Economic Impacts of Water Scarcity under Diverse Water Salinities

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Abstract

Exploitation of alternative water sources is expected to grow in the decades to come in water-stressed countries with fast population growth, especially in regions where a further decline of natural freshwater availability is expected due to climate change. Increasing utilization of non-freshwater usually leads to salinity build-up in fields and water sources as well as accumulation of various pollutants - both having a considerable impact on the suitability of non-freshwater for irrigation due to constraints associated with crop salinity tolerance and food safety regulations.

We developed a linked CGE - farm-level model of a water economy with representation for multiple water types characterized by different qualities. We employ the model to assess the impact of water shortage on the Israeli economy, where a steadily growing water scarcity is leading to an increasing utilization of alternative water sources. We simulate water shortage scenarios based on the Long Term National Master Plan for The Water Economy developed by the Israeli Water Authority (IWA).

The linked CGE - farm-level model provides a mechanism for estimating the Constant Elasticity of Substitution (CES) rates between different irrigation water types used in agriculture. This mechanism accounts for the effects of salinity on yields and takes into consideration food safety regulations for irrigating crops with treated wastewater. We demonstrate that, in contrast to previous studies, CES rates between different water types are not identical. The CES rates obtained in our study have relatively low values, which can be attributed to the constraints associated with crop salinity tolerance and food safety regulations.

Our results reveal that water shortage can lead to a significant decline of Israel's GDP, where a considerable part of the decline is attributed to the decrease in agricultural outputs. The magnitude of the impact depends on the underlying assumptions regarding future desalination capacity. To further study the effect of desalination, we run simulations under various desalination levels and examine its impact on the GDP. We also examine the extent to which the impact of water shortage is sensitive to CES rates between different irrigation water types.

Keywords: Salinity; Water scarcity; Computable general equilibrium (CGE); Positive mathematical programming (PMP)

1. Introduction

Exploitation of non-freshwater sources such as treated wastewater and brackish water is expected to grow in the decades to come in water-stressed countries with fast population growth, especially in regions where a further decline of natural freshwater availability is expected due to climate change.

Increasing utilization of non-freshwater usually leads to salinity build-up in fields and water sources as well as accumulation of various pollutants (Qadir et al., 2007). Salinity levels and pollutants in non-freshwater sources have a considerable impact on their suitability for irrigation. First, as crops differ in their tolerance to salinity, farmers refrain from irrigating saline-sensitive crops by brackish or treated wastewater. Second, irrigation with treated wastewater is subject to food safety regulations, prohibiting irrigating certain crops by treated wastewater while restricting application to others (e.g., using drip irrigation).

Natural freshwater scarcity and increasing use of non-freshwater for irrigation have economy-wide impacts. Computable general equilibrium (CGE) models are most suitable for analyzing the distributional impacts of policies whose effects may be transmitted through multiple markets. Analyzing these impacts with CGE models requires an adequate representation of the water sector; particularly capturing the correct substitutability between all water types that differ in their salinity levels and other relevant qualities. We employ a meta-analysis procedure for estimating elasticity of substitution rates between irrigation water with different qualities, and use these rates for assessing the impact of freshwater scarcity in the case of Israel, where a steadily growing water scarcity is leading to an increasing utilization of alternative water sources.

A large number of economy-wide water-related studies (mainly CGE) have been published in the economic literature, but only little can be generalized since these studies use different assumptions and structures (Dinar, 2012). Thorough literature reviews on employing CGE models for water-related studies can be found in Johansson (2005), Dudu and Chumi (2008), and more recently in Dinar (2012).

Most CGE-based studies have difficulties adequately representing water due to the lack of an explicit economic value which is commonplace in water-abundant countries. In the majority of these studies, the adopted procedure is to split the value of this natural resource from existing economic transactions according to assumed proportions. The substitutability between water and other factors of production in CGE models are usually assumed, where key parameters of substitution elasticity rates are either based on expert judgment, taken from the literature, or used as a mechanism for calibrating the model. In most of the studies, only potable water is modeled (Horridge et al. 2005, Berrittella et al. 2007, Diao et al. 2008). In some of them a distinction is made between irrigated and rain-fed agriculture but there is usually only a single type of irrigation water (Hassan et al. 2008, Calzadilla et al. 2013). This modeling approach is not suitable for a water economy that relies on alternative water sources since it does not reflect the constraints associated with utilizing low-quality water sources, thereby overstating the ability of an economy to cope with an increasing water shortage.

Luckmann et al. (2014) are an exception. Using Israel as a case study, they model an economy with a representation for multiple water sources. Such a detailed specification is particularly required in the case of Israel, where more than 75% of the wastewater generated by the urban sector is treated and diverted to agriculture, constituting approximately 50% of the country's irrigation water (Kislev 2011). While the irrigation share of treated wastewater in other regions is lower (e.g., 17% in Spain and only 6% in California (Sato et al., 2013)), wastewater reuse is on the rise. In California, for instance, reuse has more than doubled from 1989 to 2009 (NWRI, 2012). Thus, modeling variations in water scarcity in such countries should account for the substitution between freshwater and alternative sources. Luckmann et al. (2014), however, assume in all non-water activities, including agriculture, an identical elasticity of substitution rate in the combination of the three water commodities (potable, brackish, and reclaimed water)[1]. This approach is part of a general weakness of many water-related CGE studies that treat irrigated agriculture as a one sector activity, where the underlying assumption is uniformity across regions/sectors; i.e., similar characteristics such as soil quality, water availability, crop mixes, farm size, etc. (Dinar, 2012). In our study, also based on the Israeli case, we provide evidence that this is an unrealistic assumption and demonstrate that substitution levels between irrigation water sources can differ significantly. The substitution rates obtained in our study have low values, which can be attributed to the aforesaid constraints associated with crop tolerance to salinity and food safety regulations.

In our study we assess the impact of projected future water shortages on Israel's economy, while accounting for the diversity of water sources with different salinity levels. For this purpose, we developed a CGE model (hereafter IGEM: Israeli General Equilibrium Model) representing Israel's economy, encompassing the water system with

[1] It should be noted that in Luckmann et al. (2014) each of the nine agricultural sectors consumes different water sources and a sector specific aggregate. However, within agricultural sectors that consume multiple water sources the same substitutability rate, adopted from the literature, is assumed among these sources.

its heavy reliance on a mix of water types. To reflect the substitutability between the various irrigation water sources, we employed a meta-analysis procedure for estimating elasticity of substitution rates. The data for the estimation were produced by the vegetative agricultural land-use economic (VALUE) model; this is a land- and water-use positive mathematical programming (PMP) model which accounts for both the negative effects of salinity on yields and the limitations associated with irrigating with treated wastewater.

We reflect in our analysis water shortage by simulating various scenarios considered by the Israeli Water Authority (IWA) in its Long Term National Master Plan for the Water Economy (IWA, 2011). Our results indicate that the projected water shortages are expected to have a significant negative impact on Israel's economy. According to our analysis, mitigating these shortages by increasing the desalination capacity is generally warranted.

The modeling framework is described in Section 2. Section 3 presents the methodology and analysis employed to assess the impact of increasing water scarcity on the Israeli economy. In section 4 we provide a summary and conclusions.

2. The modeling framework

We developed a linked CGE-PMP modelling framework of a water economy with representation for multiple water types characterized by different qualities. VALUE, the PMP model which is a land- and water-use positive mathematical programming model - containing 45 crops, 21 regions and four water types that vary in their salinity levels and prices - provides the intra-agricultural sector effects while accounting for both the negative effects of salinity on yields and the limitations associated with irrigating with treated wastewater. IGEM, a CGE model, into which the salinity effects are passed through the CES rates, provides the macro-economic framework to assess inter-sectorial effects and the impacts on the economy as a whole.

In the subsequent sections we present the two models, IGEM and VALUE, and then describe the mechanism for estimating the substitution rates between different types of irrigation water.

2.1 IGEM

IGEM is a CGE-type model for the entire Israeli economy, originally presented by Palatnik and Shechter (2010). It is a structural, real, static model of a small open economy with five energy commodities, fourteen other commodities, government, an investment agent, a foreign agent, and a single representative household. The standard assumptions of market clearing, zero excess profits and a balanced budget for each agent apply. Commodity markets merge primary endowments of households with producer outputs. In equilibrium the aggregate supply of each good must be at least as great as the total intermediate and final demand. Producer supplies and demands are defined by producer activity levels and relative prices. Final demands are determined by market prices. With world prices fixed, the market for foreign exchange is cleared by fluctuations in the exchange rate. Labor and capital supplies are exogenously fixed. The output is divided among the produced commodities with a Constant Elasticity of Transformation (CET) function. The production processes in the various sectors are defined using CES functions.[2] The nesting structure is designed to allow flexibility in setting elasticities of substitution particularly with regard to the use of different water types in agriculture. There is a separation of activities from commodities which permits activities to produce multiple commodities, while any commodity may be produced by multiple activities. In addition, the model allows for heterogeneity between domestic and imported goods, adopting the Armington assumption.

The household sector is represented by a single Representative Agent (RA). The RA demands consumption goods and saves the remaining disposable income. The consumer's objective is to maximize a Cobb-Douglas type utility, subject to a budget constraint. The RA's income is made up of a net income deriving from the supply of labor and from the rental of capital plus net transfers. Household savings are exogenously fixed and equal to the sum of the government's budget surplus and the balance of trade surplus less investments and the value of increases in stock. This ensures that the financial cycle is closed. RA consumption is taxed at a constant rate.

Government consumption and export are driven by the maximization of a Leontief utility function subject to a budget constraint. The government raises taxes to obtain public revenue; at the same time it gives net transfers, to the RA and abroad, and demands goods and services. Exports are traded for foreign exchange, which is used to pay for imports. Balance of payment equals net imports.

The following taxes are represented in the model: net taxes on products, net taxes on production, taxes on consumption, labor tax, capital tax, and import tariffs. Taxes on

[2] The production technology has a constant percentage change in factor proportions due to a percentage change in marginal rate of technical substitution.

consumption are the share of indirect taxes on purchased products paid for by the RA. The shares of labor and capital tax are calculated based on Ben Gad (2004) estimations.

The consumer price index was chosen as the numéraire, the price relative to which all price changes are evaluated, as absolute price levels are undetermined in the model and only relative prices can be assessed. This price, being fixed at unity, means that the total quantity of consumption equals the total value of consumption at all times. In IGEM welfare is measured focusing solely on private household consumption, while government purchases are fixed. A change in total household consumption therefore equals a welfare change as measured by the Hicksian equivalent variation (EV).

The model is calibrated to the benchmark data. It is assumed that the economy is at equilibrium at the benchmark. A policy simulation is implemented by introducing a set of exogenous shocks to the system, where the model output shows the state of the economy after all markets have reached a new equilibrium.

A more detailed description of IGEM can be found in Palatnik and Shechter (2010). We present herein the enhancements to the model developed to reflect the special characteristics of the Israeli water economy. These enhancements include: (i) separating the original water sector into five sectors, (ii) adjusting the social accounting matrix (SAM) to correspond to the multi-sector representation of the water economy and (iii) introducing in the model a nested CES structure for irrigation water. The separation of the water sector and the SAM adjustment are discussed below. The estimation of the irrigation water CES rates and the creation of the nested CES structure are discussed in section 2.3.

As aforementioned, to represent the marginal water sources, the original water sector in IGEM has been separated into five sectors - natural freshwater, desalinated freshwater, brackish water, secondary- and tertiary-treated wastewater.

Introducing marginal water sources into IGEM required adjustment of the social accounting matrix – a multi-sector dataset, recording and combining the transactions between different industries, consumers and government agents. The available SAM for the Israeli economy represents the year 2004, and contains information on 18 sectors of the economy including the water sector. The water sector in the SAM aggregates information on the value of water sales to the remaining 17 sectors, households, government, water import and export, as well as the value of the input factors purchased by the water sector from the other activities. To adjust the SAM we divided and allocated the aggregated data for the water sector across the various water types based on the Satellite Account of Water in Israel (CBS, 2011). This report contains a comprehensive nationwide characterization of the economic value of the flows of the different types of water across the economic sectors. In addition, the characterization of the inputs used for the production of the different water types was performed based on Dreizin, et al. (2008) and IWA (2011). This includes the assessment of the values of production factors such as energy and labor, as well as the values of inputs purchased from other economic sectors for the purpose of desalination and purification of effluents.

2.2 The VALUE Model

The VALUE model was developed to evaluate impacts on the Israeli farming sector stemming from changes in external factors and policies with respect to various topics, including rural landscape (Kan et al., 2009), organic-waste management (Kan et al., 2010), and water management (Kan and Rapaport-Rom, 2012), . A formal description of the model is available in Palatnik et al. (2011). VALUE is a PMP model of agricultural land and water use, containing 45 crops, 21 regions and four water types that vary in their salinity levels[3] and in their prices. The model is static. It incorporates crop-specific production functions that account for water applications under saline conditions, as well as production costs and demand functions for agricultural products. The direct effect of salinity on each crop is represented by a calibrated production function using the simulation model suggested by Shani et al. (2007). Restrictions on the use of treated wastewater are taken into account by assigning the treated wastewater to specific crops and irrigation systems, where the effect of the irrigation system is reflected by the parameters of the calibrated production function (see Kan, Schwabe and Knapp, 2002). The model is calibrated for 2004, and then run to search for new equilibria under changes in exogenous factors. Here we use VALUE to simulate changes in the relative prices of the four irrigation water sources.

2.3 Estimating CES rates between water types in agriculture

We employ a procedure, which relies on the method presented in Okagawa and Ban (2008), who empirically estimated CES rates for energy, capital and labor. In our case, the CES rates apply to different water types, and can be defined as follows (based on Perroni and Rutherford, 1995):

[3] Freshwater with salinity of 1 dS/m(decisiemens per meter), brackish water salinity of 4 dS/m and secondary- and tertiary- treated wastewater salinity of 2 dS/m for both.

At a certain level, the elasticity of substitution σ_{12} that exists between two water types marked as 1 and 2 is interpreted as follows: if the relative price of the two water types P_2/P_1 changes in 1%, their relative quantity W_1/W_2 will change by σ_{12}%.

The CGE modeling approach ranks production factors according to their substitutability rates, and permits the use of more than two production factors at a given level of the rank, provided that there is an identical elasticity of substitution between all pairs in that level. If this condition is not met for all factors, a multi-level hierarchal structure needs to be determined, where at every level of the structure the CES rate determines the degree of substitutability between the production factors in that level, and the substitutability rates increase from the highest to the lowest levels.

Our estimation procedure is based on a dataset obtained by running the VALUE model multiple times while changing the relative prices of the four water types used as inputs to crop production. The price of each water type in each of the 21 regions was shocked with variations ranging from -90% to +90%, at 10% intervals. The dataset represents for each pair of water types the relative changes in quantities - aggregated over all regions and crop types[4] - that correspond to relative changes in their prices.

The aforementioned price changes affect optimal agricultural management in both the field and regional (or farm) levels. In the field level, the optimal applications of the four water sources vary; this stems not only due to the change in the relative prices, but also because the water sources have different salinity levels, and therefore they differ in the response of their value of marginal production (VMP) to changes in water applications. In the regional level, the changes in the field-level water applications alter

[4] In IGEM there is one aggregate agricultural sector.

the relative profitability of the crops, and thereby change the optimal allocation of land among crops. Thus, the salinity impact is reflected both in the intensive (field level) and extensive (regional scale) margins (see Schwabe, Kan and Knapp, 2006). These salinity effects are passed on into IGEM through the CES rates, which are estimated based on the simulation data produced using VALUE.

To determine the nested structure of CES for irrigation water sources we apply the following multi-stage procedure (see figure 1): In the first stage, we estimate CES rates for all the possible pairs of the four water types[5]. We found that the CES between freshwater (denoted *F*) and tertiary-treated wastewater (*T*) is the largest ($\sigma_{F,T} = 1.54$), and is statistically different from the CES rates estimated between all the other pairs of water types. Thus, we assigned the pair *F* and *T* to the lowest level of the nested CES structure. In the second stage, we computed for the pair of freshwater and tertiary-treated wastewater (denoted *FT*) their composite quantities and prices (see Appendix A), and estimated the CES between this composite and all the other water types. We found that the CES between the composite *FT* and brackish water (*B*) is the largest ($\sigma_{FT,B} = 1.08$), and that it is statistically different from the CES rates between all other pairs of water types. Hence, we assigned the pair *FT* and *B* to the second level of the hierarchy. In the third stage we calculated the composite quantities and prices for the composite of *FT* and *B* (denoted *FTB*) and estimated the CES between this composite and the remaining water source, secondary-treated wastewater (*S*); we got $\sigma_{FTB,S} = 0.68$.

Figure 1 about here

[5] As desalinated seawater and natural freshwater possess, as far as irrigation is concerned, identical qualities, they are represented as one water type referred to as freshwater.

Contrary to Luckmann, et al. (2014), our results indicate that fresh, tertiary-treated wastewater, secondary-treated wastewater and brackish water inputs are not equally substitutable, in agricultural production in Israel. Similar to Luckmann et al. (2014), the estimated rates of substitution are low, where in our case they reflect the constraints associated with crop salinity-tolerance and food-safety regulations that are explicitly accounted for by VALUE. The resultant nested structure of CES for irrigation-water sources was implemented into IGEM for representation of the substitutability between water sources in agriculture[6].

3. Simulations of water shortage under different salinity levels

For our simulation we have chosen the Israeli case which is characterized by a steadily growing natural freshwater scarcity and an increasing utilization of alternative water sources. In the subsequent sections we present a short description of Israel's water economy, describe our simulation methodology, outline the scenarios that were evaluated and present our results.

3.1 Israel's water economy

Israel has encountered an ongoing drought in recent years (Shachar, 2009). According to the Israeli Water Authority (IWA)[7], the average annual replenishment of natural freshwater aquifers declined from nearly 1,400 million cubic meters (MCM) in the last 80 years to 950 MCM in the first decade of the 21st century. This general trend is expected to

[6] The estimated CES rates are only incorporated in the agricultural production function and do not affect all the other sectors in the model.

[7] IWA controls water allocations and management throughout the country by setting prices and quotas (World Bank, 2009) and developing long-term plans.

remain due to climatic, demographic and socioeconomic changes. To satisfy the annual demand (currently about 2,200 MCM) without overusing aquifers, utilizations of alternative water sources have been explored, including reclaimed wastewater, desalinated seawater and extracted brackish groundwater (Kislev, 2011). Extensive investments were made over the years in building an integrated water resource extraction, diversion and conveyance system, with a national water carrier transferring water from the northern Jordan River basin throughout the country (World Bank, 2009). Israel's water economy entered the stage of energy intensive seawater desalination in 2005 with facilities built on the Mediterranean coast. Seawater desalination plants provided 280 MCM of potable water in 2010 at a price of about 0.50 US$ per cubic meter (Hoffman, 2011; Spiritos and Lipchin, 2014), with more plants planned to provide up to 750 MCM yearly by 2020. The dramatic decrease in freshwater allocation to the agricultural sector during the drought of 2007–2008 was made possible due to the availability of treated wastewater (Kislev, 2011).

Climate models for Israel predict rising winter temperatures and reduction in precipitation (Krichak et al., 2011). Hence, non-natural freshwater sources such as desalinated seawater, treated wastewater and brackish water are expected to play an even more critical role in the future in coping with the growing water shortage, with higher impact on the Israeli water system, the agricultural and energy sectors, and the economy as a whole.

3.2 Simulation Methodology

We assess the economic impact of water shortage by simulating in IGEM various scenarios of shortage in the supply of potable water relative to the benchmark. As will be elaborated below, these scenarios project gaps between supply and demand of potable water, given different seawater desalination volumes and desired water supply reliability levels.

The starting point for carrying out the simulation was calibrating the model to the state of the Israeli economy in 2004 in equilibrium (the benchmark). We fed into the model, at this initial state, limits on the availability of potable water, expressed in relative terms, corresponding to the various scenarios. In addition, as tertiary- and secondary-treated water diverted to agriculture are produced from wastewater, whose quantities depend on the consumption level of potable water, the available quantities of treated wastewater were linked to the availability of potable water.

The changes described above violated the equilibrium conditions prevailing in the benchmark. IGEM then recalculated a new equilibrium, under the restricted quantity of potable water, and reported the new values of the economic indicators defined in the model, expressing each in percentage change relative to its value in the benchmark. These indicators include, among others, the output quantities and prices of all the economic activities defined in the model, including those of agriculture and the various water types.

3.3 Scenario definition

The scenarios fed into IGEM were derived from the Long Term National Master Plan for The Water Economy (IWA, 2011) - hereafter referred to as “Master Plan.” The future water balance included in the Master Plan presents the projected water supply against the expected needs based on data, assumptions and basic parameters of the water economy, coupled with design goals and water allocation policies[8]. As to the future availability of natural freshwater, it takes into account a gradual reduction of 15% in the availability until 2050, (relative to the historic average between 1993- 2008), particularly due to climate change.

The water balance presented in the Master Plan does not present an accurate forecast but rather predicted trends until 2050. This stems from the fact that there is an uncertainty with respect to events that influence both the supply and demand of water, including uncertainty related to future dependence of the water economy on international agreements and decisions related to desalination. In order to prepare the water economy for extreme events in the various areas, the Master Plan includes a probabilistic analysis of the gap between the forecasted demand and supply based on analyzing statistical variances of both.

The scenarios are summarized in Table 1. It lists the expected shortage in potable water in millions of cubic meters a year (MMY) and as a percent of the total demanded quantity for the years 2020, 2030 and 2050, under two levels of desalination: the 2010 level of 280 MMY and a level of 750 MMY – the level approved by the government for implementation by 2020. The shortage in each scenario was calculated in the Master Plan under four desired water supply reliabilities (hereafter "reliability"): 75%, 90%, 95%[9]

[8] Among other things, the Master Plan accounts for expected future changes until 2050 in the following areas: availability of natural freshwater, population growth, average per capita water consumption, industrial water consumption, availability of treated wastewater, agricultural consumption and supply to neighboring countries.

[9] For example, shortage of potable water at a reliability of 95% means that there is a probability of 5% that the shortage will be greater than the given value.

and 100%. These levels refer to the desired reliability of water supply to the economy and are derived from the probability of encountering a shortage in potable water – probability that stems from a statistical analysis of the gap between the projected future demand and anticipated future availability of natural potable water[10]. A more detailed explanation of how the scenarios were defined is presented in Appendix B.

Table 1 about here

3.4 Simulation Results

For each scenario IGEM reports the percentage change in the value of key economic indicators relative to their value in the benchmark. The key indicators include the price of potable water, agriculture production, the price of agricultural products, and the GDP.

As aforementioned, Israel's water economy is centrally managed by the IWA and the prices of water are administratively determined. Hence, the relative increase in the price of potable water obtained in the simulation represents the price that ought to be set by the IWA in order to reduce demand to match the available quantities. Alternatively, if the government decides to maintain the base-year water prices and limit consumption by setting quotas, the price increase would represent the shadow value of these quotas.

The simulation results are presented in Table 2; they exhibit a wide range of changes in the economic indicators. The magnitude of the impact of water shortage depends on the underlying assumptions regarding future desalination capacity and the supply reliability of potable water. As expected, in all cases the price of potable water increases, agricultural production decreases, agricultural output prices rise, and the GDP declines. These changes increase over time as the shortage of potable water grows. Larger changes

[10] The reliability level reflects the degree of conservatism in the design of the water system. A higher reliability level corresponds to a more conservative design, i.e., there is a lower probability that the actual potable water shortage will be greater than the assumed value.

are obtained for higher water supply reliabilities; smaller changes are obtained for the higher desalination capacity of 750 MMY.

Table 2 about here

As expected, IGEM predicts that desalination can efficiently mitigate the negative impact of water shortage. To further study the effect of desalination, we run IGEM under various desalination levels, assuming a reliability level of 90%. Figure 2(a) presents the impact of the desalination levels on the GDP. In Figure 2(b) we show the impact of the desalination level on some key components of the GDP. Large fractions of the GDP decline are attributed to the impact on the value of agricultural and manufactured outputs. The agricultural sector suffers a larger decline than the manufacturing sector, but with GDP shares of 1.6% and 11.5% respectively, the impacts on both sectors equally contribute to the GDP decline.

Figure 2 about here

To examine the extent to which the impact of water shortage is sensitive to CES rates between different irrigation water types, we simulate increasing levels of potable-water shortage under three alternatives: (1) Using the CES rates obtained specifically for each irrigation water type, based on the aforementioned methodology; (2) Using an average of the CES rates obtained in our study, which equals 1.1; (3) Using a CES rate of 3.0 between all water types, representing a high degree of substitutability. Figure 3 displays the results. The impact of the assumed CES rates on agriculture output, agriculture price, potable water price and GDP grows with the increase in water shortage. The relatively low substitutability between water types, estimated in our study, entails a larger negative impact of water shortage on the agricultural outputs and the GDP. This impact is attributed to constraints associated with crop salinity-tolerance and food-safety regulations.

Figure 3 about here

4. Summary and concluding remarks

We developed a linked CGE - farm-management model of a water economy with representation for multiple water types characterized by different qualities. We employed the model to assess the impact of water shortage on the Israeli economy with particular focus on the agricultural sector - the largest water consumer in the economy. The CGE model incorporates a water sector with five water types: potable water, desalinated water, brackish water and secondary- and tertiary- treated wastewaters. The CES rates of substitution between different irrigation water types were estimated using data produced by a PMP model of land and water allocations (VALUE), which accounts for constraints associated with crop salinity-tolerance and food-safety regulations. We simulated water shortage scenarios based on the Long Term National Master Plan for The Water Economy (IWA, 2011). The results reveal that water shortage can lead to a significant decline of Israel's GDP, where a considerable part of the decline is attributed to the decrease in agricultural outputs. Yet, mitigating the negative impact by desalination is warranted.

From a methodological perspective, this study contributes to the existing literature by extending the representation of the water sector in a macro-level CGE model, with estimation of CES rates based on a micro-level land- and water-allocation model. The study is unique in that it captures potable and non-potable water characteristics within an economy-wide CGE model[11]. An adequate representation of qualities that vary among different water types is crucial for a reliable analysis of water management policies. We show that the level of substitution between different irrigation water types is not identical, and due to irrigation constraints related to water quality, is generally lower compared with rates used in previous studies. The lower substitution rates result in a larger impact of water shortage on the economy, hence increasing the benefit provided by desalination.

The approach adopted in this study can be improved in several areas. First, the representation of desalination as a water-shortage mitigation instrument can be improved. The CES rates estimated in this study do not change with the desalination levels; that is, they do not capture potential increase in the substitution between freshwater and treated wastewater, which is expected because the salinity of sewage reduces as the share of desalinated water in the potable water delivered to domestic use becomes larger.

Second, rather than using the micro-level model for estimating CES rates, one could create a hard bidirectional link between the macro- and micro-level models, and thereby improve the representation of the agricultural sector and the production effect of water sources with various salinity levels.

Third, in our CGE model there is one aggregate agricultural sector. As in Luckmann et al. (2014), a higher accuracy level can be obtained by dividing the agricultural sector into multiple sectors, grouping the various crops that are represented in VALUE based on

[11] Luckmann et al. (2014) also capture potable and non-potable water in their CGE model for the Israeli economy but have only two non-potable water types – brackish and reclaimed water – where no distinction is made between secondary and tertiary treated wastewater which possess significantly different qualities.

their suitability for non-freshwater irrigation which stems from salinity tolerance and food safety regulations.

Fourth, the household sector is represented in the CGE model by a single representative agent. Introducing multiple household agents in the model can provide a framework for addressing income distribution issues.

Finally, our CGE model is static. Expected future structural changes are accounted for only with respect to the water economy by relying on the Long Term National Master Plan developed by the Israeli Water Authority. Developing a dynamic model could capture future structural changes in the economy as well as long-run inter-temporal effects of water shortage.

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Appendix A. CES Estimation

Following Okagawa and Ban (2008), for some agricultural product *i* produced by two water types, the production level Q_i, is expressed by the CES production function

$$Q_i = A_i\left(\alpha_i W_{1i}^{\frac{\sigma_{12i}-1}{\sigma_{12i}}} + (1-\alpha_i) W_{2i}^{\frac{\sigma_{12i}-1}{\sigma_{12i}}}\right)^{\frac{\sigma_{12i}}{\sigma_{12i}-1}} \quad \text{(A1)}$$

where W_{1i} and W_{2i} are, respectively, the quantities of water types 1 and 2 used for producing product *i*, A_i is a production parameter, α_i is a distribution parameter and σ_{12i} is the elasticity of substitution between water types 1 and 2. Let P_1 and P_2 denote the prices of water types 1 and 2, respectively. From the first order conditions of a profit-maximizing firm we get

$$\frac{\alpha_i}{1-\alpha_i}\left(\frac{W_{1i}}{W_{2i}}\right)^{-\frac{1}{\sigma_{12i}}} = \frac{P_1}{P_2} \quad \text{(A2)}$$

Taking the logarithm and rearranging we get the regression equation:

$$\ln\left(\frac{W_{2ij}}{W_{1ij}}\right) = \beta_{12i} + \sigma_{12i}\ln\left(\frac{P_{2j}}{P_{1j}}\right) + u_{ij} \quad \text{(A3)}$$

where j denotes observation, $\beta_{12i} \equiv \sigma_{12i}\ln\left(\frac{1-\alpha_i}{\alpha_i}\right)$, and u_{ij} represents the errors stemming from the difference between the specifications in the VALUE model and the specifications in the herein described production model yielding Eq. (A3).

Composite water types are computed for use in the procedure employed for determining the hierarchical structure of irrigation water in IGEM. For the composite incorporating the pair of water types 1 and 2, the price P_{12} and quantity W_{12} are computed by

$$P_{12} = \left[\alpha_{12} P_1^{(1-\sigma_{12})/\sigma_{12}} + \left(1 - \alpha_{12}\right) P_2^{(1-\sigma_{12})/\sigma_{12}} \right]^{\sigma_{12}/(1-\sigma_{12})} \quad \text{(A4)}$$

$$W_{12} = \left[\alpha_{12} W_1^{(1-\sigma_{12})/\sigma_{12}} + \left(1 - \alpha_{12}\right) W_2^{(1-\sigma_{12})/\sigma_{12}} \right]^{\sigma_{12}/(1-\sigma_{12})} \quad \text{(A5)}$$

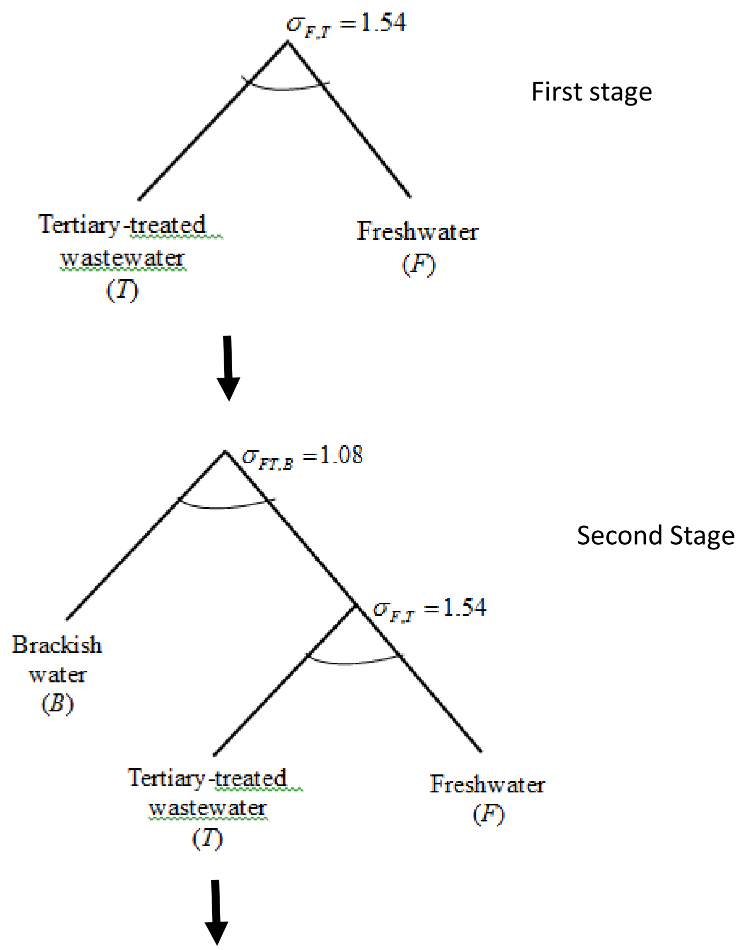
where $\alpha_{12} = W_1 / \left(W_1 + W_2 \right)$.

Appendix B. Scenario Definition

The scenarios fed into IGEM are based on data extracted from the Long Term National Master Plan for The Water Economy (IWA, 2011) and reflect the expected shortage in potable water expressed in MMY and in shortage percentages for two levels of desalination: 1) the 2010 level of 280 MMY; 2) Future level of 750 MMY which has been approved by the government for implementation by 2020. In each scenario, both the shortage and the relative shortage were calculated under desired water supply reliabilities (hereafter "reliability") of 75%, 90%, 95% and 100%.

The relative shortage in potable water expresses the expected shortage of potable water as a percentage of the overall needed quantity of potable water in that period, for given levels of desalination and reliability. The reliability levels in the IGEM model's scenarios correspond to the reliability levels in the Master Plan. These levels refer to the desired reliability of water supply to the economy and are derived from the probability of encountering a shortage in potable water – probability that stems from a statistical analysis of the gap between the projected future demand and anticipated future availability of natural potable water. Shortage of potable water at a reliability of 95% means that there is a probability of 5% that the shortage will be greater than the given value. Shortage at a reliability level of 100% means that the probability for a shortage greater than the given value is negligible. At the same time, it is important to note that even though the probability of having extreme values in all the events that influence the result in parallel, where each one is represented by a statistical distribution, is remote, this probability is nevertheless not zero. Hence, probabilistically what exists is not a reliability level of 100%, but only a reliability level that approaches 100%.

The shortage and relative shortage in potable water were calculated as follows. The expected quantities of natural potable water (natural freshwater) in the years 2020, 2030 and 2050 for different level of supply reliability were taken from the Master Plan's basic scenario (IWA, 2011, page 21) and appears in column 4 of the scenario table. The overall shortage (not counting desalination) is taken from the Master Plan's chart (IWA, 2011, page 23) which presents the result of a probabilistic analysis of the predicted gaps between supply and demand of natural potable water. Based on these results the shortage and relative shortage were calculated where the shortage is calculated by deducting the desalination level (either 280 or 750 MMY according to the scenario) from the overall shortage (for a given reliability level) whereas the relative shortage in percentages is calculated by the ratio between the shortage in MML and the summation of the shortage in MML and the quantity of available natural potable water.



$\sigma_{F,T} = 1.54$
First stage
Tertiary-treated wastewater (T)
Freshwater (F)
$\sigma_{FT,B} = 1.08$
Second Stage
$\sigma_{F,T} = 1.54$
Brackish water (B)
Tertiary-treated wastewater (T)
Freshwater (F)

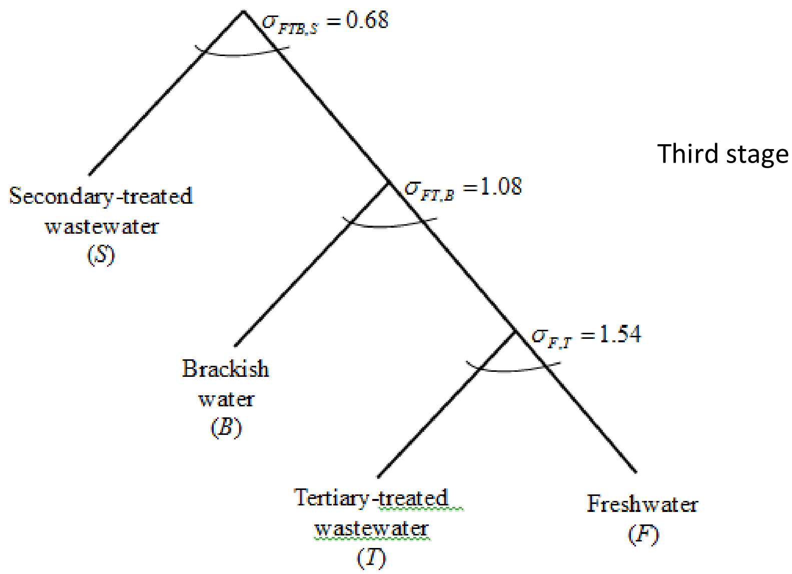


Figure 1 - Estimated nested CES structure of irrigation water inputs

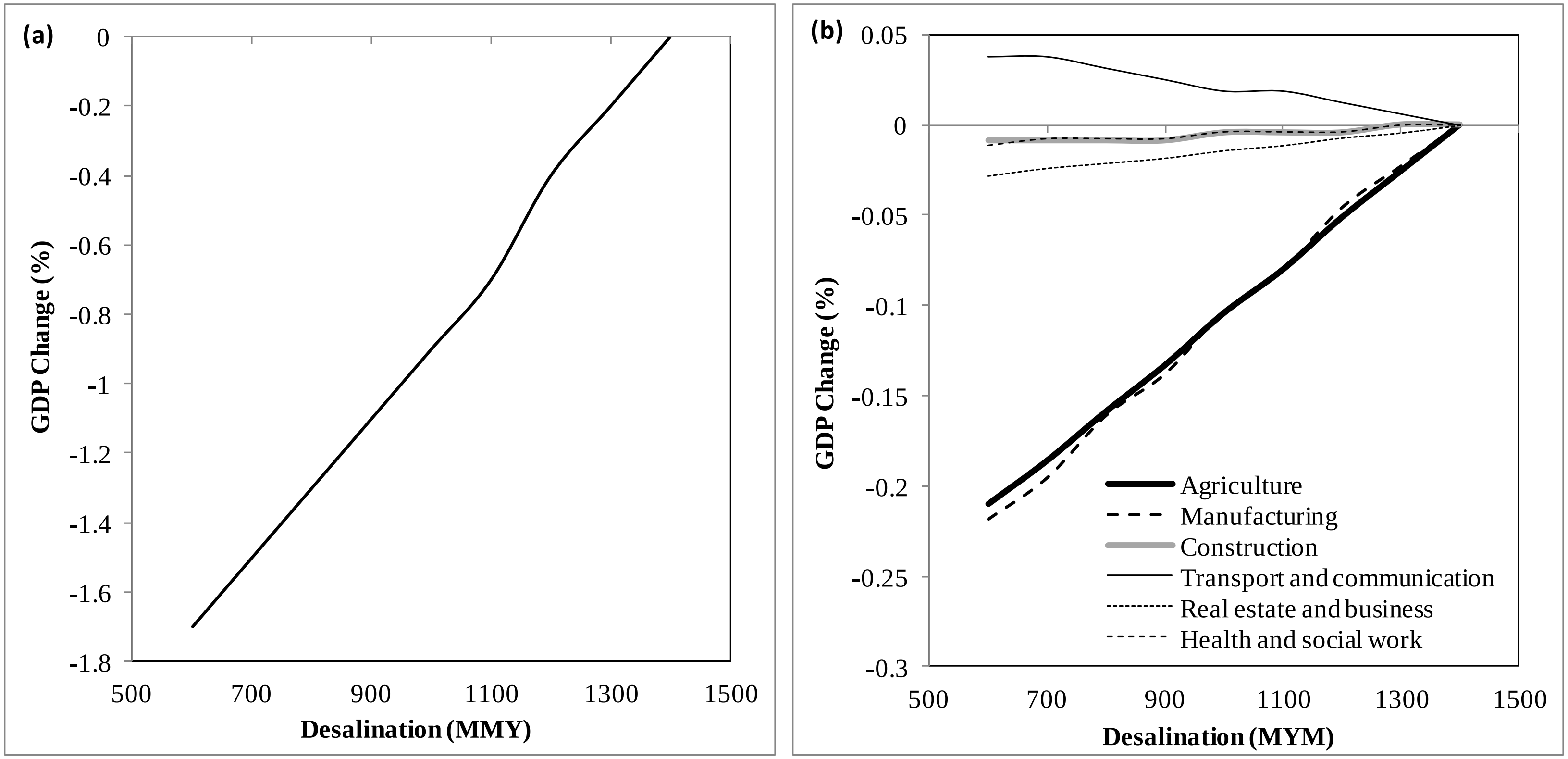


Figure 2 – Impact of desalination levels on GDP under reliability level of 90% in 2050.

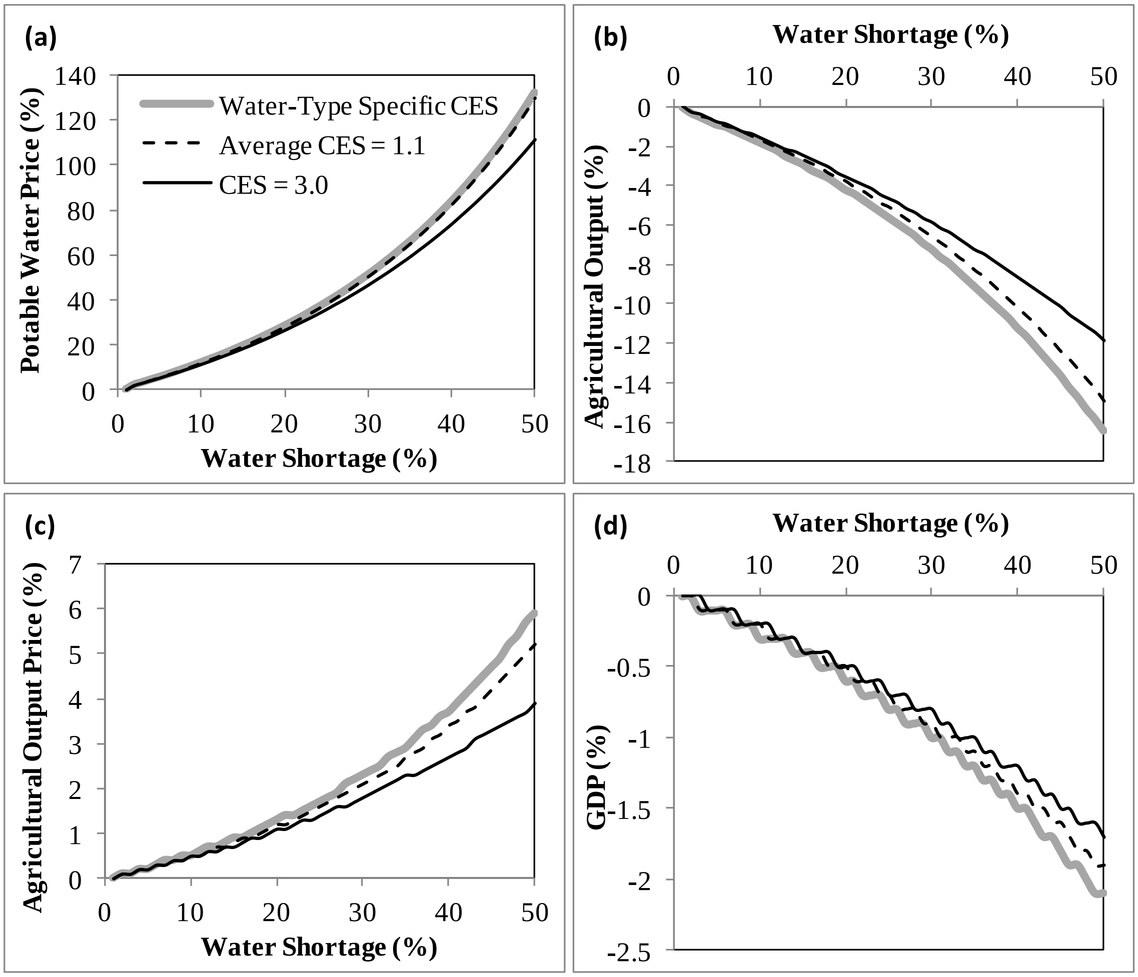


Figure 3 – Sensitivity to CES rates between irrigation water types