Is Improving Nile Water Quality 'Fruitful'?

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Abstract

Egypt's irrigation systems are inefficient; the use of water is profligate and soil salinity levels have risen. This has reduced agricultural yields and biased production patterns away from high value crops in favour of salt resistant crops. The need to improve irrigation water quality is accentuated by increasing demand for, and declining supplies of, water resources. This study uses a computable general equilibrium model, calibrated to an extended SAM and detailed satellite accounts for water quality, to assess the impacts of the huge investments needed to raise water quality. The results indicate strong positive economy-wide impacts in Egypt, which exceed the investment cost. Income increases by 4% and induce increases in the production of high-value crops; i.e., fruits (almost triple), seasonal vegetables (30-37%) and rice by (13%) with a 64% increase in rice exports. The study illustrates the importance of including water quality as a variable in the analyses of water systems.

Keywords Water Pollution, Irrigation Efficiency, Agricultural Productivity, Egypt, Computable General Equilibrium (CGE) Models.

JEL code Q53, Q15, D24, O55, C68

1. Introduction

Egypt's irrigation system relies on the Nile River, which has been subject to overexploitation and continuous water quality deterioration. Egyptian agriculture is dependent on irrigation, but inefficient systems have contributed to increased salinity and declining soil quality, with associated reductions in yields and the biasing of cropping patterns in favour of salt resistant crops. The estimated annual cost of using low quality water is 1.8% of GDP (MWRI, 2005a). One response, by the Egyptian government, was an Integrated Water Resources Management Plan (IWRMP) for 2000-2017 designed to improve water quality and reduce salinity levels. This study provides quantitative assessments of improving irrigation water and soil quality on crop yields across different irrigation seasons in Egypt.

The impacts of reduced agricultural yields and distorted cropping patterns have complex impacts. The volumes and patterns of agricultural exports and imports are affected, and domestic food prices are elevated. These effects have implications for the costs of production and the welfare of households. To explore these impacts a single-country Computable General Equilibrium (CGE) model, STAGE 2, is used. The model is calibrated to a Social Accounting Matrix (SAM) for Egypt 2008/09 that has been extended with detailed accounts for the Egyptian agricultural and irrigation systems (Osman *et al.*, 2015a and 2015b). Water quality indicators are incorporated using satellite accounts, allowing the modelling of key agronomic relationships, e.g. water/land salinity, soil fertility, and agricultural productivity. The study simulates the costs and the effects of an Egyptian Government programme to improve water quality and reduce salinity, and thereby increase agricultural yields and alter cropping patterns.

The results indicate that better quality irrigation water facilitates changing cropping patterns, expands the production of high value crops, boosts agricultural exports and reduces agricultural imports. These changes induce a decline in processed food exports and an increase in food imports. GDP increases markedly, more than compensating for the required costs to finance the investment, as do household incomes, welfare and consumption, with large increases in agricultural exports while agricultural imports decrease. Overall, there are strong positive economy-wide impacts, indicating that public investments in improving irrigation water quality are ‘fruitful’ for the Egyptian economy.

The paper is organized as follows. Section 2 provides a context for this study. The model, water quality satellite accounts and simulation scenarios are described in Section 3. Section 4 provides analyses of the results across sectors, seasons as well as socioeconomic impacts on households. Section 5 has concluding comments.

2. Context

Egypt is defined by the waters of the Nile.[4] Without the Nile, the Egypt of antiquity and today would not exist, which make the quantity and quality of the Nile waters available to Egypt critical. The abundance of Nile waters has been accompanied by serious water quality problems, from water borne infections, e.g., ecoli/bacterial infections associated with effluent discharges, to soil pollution issues (Osman *et al*., 2011) deriving from inefficient irrigation practices. Now Egypt faces multiple threats to its historic ability to rely on the Nile: the population (97 million in 2017) has grown rapidly (27 Million in 1960), and continues to grow rapidly (2.4% per annum in 2017 (CAPMAS, 2017)), which is placing increasingly large demands on the quantity of water while contributing to water quality problems. Downstream nations, especially Ethiopia, are demanding a more equitable distribution of the waters; and there are fears that climate change will reduce the rainfall in the Ethiopian highlands, the source of some 85% of the Nile waters, and increasing evaporation rates, thereby reducing the volume of water reaching Egypt.

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[4] In this paper, the river is called the Nile, but along its 6,650 km length it is known by various names.

The distribution of Nile waters is 'governed' by two main treaties. The Anglo-Egyptian treaty of 1929 ceded 48 Billion Cubic Metres (BCM) of the water to Egypt and 4 BCM to Sudan out of a total of 84 BCM (Howell, 1994; Lumumba, 2007). Notionally, the British represented the interests of its riparian colonies, but Ethiopia had no representation and never accepted this treaty. In 1959, Egypt and the Sudan, alone, revised the 1929 treaty: Egypt's allocation increased to 55.5 BCM and Sudan's to 18.5 BCM; after allowance of 10 BCM for seepage and evaporation, little was left for the other unrepresented riparian states. The Cooperative Framework Agreement (CFA) of 2010 was accepted by the downstream riparian states but Egypt and Sudan have indicated they will not accept the CFA. An agreement in 2015 between Egypt, Sudan and Ethiopia, which appears to provide recognition of the Grand Ethiopian Renaissance Dam (GERD), may indicate a more enlightened future.

Until the early 20th century, the Nile delta was subject to annual floods when the Nile is in spate. The floods are linked to the annual rains in the Ethiopian highlands, which massively increase the flow of the Blue Nile. Through history, there have been Egyptian attempts to control these floods, culminating in the construction of the Aswan Low Dam, from 1902 to 1933, and the Aswan High Dam, from 1960 to 1970.[5] Although these dams have greatly reduced the annual flooding of the Nile delta, and provided a method for controlling the year round availability of water in Egypt, they have also limited the deposits of fertile silts that were, overwhelmingly, from the Ethiopian highlands.[6] Economy-wide assessments of the High Aswan Dam indicate that Egypt has benefited greatly from control over the flow of water (Strzepek *et al.*, 2008).

There are increased demands in Egypt for potable water, domestic (non-potable) water and irrigation water. At the same time, supplies are reducing due to climate change and

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[5] Various dams on the Nile in Sudan have also contributed to managing the flow of Nile waters and the adverse impacts of floods.

[6] In parts of Sudan, especially south of Khartoum, on the White Nile, floods continue to deposit silts and raise soil fertility.

increases in take-off by downstream nations, especially Ethiopia and (North) Sudan. The effects, combined with water and soil pollution, mean Egypt must change how it uses the Nile waters.

The implications of climate change on water availability in the context of Egypt indicate the sensitivity of the Egyptian economy to restrictions on the volumes of irrigation water, with substantial reductions in agricultural wage rates and agricultural self-sufficiency and GDP growth, e.g., Yates & Strzepek (1996); Yates & Strzepek (1998); Strzepek & Yates (2000); Elshennawy *et al.* (2016). These studies also indicate the importance of including water resources, crop water use and the agronomic characteristics of land resources. There are no known CGE studies of water quality in Egypt.

This study focuses on the twin issues of irrigation and water quality in agricultural production. It builds on the limited number of studies of water quality, e.g., Brouwer *et al.* (2008) and Dellink *et al.* (2011) and water as an input to agricultural production, e.g., Robinson & Gueneau (2013), Luckmann *et al.* (2014) and Osman *et al.* (2016).[7]

Agriculture in Egypt is dependent on irrigation and relies on the Nile River.[8] Salinization levels are critical: 35% of Egypt's agricultural land suffers from high salinity, especially in the (over-populated) Nile Delta, where 60% of cultivated land in the northern Delta is salt affected (ICARDA, 2011).[9] Irrigation waters of various quality levels have distinct characterises with different impacts on crop yields, and biased cropping patterns

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[7] The literature of water related CGE is vast, see Liu *et al.* (2016) for global analysis; Beyene *et al.* (2018) and Schuenemann *et al.* (2018) for developing countries; Lennox & Diukanova (2011) and Llop & Ponce-Alifonso (2016) for regional analysis and Dinar (2014) for a recent survey.

[8] Nile contributes 83% of water followed by groundwater (11%) and non-conventional sources; i.e., recycling drainage water, treating sewage water and desalinating seawater. 90% of (8.4 million feddans) agricultural land is irrigated (a feddan is a non-metric measurement unit of land area equivalent to 1.037 acres, 0.420 hectares or 4,220 m^2.) Based on water resources, there are four agro-ecological zones: 1) old land located in the Nile Valley and Delta; 2) new land reclaimed from the desert surrounding the Nile Delta; 3) several oases around groundwater resources; and 4) rain-fed land located mainly in a narrow coastal strip along the Mediterranean in the Western Desert and Sinai.

[9] Nile Delta accounts more than 60% of total irrigated land. It is also the most populated area in Egypt with more than 60% of total population.

towards salt resistant crops (cotton, sugar beet and wheat). If water is specified as a homogenous production factor, it can/will generate misleading results (Tsur, 2005).

The IWRMP was launched for 2000-2017 with total buget of 162.7 billion L.E.[10]: 77% of the budget was allocated to improve water quality. IWRMP aims, *inter alia*, at discontinuing "of the practice of discharging untreated domestic wastewaters into irrigation drains, canals, or storm drains" in all houses in 27,000 small villages; implementing non-conventional treatment methods to reduce pollution loads; and upgrading the self-purification capacity of open drains (MWRI, 2005a, pp. 17, 43 and 70).[11] The cost-effectiveness of this project is important, particularly for a country with a debt-to-GDP ratio growing from 72% to 103% over the project's timespan (IMF, 2018).

Key salinity indicators are Electric Conductivity of Water (ECw) and Electric Conductivity of Saturated Soil Extract (ECe): ECw and other salinity indicators, in the Middle Delta, are strong correlated (Ali *et al.*, 2014). Studies have identified critical values for ECw and ECe and derived estimates of the adverse impacts on crop yield and productivity. High levels of ECe in different types of soil in the North East Delta are estimated to have reduced soil productivity by 46% between 1976-2011 (Kawy & Ali, 2012).

3. Model and Simulations

3.1 Model Specification

The CGE model is a variant of STAGE 2 (McDonald & Thierfelder, 2015) that encompasses the characteristics of the Egyptian agricultural and irrigation systems. The model is calibrated to an extended version of 2008/09 Egypt SAM (Osman *et al.*, 2015a and 2015b) with 102 accounts: 54 activities (23 of which are agricultural activities), 16 commodities, 19 factors, 5

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[10] L.E. is the abbreviation of the French caption of the Egyptian pounds - *livre égyptienne.* In 2008/09, an Egyptian pound was equivalent to 0.18 USD (WB, 2010).

[11] The project seeks to increase supply by securing 14% of future water requirements, by increasing the recycling of drainage water by 9.6 BCM.

institutions, 4 tax instruments, trade margins, savings/investment and rest of the world. The database distinguishes irrigated land from rain-fed land. For the former, water and irrigated land are segmented by irrigation season, i.e., winter, summer, *Nili*[12] and year-round, and by type of water, i.e., Nile water and groundwater. There are 16 water/land production factors for irrigated agriculture. The SAM accounts are listed in Table A1.[13]

The production activities have a 5-level nested constant elasticity of substitution (CES) structure (Figure 1). Intermediate inputs are combined using Leontief input-output coefficients. CES production technologies define aggregate value added from labour, capital and various types of irrigation water and land across irrigation seasons.

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[12] Before building the Aswan High Dam in 1970, the term *Nili* has been historically used referring to the Nile flood period from September to November.

[13] The SAM includes a 'Water Supply' activity providing water for non-agricultural uses as part of the account for trade and utilities distribution services; i.e., 'Trade' (Table A1).

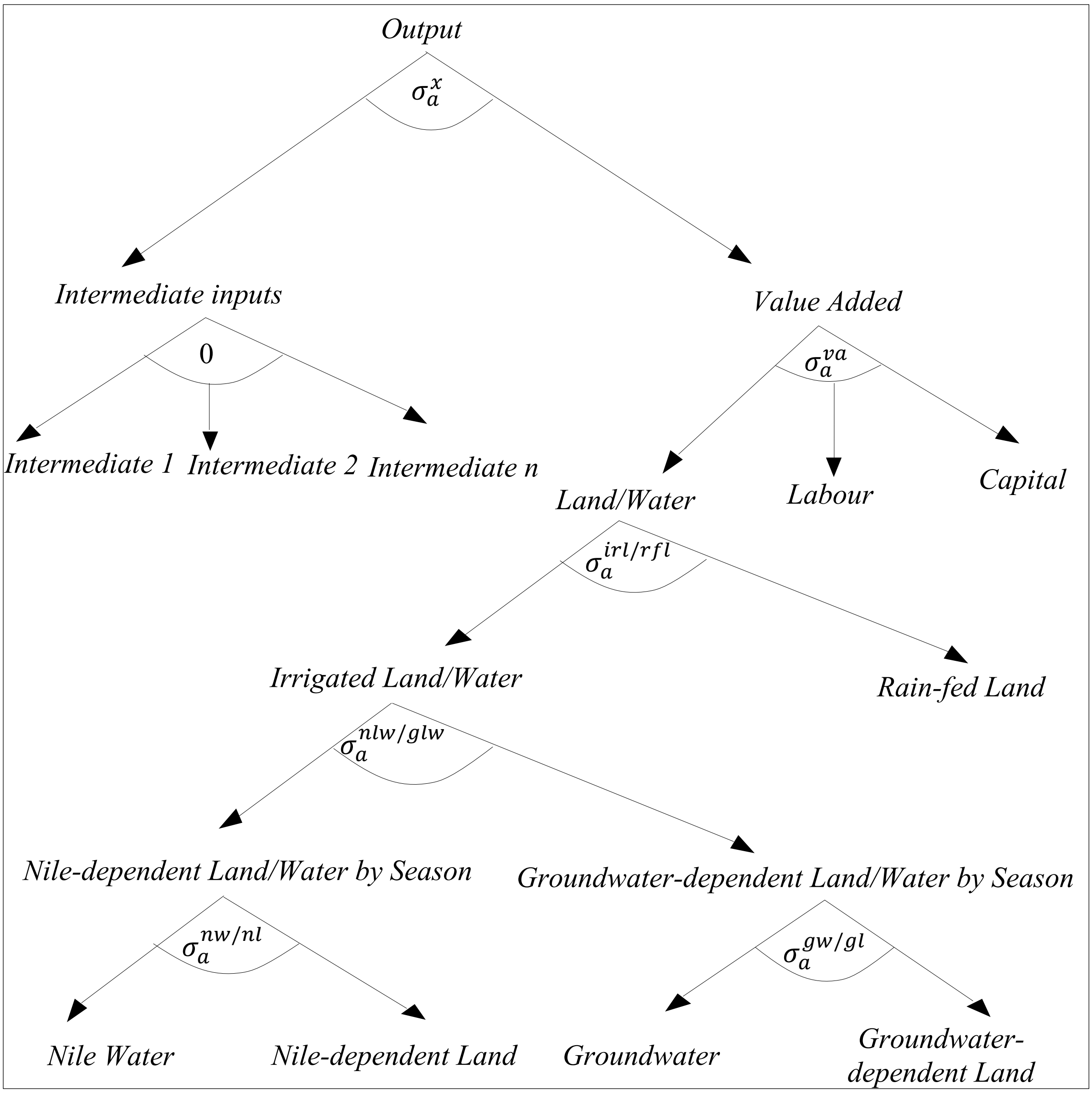

Figure 1: Agricultural Production Flows in the Model

Note: Here and thereafter, elasticity of substitution between Irrigated Land/Water and Rain-fed Land is $\sigma_a^{irl/rfl}$; between Nile-dependent Land/Water and Groundwater-dependent Land/Water is $\sigma_a^{nlw/glw}$; between Nile Water and Nile-dependent Land is $\sigma_a^{nw/nl}$; and between Groundwater and Groundwater-dependent Land is $\sigma_a^{gw/gl}$.

Source: Osman *et al.* (2016).

For Nile-dependent and groundwater-dependent activities, water and land are fully employed but season-specific, with fixed physical supply constraints for water and land (in thousands of feddan). Water and land supplies are fixed for each irrigation season, but flexible across agricultural activities within each season providing distinct seasonal water and land prices.

The model solves for water and land seasonal prices that ensure efficient allocation of water and land across crops cultivated in the same season.

Due to lack of estimated parameters for Egypt in general, and particularly for this highly disaggregated SAM, cautious guesstimates from the empirical literature are used. Section 4.4 tests the robustness of the results to different parameter values using systematic sensitivity analysis (SSA). Following Haddad *et al.* (2016) Egypt study, the elasticity of substitution between intermediate demand and value added ($\sigma_{\mathrm{a}}^{\mathrm{x}}$) is 2 and substitution between production factors ($\sigma_{\mathrm{a}}^{\mathrm{va}}$) is 0.8. Based on Calzadilla *et al.* (2011), elasticities of substitution between water and land ($\sigma_a^{irl/rfl}$, $\sigma_a^{nlw/glw}$, $\sigma_a^{nw/nl}$ and $\sigma_a^{gw/gl}$) equal 0.06. Agricultural commodities produced by different seasonal activities are aggregated using constant elasticity of transformation (CET) functions (Punt, 2013) with value of 4, which means that farmers are highly responsive to commodity price changes.

Household consumption is defined by a linear expenditure system (LES) with fixed minimum subsistence consumption and the remaining discretionary expenditures dependent on price and income. Income elasticities of demand range between slightly inelastic 0.4 (for food) and elastic 2.2 for non-food commodities (Aguiar *et al.*, 2016).

Egypt is assumed to be a price-taker on world markets (small-country assumption), and export demand is perfectly elastic at fixed world prices. CES demand functions define the optimal mix between imported and domestic goods while CET functions determine the optimal allocation of products between domestic and foreign markets. Following empirical studies (Aragie *et al.*, 2018; Hendy & Zaki, 2013; and Haddad *et al.*, 2016), the CES and CET elasticities are 2.0, and the results are then subject to SSA.

The factor market clearing conditions assume that (physical) capital is mobile and fully employed. Labour is assumed to be mobile, but in excess supply. Real wages are thus fixed until full employment is achieved. Underemployment in labour market is a reasonable assumption in a country where unemployment rate has been constantly increasing from 9% in 2008/09 to 13% in 2015 (ILO, 2017).

3.2 Satellite Accounts for Water Quality

Satellite accounts are used by the model to quantify direct, and indirect, requirements for water and land use in agricultural production.[14] Water and land satellite accounts have been used to analyse, *inter alia*, the impacts of water restrictions (Berrittella *et al*., 2007); model heterogeneity in land quality across different AEZs; and quantify water supply and demand at the river basin level (Taheripour *et al*., 2013). Linking water satellite accounts to other economic flows provides insights into the relationships between physical water systems and the economy (van der Veeren *et al*., 2004).

Crop tolerance to salinity depends, *inter alia*, on the type of crop and its stage of growth: cotton is unaffected at EC_e level of 7.7dS/m, while rice is sensitive to salt and its yield falls with salinity levels as low as 3.0 dS/m. Egyptian water quality satellite accounts were constructed: these identify crop yields with water of different qualities, and provide information on hydrological and agro-economics specifications of irrigation water and soil across crops and irrigation seasons in Egypt.

Data on potential yield reductions under various levels of water and land salinity (measured by EC_w and EC_e respectively) were collected for 71 crops (Table A2). These data were used to define (linear) yield-response relationships between water and land salinity levels and crop yields (Figure 2). Estimates of crop yields under different salinity levels (Rhoades *et al.,* 1992) and water and land quality in Egypt (NWRC, 2004) were used to identify the prevailing relationship between salinity and the yield shortfall for each crop.

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[14] The introduction of the European Water Framework Directive (European Commission, 2000) gives impetus to the demand for information about the economic value of water and the wider economic consequences of water policy and management in Europe.

These relationships define the yields of crops with different salinity levels and the level of salinity for each crop consistent with its full potential yield.

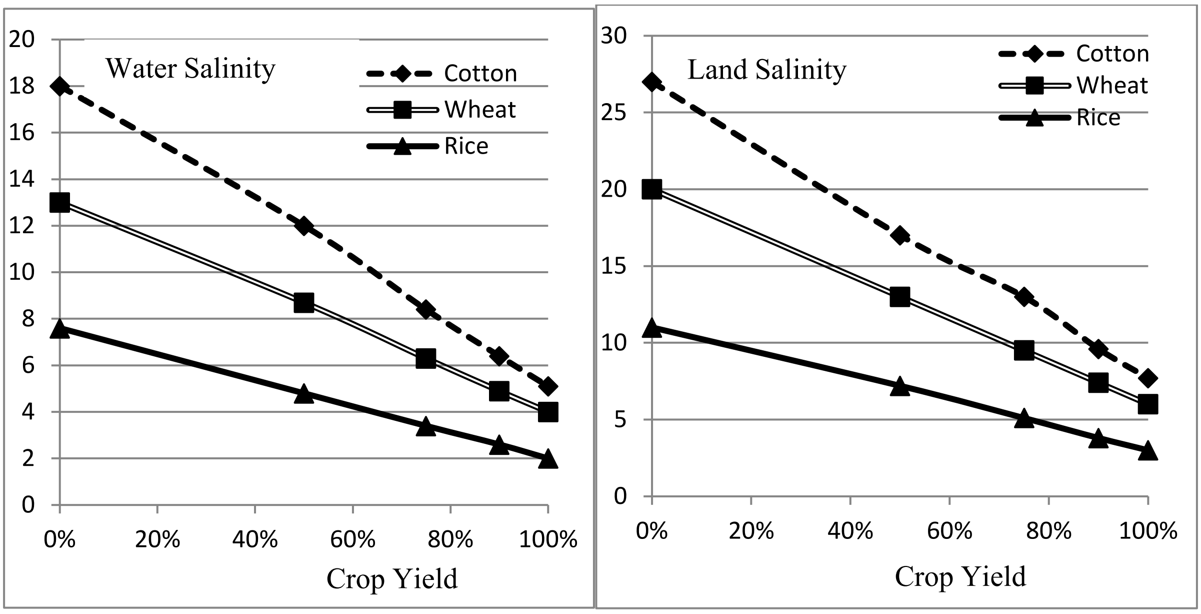

Figure 2: Crop Tolerance to Variations in Water and Land Salinity
Source: authors' elaboration based on Table A2.

The soils in the Nile Valley and Nile Delta are basically clay soils with typical flood plain characteristics (FAO/UNESCO, 1977). Using satellite images for the North East Nile Delta, Kawy & Ali (2012) identify three types of soil with distinctive properties: flood plain, lacustrine plain and marine plain and show high values of EC_e in different types of soil, with ranges (1.48 - 12.53), (11.40 - 15.45) and (17.40 - 20.34) dS/m respectively. Based on this empirical evidence, the model assumes that the initial levels of land and water salinity are those for flood plain. For cotton, only, it uses the parameters for lacustrine plain, which reflects cotton’s high tolerance to salinity.

Crop yield responses to changes in water salinity were then calculated. Improvements in water quality increase yields according to the yield-response relationships depicted in Figure 2. Reductions in water and land salinity induce percentage changes in yields for all crops across irrigation seasons (Table A3).

3.3 Simulation Scenarios

The study simulates a main scenario and two sets of sensitivity analyses (Table 1). All scenarios simulate the cost the Egyptian government incurs to finance the water quality improvement project and the economic benefits due to the achieved improvement.

Table 1
Simulation Scenarios

Scenario Name	**Scenario Code**	**Scenario Description**	
Main Scenario			
High Crop Yield	H-Yld	34% increase in government expenditure	Full potential reduction in water pollutants; by 10%
Sensitivity Analysis Set 1			
Partial Crop Yield	P-Yld	34% increase in government expenditure	Partial potential reduction in water pollutants; by 7%
Low Crop Yield	L-Yld	34% increase in government expenditure	Low potential reduction in water pollutants; by 5%
Sensitivity Analysis Set 2			
SSA Water/Land Substitution Elasticity	SSA_H-Yld	SSA for Water/land substitutability under the main scenario H-Yld	

Source: authors' elaboration.

Government expenditures on water quality improvements were around 9.5 billion L.E. per annum (MWRI, 2005a). The model adopts an investment-driven closure rule, where saving rates adjust to generate the required savings to finance the base year investment.[15] Hence, this expenditure is specified as an increase in exogenous government investments equivalent to 34% of the baseline government expenditure. This expenditure is assumed to be financed domestically, thereby avoiding a ‘free-lunch’ from unrequited external loans. The required additional government income is generated by an endogenous increase in public savings financed by changes in personal income tax, a non-distortionary lump sum tax.

The IWRMP aims to reduce the concentration of pollutants in irrigation water by 10% (MWRI, 2005a). The potential improvements in water quality are translated into enhancements in crop yields shocking the productivity at the second level of the production

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[15] The combination of exogenous investments and foreign savings, known as Johansen closure, avoids misleading changes in household welfare due to changes in foreign savings and investments in a single-period model.

nest (Figure 1) which aggregates water and land. The simulated shocks reflect heterogeneous increases in crop yields according to different soil resilience, water salinity and crop salinity tolerance, as described in Section 3.2.

The main scenario (H-Yld) assumes that the full potential increases in productivity generated by the improvements in water/land quality are achieved. The estimated increases in crop yields generated under the planned 10% reduction in water pollutants are reported in Table A3.

To explore the robustness of the results, two other scenarios are implemented; these assume less than the full potential productivity increases without cost savings. The second and third scenarios (P-Yld and L-Yld) assume 7% and 5% reductions in water pollutants respectively (Table A3), i.e., only 70% and 50% of the potential productivity gains are achieved. These scenarios assess the extent to which less than target crop yields, produce cost effective returns. The results from all scenarios were then subject to SSA (only SSA_H-Yld are reported) to assess the robustness of the results to changes in crucial model parameters.

Table 2
Macroeconomic and Welfare Results

	H-Yld	P-Yld	L-Yld
	Real percentage change		
GDP (expenditure)	3.98	2.73	1.92
Private consumption	3.49	2.05	1.11
Government consumption	2.91	2.00	1.42
Investment consumption	4.66	4.66	4.66
Import demand	3.68	2.04	1.26
Export supply	5.14	2.88	1.78
Absorption	3.64	2.51	1.78
Total domestic production	3.96	2.80	2.04
Total intermediate inputs	3.49	2.76	2.17
	Billion LE		
EV on household consumption	28.21	16.63	9.01
Household Income	4.12	2.84	2.02
	Percent		
Household savings rate	-6.09	-3.63	-1.98
Household income tax rate	60.00	59.76	60.81

Source: authors' elaboration on model results.

4. Results and Discussion

Economy-wide impacts are positive under all scenarios (Table 2). The full potential water quality improvement scenario (H-Yld) generates 4% increases in GDP. With partial and low yield scenarios (P-Yld and L-Yld), changes in GDP remain favourable, indicating that the planned investments in water quality are worthwhile even with lower crop yield responses. The three scenarios are welfare improving. Households are better off under H-Yld with gains worth 28 billion L.E. measured by equivalent variation. Income and substitution effects explain the generated welfare gains. Households experience 4% increase in income (Table 2), and prices for most of the consumption goods decline as supplies increase (Table 3).

The results across sectors, seasons and production factors indicate that the results for the three scenarios are monotonically increasing with the improvements in water quality. Hence, the rest of the analyses are concentrates on the main scenario, H-Yld, with results of P-Yld and L-Yld presented for comparison.

Table 3

Domestic Markets: % Change relative to baseline

	Supply Price			Supply Quantity		
	H-Yld	**P-Yld**	**L-Yld**	**H-Yld**	**P-Yld**	**L-Yld**
Wheat	-0.80	-0.32	-0.14	1.61	1.24	0.90
Cereals	-0.97	-0.15	0.14	2.01	1.48	1.03
Rice	-20.38	-15.14	-11.33	3.89	2.69	1.84
Vegetables	-20.91	-15.54	-11.58	4.90	3.26	2.15
Fruits	-37.43	-23.64	-11.95	33.53	14.30	6.04
Coffee Tea	-12.54	-8.91	-6.44	4.13	2.85	1.93
Other agri	-7.19	-5.03	-3.55	0.49	0.31	0.12
minerals gas	4.78	3.40	2.44	2.41	2.02	1.54
Food products	1.81	0.87	0.32	3.62	2.24	1.33
Other transportable goods	0.80	0.93	0.90	3.36	2.54	1.93
Metal machinery	0.05	0.58	0.73	2.59	2.15	1.79
Construction	1.78	1.49	1.20	8.41	8.31	8.25
Trade	3.73	2.59	1.82	3.21	2.09	1.32
Financial services	3.67	2.68	1.96	3.38	2.13	1.26
Business services	2.89	2.19	1.64	3.12	1.99	1.20
Social services	1.07	0.85	0.65	3.38	2.16	1.36

Source: authors' elaboration on model results.

4.1 Cross-sectoral Analysis

The results are driven by the different degrees of tolerance to salinity by, and water intensity of, different crops. As salinity levels decline so the yields of crops that are less salt tolerant increase, relative to other crops, and the optimal output mix changes: reflecting the importance of the salinity constraint on the optimal mix of crops. Hence, there are favourable impacts for many crops, Tables 4 and 5. Significant output expansions are reported for fruits (almost triple) and seasonal vegetable sectors (30-37%), which induce increases in their exports. Fruits and vegetables are salt-sensitive, hence, reducing salinity level entails greater increases in yields compared to other crops (Table A2). Fruits and vegetables are crucial sectors for the Egyptian economy. Fruits contribute 7% of agricultural GDP and virtually half of agricultural exports. Vegetables comprise 26% of agricultural GDP, evenly spread over the winter and summer seasons, and consume some 6% of Nile water used in each of the irrigation seasons. The expansions of these two sectors contribute significantly to the positive economy-wide impacts.

Table 4

Real GDP (value-added)

	Baseline			Production, % Change relative to baseline		
	Level, Billion LE	GDP (share, %)	Agri. GDP (share, %)	H-Yld	P-Yld	L-Yld
W. Wheat & Cereals	20.36	1.9%	14.7%	2.16	1.92	1.55
W. Legumes	0.70	0.1%	0.5%	12.73	9.98	7.68
W. Sugar Beet	2.52	0.2%	1.8%	-48.88	-37.27	-29.20
W. Fodders	21.88	2.0%	15.8%	34.14	24.22	17.36
W. Fibbers	0.12	0.0%	0.1%	46.94	32.61	23.11
W. Medical Plants	0.34	0.0%	0.2%	33.32	23.41	16.70
W. Vegetables	16.75	1.6%	12.1%	30.15	21.23	15.24
S. Rice	9.74	0.9%	7.0%	12.78	8.73	6.05
S. Other Crops	10.61	1.0%	7.7%	-13.11	-9.47	-7.19
S. Sugar Cane	4.26	0.4%	3.1%	-37.31	-29.03	-22.36
S. Cotton	3.49	0.3%	2.5%	-12.49	-8.99	-6.62
S. Fodders	3.08	0.3%	2.2%	-12.02	-8.65	-6.36
S. Oily Crops	1.81	0.2%	1.3%	-20.42	-15.81	-12.10
S. Medical Plants	0.13	0.0%	0.1%	-9.19	-6.45	-4.65
S. Vegetables	16.31	1.5%	11.8%	35.22	24.77	17.77
N. Rice	0.04	0.0%	0.0%	8.50	5.55	3.64
N. Other Crops	1.66	0.2%	1.2%	-13.92	-10.57	-8.02
N. Fodders	0.36	0.0%	0.3%	11.19	8.35	6.11
N. Oily Crops	0.01	0.0%	0.0%	-14.54	-11.13	-8.43
N. Medical Plants	0.00	0.0%	0.0%	24.94	18.08	13.12
N. Vegetables	2.51	0.2%	1.8%	37.31	26.26	18.82
Fruits	9.29	0.9%	6.7%	195.06	76.51	29.36
Other agri	12.29	1.1%	8.9%	0.49	0.31	0.12
Agri. GDP	**138.27**	**12.9%**	**100%**			
Non-Agri. GDP	**932.23**	**87.1%**				
Total	**1070.50**	**100%**				

Note: Here and thereafter W., S., N. and Y. refer to the irrigation seasons: winter; summer; Nili and year-round.

Source: authors' elaboration on model results.

Rice contributes 7% of agricultural GDP, and rice exports are the second important exporting crop (after cotton). Rice output and exports expand by 13% and 64%, respectively. Variations in water availability and quality are main determinants of rice production. Rice is a water-intensive crop, cultivated mainly in the Northern Delta, and consumes more than 30% of annual Nile water and more than half of summer water. The irrigation of rice with large quantities of water improves soil quality by 'flushing' out salts. Consequently, "… 700,000 feddans of rice cultivation are required annually in order to prevent salt-water intrusion and to maintain soil quality" (MWRI, 2005b, p. 34). Without the simulated water quality improvement, the increase in rice production would have required some 4% (1.4 BCM) of Nile water.

Table 5

External Trade

	Baseline Exports		% Change relative to baseline		
	Level (Billion LE)	**Share (%)**	**H-Yld**	**P-Yld**	**L-Yld**
Wheat	0.02	0.0%	4.08	4.32	3.86
Cereals	0.06	0.0%	24.89	19.46	14.97
Rice	1.56	0.6%	64.04	44.51	31.55
Vegetables	4.16	1.6%	71.98	49.44	34.59
Fruits	5.14	2.0%	323.34	128.30	49.38
Coffee Tea	3.32	1.3%	68.91	47.87	33.82
Minerals, gas	53.01	20.4%	-9.74	-5.28	-2.99
Food products	20.90	8.0%	-2.13	1.19	2.37
Other goods	47.41	18.2%	-0.07	1.02	1.09
Metal machinery	22.90	8.8%	1.36	1.72	1.39
Construction	3.75	1.4%	4.26	6.18	7.07
Trade	86.83	33.4%	-4.58	-2.12	-1.04
Financial services	1.50	0.6%	-4.15	-2.18	-1.31
Business services	7.70	3.0%	-4.48	-2.23	-1.25
Social services	1.77	0.7%	0.68	1.42	1.39
Total	**260.00**	**100%**			
	Baseline Imports		**% Change relative to baseline**		
	Level (Billion LE)	**Share (%)**	**H-Yld**	**P-Yld**	**L-Yld**
Wheat	10.21	3.3%	0.27	-0.43	-0.71
Cereals	5.05	1.7%	0.33	0.13	-0.03
Rice	0.05	0.0%	-33.95	-26.81	-20.98
Vegetables	2.19	0.7%	-34.20	-27.10	-21.19
Fruits	0.87	0.3%	-47.58	-34.03	-18.88
Coffee Tea	12.96	4.2%	-20.12	-15.53	-11.96
Minerals, gas	18.92	6.2%	12.76	7.97	5.15
Food products	32.24	10.6%	7.71	2.97	0.63
Other goods	72.93	23.9%	5.32	3.39	2.40
Metal machinery	121.13	39.7%	3.00	2.29	1.92
Construction	1.45	0.5%	12.61	10.43	9.41
Trade	4.84	1.6%	11.38	6.35	3.66
Financial services	0.50	0.2%	11.42	6.59	3.89
Business services	12.94	4.2%	9.48	5.42	3.17
Social services	9.21	3.0%	5.91	2.84	1.34
Total	**305.49**	**100%**			

Note: Given the small country for Egypt, world prices are fixed. The exchange rate adjusts in order to clear the external balance, which is fixed at its initial level (in foreign currency units).

Source: authors' elaboration on model results.

Despite its importance as a subsistence crop (accounting for 24% of domestic agricultural demand), wheat production experiences trivial expansions under all scenarios. ‘Wheat & Cereals’ represents 15% of agricultural production, and is one of the main users of Nile land (almost 30%) using a tenth of Nile waters. Wheat (and barley) tolerates high salinity, thus, water quality improvements have lesser impacts compared to other crops.

High salinity tolerance explains the prevalence of cotton production; the Egyptian ‘white gold’. Cotton has been a major income source for farmers providing, with the textile industry, employment to several million workers. But the falling price of long staple fine Egyptian cotton and increases in cropping options, induce farmers to reduce cotton production.

4.2 Cross-seasonal Analysis

All bar one winter crop expand output under all scenarios. Winter is the main agricultural season in Egypt; contributing 45% of total agricultural products. Reducing water salinity is more effective during winter, when crops use 32% of Nile waters with lower quality. The expansion of winter crop production, together with year-round fruits and vegetables, generate most of the economy-wide positive impacts.

Sugar beet and sugar cane can be cultivated in saline soil (Mohamed *et al.*, 2007, p. 121). Production sugar beet, a winter crop, and sugar cane, a summer crop, decrease by 49% and 37%. Although, Egyptian sugar cane yields are among the highest in the world, and it occupies land for 3 successive years, it is a water-intensive crop that consumes 15% of the summer Nile water. Water quality improvement leads to the reallocation of irrigation water to other summer crops (i.e., rice and vegetables) but at the expense of reducing raw sugar output and, hence, processed food.

4.3 Factor Income and Unemployment

Returns to capital increase markedly, while the unemployment rate decline by 53%, 38% and 28% under the three scenarios. Thus both labour and capital realise strong increase in incomes (Table 6). In contrast, returns to land decline for many land types.

Table 6

Agricultural Factor Income (Percentage change)

	H-Yld	**P-Yld**	**L-Yld**
Capital	4.16	3.04	2.22
Labour	4.74	3.42	2.51
Rain-fed Land	-7.41	-5.59	-4.35
Nile-depenent Factors			
W. Land	-1.25	-0.70	-0.55
S. Land	-13.47	-10.17	-7.78
N. Land	-9.81	-7.50	-5.77
Y. Land	187.19	68.84	25.45
W. Water	3.70	3.02	2.23
S. Water	-16.77	-13.00	-10.11
N. Water	-17.94	-13.78	-10.58
Y. Water	187.19	68.84	25.45
Groundwater-depenent Factors			
W. Land	1.05	1.10	0.86
S. Land	-15.33	-11.58	-8.85
N. Land	-11.14	-8.49	-6.52
Y. Land	187.19	68.84	25.45
W. Water	0.81	0.91	0.71
S. Water	-15.47	-11.52	-8.73
N. Water	-15.22	-11.68	-8.96
Y. Water	187.19	68.84	25.45

Source: authors' elaboration on model results.

The prices for many water and land categories decline and incomes drop. The changes in Nile-dependent factor prices are the main determinants of structural changes, even when decreases in groundwater-dependent factor prices are greater. Nile water/land accounts for some 85% of agricultural value added and 90% of irrigated agriculture. Groundwater and land irrigated by groundwater have small shares in agricultural value added (less than 2%) and of irrigated agriculture (8%).

As Nile water and land qualities improve, their rents decrease, particularly in the summer season, because of the increased flow of factor services from fixed quantities of land and water. This increases the effective land and water factor endowments, relative to other factors, and relaxes the constraints imposed by the relative scarcity of land and water. The combination of increased economic activity and relative unimportance of agriculture as a source of demand for labour and capital results in the price of land declining.

The expanding summer activities, i.e., rice and vegetables, attract capital from other activities, cause the price of capital to increase, and reduce unemployment. These structural changes push capital price to rise and labour unemployment to drop. This increases the production costs for summer crops and contributes to the incentives to change output mix.

Apart from slight increases in factor incomes during winter season, all other seasonal factor incomes drop markedly. EC_w is higher in Nile waters during the winter season: "[A] decrease the flow level of Nile in winter tends to concentrate the ions, resulting in the EC levels increase [sic], where EC and the water level were inversely related" (Abdel-Satar *et al.*, 2017, p. 24). Due to dilution impact, pollutant levels drop in summer when crops absorb 58% of total Nile waters, which explains the increased production of most of the winter crops. Reducing in water salinity is particularly advantageous to winter crops, which is consistent with FAO guidance that "If possible, drainage should be limited to wet seasons only, when the salty effluent inflicts the least harm" (Mateo-Sagasta & Burke, 2012, p. 38).

Year-round water and land factors experience almost threefold-increases in income under the H-Yld scenario. This is explained by the huge expansions in fruits. Fruit farms owners are the most beneficial of the water quality improvement.

Overall, the results show that, without increasing water requirements, Egypt can expand the production and exports of high value crops, e.g., fruits, vegetables and rice, by improving water quality. These increases in output and exports can be used to fund imports of staples, e.g., processed food and wheat, without adversely impacting on the trade balance and thereby improving food security.

4.4 Systematic Sensitivity Analysis

With deductive economic models the results cannot not be validated or contradicted against historical records. A validation process, following Dixon & Rimmer (2012), was performed to verify that the results were computed correctly (they are derived from model's theory and data) and that the results reflect the behavioural relationships in the model works. For CGE models, the ability to explain the results is vital in assessing what has been taken into account in an analysis, whether the model's data are up-to-date and accurate, and whether the model mechanisms are adequate to represent the behaviour of the analysed economy (Tonini *et al.*, 2013).

The robustness of the model's results to changes in exogenously defined parameters was evaluated using SSA with a Monte Carlo approach;[16] Osman *et al.* (2016) show that SSA demonstrates the robustness of the model results against the choice of the exogenous parameters. The sensitivity of the results to the elasticities of substitution between water and land, and the production and export transformation elasticities, were evaluated; the discussion in the text focuses on the elasticities of substitution between water and land.[17] It is assumed that the elasticity of substitution between water and land for each agricultural activity follows an independent identically distributed (i.i.d.) normal distribution, N (μ,σ^2), where the mean is the employed elasticity value used in the model, 0.06 (see above), and the variance is one third of the mean.[18] SSA performs 5,000 Monte Carlo independent draws for the H-Yld scenario. For each draw, a new elasticity parameter is selected for each commodity. For each commodity, the selected parameter is not related to the one for other commodities. Once the new elasticity is selected, it remains constant along the other lower levels of the production tree.

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[16] For an explanation of the Monte Carlo approach, see (Belgodere & Vellutini, 2011).

[17] Results for a series of other SSA scenarios for σ_a^{va} and CET parameters are available upon request.

[18] The distribution is truncated on the left side to keep a well-behaved functional form of the CES production function (the elasticity values enter the CES function as a power in the equivalent terms).

SSA reports the minimum and maximum values, as well as the percentage change between them, the mean and the standard deviation (SD) for sectoral agricultural production. Figure 3 depicts the absence of any direct relationship between percentage change of Fruits output and elasticity values. The SSA affirms the robustness of the results to variations in values of the elasticity of substitution between water and land, which demonstrates that the agricultural production results are mainly determined by the simulated shocks and by the initial share parameters of each production function.

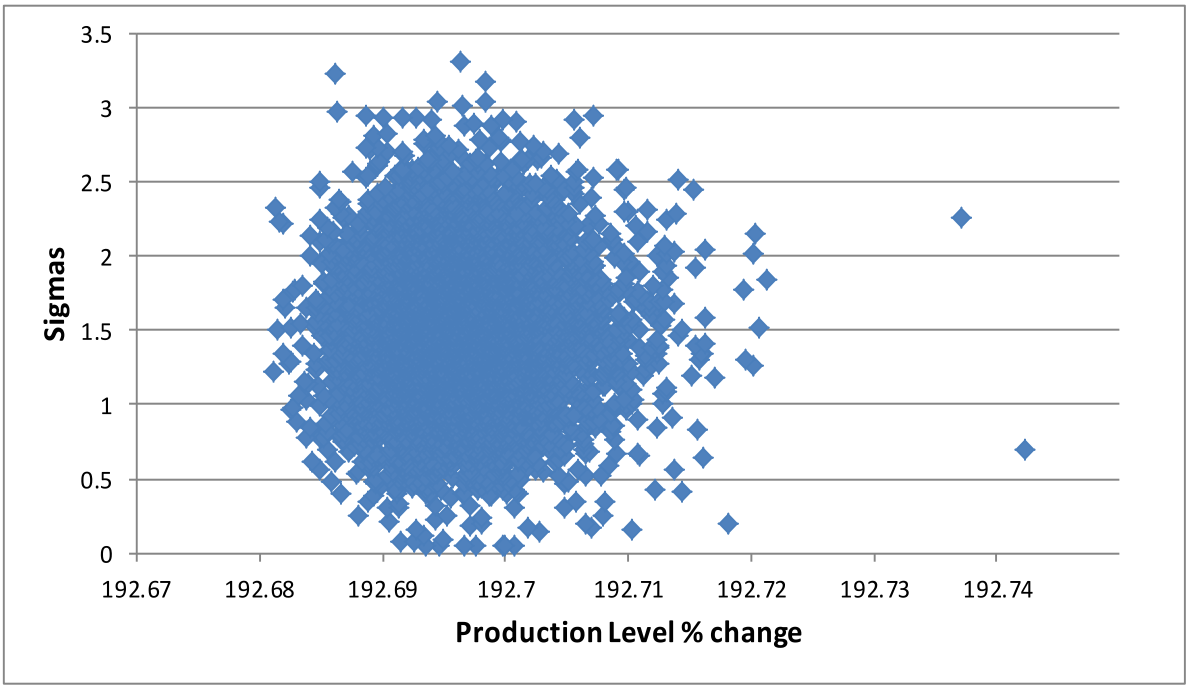

Figure 3: SSA Scatter, Fruits (% production change versus sigma values)

Source: authors' elaboration on model results.

5. Conclusions

Globally increasing demands for, and decreasing supplies of, water will have important implications for global food production systems that are increasingly dependent on irrigation schemes. Irrigation is globally the largest source of demand for water resources, yet the economic implications of improving the efficiency of water use in irrigation schemes has been underexplored with many studies emphasising changes in per capita water supplies due to climate change and population pressures. Among the issues raised by irrigation schemes are the adverse impacts of poorly designed schemes for water and land quality; this study illustrates the importance of including water and land quality as variables in analyses of water systems.

Countries will need to economise on water use, which strongly implies the need for changes in irrigation systems. Economic analyses of such changes will need to include more systems analyses of irrigation methods that capture the changes in production costs associated with different irrigation methods, including information about related water and soil qualities. The results from this study demonstrate that, despite the high costs of addressing water quality problems, the potential economic benefits are large. The serious water quality issues in Egypt indicate that future studies will need to treat water quality issues on a par with water quantities.

This study has examined some of the implications of improving the water quality in Egypt's profligate and inefficient irrigation systems, and thereby provides useful insights into the economic implications of improved water quality. The potential economic benefits to Egypt from addressing irrigation-water quality problems are large. Improving water quality, even without reducing water requirements, should allow Egypt to achieve large increase in the production of various high value crops, e.g. fruits, vegetables and rice, which can be traded to purchase staples, e.g. wheat, and raise national income. Investing in improving water quality will increase the availability and affordability of major crops and, hence, improve food security in Egypt.

Such investments are increasing likely to be important since " … ongoing salinization of the agricultural lands of the Nile Delta could rapidly accelerate due to increased upstream withdrawals …….. resulting in Egypt having less water available to flush residual salts into the Mediterranean" according to the International Non-partisan Eastern Nile Working Group (J-WAFS, 2015, p. 12).

In the future, Egypt will need to further economise on water use, which strongly implies the need for further changes in its irrigation systems. Moreover, Egypt's growing population will produce ever greater demands for potable water, which suggests the desirability of economic studies for an integrated water system in Egypt.

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Appendix

Table A1: Egypt SAM Accounts (2008/09)

SAM Activity					
1	Winter Wheat & Cereals	19	Nili Oily Crops	37	Education
2	Winter Legumes	20	Nili Medical Plants	38	Social Services
3	Winter Sugar Beet	21	Nili Vegetables	39	Arts Entertainment
4	Winter Fodders*	22	Fruits	40	Other Services
5	Winter Fibres	23	Other Agriculture, Forestry, Fishing	41	Financial Services
6	Winter Medical Plants	24	Mining	42	Insurance
7	Winter Vegetables	25	Manufacturing	43	Public Services
8	Summer Rice	26	Electricity gas	44	Defence
9	Summer Other Crops	27	Water Supply	45	Public Safety
10	Summer Sugar Cane	28	Construction	46	Economic Affairs
11	Summer Cotton	29	Trade	47	Environmental Protection
12	Summer Fodders*	30	Suez Canal	48	Housing & Community Amenities
13	Summer Oily Crops	31	Transportation	49	Health
14	Summer Medical Plants	32	Accommodation Services	50	Recreation, Culture and Religion
15	Summer Vegetables	33	Information Communication	51	Education
16	Nili Rice	34	Real Estate	52	Social Protection
17	Nili Other Crops	35	Professional Services	53	Non-profit Activities Serve Households
18	Nili Fodders*	36	Administrative Services	54	Subsistence Household Activities
SAM Commodity					
55	Wheat	60	Beverages	65	Metal & Machinery Equipment
56	Cereals	61	Other Agriculture, Forestry, Fishery	66	Construction
57	Rice	62	Ores, Minerals & Gas	67	Trade
58	Vegetables	63	Food Products	68	Financial Services
59	Fruits	64	Other Transportable Goods	69	Business Services
				70	Social Services
SAM Production Factor					
71	Labour	77	Winter Nile Water	83	Nili Groundwater-dependent Land
72	Capital	78	Summer Nile Water	84	Year-round Groundwater-dependent Land
73	Winter Nile-dependent Land	79	Nili Nile Water	85	Winter Groundwater
74	Summer Nile-dependent Land	80	Year-round Nile Water	86	Summer Groundwater
75	Nili Nile-dependent Land	81	Winter Groundwater-dependent Land	87	Nili Groundwater
76	Year-round Nile-dependent Land	82	Summer Groundwater-dependent Land	88	Year-round Groundwater
				89	Rain-fed Land
SAM Institutions					
90	Non-financial Enterprises	94	Government	98	Tariffs
91	Financial Enterprises	95	Sales Tax	99	Savings-Investment
92	Non-profit Institutions Serve Households	96	Indirect Tax	100	Trade Margins
93	Households	97	Direct Tax	101	Rest of the World

* Egyptian clover.

Source: Osman *et al.* (2015b).

Table A2: Potential Yield Reduction from Saline Water (EC_w) and Saline Land (EC_e) (Selected crops, dS/m)

Crop	Yield Reduction (%)									
	0%		10%		25%		50%		100%	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Barley	8.0	5.3	10.0	6.7	13.0	8.7	18.0	12.0	28.0	19.0
Cotton	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0	27.0	18.0
Sugarbeet	7.0	4.7	8.7	5.8	11.0	7.5	15.0	10.0	24.0	16.0
Wheat	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20.0	13.0
Rice	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11.0	7.6
Sugarcane	1.7	1.1	3.4	2.3	5.9	4.0	10.0	6.8	19.0	12.0
Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10.0	6.7
Broadbean	1.5	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12.0	8.0
Beet, red	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15.0	10.0
Squash, scallop	3.2	2.1	3.8	2.6	4.8	3.2	6.3	4.2	9.4	6.3
Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13.0	8.4
Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10.0	6.7
Pepper	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Bean	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Turnip	0.9	0.6	2.0	1.3	3.7	2.5	6.5	4.3	12.0	8.0
Barley (forage)	6.0	4.0	7.4	4.9	9.5	6.4	13.0	8.7	20.0	13.0
Wheatgrass	3.5	2.3	6.0	4.0	9.8	6.5	16.0	11.0	28.0	19.0
Alfalfa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16.0	10.0
Lovegrass	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14.0	9.3
Corn	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15.0	10.0
Clover, berseem	1.5	1.0	3.2	2.2	5.9	3.9	10.0	6.8	19.0	13.0
Orchard grass	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18.0	12.0
Foxtail, meadow	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12.0	7.9
Clover, red	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, alsike	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, ladino	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, strawberry	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Date palm	4.0	2.7	6.8	4.5	11.0	7.3	18.0	12.0	32.0	21.0
Grapefruit	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0	5.4
Orange	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0	5.3
Peach	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12.0	7.9
Almond	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.8	6.8	4.5
Plum, prune	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Blackberry	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Boysenberry	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Strawberry	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4.0	2.7

Notes: 1. $EC_e = 1.5\ EC_w$; 2. For a full list of the 71 crops, see the original source.

Source: Ayers & Westcot (1985, pp. 31-33).

Table A3: Crop Yield Responses to Changes in Water Salinity (Percentage change)

	H-Yld	**P-Yld**	**L-Yld**
	Winter Crops		
Wheat & Cereals	0.0357	0.0250	0.0179
Legumes	0.0836	0.0586	0.0418
Sugar Beet	0.0336	0.0321	0.0230
Fodders	0.2630	0.1841	0.1315
Fibbers	0.2945	0.2062	0.1473
Medical Plants	0.2630	0.1841	0.1315
Vegetables	0.3730	0.2611	0.1865
	Summer Crops		
Rice	0.1925	0.1347	0.0962
Other Crops	0.1613	0.1154	0.0824
Sugar Cane	0.0705	0.0493	0.0352
Cotton	0.0982	0.0687	0.0491
Fodders	0.0981	0.0687	0.0491
Oily Crops	0.1470	0.1029	0.0735
Medical Plants	0.0981	0.0687	0.0491
Vegetables	0.3730	0.2611	0.1865
	***Nili* Crops**		
Rice	0.1925	0.1347	0.0962
Other Crops	0.1630	0.1145	0.0819
Fodders	0.1806	0.1264	0.0903
Oily Crops	0.1470	0.1029	0.0735
Medical Plants	0.1806	0.1264	0.0903
Vegetables	0.3730	0.2611	0.1865
	Year-round Crops		
Fruits	0.5876	0.3052	0.1422
Other Agri, Forestry & Fishing	0.1960	0.1329	0.0915

Source: authors' calculations.