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Cost of water for peace and the environment in Israel: An integrated approach

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Key Points:
- This paper presents a framework for discovering a water sharing plan
- Findings show results from a constrained optimization analysis
- Results identify a $US 1.46 billion price tag

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Abstract This paper presents a framework for discovering an economically viable water sharing plan among neighboring communities for promoting peace and environmental protection. Its application is to the Middle East in which Israel may be facing water supply obligations to address environmental requirements and for a possible a peace agreement with its Palestinian neighbors. The framework consists of integrating external factors, constraints, policy instruments, and targets. Our findings from a constrained optimization analysis of Israel's national water system show that the costs of increased deliveries are dependent on two major issues: (1) achieving integrated water resources management (IWRM) in which efficient combinations of expansion from several supply sources and reductions in demands occur over time, and (2) the cost of desalination technologies. We identify a $US 1.46 billion price tag, in present value terms, from using integrated management of demand reduction and supply expansion under current desalination costs. Adjustment costs will decline both with anticipated reductions in desalination costs and with an efficient implementation of IWRM. These adjustments can contribute to moderating regional tensions and protecting key ecological assets while addressing water scarcity in a volatile corner of the world.

1. Background

The world's population, currently estimated at just over 7 billion, is expected to grow to 9 billion or more by 2050 [*Godfray et al*., 2010]. In many areas, water use has overdrafted supplies for basic human consumption. Growing economic pressures on water resources have caused many communities to rethink various mechanisms to improve the economic performance from scarce water [*Johansson et al*., 2002]. There are few panaceas in the search for sustainable water institutions to handle growing water scarcity [*Meinzen-Dick*, 2007; *Ostrom*, 2007]. Especially for transboundary waters, conflict resolution mechanisms are an important element of sustainable water sharing agreements [*De Bruyne and Fischhendler*, 2013].

The Middle East in particular has been plagued by water scarcity throughout recorded history [*Kaniewski et al*., 2012; *Swain*, 2013]. Human conflict over water in that region dates to biblical times. In recent years, conflict over water is associated with increased demands and potentially reduced supplies in the face of growing evidence of climate warming, rising values of key ecological assets supplied by water, and few affordable options for avoiding shortages. Among the water-related issues that call for resolution are the ownership, allocation, and control of the waters of the Jordan River system including the aquifers underlying Israel and the West Bank (WB). Conflict among communities there is heightened by numerous factors. While it is difficult to disentangle the interrelated causes of conflict, competition over low and shrinking water supplies continues to play a dominant role in this region [*Aggestama and Sundell-Eklunda*, 2014].

A significant part of Israel's water supply (Figure 1) is pumped from shared aquifers that lie beneath the West Bank. Although the verdict remains out, some estimates find that about 35 percent of aquifer water used by Israel is pumped from aquifers beneath the Palestinian territories. Israel as of 2015 uses 480 MCM from the mountain aquifer. The Palestinians use the remainder, about 120 MCM [*Becker*, 2013]. Israel used the same amount before 1967. An important difference between then and now is that before 1967 there were fewer water stress problems due to low water demands from a smaller population in the West Bank. With a larger population, the situation has changed significantly since that time.

Control of water secured from these underground sources is a major source of conflict between the Israelis and Palestinians [*Gleick*, 1994]. Among the questions still unanswered are the characteristics and sustainability of aquifer pumping and debates over their ownership and control. Still, recent advances in desalination technology have raised the percentage of Israel's domestic water supplies secured from desalination and treated wastewater [*State of Israel Water Authority*, 2012b]. The costs of both have dramatically decreased. As of 2014, the cost of both sources stand at only 60–70% of their levels in the year 2000 [*Ghaffour et al*., 2013].

Despite a large number of studies that have been conducted on Israel's future water management [*Becker*, 2013; *Becker et al*., 2014; *Feitelson et al*., 2007; *Fisher et al*., 2002; *Luckmann et al*., 2014], little work has been done to present an integrated framework to guide the conduct of water policy to a sustainable path for environment, development, justice, and reduced conflict [*Feitelson et al*., 2012; *Fischhendler and Heikkila*, 2010; *Zeitoun*, 2011]. In light of these gaps, this paper's aim is to present a framework for characterizing an economically efficient set of measures for Israel to implement a water-related peace treaty with the Palestinians and improve the water-related environment. The framework consists of integrating external factors, constraints, policy instruments, and targets [*Tinbergen*, 1952]. The need for these insights is especially timely in light of stalled peace talks, of which the development and allocation of water in the Jordan River Basin plays a part.

The 1990s saw several studies aimed at water trading as a measure to reduce tensions from water disparities between Israel and Palestine [*Fisher*, 1995; *Zeitouni et al*., 1994]. These studies found that by trading water for money in a market arrangement, water has a better chance of moving to its highest valued use, which could create a framework to restart to the peace process. However, none of these studies addressed the issue of property rights for water to support Palestinians claims.

The present study is motivated by the need to assess the economic cost associated with future water-related contributions by Israel to support (1) a peace treaty with Palestine and (2) and flows for environmental restorations in Lower Jordan River (LJR) and the Dead Sea (DS). An important contribution of this paper is to show that recent decreases as well as potential future reductions in the cost of desalinated water have raised the affordability of Israel's capacity to supply water to make a dent in the two challenges. We conduct an analysis of two possible policy options for Israel to supply water for these two potential obligations.

One policy would contribute to potential new water delivery obligations by expanding the supply and use of fresh water, marginal saline water, or desalinated water. The second would decrease the demand for water. We review the performance of each of these policies by the use of an empirical constrained optimization framework, extending the theory of economic policy originally developed by Tinbergen [*Tinbergen*, 1952]. Our implementation of that framework assigns special attention to the role of fresh water demand by irrigated agriculture in Israel as having the most flexibility for adjusting to water prices, while treating other elements of demand as less affected by price but growing with time. Agriculture remains the most price-sensitive water user in Israel, and has the greatest capacity to adjust use to increased water prices that could occur with expanded water delivery obligations facing Israel. Industrial and domestic uses have less price sensitivities with fewer options for conservation in the face of increased prices. Water conservation can occur for the case of domestic use for homes that have water-using landscapes, but there are few of those homes in Israel. In addition, many of the options for reduced water use for domestic and industrial use often require expensive investments in capital and machinery to reduce water use. After installing low flush toilets and low flow showerheads in homes, there are few affordable options for further reducing water use.

Following the establishment of Israel in 1948, its government invested extensively in developing water infrastructure and institutions to support a safe, secure, reliable, and affordable water supply. Facing the need for domestic food self-sufficiency in the early years combined with the important role of domestic farms in encouraging settlement while protecting borders, priority was assigned to irrigated agriculture. Water for irrigation was extensively developed [*Fietelson*, 2013].

By the early 1960s, Israel finished building its National Water Carrier (NWC), which conveys water from the Sea of Galilee (Lake Kinneret) in the wetter north to the drier central and southern regions. Two important features of a national water policy emerged: allocation of a considerable percentage of water for agricultural uses, and a conscious plan to avoid use of marginal cost pricing to limit irrigation water demands [*Menahem and Gilad*, 2013].

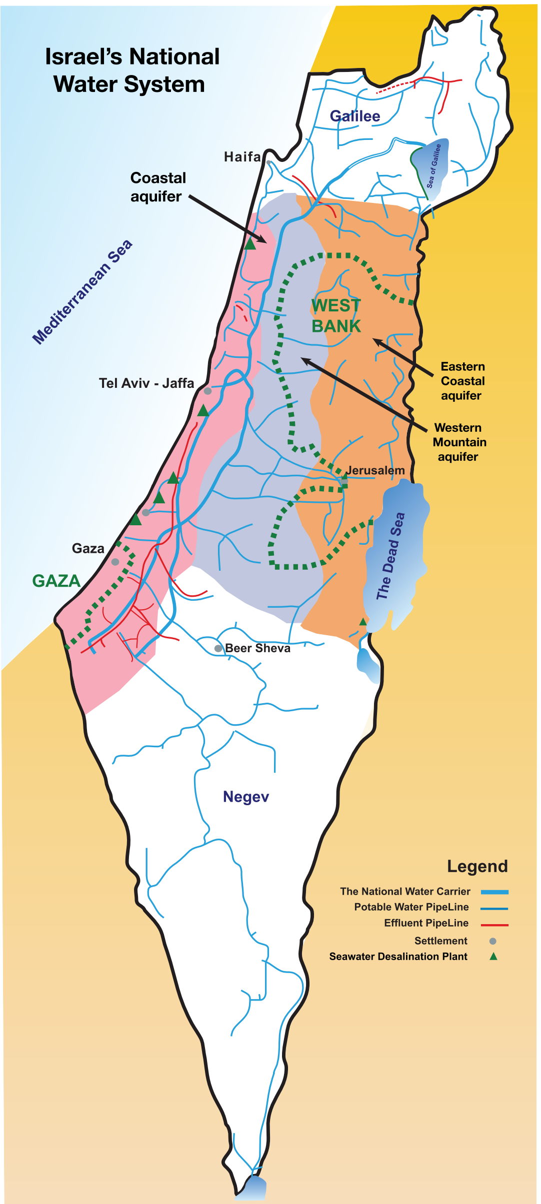

Figure 1. Map of Israel.

Increased quantities of water use from the Jordan river basin have been appropriated not only by Israel but by Jordanand Syria as well [*Becker et al.*, 2012; *Bohannon*, 2006]. As a result, flows of the River have been reduced from 1.5 billion cubic meters to a much lower average of about 10 million cubic meters per year, less than one percent of historical levels. An important consequence of this considerable decline in flows is falling levels of the DS and degraded riparian flows in the LJR. Various plans to address water allocation in the Jordan River basin have been debated in Israel for many years. Two of the more commonly discussed measures are an increased scale of seawater desalination combined with an increase in treated wastewater [*Dreizin et al.*, 2008; *Fishendler et al.*, 2013; *Kais*, 2013].

Since the 1940s, a tenfold increase in population combined with considerable industrial growth and economic development has placed increased demands on Israel's scarce water [*Zeitoun*, 2011]. With demand continuing to rise throughout the 1990s and 2000s, supply shortages became even more acute. Meanwhile, a series of studies concluded that in the face of climatic change, future rainfall supplying the country could fall by up to 30% from historical patterns, with more frequent and prolonged droughts combined with increased evaporation [*Becker et al.*, 2012; *Chenoweth et al.*, 2011b; *Sowers et al.*, 2012]. We pay special attention to two major requirements that have received growing traction in the national water policy debate: environmental protection, as measured by minimum instream flow protection along the LJR as it flows to the DS, and peace treaties obligations. We discuss each in more detail below.

1.1. Environmental Protection

Three water bodies carry special importance for Israel's water future environmental protection: The Sea of Galilee, the Lower Jordan River, and the Dead Sea (DS). All three have taken on growing significance since 2000. Water levels of the Dead Sea have fallen considerably since the 1960s due mostly to reduced flows entering it from the Jordan River. A growing segment of the Israeli population sees protection of the DS's levels as an environmental constraint that must be met for future years, for which the DS's protection is seen as essential to national heritage. If implemented as a matter of national policy, constraints placed on flows of the lower Jordan River and on resulting storage levels of the DS could raise required outflows from the upstream Sea of Galilee. Those three waters are a connected hydrologic system. The lower Jordan connects the Sea of Galilee in the north and the DS in the south. Reduced outflow from the Sea of Galilee shows up as reduced flows into the Jordan River and reduced storage levels of the DS. Reduced inflow from the Upper Jordan into the Sea of Galilee, with no change in outflow, shows up as reductions in its storage levels [*Becker et al.*, 2012].

1.2. Treaty Obligations

The 1995 agreement described above included a delivery requirement of 25 MCM to Jordan annually and an additional 28.6 MCM delivery requirement per year to the Palestinian Territories, with an additional

80–125 MCM expected by some observers needed to support implementation of a final peace agreement [*Bohannon*, 2006]. Currently the allocation of water use from the mountain aquifers (Figure 1), a common water resource between the Israelis and Palestinians, is about 80:20 in favor of the Israelis. The definition, allocation, and implementation of water rights will be a major part of a planned peace treaty.

Both demand and supply management policies are part of the national debate for measures to avert shortages. Neither is comparable in scale to the potential gains from growing use of desalinated water. Desalination has seen major technical breakthroughs in recent years and has the potential to emerge as a drought and climate change adaptation response, with a potential to reduce future water supply vulnerabilities [*McEvoy and Wilder*, 2012]. In Israel, the cost of desalination, currently at about $US 0.71 per cubic meter (2014), has made it more economical as a way to eliminate water shortages compared to investments in conservation by urban or irrigation users. There are many estimates for the current cost of desalination in Israel. But most put it in the range of 2–3 NIS per CM. A study from 2013 put it in the range of 2.2–2.7 NIS per CM [*Tenne et al*., 2013]. We used the midpoint estimate of 2.45 NIS and an exchange rate of 3.45 $US/NIS to calculate a cost of 0.71 $/CM. This estimate excludes external effects. A 2011 study estimated an additional 0.055 $US/CM (8%) to count for these external effects [*Lavee et al*., 2011]. Currently, a combination of modern membrane technologies, reduced energy use, and scale economies yield high-quality drinking water produced on Israel's Mediterranean coast that can be supplied at a lower cost than at any time in history. These changing economic facts led to a 2002 national decision to build five desalination plants with an expected capacity of 600–1000 MCM [*Dreizin et al*., 2008]. Israeli water planners, decision makers, and users all face hard choices for averting water shortage, with little guidance from the research literature to date. An important gap that acts as a barrier to the best path forward for averting shortages is the lack of a unified framework for ranking the performance of an array of water management choices facing planners in Israel.

In light of those unmet needs, our objective is to conceptualize, formulate, illustrate, and apply such a unified framework. That framework integrates several elements related to the motivation, conduct, and performance of water policy. Our mission is to develop a framework for discovering the most economically efficient measures to deliver on potential future water requirements to support peace and environment in case those commitments are made. An important innovation of our approach is the use of a constrained optimization framework for discovering the most economically efficient set of measures to satisfy these two constraints.

2. Conceptual Framework

Our framework rests on the ideas for approaching economic policy in an organized way, originally proposed in the early 1950s [*Tinbergen*, 1952]. The building blocks consist of four elements:

1. External factors [*de Rooij*, 2013]: a set of externally defined elements faced by policymakers that lie outside their control. These factors exert an important influence on policy choices and on the outcomes of those choices. In Israel, one important external factor includes renewable freshwater supplies as well as their possible changes due to climate variability and climate warming.
2. Constraints [*Wohl et al*., 2005]: a set of restrictions on policy choices that must be respected for any policy to be acceptable. Three especially important constraints require the respect of Israeli water planners in our analysis: environmental needs, treaties, and requirements for national domestic use. Achieving each of these constraints requires incurring costs not required absent the constraint.
3. Policy instruments [*Moore*, 1991]: a set of quantities, prices, regulations, or other actions that can be controlled by a policy maker for which the path over time represents alternative courses of action taken over that period. These instruments may take several forms but can be classified for purposes of our work in three important ways: supply expansion, demand management, or integrated management:
    - 3.1. Supply expansion [*Chenoweth et al*., 2011a]: desalination of sea water and wastewater treatment are the two major options in Israel but other measures such as soil erosion control, and fire management also exist [*Osem et al*., 2008; *Zaide*, 2009].
    - 3.2. Demand management [*van der Zaag and Gupta*, 2008; *Zaide*, 2009]: this is can be implemented by establishing conservation pricing for irrigated agriculture or by other means to reduce demand [*Bar-Shira et al*., 2005; *State of Israel Water Authority*, 2012a; *Zaide*, 2009].

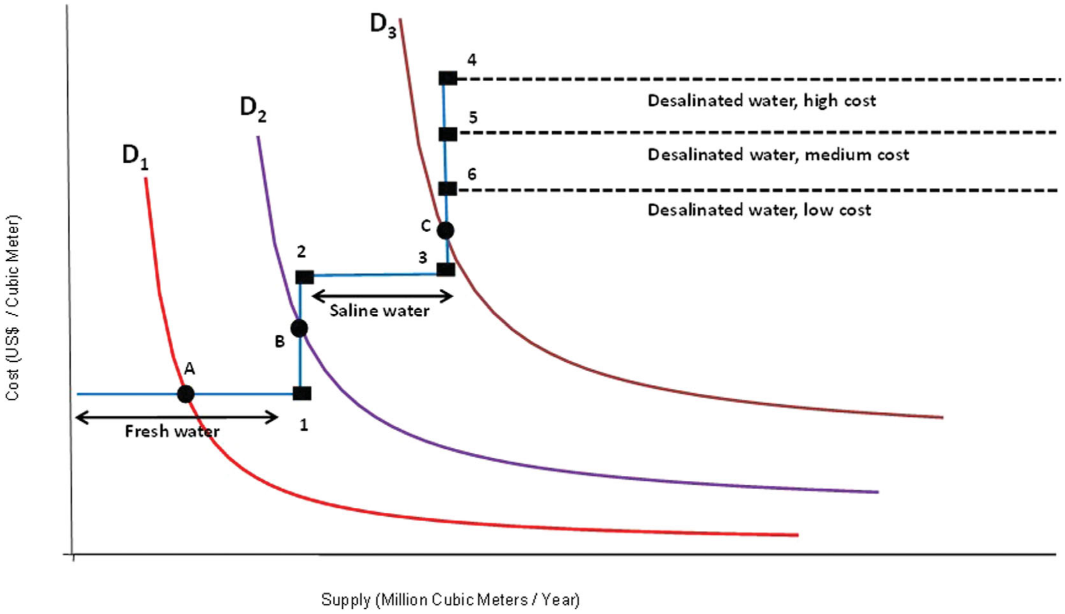

Figure 2. Conceptual water demand and supply framework.

3.3. Integrated management [*Biswas*, 2004]: it refers to the least cost combination of demand and supply adjustment to avert shortages. With proper planning, it can be achieved at a lower cost than either demand management or supply expansion alone. Integrated management is preferred to partial supply side management or partial demand side management because it looks for the least cost combination to manage shortages. Integrated management done properly will never exceed the cost of either of the other two approaches to avert shortages in isolation. Nevertheless it is important to present all three options in order to show the scale of savings produced by integrated management for our case study. In fact the solution to the supply expansion model can be secured by setting demand to a fixed level. The solution to the demand management model can be had by holding supply constant at zero elasticity of supply.

4. Targets [*Arabi et al*., 2006]: aims that can be represented by an explicit objective. Its empirical measurement permits a ranking of alternative combinations of policy instruments implemented over a time period. The objective of maximizing net economic benefits (economic efficiency) is both practical and comprehensive. The use of that objective for planning can help design a time path of policy instruments that maximizes this function, consistent with requirements of respecting the relevant constraints while also accounting for the external factors.

Integrating these building blocks can guide the path forward. Using this architecture, the question becomes: given the external factors and respecting the required constraints, which combination of policy instruments can maximize the difference between total benefit and total cost of water development and use? Figure 2 shows a conceptual framework. It identifies water resources programs that contribute the largest amount to economic efficiency while respecting the relevant constraints. The figure shows how growing demands for water, driven in part by price-inelastic needs, makes it economically efficient to bring in successively higher marginal cost sources into the supply mix.

Conceptual Figure 2, drawing on a similar one published in 2008 in this *journal* [*Rosenberg et al*., 2008], adapts to constraints on potential future water delivery obligations if those obligations are accepted. It allows demands to both support a peace treaty and improve the environment, independent of price, to materialize or grow in future years, shown by a horizontal shift in the water demand to the right. This is shown in the figure as the outward movement from D_1 to D_2 to D_3. In this figure, agriculture is the most price-sensitive use, with the highest price elasticity of demand. Domestic and industrial uses have lower price elasticities of demand, for which price increases have only a modest influence on use.

The figure can be used to see that three instruments for adjusting to demand growth for either peace or the environment are demand management, supply expansion, or integrated management. Demand management averts shortage by reducing water use in agriculture, domestic, or industrial use accompanied by an increased price of water. Supply expansion averts shortages by expanding supply from the least cost available supply source. Integrated management averts shortage by seeking the least cost combination of both.

The policy choice and the conditions under which the choice is made have an important effect on the most efficient time period at which desalination enters the water supply mix to meet new water obligations. Conceptual Figure 2 shows three points A, B, and C. They are three equilibrium intersections of the three demand curves with the stair-step supply schedule. The black-filled round equilibrium points are the prices and quantities of water that avert shortages. The six black-filled rectangles of Figure 2 indicate six alternative switching points. Each switching point has an important interpretation—showing the condition at which a change in method occurs for adjusting to shortage. Switch point rectangles 1 and 3 in the figure show an adjustment from supply expansion to demand reduction. Rectangles 2, 4, 5, and 6 illustrate a change from demand reduction to supply expansion. Either population growth (an external factor) or implementation of a policy obligating more water deliveries can expand demand to the right. Any factor that moves demand past a switching point requires a change in method to avert a shortage.

Switching point 1 represents a level of total use at which freshwater supply is at full capacity and is unable to expand. Any point that lies on the vertical line between points 1 and 2 represents a condition in which adjustments to growing demand requires demand management (reduction) as the most efficient measure to avert shortage. For each point in the range between points 2 and 3, a one unit increase to accommodate a new water delivery obligation requires a supply management strategy, for which its price of adjustment is the cost per unit of supplying saline water.

Each of the far right three switching point rectangles (4, 5, and 6) occurs when total nondesalinated water capacity is too little to satisfy all demands. The vertical line running from point 3 to point 6 represents points at which there is no more capacity from any of the nondesalinated water sources. At any location on that vertical line, an increased price is the most efficient choice to avert shortage. Even at a place like point C, the price is still too low to make any form of desalination affordable.

The three demand curves intersecting at points A, B, and C, can move to the right over time due to population growth or from increased obligations for peace or the environment. The rightward expansion in demand grows faster as additional obligations (constraints) are taken on by the country. For that reason, taking on a new obligation can be seen as moving faster in time to the present to enter the age of desalination. Moreover, a lower desalination cost accelerates the last switching point by bringing it closer to the present entry of the country into a backstop technology era, thus averting a painful price escalation.

3. Methods and Materials

3.1. Data

Data were secured for applying the conceptual framework shown in Figure 2, including data for several characteristics of the supply and demand for water in Israel. Noncrop water demands were estimated for years 2015 and 2030, with and without 150 MCM peace treaty obligations, and with and without 125 MCM environmental flow requirements. For environmental flows, there has been much debate over what those requirements might be. Many approaches and estimates are possible. We chose an approach based on two sources of published literature. For the Lower Jordan River, we used one third of the low estimate from [*Becker et al*., 2014], 220 MCM per year. We used one third because the water is shared by three communities: Israel, Palestine, and Jordan. In addition, as concluded by [*Juanico and Friedler*, 1999], about 50 MCM of water could be set aside for stream restoration. In total these sources yields just over 123 MCM per year, a conservative estimate.

Based on recent historical patterns, a 1.8% annual percentage growth rate was estimated for domestic water use with a price elasticity of demand equal to −0.10 [*Bar-Shira et al*., 2005; *Lavee et al*., 2013; *Kislev*, 2003], and 690 MCM water use observed for the year 2010. Industrial demands in 2012 were 128 MCM, with a price elasticity of −0.10 [*Bar-Shira et al*., 2005; *Lavee et al*., 2013; *Kislev*, 2003], and a 1.8% annual percentage growth rate, based on recent history [*State of Israel Water Authority*, 2012a].

The observed data for irrigation demand (excluding treated wastewater) were a quantity price combination of 584 MCM at a price of $US 0.325 per cubic meter. That price is based on a year for which the irrigation demand for freshwater was 584 MCM (2004). Today (2015) the price is higher and quantity demanded is lower. This is seen in Table 1 when no additional obligation is met. The reason for choosing that price-quantity relationship is to secure a price observation that is about equal to the average production cost of delivering freshwater. The current weighted observed price is higher largely because water contains elements of high cost water sources, including saline and desalinated water.

Any increased obligation for peace or the environment without added capacity for supply from the marginal technology in use requires an increase in price and corresponding reduction of use of water for irrigation, domestic, and industrial use. Such an obligation shows up as a movement along the price (demand) schedules to higher prices and corresponding lower use rates.

In Israel, agriculture is the marginal user, and is the most important use of water that adjusts through price changes to avert shortages. Data for quantities demanded at alternative water prices for all three uses were estimated with a constant elasticity of demand functional form. Data on water use and crop water use per hectare came from national agricultural statistics data secured for 45 crops [*State of Israel Agriculture Ministry*, 2009].

These data were used to estimate the residual farm income per cubic meter after subtracting all nonwater costs of production. This approach, the method of residual imputations [*Young*, 2005], was used to approximate the value of marginal product of fresh water in agriculture. Treated wastewater is not addressed in this analysis since equal amounts of these waters are consumed by the agricultural sector with and without the two new policies we examine.

The best fit price function for irrigated agriculture was found to be:

$$\text{Price} = 1423 * \text{Quantity}^{-1.32} \tag{1}$$

$$R^2 = 0.88$$

In which the price elasticity of demand is $(1/-1.32) = -0.76$. A total of 88% of the variance in agricultural water demand was explained by (1) and both coefficients are significant at the 99% significance level. Price is measured in $US per cubic meter. Quantity is measured in national irrigation water use annually, in million cubic meters (MCM). Price was measured as the value of the marginal product of water in irrigated agriculture. The total gain in farm income for any scenario is measured by the definite integral from a baseline price/quantity to the level that would be achieved by the scenario. For domestic and industrial uses, a linear demand curve was fit through the existing observed consumption level. Linearity was required for those uses because the very low price elasticity (−0.10) does not produce a finite level of total benefits for the constant elasticity in equation (1) (Appendix A).

Treated wastewater is not addressed in this analysis since equal amounts of these waters are consumed by the agricultural sector with and without the two new policies we examine. We decided against including treated wastewater because, in contrast to desalination, its quality effect can have a major effect on farm income. Because of the large difference on farm income from the quality effect, the irrigated agriculture sector was split into two parts, that which uses freshwater or desalinated water and that part using treated wastewater. This includes crops that can use either level of water quality and those that cannot. When the quantity of treated wastewater is altered by either peace or environmental flows, this does not affect directly the freshwater irrigation water use sector. For this reason, equation (1) addresses the fresh water sector only. For example, the domestic quantity increases from 690 at base year to 860 in 2030. Considering an effluent coefficient of 0.6 [*State of Israel Water Authority*, 2012b], there is an approximate 102 MCM added as treated wastewater to the water sector. Nevertheless, this outcome would have occurred with or without any peace or environmental obligation. So we excluded treated wastewater from the analysis.

Data were also secured on the cost per unit and capacity of three water supply technologies [*State of Israel Water Authority*, 2012a]. Freshwater supplies are limited to their long-term average of 1382 MCM per year at

Table 1. Price and Use of Water in Israel, by Year, Peace Treaty Obligation, Environmental Flow Requirement, Cost of Desalination, and Use ($US Million Per Year)

Conditions				Water Use (Million Cubic Meters/Year)						
Year	Peace Treaty Flows	Environmental Flows	Desal Cost	Environmental Flows	Peace Treaty Flows	Domestic Use	Industrial Use	Ag Use	Total Use	Water Price ($US/Cubic Meter)
1–2015	wo_new_peace_treaty	wo_new_env_flows	1–2000 cost desal	0	0	729	124	529	1382	0.435
			2–2015 cost desal	0	0	729	124	529	1382	0.435
			3-future cost desal	0	0	729	124	529	1382	0.435
		wi_new_env_flows	1–2000 cost desal	125	0	718	122	491	1456	0.480
			2–2015 cost desal	125	0	718	122	491	1456	0.480
			3-future cost desal	125	0	718	122	491	1456	0.480
	wi_new_peace_treaty	wo_new_env_flows	1–2000 cost desal	0	150	718	122	491	1481	0.480
			2–2015 cost desal	0	150	718	122	491	1481	0.480
			3-future cost desal	0	150	718	122	491	1481	0.480
		wi_new_env_flows	1–2000 cost desal	125	150	707	120	455	1556	0.531
			2–2015 cost desal	125	150	707	120	455	1556	0.531
			3-future cost desal	125	150	714	121	476	1586	0.500
2–2030	wo_new_peace_treaty	wo_new_env_flows	1–2000 cost desal	0	0	948	122	486	1556	0.486
			2–2015 cost desal	0	0	948	122	486	1556	0.486
			3-future cost desal	0	0	948	122	486	1556	0.486
		wi_new_env_flows	1–2000 cost desal	125	0	915	116	400	1556	0.629
			2–2015 cost desal	125	0	915	116	400	1556	0.629
			3-future cost desal	125	0	945	121	476	1667	0.500
	wi_new_peace_treaty	wo_new_env_flows	1–2000 cost desal	0	150	907	115	384	1556	0.663
			2–2015 cost desal	0	150	907	115	384	1556	0.663
			3-future cost desal	0	150	945	121	476	1692	0.500
		wi_new_env_flows	1–2000 cost desal	125	150	860	107	314	1556	0.865
			2–2015 cost desal	125	150	896	113	365	1649	0.710
			3-future cost desal	125	150	945	121	476	1817	0.500

a supply price of $US 0.325 per cubic meter. Marginal saline water has a current capacity of 174 MCM per year at a price of $US 0.480 per cubic meter. Desalinated seawater is unbounded in the long term. Its price in the year 2000 was $1.00 per cubic meter, while its current (2015) price is $0.71 per cubic meter as described earlier in this paper. Its potential future price was specified (optimistically) at $0.50 per cubic meter, although no desalination is available at that price at the time of this writing.

3.2. Analysis

An optimization model was developed with the intent of producing a unified framework for water policy analysis. Our analysis is motivated by a long line of works over the last several years published by Franklin Fisher and his colleagues. A book in 2005 summarized several years of their work going back to the 1990s [*Fisher et al*., 2005]. Fisher et al. show that disputes over ownership of water can be reduced to debates over monetary values of different measures for managing water. In some cases the benefits of a change in ownership can be small in comparison to the benefits of more efficient management of water as a shared resource. By calculating the economic value of water and viewing water as a tradable asset, competitors for water might discover that gains from cooperation are larger than gains from winning a debate over ownership.

The work of Fisher et al. continues to this day, much of which is based on the development of economic optimization models. In their work, the models are used to guide discovery of patterns of water development, allocation, and use among three Middle East Countries (Israel, Jordan, and Palestine) that achieves a maximization of the discounted present value of net benefits. In their 2002 analysis along with more recent work, the authors showed that it is possible to build optimizing models that take account of both water demand and supply factors. Accounting for both demand and supply is a major improvement over the simpler goal of simply minimizing the costs of meeting fixed water demands [*Fisher et al*., 2002].

Such models can guide the design of water policies, because they account for economic values of water as well as specifying constraints that must be respected for any given policy objectives to be acceptable. These optimization models provide insightful and powerful tools for system-wide cost-benefit assessments of proposed programs, including institutions and infrastructure. The authors provided some empirical findings illustrating their approach, which, in 2002, they labeled as WAS, or Water Allocation System [*Fisher and*

Huber-Lee, 2011; *Fisher et al*., 2002]. An important and ambitious mission of their more recent development is the need to address the classic challenge in water resource development: the optimized timing, sizing, and sequencing of proposed water resources developments. More recently, Fisher et al. continue the development an updated version of WAS, labeled MYWAS, for Multi Year Water Allocation System [*Fisher and Huber-Lee*, 2011]. Like the work of Fisher et al., our analysis also assembles a constrained optimization model, for which our two most important constraints are contributions to support a potential peace treaty and to an improved environment. An important difference between the MYWAS model and ours is that ours identifies the least cost combination of measures to expand water deliveries by Israel to meet demands for a potential peace treaty and for enhanced environmental flows. It does so by requiring the total demand for water to shift out to the right by a large enough amount to meet these two constraints. After this demand shift, our model calculates the cost of that outward demand expansion. Cost is defined here to mean the cost of consumer surplus displaced plus the cost of supply expansion.

Our implementation of a constrained dynamic optimization was achieved by maximizing consumer surplus plus farm income minus the cost of water supply for each of two periods: 2015 and 2030. Results are predictions of water price, quantity, total cost of supply, total economic benefits consisting of consumer surplus and farm income for each of several scenarios described below. The analysis conducts several separate optimization model runs. The objective of each run is to identify water development and use patterns that maximize the total agricultural, domestic, and industrial benefits of water minus the cost of supplying water from the three sources of water described above (Appendix A).

Constraints take on special importance for our work. Our model is constrained to meet all demands delivered from three possible supply sources. The capacity of each source is limited by the upper bounds and/or marginal costs of each: freshwater, marginally saline, and desalinated water. Deliveries of water to support the requirements of peace and the environment are treated as constraints that must be achieved. Neither constraint is part of the objective. That is, deliveries for these two uses are fixed constraints that must be achieved, and are independent of the cost of water that must be incurred to supply it (Appendix A).

Our analysis assesses economic costs and impacts on water price and use from a peace treaty and environmental flows. It implements that cost assessment by setting lower bounds on flows that must be delivered for each of those two purposes. The model respects these requirements by treating them as constraints that must be achieved. The model effectively sets aside that water for the two purposes and protects against its use by the other three sectors. It does so by maximizing net economic benefits in each period subject to the requirements of respecting either constraint or both. The loss in net benefits incurred by the added cost of respecting either of the two constraints could produce the same result as an exogenous reduction in overall water supply, but not likely. This is because when reducing water supply, it is not possible to know which water source from which to reduce supply. However, when setting the constraints as lower bounds for either or both uses that must be respected, the model chooses the least cost adaptation method for delivering either of the two requirements. That can be supply expansion, demand reduction, or a combination. An earlier and simplified version of the mathematical model is described elsewhere [*Becker and Ward*, 2014]. Access to the posted model code in GAMS is described in Appendix A.

4. Results

4.1. Price and Use

Table 1 shows results of the optimized price and use of water by year, peace treaty obligation, environmental flow requirements, cost of desalination, and type of water use. It shows outcomes for 24 combinations of time periods (2), treaty obligations (2), environmental flow requirements (2), and average cost of desalination (3), for a total of $2 \times 2 \times 2 \times 3 = 24$ combinations. Unless otherwise constrained, adjustments take place through the optimal mix of supply expansion and demand management, where optimality is defined previously. Detailed results from 48 additional combinations are available from the authors.

Obligations taken on to supply either peace treaty or environmental flows require action. As a consequence, taking on either of those obligations must be met by a combination of increased supply from one of the three sources described or reduced water use by agriculture, industry, or domestic uses. When the most economically efficient (least cost) source of water to support new peace or environmental obligations comes from

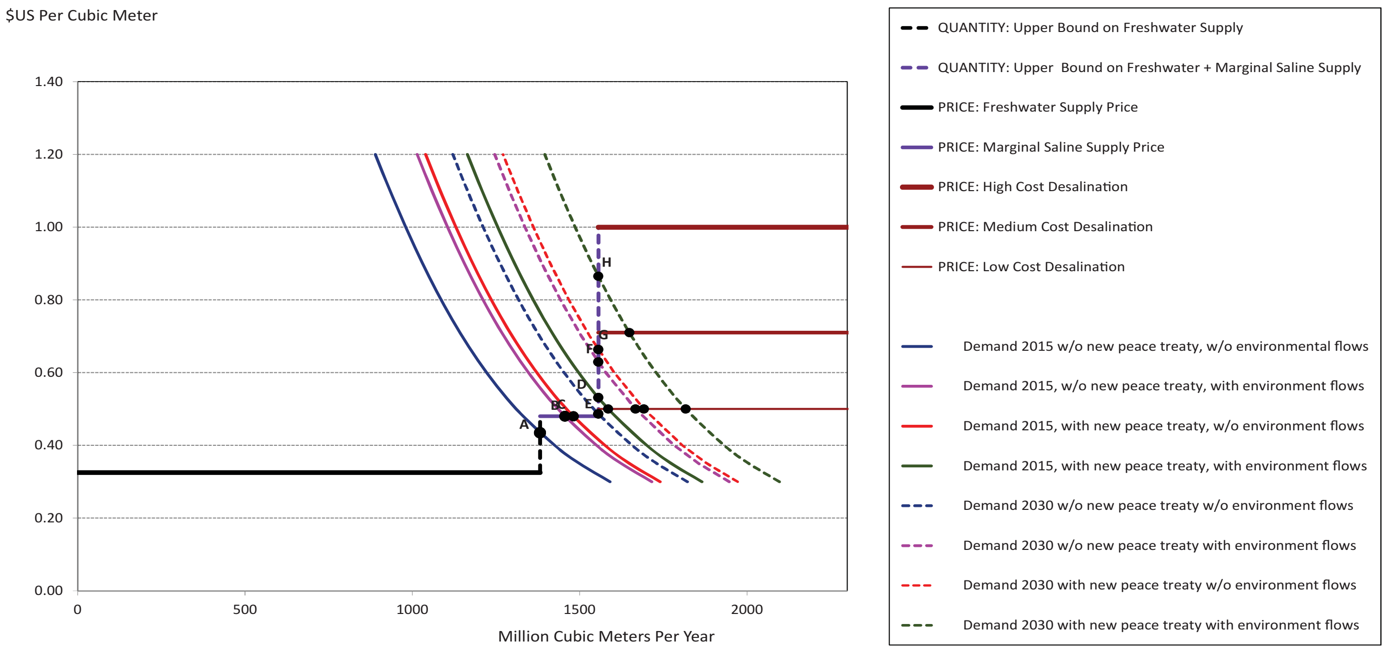

Figure 3. Water's economic value, sources, choices, and outcomes, Israel.

supply expansion, then the price of water is unchanged. If deliveries for peace or environmental flows are more expensive from supply expansion than from demand reduction, the most economically efficient policy for the first unit of water to meet the obligations will come from reduced demand.

Water use in future years is expected to increase in Israel because of growing domestic and industrial use in the face of anticipated population growth even with a constant per capita use, based on recent historical evidence. Table 1 shows that domestic use increases from 729 MCM in the year 2015 to 948 MCM for the year 2030 without peace treaty and without flow obligations, based on a constant 1.8% annual growth rate in domestic water use for that period and a price increase from $0.435 to a slightly higher $0.486 per cubic meter. Obligations for a new peace treaty and for new environmental flows generally place upward pressure on Israel to expand water supply from marginal sources or to reduce demand from all its price-sensitive sources, with the largest burden falling on irrigated agriculture. Several examples of these adjustments are illustrated in Figure 3, showing several possible adjustments to meet requirements for peace or environmental flows. As expected, results for the year 2030 typically show a higher price and higher equilibrium quantity.

Reductions in costs of supply from desalination from 2000 levels ($US 1.00 per cubic meter) to 2015 levels ($US $0.71 per cubic meter) to the even more optimistic future levels ($US 0.50 per cubic meter) take an enormous adjustment burden off irrigated agriculture and also reduce the burden on domestic and industrial use in the face of increased demand for peace or environmental obligations. This is described below in more detail.

4.2. Price of Flows for Peace

Table 2 shows the total cost to Israel of taking on a water delivery obligation if needed to support a new peace treaty. Results are shown by year, environmental flow obligation, and desalination costs. The table shows that the need to meet additional obligations can be managed by a least cost combination of supply expansion and demand reduction, which we characterize as integrated management. The percentage of adjustment shouldered by reductions in price-sensitive demands ranges from a low of 0% to a high of 100% depending on which of 24 combinations of conditions occurs, as shown in the table.

The table shows that the year 2015 is the optimal time for the foreseeable future in terms of costs incurred by Israel to obligate itself to supply 150 MCM water per year to contribute to a permanent

Table 2. Total Cost to Israel of Water Deliveries to Support a New Middle East Peace Treaty by Source of Water, Year, Environmental Flow Requirement, and Desalination Costs

			Total Cost of Water Supply ($US Millions/Yr)			Total Economic Benefit from Water Supply ($US Millions/Yr)									Distribution of Adjustment Costs	
						Without Peace Treaty				With Peace Treaty						
Year	Environmental Flows	Desalination Cost	Without Peace Treaty	With Peace Treaty	Increased Supply Cost from Peace Treaty	Domestic	Industry	Agr	Total	Domestic	Industry	Agr	Total	Reduced Benefits from Price Hikes due to Peace Treaty	Pct Adjustment Paid by Reduced Demand	Cheapest Measure to Deliver Water for Peace
1–2015	wo_new_env_flows	1–2000_cost_desal	449.15	496.72	47.57	1,461.38	247.96	3,920.22	5,629.56	1,456.55	247.14	3,902.62	5,606.31	23.25	32.83%	Reduce Demand and Expand Supply
		2–2015_cost_desal	449.15	496.72	47.57	1,461.38	247.96	3,920.22	5,629.56	1,456.55	247.14	3,902.62	5,606.31	23.25	32.83%	Reduce Demand and Expand Supply
		3-future_cost_desal	449.15	496.72	47.57	1,461.38	247.96	3,920.22	5,629.56	1,456.55	247.14	3,902.62	5,606.31	23.25	32.83%	Reduce Demand and Expand Supply
	wi_new_env_flows	1–2000_cost_desal	484.72	532.67	47.95	1,456.55	247.14	3,902.62	5,606.31	1,450.57	246.13	3,884.32	5,581.01	25.30	34.54%	Reduce Demand and Expand Supply
		2–2015_cost_desal	484.72	532.67	47.95	1,456.55	247.14	3,902.62	5,606.31	1,450.57	246.13	3,884.32	5,581.01	25.30	34.54%	Reduce Demand and Expand Supply
		3-future_cost_desal	484.72	547.51	62.79	1,456.55	247.14	3,902.62	5,606.31	1,454.28	246.76	3,895.28	5,596.31	10.00	13.74%	Reduce Demand and Expand Supply
2–2030	wo_new_env_flows	1–2000_cost_desal	532.67	532.67	0.00	2,398.72	247.02	3,900.27	6,546.01	2,375.13	243.02	3,842.47	6,460.62	85.39	100.00%	Reduce Demand
		2–2015_cost_desal	532.67	532.67	0.00	2,398.72	247.02	3,900.27	6,546.01	2,375.13	243.02	3,842.47	6,460.62	85.39	100.00%	Reduce Demand
		3-future_cost_desal	532.67	600.74	68.07	2,398.72	247.02	3,900.27	6,546.01	2,397.15	246.76	3,895.28	6,539.18	6.83	9.12%	Reduce Demand and Expand Supply
	wi_new_env_flows	1–2000_cost_desal	532.67	532.67	0.00	2,380.25	243.89	3,852.63	6,476.77	2,339.33	236.95	3,789.39	6,365.67	111.10	100.00%	Reduce Demand
		2–2015_cost_desal	532.67	598.60	65.93	2,380.25	243.89	3,852.63	6,476.77	2,367.66	241.75	3,829.15	6,438.56	38.21	36.69%	Reduce Demand and Expand Supply
		3-future_cost_desal	588.24	663.24	75.00	2,397.15	246.76	3,895.28	6,539.18	2,397.15	246.76	3,895.28	6,539.18	0.00	0.00%	Expand Supply

Palestinian peace treaty. Should Israel be obligated to the same 150 MCM peace treaty flows in years following 2030, the country will likely bear higher costs through either increased costs of supply or in benefits displaced by price-sensitive uses. These increased costs occur in future years due to increasing domestic use. Furthermore, the potential for higher environmental flow obligations will require incremental water supplied to support a peace treaty to come from desalinated water. Assuming use of current (2015) technology, costs of $US 0.71 per cubic meter are higher than the costs of the cheapest nondesalinated supply source, a freshwater cost of $US 0.325 per cubic meter. Supplying 150 MCM to support peace treaty flows in 2015 rather than in 2030 will reduce the incremental adjustment costs from ($US 85 million in 2030) to ($US 71 million in 2015), saving about $US 14 million per year if there are no environmental flow obligations required. While $14 million is less than 1 percent of the total direct economic value of water in irrigated agriculture that we modeled (about $3.9 billion), it is still a sizeable savings.

Table 2 illustrates the importance of investments that advance desalination technology in making peace treaty flows affordable and practical. The importance of growing efficiency of desalination is illustrated, both in the total cost of supporting peace flows and in the distribution of those costs shouldered by irrigated agriculture. The table shows a wide range of results, but one example stands out: with successful advances in desalination technology and without consideration of environmental flow requirements, results show that by the year 2030, the economic benefits from price-sensitive uses will only fall from $US 6.546 billion to $US6.539 billion to support added peace flows if desalination costs are reduced to $US 0.50 per cubic meter. These results are shown in Table 2 in the fourth row from bottom, comparing columns 10 and 14.

What is the likelihood that those costs of desalination will be reduced? A recent article summarizing the outlook for desalination found that despite several important advancements in desalination technologies, seawater desalination is still requires considerably more energy compared to conventional methods for freshwater treatment. Energy consumption seems to be the place to look for technical efficiency gains. Nevertheless the authors found some cause for optimism by examining potential reductions in energy intensity by current modern seawater desalination technologies [*Elimelech and Phillip*, 2011].

Furthermore, with the environmental flows obligated by 2030, future advances in desalination take on an even more important role in making treaty flows affordable, if enacted. If there are also higher environmental obligations, faced with added flows to support the treaty, advances in desalination can completely eliminate the burden shouldered by price-sensitive users. The entire increment of peace treaty flows is supplied by (optimistically) low-priced desalination, while price-sensitive uses need only to pay the desalination price of $0.50 per cubic meter with zero percent of the treaty adjustment borne by those uses. This remarkable finding gives insight into the very considerable importance of advances in desalination technology toward making peace treaty flows affordable and practical as well as serving to protect the farming, domestic, and industrial water users. Farming which is economically important to Israel's economy, has water demands that are especially price sensitive, so reductions in desalination costs will produce a disproportionate gain for irrigated agriculture in reducing their costs for contributing to peace or the environment.

4.3. Adjustment Costs: Flows for Peace and Environment

Table 3 shows the importance of integrated management as an adjustment mechanism for contributing to peace and environmental obligations. It shows the savings in adjustment costs measured as a reduction in net economic benefits displaced through alternative adjustment mechanisms. It compares the results of economic benefits displaced by integrated management compared to adjustment from demand management or supply expansion alone. Integrated management refers to the least cost combination of demand and supply adjustment to meet future obligations. Table 3 also shows a significant cost savings can be secured by implementing the additional obligations through integrated management compared to use of either demand management or supply expansion options. These comparisons among adjustment mechanisms can be seen by comparing the top, middle, and bottom thirds of the table.

At current (2015) desalination costs, meeting increased peace obligations through supply expansion alone costs $72 million per year in year 2015 ($107 million in 2030) without environmental obligations and $95 million per year ($107 million in 2030) if environmental commitments are made. Complete specialization in demand management as an adjustment mechanism also poses higher costs. Meeting the same increased

Table 3. Adjustment Costs to Israel to Support a New Middle East Peace Treaty by Source of Water, Year, Environmental Flow Requirement, Desalination Costs, and Adjustment Mechanism ($US Million/Year)

Adjustment Mechanism	Year	Env_Constraint	Desal_Cost	Total Net Economic Benefits of Water to Israel: Agricultural, Domestic, and Industrial Benefits		Adjustment Cost of Adapting to New Peace Treaty Measured in Net Benefits Displaced	Cost of Implementing New Peace Treaty as a Percentage of Total Economic Benefits of Water Without It	Percent of Adjustment Cost of Implementing a New Peace Treaty Compared to Integrated Management
				wo_new_ peace_treaty	wi_new_ peace_treaty			
1-integrated	1–2015	wo_new_env_flows	1–2000_cost_desal	5,180	5,110	71	1.37%	100.00%
			2–2015_cost_desal	5,180	5,110	71	1.37%	100.00%
			3-future_cost_desal	5,180	5,110	71	1.37%	100.00%
		wi_new_env_flows	1–2000_cost_desal	5,122	5,048	73	1.43%	100.00%
			2–2015_cost_desal	5,122	5,048	73	1.43%	100.00%
			3-future_cost_desal	5,122	5,049	73	1.42%	100.00%
	2–2030	wo_new_env_flows	1–2000_cost_desal	6,013	5,928	85	1.42%	100.00%
			2–2015_cost_desal	6,013	5,928	85	1.42%	100.00%
			3-future_cost_desal	6,013	5,938	75	1.25%	100.00%
		wi_new_env_flows	1–2000_cost_desal	5,944	5,833	111	1.87%	100.00%
			2–2015_cost_desal	5,944	5,840	104	1.75%	100.00%
			3-future_cost_desal	5,951	5,876	75	1.26%	100.00%
2-supply_expand	1–2015	wo_new_env_flows	1–2000_cost_desal	5,180	5,108	72	1.39%	101.67%
			2–2015_cost_desal	5,180	5,108	72	1.39%	101.67%
			3-future_cost_desal	5,180	5,108	72	1.39%	101.67%
		wi_new_env_flows	1–2000_cost_desal	5,120	4,996	125	2.43%	169.99%
			2–2015_cost_desal	5,120	5,025	95	1.86%	130.01%
			3-future_cost_desal	5,120	5,046	74	1.45%	101.68%
	2–2030	wo_new_env_flows	1–2000_cost_desal	6,013	5,863	150	2.49%	175.67%
			2–2015_cost_desal	6,013	5,907	107	1.77%	124.72%
			3-future_cost_desal	6,013	5,938	75	1.25%	100.13%
		wi_new_env_flows	1–2000_cost_desal	5,888	5,738	150	2.55%	135.01%
			2–2015_cost_desal	5,925	5,818	107	1.80%	102.27%
			3-future_cost_desal	5,951	5,876	75	1.26%	100.00%
3-demand_reduce	1–2015	wo_new_env_flows	1–2000_cost_desal	5,180	5,104	76	1.47%	107.21%
			2–2015_cost_desal	5,180	5,104	76	1.47%	107.21%
			3-future_cost_desal	5,180	5,104	76	1.47%	107.21%
		wi_new_env_flows	1–2000_cost_desal	5,119	5,020	98	1.92%	134.28%
			2–2015_cost_desal	5,119	5,020	98	1.92%	134.28%
			3-future_cost_desal	5,119	5,020	98	1.92%	135.12%
	2–2030	wo_new_env_flows	1–2000_cost_desal	6,013	5,928	85	1.42%	100.00%
			2–2015_cost_desal	6,013	5,928	85	1.42%	100.00%
			3-future_cost_desal	6,013	5,928	85	1.42%	114.00%
		wi_new_env_flows	1–2000_cost_desal	5,944	5,833	111	1.87%	100.00%
			2–2015_cost_desal	5,944	5,833	111	1.87%	106.69%
			3-future_cost_desal	5,944	5,833	111	1.87%	148.14%

peace obligations through demand management alone costs $76 million per year in year 2015 ($85 million in 2030) without environmental obligations and $98 million per year ($111 million in 2030) with the requirement of environmental obligations adopted.

The table illustrates the considerable cost savings that can be achieved with integrated management. When facing current (2015) desalination costs, delivering water through integrated management for a new peace treaty costs $71 million in year 2015 ($85 million in 2030) without environmental obligations and $73 million per year ($104 million in 2030) if environmental deliveries are also required.

For low costs of desalination at $US 0.50 per cubic meter, adjustment costs from integrated management are equal to those through supply management alone because desalinated water is so affordable. This means that the costs of mistakes made by a choice of a poor adjustment mechanism are more forgiving as desalination costs fall. Table 3 illustrates the importance of this principle. It shows that supply expansion by itself for supporting peace treaty flows, even if demand management is ignored completely for the year 2030, reduces in cost from $150 million to $107 million to $75 million in the face of technical advance in desalination, if environmental flows are also required. Integrated management is not cheaper at the lowest desalination price of $0.50 per cubic meter, and also costs $75 million (row 12 data column 3 compared to row 24 data column 3).

Table 4. Year at Which Switching Point Occurs in Source of Water Supply, by Environmental Obligation and Peace Treaty Delivery Level, Israel[a]

Switching Point	Without Environment Flows Without Peace Flows 0 MCM	With Environment Flows Without Peace Flows 125 MCM	Without Environment Flows With Peace Flows 150 MCM	With Environment Flows With Peace Flows 275 MCM
1	2002	1988	1985	1967
2	2019	2009	2007	1994
3	2030	2022	2021	2011
4	2053	2047	2045	2038
5	2042	2035	2034	2026
6	2032	2024	2022	2013

[a]Notes: based on Figures 2 and 3; rounded to nearest year; point 1-Reach fresh water supply limit; point 2 - Commence using saline water; point 3 - Reach fresh and saline water supply limit; point 4 - Commence desalination, supplied at $US 1.00/cubic meter; point 5 - Commence desalination, supplied at $US 0.71/cubic meter; point 6 - Commence desalination, supplied at $US 0.50/cubic meter.

Table 3 reveals at many points the large cost savings from technological improvement in the desalination process. Successful investments in advanced desalination technology save $ US 36 million by 2030 for a technical advance that reduces desalination cost from $US 0.71 to $ US 0.50 per cubic meter when facing peace treaty and environmental obligations under integrated management ($US 5.876 billion in net economic benefits compared to $ US 5.840 billion). The benefit of this advance in desalination technology is significantly higher than the reduction from $1.00 to $US 0.71 per cubic meter, which produces only $ US 7 million in benefits ($US 5.833 billion compared to $US 5.840 billion). These results dramatically illustrate the importance of continued breakthrough cost reductions in seawater desalination.

Tying together the maze of details shown in Table 3, results show that planned management designed to avoid shortage through an optimized combination of demand management and supply expansion is important. It is just as important as investing in cheaper desalination technologies. Moreover, the cost of implementing integrated management is negligible compared to investment in less expensive technologies. It requires only continued analysis of choices with an eye to watching vigilantly for the least cost combination of adjustment to peace and environmental obligations as they move from discussion and debate to policy implementation.

4.4. Transition to a Backstop Technology

Table 4 shows empirical results of the switching points described conceptually in Figure 2, based on results from our series of 24 model runs. The table shows that with 1382 MCM capacity of fresh water supply, there was no need for any water development or a price increase until 2002, at switch point 1, with zero MCM in new obligations taken on by the country. Comparing the switch points, it can be seen that taking on more obligations means moving earlier in time toward entering the desalination era. At current (2015) desalination costs, the optimal timing to bring desalinated water into the system will be 2026 when taking on a full obligation of 275 MCM (row 5, far right column). However, successful investments in desalination technology that reduce its cost to $US 0.50/cubic meter advances the starting year to 2013, shown at row 6 in the far right column. By contrast, if desalination cost had remained at $US 1.00 per cubic meter, the optimal starting year for switching into desalination is delayed to 2038, row 4, far right column.

Currently, desalination plants in Israel can provide 600 million cubic meters of desalinated seawater with an actual supply of 350 MCM. This is a large gap. This point is covered at some length in a 2011 study [*Lavee et al.*, 2011]. The gap comes from the fact that fresh water in agriculture has a high demand because of the low water price charged to farmers. The fact that water is desalinated at about 550 MCM is not a signal of efficient water use. In 2015, at the current average water cost, including desalination, there is too little demand for desalinated water. The Israeli government is compensating desalination plant operators because they currently lack a market for the entire water that could have been produced at its full capacity.

Desalination in our analysis wears the important hat of a backstop technology [*Fisher et al.*, 2005; *Koundouri and Christou*, 2006; *Tsur and Zemel*, 2000]. When the price of the backstop technology is reduced, the optimal upper bound of the previous lower cost resources is reached at an earlier time period [*Hotelling*, 1931; *Solow*, 1974]. From the view of implementing a peace treaty, that means that between the years of 2025 and 2030 there is a cost savings due to an early shift to desalination water supply that averts an additional price hike. This presents an important economic gain to irrigated agriculture and to other price-sensitive water users and also raises the affordability of meeting treaty or environmental obligations.

4.5. Impacts of Drought and Climate

The stakes grow as freshwater levels recede, either from drought or climate change, both of which are likely to pose growing challenges in the Middle East [*Kaniewski et al*., 2012]. Recent desalination plants were built in Israel starting from the early 2000s as a risk management measure to adapt to drought or climate change in case either became more severe [*Dreizin et al*., 2008; *Tal*, 2006]. These were built in anticipation that the current long-term average upper bound on freshwater (1382 MCM per year) would permanently fall to something less in the face of climate change and increased climate variability [*Barnett and Pierce*, 2009; *Cayan et al*., 2010]. This anticipation of demands that do not exist in normal water supply years is why desalination capacity is only partly used now (2014). In fact the use of existing desalination capacity requires a subsidy to irrigated agriculture to use in conditions of typical water supply (not shown in our results). Our analysis shows that an important consequence of investing in advanced desalination technology may be reduced political tensions over water and a greater potential to revive water-related ecological assets of special importance, such as the LJR and the DS.

5. Discussion and Conclusions

The paper develops and applies a constrained optimization mathematical programming model of Israel's national water system with considerable flexibility for addressing a wide range of policy challenges. The analysis compares empirically three management alternatives, taking into account the fact that Israel may be facing water supply obligations to address environmental requirements and for a possible peace agreement with the Palestinian Authority: (i) supply side management (supply expansion), (ii) demand side management (demand reduction), and (iii) integrated management (combination of demand and supply adjustments to avoid shortages).The empirical analysis yields outcomes for 24 combinations: (2 time periods) × (2 treaty obligations) × (3 average cost of desalination). The main contribution of the paper is in the findings and their associated conclusions to inform policy debates.

An important question raised by the 2002 work of Fisher and colleagues was "Will Israel need desalination?" The authors concluded that Israel would find additional desalination more expensive than other measures to avert shortages under normal water supply conditions [*Fisher et al*., 2002]. Nevertheless Israel built considerable amounts of desalination capacity since that article was written. So our paper stands on their shoulders. The follow-up question we asked is "what role will Israel's recently installed desalination capacity play in determining the cost of committing water to the peace process and to meeting environmental demands?" That question was addressed here by the use of a constrained optimization approach drawing on the power of integrated water resources management.

The constrained optimization approach has considerable flexibility as a workable and practical method to discover least cost solutions for meeting future water demands that are difficult to anticipate. Using the example of Israel, the paper identifies a method for minimizing the economic cost of securing up to 275 MCM of additional water for delivery obligations to support peace and the environment. For the year 2030, a cost of $US 107 million is the price paid for finding the new water by simply expanding supply with year 2015 technology. The same water could be found by reducing existing price-sensitive uses by that amount. Economic benefits lost by those uses to meet both sets of obligations amount to $US 111 million.

Either of those extreme measures of complete specialization poses needless costs. Integrated management is the better path. This conclusion echoes the findings of an earlier study, affirming that that the joint analysis of demand and supply can improve our capacity to find economically viable measures to address water-related conflict [*Dalhuisen et al*., 2003]. Combining an efficient package of supply expansion with price-sensitive demand reduction provides important savings. The total expense of the least cost combination of measures to supply the 275 MCM for the two potential obligations is $US 104 million, a modest 1–2 percent of the total net economic value of water in Israel in 2015. It saves $US 3–7 million compared to complete specialization.

Successful future reductions in desalination cost will reduce the real economic cost of water deliveries to support peace and environment by 28% of the above estimate. The present value of the cost of meeting those commitments with the lower future cost desalination is about $US 1.46 billion using a discount rate of 5%. This is an affordable price to pay to make a serious dent into the ancient problem of conflict from water scarcity in this small but volatile corner of the world.

Despite our treatment of environmental demands for water as a constraint, the economic value of water for the environment can sometimes be measured by the willingness to pay for environmental uses like water-based tourism, environmental protection, and tourism. These values were an important motivator for the recently signed agreement to commence work on restoring the Dead Sea. In fact, recent analysis of the economics of restoring the Dead Sea found values in the range of $US 200 million annually for an additional 300 MCM release from the Jordan River, or $US 0.67 per cubic meter, as a measure to secure the benefits of reducing declines of Dead Sea water levels [*Becker et al*., 2012]. Yet another study puts a value of restoring the LJR in the range of $US 0.23–0.87/cubic meter [*Becker et al*., 2014]. These results suggest the economic attractiveness of desalination, even at its current cost to restore these two historic water bodies.

There are other ways to reduce declines in the Dead Sea than the one considered in this study. A World Bank study published in 2014 examined a range of options to restore the Dead Sea [*Juanico and Friedler*, 1999]. Alternatives included measures to increase flows in the Lower Jordan River [*Becker et al*., 2014], water transfers to the Dead Sea from external sources, various desalination options to reduce demands on the Lower Jordan River, and various technical and water conservation options.

Our paper operates inside the boundaries of a limited scope. It sets out the modest objective of calculating the cost of meeting water deliveries designed to support a future Israeli-Palestinian peace treaty and for the environment. It is entirely possible that even if increased flows are shared by the Israelis with the Palestinians and with the environment, peace still may be a long ways off. Environmental improvements need not occur. Though not analyzed in this paper, desalination technology is associated with its own environmental costs. These externalities can delay the switching year. As shown by a study in 2011, these costs were found to be about $US 0.07/cubic meter and stand to raise desalination costs by about 10% from current levels [*Elimelech and Phillip*, 2011; *Lavee et al*., 2011]. We would be most interested in the use of Computable General Equilibrium (CGE) Models [*Luckmann et al*., 2014] to see if our findings hold up to an economy-wide analysis of costs of supporting a peace treaty and environmental needs for water.

Another limitation of our work is the need for a comprehensive accounting of impacts of future freshwater obligations on farm income currently irrigated by treated wastewater, transmitted through the channel of reductions in domestic water use. In Israel, irrigation with treated wastewater and brackish water operates in a separate market from irrigation by freshwater. While the freshwater system operates as a nationally closed system, treated wastewater is more regionally organized and designed. Treated wastewater used in irrigated agriculture comes from treatment plants for which water is supplied by nearby cities.

The two kinds of irrigation water sources operate in different regions, with different delivery systems, are supplied for different crops, with water priced at different levels. That is, there is limited direct interaction between these two irrigation sectors. For this reason, new obligations taken on by Israel to supply water for peace or for the environment will increase the demand for freshwater to meet those purposes. This increased demand for freshwater to support the obligations will come from five possible sources in our analysis: (1) reductions in freshwater irrigation use, (2) reductions in industrial use, (3) reductions in domestic use, (4) expanded supply from one of the three sources we analyzed, or (5) from a combination of these. As shown in our analysis, some of those expanded deliveries to support a peace treaty or environmental flows come from reduced domestic use despite its low price elasticity of demand. That effect is already accounted for by our model.

Nevertheless, as one reviewer suggested, if increased obligations for freshwater deliveries increase the domestic water price and reduce domestic water use, then there is less treated wastewater available for irrigated agriculture. Table 1 provides a starting point for assessing these impacts, showing a reduction from 729 to 707 (22 MCM) in the year of 2015 from 948 to 860 in 2013 (108 MCM). Every 1 unit in domestic demand has the potential to create 0.6 units of treated wastewater [*State of Israel Water Authority*, 2012b]. This would result in a reduction of 13 and 65 MCM in 2015 and 2030, respectively. The actual treated wastewater use in 2010 and 2030 (projected) is 450 and 685, respectively. That means a loss of 3% and 9% in the wastewater market for those years, an impact neglected in our analysis. There is no information on the value added of those crops, which ones would exit production, in what places, and in what sequence. For these reasons, we have no information on impacts to farm income from reductions in treated wastewater.

Assessment of these impacts needs attention in future work. The conduct of that research would need estimates of the regions in which there would be less domestic water use and the associated loss in farm income. It should also be noted that part of the benefit of this treated wastewater comes from the fact that they would reduce current amounts released into the natural outlet-rivers. Less treated wastewater also means a reduction in the cost of their treatment.

Another impact of reduced wastewater supplies is that once the supply of treated wastewater is reduced, their actual or virtual price increases. This further reduces the profitability of irrigation from that source. That reduced profitability in farm income is measured as the reduction in "consumer surplus" beneath the derived demand for irrigation water.

Success in future efforts to quantify that impact will require several important pieces of information:

1. Profitability per unit land currently irrigated by treated wastewater
2. Current land in production irrigated by treated wastewater.
3. Price charged for treated wastewater supplied to irrigation.
4. Price responsiveness associated with changes in supply of treated wastewater, which is related to the impact on farm income from those supply changes.
5. Values of environmental impacts resulting from reductions in treated wastewater.

There is some research addressing these impacts ongoing in Israel (2015), but results still await findings, analysis, reporting, and peer review. Overcoming all these limitations described above must await future work.

Appendix A: Mathematical Documentation for Middle East Constrained Water Optimization Model

This documentation presents the most important elements of the Middle East Constrained Water Optimization Model (CWOM) developed in cooperation with the New Mexico State University (USA) College of Agricultural, Consumer, and Environmental Sciences and the Department of Economics and Management at Tel-Hai College (Israel). The model and its documentation were developed for application to water supplies, demands, economics, and constraints for Israel (Figure 1). However, it is adaptable to the hydrology, land use patterns, irrigation, economics, treaty constrains, and institutional constraints for any basin.

Important variables tracked include crop water use, urban and domestic water use, farm income, and water use and benefits by domestic and industrial use associated with various constraints on peace treaty or environmental flow deliveries that Israel could face in future years. The model structure is defined below using the GAMS notation, described by the vendor at gams.com. An earlier and simplified version of this documentation is published [*Becker and Ward*, 2014].

Table A1. Sets[a]

Set	Set Name	Set Elements
i	minimum flows	/environment, peace treaty/
j	water source	/fresh water, marginal saline, desalinated/
c	use	/crops, domestic, industry/
t	year	/2015, 2030/
s	desalination costs	/2000 cost, 2015 cost, future cost/
e	environmental flows	/wo new env flows, wi new env flows/
p	peace treaty flows	/wo new peace flows, wi new peace flows/
d	shortage adjustment mechanism	/IWRM, supply expansion, demand management/
cc(c)	crop uses	/crops/
cn(c)	non crop uses	/domestic, industry/

[a] Sets are the dimensions over which CWOM is defined. A similar structure could be used for optimizing water 685 development and use patterns when facing political or other constraints anywhere where water is scarce.

Table A2. Data[a]

Parameter Name	Parameter Description
nc_demand_p(i,t,e,p)	minimum freshwater delivery (million cubic meters –mcm- per year)
base_dom_use_p	domestic use year 2010 (mcm/yr)
base_ind_use_p	industrial use year 2010 (mcm/yr)
bnc_demand_p(cn,t)	base non crop demand by time period
capacity_p(j,t)	upper bound capacities by supply source (million cubic meters per year)
av_cost_p(j,s)	average cost by supply source ($US per cubic meter)
base_ag_use_p(cf)	base ag water use (mcm/yr)
rho_d _p	domestic demand annual growth rate (unitless)
rho_i_p	industrial demand annual growth rate (unitless)
B0_p	ag price intercept estimated with nonlinear least squares
B1_p	price flexibility in price dependent ag price function
eta_p(cn)	price elasticity of demand for non-crop water (linear) demands
Beta0_p(cn,t)	intercept for quantity dependent industrial/domestic (linear) demand
Beta1_p(cn,t)	slope for quantity dependent industrial/domestic (linear) demand
G1_p(cn,t)	slope for price dependent industrial/domestic (linear) demand
G0_p(cn,t)	intercept for price-dependent industrial/domestic (linear) demand
ag_wat_use_base_p	base observed ag water use 2015 (mcm/yr)
farm_inc0_p	base year farm income (excl wastewater) 2015 ($US millions/yr)
q_base0_p	lower level of integration, base farm income ($US millions/yr)

[a]All of the following parameter (data) terms end in _p to distinguish parameters (known terms) from unknown variables.

Table A3. Variables (Unknowns)[a]

Variable Name	Variable Description	Units
demand_v(c,t,s,e,p,d)	priced water use	(mcm/yr)
demand_np_v (i,t,s,e,p,d)	unpriced water use	(mcm/yr)
tot_npd_v (t,s,e,p,d)	total unpriced water use	(mcm/yr)
pw_v (c,t,s,e,p,d)	priced water price (vmp)	($US per cubic meter)
pw_crop_v (t,s,e,p,d)	priced water (vmp) price for crops	($US per cubic meter)
tot_cost_v (t,s,e,p,d)	total cost of supply	($US million per year)
tot_sup_v (t,s,e,p,d)	total supply	(mcm/yr)
tot_dem_v (t,s,e,p,d)	total demand	(mcm/yr)
supply_v (j,t,s,e,p,d)	supply by source and year	(mcm/yr)
ben_c_v(c,t,s,e,p,d)	economic benefits by use	($US million/yr)
Tot_n_ben_v	total net benefits	($US million/yr)

[a]Each unknown variable ends in _v, to distinguish variables from known data. The model solves for the optimal value of each of these variables, for which the goal is to maximize total economic welfare, defined as consumer surplus minus costs of supply, summed over all sources and uses of water.

A1. Equations

Several algebraic relationships are used to characterize existing water source and use patterns. These patterns also characterize adaptation to peace and environmental delivery requirements if taken on as obligations by Israel. The most important relationships deal with water sources, water uses, water prices, equilibrium conditions, and economic benefits.

A1.1. Prices

The price of water in irrigated agriculture falls with increased water allocated to agriculture, based on the following Cobb-Douglas inverse demand schedule:

$$\mathrm{pw\_v}(\mathrm{cc},t,s,e,p,d)=\mathrm{B0\_p}*\mathrm{demand\_v}(\mathrm{cc},t,s,e,p,d)**\mathrm{B1\_p}) \tag{A1}$$

Both domestic and industrial demands are specified linear. Each has a price elasticity of −0.10 resulting from potential changes away from observed prices and quantities in the base year, 2010. The elasticity is based on published [*Fisher et al.*, 2002] and unpublished sources of literature. The linear form is selected because the very low price elasticities of these uses produces an infinite consumer surplus with the Cobb-Douglas form absent special bounds placed on it to produce a finite consumer surplus:

$$\text{pw\_v}(cn,t,s,e,p,d)=\text{G0\_p}(cn,t)+\text{G1\_p}(cn,t)*\text{demand\_v}(cn,t,s,e,p,d); \tag{A2}$$

A1.2. Demands

Total noncrop water demands for domestic and industrial uses are:

$$\text{tot\_npd\_v}(t,s,e,p,d)=\text{sum}(i,\text{demand\_np\_v}(i,t,s,e,p,d)) \tag{A3}$$

A1.3. Supplies

Total water supply in use is summed over all sources: freshwater, marginally saline, and desalinated.

$$\text{Tot\_sup\_v}(t,s,e,p,d)=\text{sum}(j,\text{supply\_v}(j,t,s,e,p,d)) \tag{A4}$$

A1.4. Equilibrium Condition

An equilibrium condition states that price adjusts to protect against shortages by ensuring that supply from all sources equals demand for water for all uses.

$$\text{Tot\_sup\_v}(t,s,e,p,d)=\text{tot\_dem\_v}(t,s,e,p,d) \tag{A5}$$

A1.5. Benefits

Consumer surplus for the Cobb Douglas crop demand functional form equals the amount by which farm income exceeds its price of water:

$$\begin{aligned}\text{ben\_c\_v}(cc,t,s,e,p,d)=[\text{B0\_p}/(1+\text{B1\_p})]*[(\text{demand\_v}(cc,t,s,e,p,d)**(1+\text{B1\_p}))\\ -\ (\text{q\_base0\_p})**(1+\text{B1\_p})]\end{aligned} \tag{A6}$$

Consumer surplus for linear demand function, industrial and domestic uses:

$$\begin{aligned}\text{ben\_c\_v}(cn,t,s,e,p,d)=\text{G0\_p}(cn,t)*\text{demand\_v}(cn,t,s,e,p,d)+(\text{G1\_p}(cn,t)/2)*\\ (\text{demand\_v}(cn,t,s,e,p,d)**2)\end{aligned} \tag{A7}$$

Total benefits from all water use sums over nonlinear and linear demand forms:

$$\text{ben\_v}(t,s,e,p,d)=\text{sum}(c,\text{ben\_c\_v}(c,t,s,e,p,d)); \tag{A8}$$

A1.6. Costs of Supply

Total cost of water supply from all sources: freshwater, marginally saline, desalinated

$$\text{tot\_cost\_v}\ \ (t,s,e,p,d)=\text{sum}(j,\text{Av\_cost\_p}(j,s)*\text{supply\_v}(j,t,s,e,p,d)) \tag{A9}$$

A1.7. Net Benefits

Net benefit, the objective, is defined as benefit minus cost

$$\text{net\_ben\_v}(t,s,e,p,d)=\text{ben\_v}(t,s,e,p,d)-\text{tot\_cost\_v}(t,s,e,p,d) \tag{A10}$$

Net economic benefit is maximized for all combinations of sets t(2), s(3), e(2), p(2), d(3), for a total of 72 optimization model runs.

A1.8. Bounds

Several bounds are established to assure that the model replicates real world data, technology, and water user behavior, while also producing realistic responses to future climate or policy adaptations to climate.

An upper bound (.up) on each supply source assures that no source of supply exceeds its capacity:

$$\text{supply\_v.up}(j,t,s,e,p,d)=\text{capacity\_p}(j,t) \tag{A11}$$

A lower bound (.lo) assures that a required demand obligations for peace and the environment is achieved.

$$\text{demand\_np\_v.lo}(i,t,s,e,p,d)=\text{nc\_demand\_p}(i,t,e,p) \tag{A12}$$

Demands for agriculture, industrial, and domestic all depend on price. So no lower bounds are required for meeting those demands.

A1.9. Objective

The objective is to maximize total national net benefits of water-related value by maximizing equation (A10) for each of 72 model runs, 24 results of which are shown in this paper. It achieves this maximization by seeking, finding, and applying the income-maximizing water use patterns by source, use, year, desalination cost, environmental flow, peace treaty flow, and shortage adjustment mechanism.

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