ j} = \sum_{i=n,r,d} \hat{q}_{ij}$ and $\hat{q}_{s\circ} = \beta(\hat{q}_{\circ D} + \hat{q}_{\circ I})$, the terms involving β can be expressed as

$$\sum_{j=D,I} \sum_{i=n,r,d} \hat{q}_{ij}\beta[c_s + \mu_s - \hat{\xi}] = \sum_{j=D,I} \hat{q}_{\circ j}\beta[c_s + \mu_s - \hat{\xi}] = \hat{q}_{s\circ}[c_s + \mu_s - \hat{\xi}].$$

The domestic and industrial proceeds, thus, become

$$\sum_{j=D,I} \sum_{i=n,r,d} \hat{q}_{ij}\hat{p}_{ij} = \sum_{j=D,I} \sum_{i=n,r,d,s} \hat{q}_{ij}[c_i + \mu_i] + \sum_{j=D,I} \sum_{i=n,r,d} \hat{q}_{ij}[c_{ij} + \mu_{ij}] + \sum_{j=D,I} \hat{q}_{nj}\hat{\theta} + \sum_{j=D,I} \hat{q}_{rj}\hat{\xi} - \hat{q}_{s\circ}\hat{\xi},$$

where it is noted that the sum over i in the first term on the right-hand side includes sewage ($i = s$). Repeating these steps for the agriculture and environmental sectors ($j = A,E$), these sectors raise the proceeds

$$\sum_{j=A,E} \sum_{i=n,r,d} \hat{q}_{ij}\hat{p}_{ij} = \sum_{j=A,E} \sum_{i=n,r,d} \hat{q}_{ij}(c_i + \mu_i) + \sum_{j=A,E} \sum_{i=n,r,d} \hat{q}_{ij}(c_{ij} + \mu_{ij}) + \sum_{j=A,E} \hat{q}_{nj}\hat{\theta} + \sum_{j=A,E} \hat{q}_{rj}\hat{\xi}.$$

Summing the two expressions gives the total proceeds

$$\sum_{i=n,r,d,s} \hat{q}_{i\circ}[c_i + \mu_i] + \sum_{j=D,I,A,E} \sum_{i=n,r,d} \hat{q}_{ij}[c_{ij} + \mu_{ij}] + \sum_{j=D,I,A,E} \hat{q}_{nj}\hat{\theta} + [\hat{q}_{r\circ} - \hat{q}_{s\circ}]\hat{\xi},$$

where $\hat{q}_{i\circ} = \sum_{j=D,I,A,E} \hat{q}_{ij}$ was used to write $\hat{q}_{r\circ} = \sum_{j=D,I,A,E} \hat{q}_{ij}$. Now, the right-most term above vanishes, because either constraint (2.3) is binding, in which case $\hat{q}_{r\circ} - \hat{q}_{s\circ} = 0$, or it is not binding, in which case $\hat{\xi} = 0$. Moreover, Eqs. (2.6) and (2.9) give

$$\hat{q}_{i\circ}\mu_i = (\rho + \delta)\hat{K}_i, \ \ i = n, r, d, s, \ \text{ and } \hat{q}_{ij}\mu_{ij} = (\rho + \delta)\hat{K}_{ij}, \ \ i = n, r, d, \ j = D, I, A, E.$$

Thus,

$$\sum_{j=D,I,A,E} \hat{q}_{\circ j}\hat{P}_j = C(\hat{Q}, \hat{q}) + (\rho + \delta)\hat{\mathbf{K}} + \hat{q}_{n\circ}\hat{\theta}, \tag{A.4}$$

verifying Property 4.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolecon.2019.106429.

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