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A hydrologic-economic-agronomic model with regard to salinity for an over-exploited coastal aquifer

Ahmed E. M. Al-Juaidi[1]

Abstract

The present work considers a management model for the sustainable development of an exploited coastal aquifer of the Gaza Strip, which includes different demands depending on water quality types into a regional hydrologic-economic-agronomic model. The uniqueness of this study is its consideration of two-separated demand functions one for fresh water and the other one for saline water, as well as effect of saline-water quality relationship on agriculture. This study identifies the optimum infrastructure of desalinated seawater and treated wastewater to fresh and saline levels. It also allocates water of different qualities (fresh and saline) among water sectors and between districts. Results show several important management outcomes: (i) the shadow value of saline water for all districts is larger than the cost of treating brackish water to fresh level is $0.30/m^3. Therefore, the desalination of saline groundwater water to saline water level may be beneficial in Gaza districts. (ii) The shadow value of fresh water for all districts is larger than the cost of desalination ($0.6/m^3). Accordingly, the desalination of brackish water to fresh water level is also beneficial. (iii) The areas of potential crops that use treated wastewater to saline level are proportionally increased to reduced abstraction from groundwater. Moreover, the sensitivity analysis indicated that, reduced abstraction from the groundwater would better allocate scarce water among competing users and better predict infrastructure sizing to fresh and saline treatment levels.

Keywords Salinity · Water demand · Supply enhancement · Integrated management · The Gaza Strip

Introduction

There is always competition on water between different water use sectors, such as municipal, industrial, and agricultural users. Population growth exacerbates the competition and often results in an increased share of freshwater to agriculture (Tilman et al. 2002; Al-Juaidi 2017a; Al-Juaidi 2017b). Therefore, there is an urgent need to discover alternative water sources for agriculture that typically demand more than 80% of available water. Potential alternative sources include saline surface and groundwater, storm water, and treated wastewater (Rhoades et al. 1992).

Salinity has overwhelmed crop production in semi-arid regions where crop water requirements go over annual precipitation. In such areas, irrigation is required to meet crop water requirements while irrigation water typically contains salts. Unfortunately, rainfall and water use for agriculture are insufficient to drain salts from the root zone. Thus, increasing salinity in such cultivated lands is reducing crop productivity (Francois and Mass 1994). In the Gaza Strip, salinity is elevated due to scarce groundwater. The Gaza Strip has real issues with contaminated groundwater due to illegal abstraction, seawater intrusion, and dumping of untreated wastewater into the coastal aquifer (Al-Yaqubi et al. 2007; Al-Juaidi et al. 2009a, b; Al-Juaidi 2018a, b; Al-Juaidi 2019).

Water authorities in Palestine are trying to establish a new managing tool to cover the cost of treatment and supply of water such as tariff structures. Water authorities in Palestine are offering public workshops and training programs for water users and farmers on stormwater collection, and the recycle of treated wastewater in irrigation (Al-Juaidi et al. 2011a, b; Al-Juaidi 2018a, b).

In spite of these policies, Palestinian water authorities still face several obstacles. Almost the whole Gaza Strip water supply is brackish due to the over-drafted coastal aquifer from

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✉ Ahmed E. M. Al-Juaidi
aealjuaidi@gmail.com; ahmed.aljuaidi@gmail.com

1 Civil Engineering Department, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia

the illegal agricultural wells leading to seawater intrusion. In Gaza, saline water use is widespread due to high illegal abstractions from agricultural wells. However, saline water supply is considered as a component of the fresh water supply. This practice disregarded the reduced economic benefits due to reduction in agricultural production, and the extra costs that users acquire to use saline groundwater (Al-Juaidi and Hegazy 2017a, b). The use of saline supplies has not given a priority of how to be incorporated into the hydrologic-economic water system. Also, it was not given attention how to desalinate water to fresh and saline levels, treat wastewater to fresh and saline levels, and conveyance of fresh and saline infrastructure needed, and how saline and fresh water could be distributed among districts and sectors.

To help evaluate potential actions and integrate the existing saline water supply into the overall supply system, this paper extends prior work to accommodate the demands of different water qualities (fresh and saline) in a regional water allocation system model. The work allocates water of different qualities to maximize the net benefits from saline and fresh water use. The paper also identifies the impacts of using saline water on the whole water system. To facilitate the analysis, water allocation system (WAS) model of Fisher et al. (2005) was extended to incorporate demand functions and decision variables associated with different salinity concentrations and to include the effect of salinity on agricultural practices (see Fig. 3).

Prior related work

Many early applications of hydrologic-economic models consider allocation of water for entire river basins (Rogers 1993; Rosegrant et al. 2000; Draper et al. 2003; Fisher et al. 2005). For example, Rogers (1993) studied the Ganges basin in terms of the value of cooperation between different countries with one water quality. Rosegrant et al. (2000) developed an optimization framework from benefits for different water uses taking into account the transferring and storing water in Chile. Draper et al. (2003) established a relation on the water use (surface and groundwater) with the reuse of wastewater, environmental flow, and water market transfers in California.

More recent hydro-economic models that took into consideration the benefits and costs of demand and supply and allowing for different water quality for agricultural production across entire river basins or regions (Lefkoff and Gorelick 1990; Lee and Howitt 1996; Percia et al. 1997; Huber Lee 1999; Gordon et al. 2001; Cai et al. 2003; Addams 2004; Gregory et al. 2005; Khan et al. 2008). Lefkoff and Gorelick (1990) evaluate the relations between hydrology, agricultural economics, and water marketing in a saline aquifer used heavily for irrigation. Lee and Howitt (1996) determined quality standards for agricultural production, and measures to control salinity for water quality analysis. Percia et al. (1997) optimize the operation and control of a multiple

water quality regional water system with cost minimization as the objective. Huber Lee (1999) optimizes benefits for agricultural, urban, and industrial uses and brings together issues of long-term aquifer deterioration as a function of economical benefits. Gordon et al. (2001) maximizes the amount of water pumped in regional aquifer under salinization for use and reducing the total amount of salt extracted with water. Cai et al. (2003) modeled for conflicts between different water users where irrigation water use is the dominant while salinity represents a major water problem. Addams (2004) developed a water allocation model the irrigation district of Yaqui-Valley and included yield response to salinity of irrigated water. Gregory et al. (2005) assessed benefits from salinity management and considered desalination and salinity and salinity and water use change patterns. Khan et al. (2008) modeled water and salinity to find the best mix of cropping pattern and land use while having salinity and ground water levels under the adequate levels.

In this work, salinity impact on agricultural practices and of different water quality is included as decision variables and input parameters in a water allocation system. Then, water quality was grouped into common demand functions to identify the optimum infrastructure of treated sea water and treated wastewater to fresh and saline levels. The work also allows distributing water of different qualities (fresh and saline) between urban, industrial, and agricultural sectors. To identify maxim mum net benefits, a non-linear optimization framework is employed for to find the best water allocations when considering different water quality types under different groundwater availability conditions.

Water allocation systems

The water allocation system (WAS) has two major points. First, water shortage gives a value or price for water. If water shortage increases, the prices of water will increase. Second, costs of seawater desalination represent the highest cost of water. In other words, the price of water has to be less than $0.6/m^3$ (Fisher et al. 2005; Al-Juaidi et al. 2014). Here, the value of water represents the benefit from water use minus costs to acquire, treat, and transport water to the end users. The WAS model is a deterministic optimization model, and maximizes annual net benefit from different water use subject to hydrologic, and economic constraints on water availability, use and reuse, and transport among districts. Further, the quantity demanded for water and recycled water should balance the abstracted water from local sources, imported from and exported to other districts. This study extended Fisher's et al. (2005) and Al-Juaidi et al. (2009a) to include demand for two different quality of water (fresh and saline) as well as the impact of salinity-water quality relationship on agriculture. Then, the model can consider two demand groups, one for

fresh and the other for saline. This model allows desalination of seawater to both fresh and saline levels, and wastewater treatment to fresh and saline levels, as well as conveying of both fresh and saline water. The model is called saline water allocation model (Saline-WAM).

Study area

The Gaza Strip is surrounded by Israel on the east and north east and Egypt on the south and the Mediterranean on the west (see Fig. 1). The Gaza Strip has five districts including North Gaza, Gaza, Deir Al-Balah, Khan Younis, and Rafah.

Water resources

Groundwater is the only water source in Gaza. The safe yield of the Gaza coastal aquifer varies from 55.0 MCM to 100 MCM. The current total water abstractions from agricultural and municipal and agricultural are 145 MCM. Gaza Strip receives rainfall averaging about 370 mm. In North districts (e.g., Beit Hannoun and Beit Lahia), the rainfall averaging is about 436 mm, while and declines to 270 mm in the south districts (Rafah and Khan Younis).
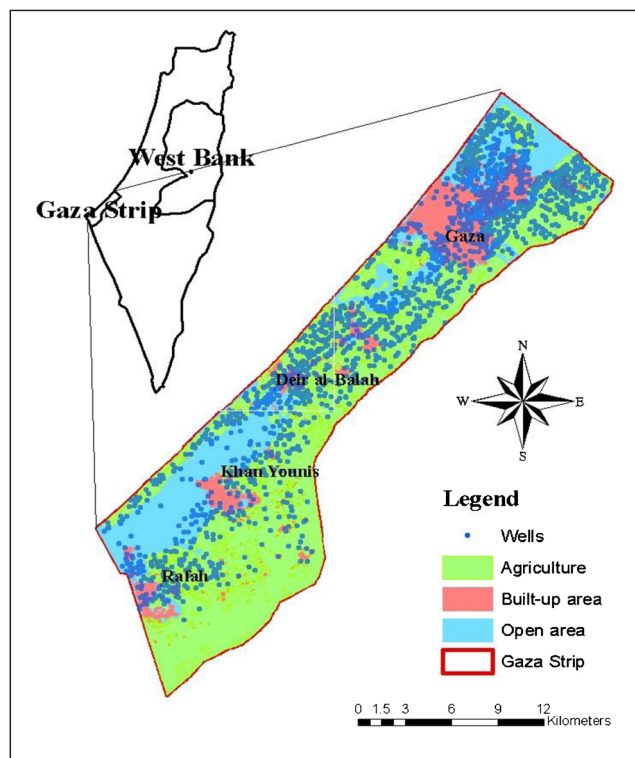
Fig. 1 Physical layout of Palestine showing different districts in the Gaza Strip

Wastewater treatment

In Palestine, the reuse of TWW in agriculture is very limited due to public unacceptability by farmers. Most of the wastewater sources are municipal. The industrial wastewater is discharged for treatment to the same treatment plants. In Gaza, the capability of the five wastewater treatment units are 20, 40, 25, 15, 15 MCM/year for North Gaza, Gaza, Deir Al-Balah, Khan-Younis, and Rafah, respectively.

Desalination

There are two small desalination units of 1.83 MCM each facility in North Gaza and Deir Al-Balah districts, but other districts do not have desalination. There is also no transport of water between these districts. The Palestinian Water Authority (PWA) plans to consider desalination plant with a capacity of 15.0 MCM/year in all districts except for one large desalination unit of capacity 54.8 MCM/year in Gaza district.

Conveyance

Currently, Gaza Strip does not have conveyance system between districts. Conveyance system in each district is in existence but experiences high leakages and illegal water connections. It is expected that, water losses and leakages account for about 40% of the water supply (Fisher et al. 2002, 2005). It is assumed that the PWA will reduce the losses to 20% through prohibiting illegal connections.

Agriculture and salinity

The safe yield of the Gaza Strip aquifer is established to be 55 MCM (Fisher's et al. 2005). The current abstraction of groundwater for agriculture is around MCM Thus, salinity of groundwater is rising because of sea water intrusion. The average groundwater salinity in the Gaza Strip is 1800 mg/l. The maximum groundwater salinity is 4000 mg/l which is the closest to Mediterranean coast (Al-Juaidi et al. 2010). Table 1 shows the distribution of agricultural crops in the Gaza Strip districts (Al-Juaidi et al. 2010). When saline water increases, the agricultural production decreases (Ayers and Westcot 1994).

Demand

Water demand functions were obtained for 2010, and 2030 using information gathered from different sources (Fisher et al. 2005; Metcalf and Eddy 2000; Palestinian MoPIC 1998a, b) and are given in (Table 2). They were employed to establish the demand curves for fresh and saline water (see Table 2). The elasticity of water demand in Gaza is − 0.6, − 0.33, and − 0.5 for urban, industrial, and agricultural uses (Fisher's et al. 2005).

Table 1   Current cultivated crops in the Gaza Strip districts

Crop name	Total area hectare (ha)	Variable cost US$/ha	Price ($/ton)	Yield (ton/ha)	Water requirement (m3/ha·year)
Citrus					
Shamoti*	501.2	1500	263	219	7655
Lemon*	336.6	1500	473	33	6105
Grapefruit*	130.0	1500	145	172	7341
Valencia*	1930	1500	158	165	7655
Clementina*	340	3500	339	200	3809
Fruits					
Guava*	450	1500	377	278	7075
Strawberry	166	1500	673	219	5320
Watermelon	133	4000	160	155	5031
Vegetables					
Cucumber	291	3480	412	276	3718
Squash	180	500	408	281	3454
Cabbage	209	3320	323	309	2953
Cauliflower	115	3500	420	239	2289
Tomato	180	3280	367	311	6346
Sweet pepper	83.1	4350	502	187	7232
Eggplants	110	5400	309	431	8109
Potato	557	3200	242	234	3110
Sweet potato	295	3200	273	174	3205
Olive*	2689	1500	850	232	3109

*Potential crops for use treated wastewater

Water quality

In this paper, three water quality types are considered: (i) freshwater with a TDS concentration below 250 mg/l; (ii) saline (brackish) water with a TDS of 450 mg/l; and (iii) TWW with an unspecified TDS concentration between fresh and saline water. The current desalination costs of $0.60 and $0.40/m^3 are considered, respectively to treat seawater to fresh and saline water levels (WHO 2004). The cost of desalinating brackish water to fresh water is $0.30/m^3. The saline TDS of 450 mg/l is tolerable for all irrigable crops in Palestine (Ayers and Westcot 1994). The cost of treatment of wastewater is $0.10/m^3 and $0.07/m^3 to fresh and saline water levels, respectively (Ayers and Westcot 1994). For freshwater, nitrogen, phosphorus, and potassium concentrations are 2.0, 0.4, 0.3 mg/l, respectively. Concentrations of nitrogen, phosphorus, and potassium in TWW are 5.0, 1.0, 0.7 mg/l, respectively for saline water (Ayers and Westcot 1994).

Model implementation

This model incorporates salinity into a water allocation optimization model by allowing decision-makers to (i) specify the

water quality types to include in the analysis, (ii) group those water quality types into common demand functions that define the objective function, and (iii) indicate what water use sectors can use and reuse each water quality types. Each feature is described as follows: First, this model uses water quality types to include in the analysis. For example, one can add saline water to the fresh and recycled water qualities that were only allowed in prior versions of WAS. The model objective function is then defined as the net benefits, which are considered as the areas under the grouped demand functions minus costs to supply, convey, and treat the water used (see Eq. 2). Mathematically,

$$Max\ (net\ benefits) = \sum_i \sum_g \left(crop_{iq}, yield_{iq}, A_{iq} \right)$$
$$- \sum_i \sum_g \frac{b_{ig}}{\alpha_{ig} + 1} \left(\sum_{q \in Q(g)} quantity\ demand_{iq} \right)^{\alpha_{ig}+1} \quad (1)$$
$$- \sum_i \sum_q Cost \begin{pmatrix} local\ sources_{iq}, imports_{iq} \\ exports_{iq}, wastewater \\ treatment_{iq} \end{pmatrix}$$

where i is the district, g is the demand group (many water quality types that contribute to a single demand function), $Q(g)$ is the set of water quality types q that are grouped into demand function g, β_{ig} is the position in the demand curve for district i and demand group g, α_{ig} is the demand curve

Table 2 Fresh and saline water demand function parameters for Gaza districts for 2010, and 2030. The demand function is given as $P_{ig} = \sum_i \sum_g \beta_{ig} \times \sum_{q \in Q(g)} quantity\ demand_{iq}^{\alpha_{ig}}$ (Espey et al. 1997; Fisher's et al. 2005; Al-Juaidi et al. 2009a, b)

| | 2010 | | 2030 | | 2010 | | 2030 | |
| | Saline water | | | | Fresh and recycled water | | | |
	β	α	β	α	β	α	β	α
Urban								
North Gaza	1.34	− 0.26	1.37	− 0.31	4.02	− 0.6	4.10	− 0.6
Gaza	0.98	− 0.29	1.38	− 0.29	2.94	− 0.6	4.15	− 0.6
Deir Al-Balah	0.97	− 0.32	1.37	− 0.33	2.92	− 0.6	4.12	− 0.6
Khan-Younis	0.98	− 0.29	1.37	− 0.31	2.93	− 0.6	4.12	− 0.6
Rafah	0.98	− 0.29	1.38	− 0.29	2.95	− 0.6	4.15	− 0.6
Industrial								
North Gaza	1.27	− 0.31	2.73	− 0.32	3.80	− 0.33	8.20	− 0.33
Gaza	1.20	− 0.3	2.67	− 0.29	3.60	− 0.33	8.00	− 0.33
Deir Al-Balah	1.25	− 0.32	2.71	− 0.3	3.75	− 0.33	8.13	− 0.33
Khan-Younis	1.24	− 0.29	2.67	− 0.31	3.71	− 0.33	8.00	− 0.33
Rafah	2.00	− 0.3	10.0	− 0.29	6.00	− 0.33	30.0	− 0.33
Agricultural								
North Gaza	1.55	− 0.29	3.18	− 0.31	4.64	− 0.5	9.55	− 0.5
Gaza	1.04	− 0.29	1.04	− 0.29	3.11	− 0.5	3.11	− 0.5
Deir Al-Balah	1.24	− 0.32	1.24	− 0.29	3.72	− 0.5	3.72	− 0.5
Khan-Younis	4.13	− 0.29	4.13	− 0.31	12.38	− 0.5	12.4	− 0.5
Rafah	0.75	− 0.29	0.75	− 0.29	2.25	− 0.5	2.25	− 0.5

elasticity for district i and demand group g, and q is the water quality type (Eq. 3).

The inverse demand term describing benefits in the objective function assumes constant elasticity and is represented as:

$$P_{ig} = \sum_i \sum_g \beta_{ig} \times \sum_{q \in Q(g)} quantity\quad demand_{ig}^{a_{ig}} \qquad (2)$$

P_{ig} is the water price in district i of demand function g (\$/m³); Q_{iq} is the quantity demanded in district i of quality q (m³); third, it has to be known whether water use sectors can use or reuse the new water quality type, to specify which water use sectors can use each water quality type. Together, specifying the water quality types, grouping water quality types into common demand functions, and indicating how different water quality types can be used and re-used provides a structured but flexible way to include saline water (or waters with other water quality attributes of interest) into the water allocation system optimization model's objective function, decision variables, and constraints. After specifying a new water quality type, the model generates continuity constraints for that water quality type q in each district i (Eq. 1).

$$Quantity\ demanded_{iq} \leq \begin{pmatrix} local\ sources_{iq} + imports_{iq} \\ -exports_{iq} + treated\ wastewater_{iq} \end{pmatrix} \\ \times (1 - loss\ rate_{iq}), \forall i, q \qquad (3)$$

This specification restricts water consumed of quality type q from exceeding the amount produced there, plus net imports and reuse of treated wastewater, and losses from leakage. This also simultaneously generates new decision variables for consumption, supply, conveyance, waste-water treatment, and leak-reduction actions associated with the new water quality type. For example, desalinating seawater to water quality type (level) q would be one of potentially multiple local source options available in district i.

Second, water quality types are grouped into common demand functions. Grouping water quality into common demand functions will allow to identify the optimum infrastructure of treated sea water and treated wastewater to fresh and saline levels, with transporting and allocating water of different qualities (fresh and saline) among water users and districts (see Fig. 2).

Appendix 1 provides the full mathematical formulation for the model. The model contains two demand groups, fresh and recycle, and saline. Table 3 shows the water quality types which are grouped together into demand functions. Since the model produces a water balance equation for each water quality type, there are decisions for each water quality type related to the quantity of local sources to use, convey (import and export), and wastewater to treat. Considering desalination as one type of local source and looking across the different water quality types, there are also decisions related to the final effluent water quality for desalinated water as a supply source. If the difference

of shadow value of water between district (2) and district (1) is more than the cost of transportation (see Fig. 3), then water can be transferred from district a to district b through building a pipeline (Al-Juaidi et al. 2009b; Fisher's et al. 2005).

Table 3 shows water use sectors can use each water quality type. Al-Juaidi et al. (2009a) introduced the index g (demand group) to Rosenberg's et al. (2008) to denote a grouping of water quality types that contribute to two demand functions, and include the following points: (i) introduces the set $Q(g)$ to specify the water quality types that are grouped into a common demand function, (ii) extends several parameters to be indexed across demand groups, and (iii) decision variables to be indexed across the water quality types that contribute to the demand group. These factors allows to include two demand functions which have been considered earlier by Al-Juaidi et al. (2009a) and applied on Stochastic-WAS developed by Rosenberg et al. (2008). In this paper, the same factors have been adopted from Al-Juaidi et al. (2009a) and applied to Fisher's et al. (2005) model. Lingo software is used to perform the analysis (https://www.lindo.com).

Water management scenario development

In the application of this model, a base case was developed to assess the economic realities under existing conditions followed by a set of management scenarios to address the predicted deficits in an economically beneficial manner. The PWA conducted prior studies to address the existing water deficits especially with the increasing demands and decreasing water quality with seawater intrusion (PWA and SUSMAQ 2003; PWA and CDM 2003; Palestinian MoPIC 1998a, b). The scenarios simulated here are based on those management alternatives identified by the PWA. The reason for this selection is that, the proposed simulation scenarios will be practical alternatives that can be implemented if deemed justified. The proposed scenarios considers proposed future water development actions such as desalination, recycle of TWW, and building conveyance between districts.

The base case scenario does not consider TWW use, desalination, or inter-district conveyance. Thereafter, the proposed scenarios were simulated for 2030 followed by simulations to identify the infrastructure expansion required to maximize the benefits that otherwise cannot be achieved by the proposed scenarios of PWA. All the simulations will include two demand groups consisting of fresh and saline water. The proposed scenarios for the Gaza Strip in this study are as follows:

- Base-case—no constraint on abstraction from groundwater; no use of TWW.
- Option 1. 50% reduced pumping from groundwater in Gaza Strip Districts.

- Option 2. Option 1+TWW+desalination+conveyance pipeline. The conveyance pipeline is from Gaza to Khan-Yunis district with a capacity of 10 MCM. It is assumed that Gaza district will have a desalination plant of 55 MCM/year desalinate sea water to saline and fresh water level. The capacity of these conveyance pipelines were considered to transport fresh water, and the same capacity are used to transport saline water.
- Infrastructure development through unconstrained optimization—sets infrastructure capacities to large values and allows the optimization program to identify infrastructure use that maximizes net benefits.

Results and discussions

In the application of this model to Palestine, a base case was developed to assess the economic realities under existing conditions followed by a set of management options to tackle the predicted shortfalls in an economically beneficial manner.

Shadow value of water

Shadow value of water and net benefits were used to identify the economic advantages of a given scenario compared with another. Table 4 shows the shadow value of water for the base case and scenario 2 allowing for 50% reduction in fresh water supply across the different districts of Palestine using both this model and Fisher's WAS programs. Table 4 shows the details of shadow price of all districts for all the scenarios for the Gaza districts. Fig. 4 shows the shadow values of fresh water for the base case in 2030 between using a single demand function (WAS) and two demand functions (Saline-WAM). The results show that, in most of the districts, the shadow value reduced with the addition of saline water with its appropriate demand function. This difference refers to the fact that, the net benefit in the two demand groups is higher than the net benefit in one demand group. The shadow value of fresh water increases in Gaza districts when demand for saline water is included (see Fig. 4). This increase occurs because, freshwater supplies in the Saline-WAM run are drastically reduced to 5 MCM/year imported from Israel with saline groundwater is the predominately supply. The increased shadow prices for freshwater in Deir Al Balah, Khan-Yunis, and Rafah mean that desalinating seawater to freshwater may be economically viable.

Table 4 shows the impact of adapting scenario 2 which consists of reducing groundwater pumping by 50% using the two-demand group simulations using Saline-WAM. As expected, the shadow values in all districts of Gaza increased significantly with reduced availability of freshwater as the demand for saline water increased. These results show that desalination of seawater and treatment of wastewater to fresh
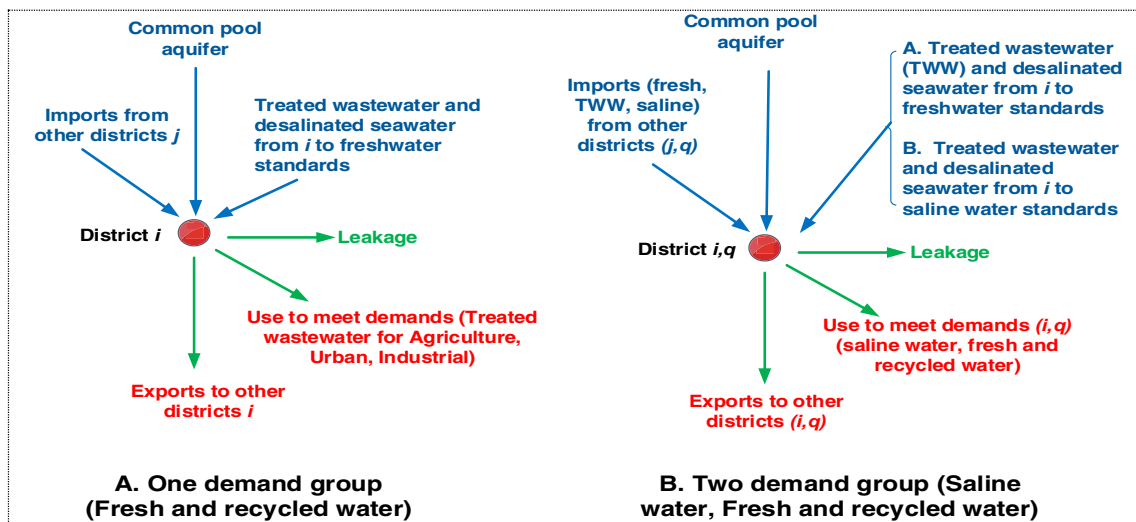
Fig. 2 Water balance for two demand groups (Al-Juaidi et al. 2009a, b)

water level may be economically beneficial. Table 4 shows the results of all scenarios for the Gaza Strip. Accordingly, the saline water availability reduces to 56 MCM with scenario 2 which is allocated to urban and industrial sectors. The results show that, the reuse of TWW in agriculture dramatically reduced the shadow value of water in Gaza Strip. These results indicate that, treating wastewater to saline level and reusing in agriculture may be beneficial when water is scarce. In the Gaza Strip, when TWW with 50% reduced pumping is considered, 40 MCM of recycled water may be used for agriculture. In the Gaza Strip when desalination is considered with 50% reduced pumping, the shadow value of water for saline water remained higher than $0.45/m^3 which is the cost of seawater desalination to saline level. Therefore, these results indicate that, desalination of seawater to saline level may be economically beneficial. Following the same discussion of saline-WAM simulations, option 3 shows a reduction in the shadow value with the introduction of desalination. The reduction in shadow value between options 2 and 2 is around ($0.20/m^3) among the Gaza Strip districts (Table 4). Therefore, the results suggest that, the over abstraction from the aquifer can be successfully alleviated using desalination
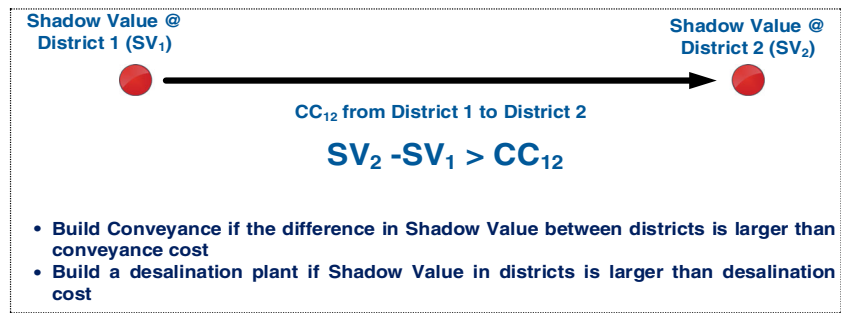
and recycle of TWW. When considering desalination with constrained pumping and recycle of TWW, the shadow value of water is less than $0.50/m^3 in all districts. Moreover, desalination of brackish water to fresh water may be beneficial in all of the Gaza Strip districts. This is because the difference between the shadow value of saline and fresh water in the Gaza Strip districts are higher than $0.30/m^3.

The cost of desalinization of brackish water to fresh water level is $0.30/m^3. Therefore, the conveyance of seawater desalinated to both saline and fresh water levels from Gaza to Khan-Younis may be an economically viable solution, as it reduces the willingness to pay for saline and fresh water, increases net benefits, and reduces water scarcity in Khan-Younis.

Infrastructure development and benefits

In the previous section, the net benefit of planned future water development actions suggested by PWA) was addressed to meet Gaza Strip future water demand in 2030. The upper capacity of municipal utilities (desalination and wastewater treatment plants) were set-up according to current practices However, model results from the previous section established that water shortages still persist. In other words, many of the Gaza districts are still have shadow value of water above the desalination cost of $0.60/m^3. Therefore, water supply enhancements may be necessary. Consequently, it is essential to identify the suitable infrastructure capacity to meet future water demand and maximize net benefit. Therefore, it is essential to find the maximum benefits from combination of desalination, wastewater treatment, inter-district conveyance along with reduced groundwater withdrawal. To facilitate the analysis, simulations of higher upper bound of 1000 MCM is considered for all infrastructures (e.g. desalination, wastewater, and conveyance) to determine the best infrastructure sizing in each district. These simulations of higher upper bound have been executed for the two models WAS and

Table 3 Grouping water quality types into common demand functions, and identifying which water use sectors can use each water quality type (Al-Juaidi et al. 2009a)

Quality/demand group	Fresh and recycle	Saline
Freshwater	Yes	Yes
Recycled	No	No
Saline	Yes	Yes
Quality/sector	Urban and industrial	Agricultural (see Table 1)
Freshwater	Yes	Yes
Recycled	No	Yes
Saline	Yes	Yes

Fig. 3 Marginal shadow value of water to obtain one additional unit of water (Al-Juaidi et al. 2009b, c)

Shadow Value @ District 1 (SV_1)

Shadow Value @ District 2 (SV_2)

CC_{12} from District 1 to District 2

$$SV_2 - SV_1 > CC_{12}$$

- Build Conveyance if the difference in Shadow Value between districts is larger than conveyance cost
- Build a desalination plant if Shadow Value in districts is larger than desalination cost

Saline-WAM. The simulations considered reduce abstraction from groundwater from the base case situation in 2030 (Table 5).

A discount rate of 5% is considered to obtain the net benefits which have established from the models minus infrastructure capital cost. To desalinate 1.0 MCM per year, then a capital cost of $2.72 million in 2010 is required (Metcalf and Eddy 2000; PWA 2003; PWA and CDM 2003). To expand the clarification of wastewater by 1.0 MCM per year, A cost of $1.2 million is needed (Metcalf and Eddy 2000). When groundwater abstraction is reduced to advance aquifer recovery; more desalination quantity has increased to maximize net benefit. The results revealed that less TWW will be available for agriculture, when reducing groundwater abstraction. Interestingly, the conveyance capacity turns to be zero because of the availability of desalination and reuse of TWW. Increasing desalination capacity along with reducing groundwater abstraction, the net benefits gradually reduce (see Fig. 4). After including the capital cost of desalination, the profits decreased with reduced groundwater abstraction. Further, reducing groundwater abstraction to 50% (from 140 MCM to 70 MCM) generated a profit of $168 million (see Table 5).

For the saline-WAM model, results suggest that desalination capacity to saline and fresh levels are increasing proportionally to groundwater abstraction reduction. Results also showed that wastewater treatment capacity to fresh and saline levels are increasing along with reduction of groundwater abstraction (see Table 5). Finally, the results revealed that the two demand function produced higher profit than the one demand function (Table 5). Further, results suggest that the areas of potential crops to use treated wastewater to saline level have increased with reducing groundwater abstractions (see Fig. 5).

Summary and concluding remarks

Most of the areas which suffer from water shortages are due to increase water demand from the population growth. The Gaza Strip is a typical example facing limited water and available water is becoming saline due to over-drafted coastal aquifer. Saline or brackish water are available, but not used properly. Therefore, water authorities must consider new policy to deliver

Table 4 Comparison of net benefit, shadow value for the Gaza Strip between different scenarios and WAS (Fisher's model) and the present model Saline-WAM

Result / District	Base Case (1)		(option1) Base Case +50% reduction in abstraction (2)		Option 1 + desalination +TWW conveyance of pipeline (3)	
	Fisher's et al. 2005 WAS	Present Model	Fisher's et al. 2005 WAS	Present model	Fisher's et al. 2005 WAS	Present model
Net benefit ($ million/year)						
North Gaza	108	108	105	97	118	111
Gaza	198	227	191	191	210	232
Deir Al-Balah	89	88	87	77	91	92
Khan Younis	118	126	113	103	123	129
Rafah	64	64	62	49	67	67
Shadow value of fresh water ($/m^3)*, the other shadow value is for saline water ($/m^3)						
North Gaza	0.54	0.51(0.76)*	0.61	0.46(0.79)*	0.20	0.42(0.52)*
Gaza	0.51	0.53(0.88)*	0.63	0.48(0.95)*	0.18	0.54(0.60)*
Deir Al-Balah	0.53	0.60(0.63)*	0.7	0.49(0.77)*	0.19	0.44(0.56)*
Khan Younis	0.54	0.65(0.65)*	0.75	0.41(0.78)*	0.21	0.48(0.57)*
Rafah	0.54	0.68(0.68)*	0.75	0.44(0.72)*	0.21	0.47(0.54)*

Fig. 4 Shadow values of freshwater and saline water in districts in 2030 for the base case scenario
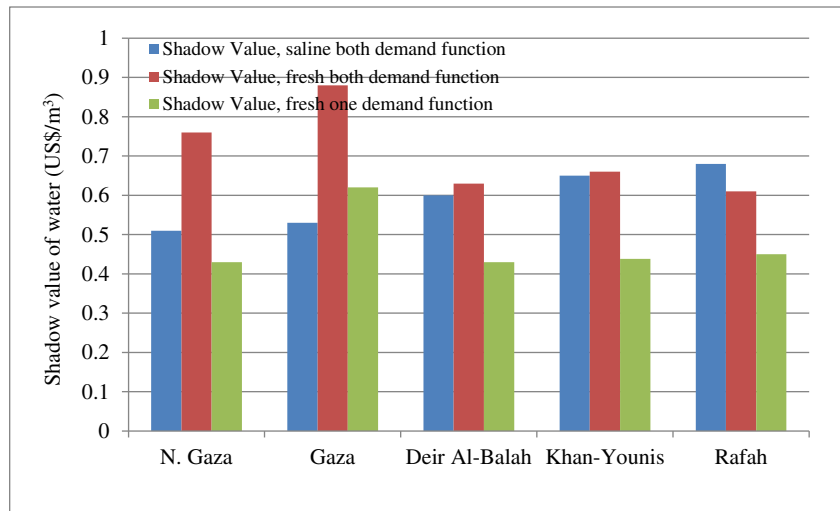

fresh and saline water to the users for their appropriate use, plus the benefits resulting from use. Water planners need to develop alternative sources with different qualities of water, to ensure water is delivered efficiently. In this work, a revised hydrologic-economic model to be able of using two types of water qualities with appropriate demand function, Saline-WAM, was used to allocate saline and fresh water to maximize the net benefit. This work showed how the system should be managed when including user's shadow value of water for saline and fresh water, both in terms of new infrastructure needs and how to allocate water to and among different water users and districts. The paper also assessed the benefits and cost of using saline water on the whole water system. The main outcomes from this work are as follows:

1. Use of saline water together with freshwater generates higher net benefits when compared with net benefits using freshwater alone. In essence, the use of both saline and fresh water increased the efficiency of the water system through the allocation of both water quality based on saline and fresh water demand.

2. Desalination of the existing brackish water to saline water level may be economically beneficial for the Gaza Strip districts. The shadow value of saline water is greater than $0.30/m^3, which is the cost of treatment brackish water to fresh water level.

3. Desalination of seawater water to fresh water level is may not be beneficial in the Gaza districts, as the shadow value of fresh for and water is higher than ($0.60/m^3), which is he cost treatment brackish water to fresh water level.

Table 5 Infrastructure development assessment for unconstrained scenario with comparisons between results of Fisher's model and the present model

Item	Reduction in pumping (%) Fisher's et al. (2005) model				Reduction in pumping (%) the present model (saline-WAM)			
	0	15	25	50	0	15	25	50
(1) Net benefit (million $/year)	52	32	27	18	57	42	34	24
(2) Total desalination capacity to freshwater level (MCM/year)	0	0	0	0	23	37	40	47
(3) Total desalination capacity to saline water level (MCM/year)	0	0	0	0	10	11	13	14
(4) Total desalination capacity (MCM/year)	22	47	54	90	0	0	0	0
(5) Total wastewater treatment capacity to freshwater level (MCM/year)	NA	NA	NA	NA	135	131	134	136
(6) Total wastewater treatment capacity to saline water level (MCM/year)	NA	NA	NA	NA	20	43	50	60
(7) Total wastewater treatment capacity (MCM/year)	77	52	39	34	NA	NA	NA	NA
(8) Total conveyance of saline water level (MCM)	NA	NA	NA	NA	0	0	0	0
(9) Total conveyance of freshwater (MCM)	0	0	0	0	0	0	0	0
(10) Total conveyance (MCM)	0	0	0	0	NA	NA	NA	NA
(11) Capital costs of treatment plant, conveyance, and desalination (million $)	53	68	70	104	73	89	96	105
(12) Present value of net benefit ($ million)	593	365	308	205	650	479	388	274
(13) Profit (million $) = (10)–(9)	540	297	238	102	577	389	292	168

Fig. 5 Computed cropping areas for base-case and 25% ground-water abstraction reduction scenarios
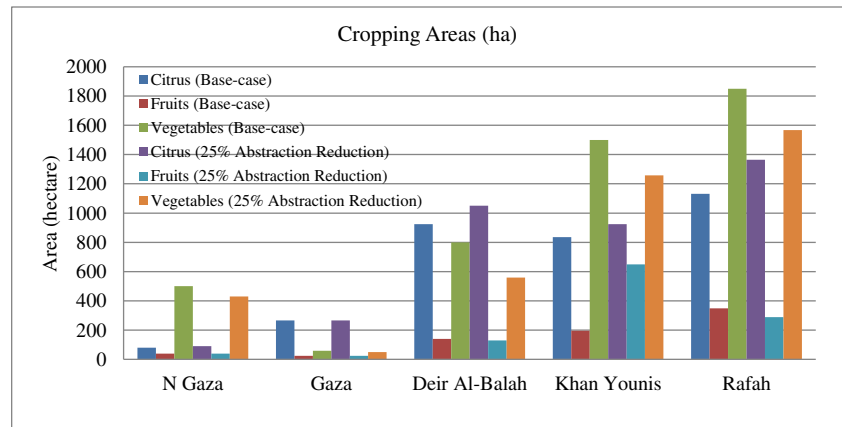
4. Conveyance of desalinated sea water to both saline and fresh water levels from Gaza to Khan-Younis reduces the willingness to pay for saline and fresh water, increases net benefits, and reduces water scarcity in Khan-Younis.

5. Wastewater reuse may be an important source to reduce future water deficits and to increase economic benefits.

When setting up unconstrained value of 1000 MCM for desalination and TWW, the results show that, reuse of treated wastewater (to fresh and saline level) for agriculture with desalination dramatically reduces shadow value of fresh water (below $0.40/m^3) in both Saline-WAM and Fisher's WAS simulations.

Appendix: Model formulation
Objective function

$$\max Z = \sum_i \sum_g \left(P_f \times PY_{cq}\right)A_{fq} - \left(VC_{cq} \times A_{fq}\right) + \sum_i \sum_d \sum_g \frac{b_{idge}\left[\sum_{q \in Q(g)}\left(QD_{idqe}\right)\right]^{\alpha_{idge}+1}}{\alpha_{idge}+1} - \sum_i \sum_s \left(QS_{is} \times CS_{is}\right) - \sum_i \sum_j QTR_{ijq}$$
$$\times CTR_{ijq} - \sum_i \sum_d QRY_{idq} \times CR_{idq} - \sum_i \sum_j QTREC_{ijq} \times CTREC_{ijq} - \sum_i \sum_d QREC_{idq} \times CRY_{idq} - \sum_i QDES_i \times CDES_i$$

(A1)

Subject to:

$$\sum_d QD_{idq} = \left(\sum_s QS_{pumpedis} + \sum_i QDES_{iq} + \sum_j QTR_{jiq} - \sum_j QTR_{ijq}\right) \times (1-LR_i)\forall i, q$$

(A2)

$$\sum_d QREC_{idq} = \sum_i QRY_{idq} + \sum_j QTREC_{jiq} - \sum_j QTREC_{ijq} \quad \forall i, q$$

(A3)

$$QRY_{idq} = PR_{id} \times QD_{idq} \quad \forall i, d, q$$

(A4)

$$PY_{icq} = A_{fc} \times PY_o\left[1 - \frac{GW_f}{ECT_c}\right]$$

(A5)

$$TWD_c = \sum_c \sum_q A_{fc} \times WD_c$$

(A6)

$$GW_f^{y+1} = GW_i^y \times (1 + \phi^y)$$

(A7)

$$\phi^y = \frac{TWA^y - SY}{SY}$$

With the following bounds

$$\sum_{q \in Q(g)} QD_{idqe} \geq \left(\frac{p_{max}}{b_{idge}}\right)^{\frac{1}{\alpha_{idge}}}, \forall i, d, g, e \quad \forall i, d$$

(A8)

$$QS_{is} \leq QS_{max\ is} \forall i, s$$

(A9)

$$PR_{id} \leq PR_{max\ id} \forall i, d$$

(A10)

$$\sum_q A_{fc} \leq A_{ofc} \quad \forall c, f, q$$

(A11)

Indices

i	Represents the district
d	The demand type (urban, industrial, or agricultural)
s	The supply source or steps
q	Water quality type (fresh, recycled water)
g	Demand group (multiple water quality types that contribute to a single demand

Parameters

P_{fq4}	Farm crop price for water quality q ($/ton)
PY_{cqf}	Production yield of crop c for water quality q (ton)
VC_{cqf}	Variable cost of farming crop c in farm f for water quality q ($/ha)
PY_{oqfc}	Initial crop yield of crop c in farm c for water quality q (ton/ha)
B_{idq}-	coefficient of inverse demand curve for demand d in district i for quality q (dimensionless)
α_{idq}	Exponent of inverse demand function for demand d in district i for quality q (dimensionless)
CS_{is}	Unit cost of water supplied from groundwater supply step s in district i ($/m^3)
CTR_{ijq}	Cost of transport fresh water from district i to district j for quality q ($/m^3)
$CTREC_{ijq}$	Cost of transport treated wastewater from district i to district j for quality q ($/m^3)
CR_{idq}	Cost of treated wastewater from sector d in district i for quality q in ($/m^3)
CRY_{idq}	Cost of treated wastewater from sector d in district i for quality q in ($/m^3)
$CDES_{iq}$	Cost of desalination water in district i for quality q in ($/m^3)
LR_i	Loss rate in district i (dimensionless)
P_{max}	Maximum price in the demand curve from sector d in district i for quality q in ($/m^3)
$GW_f{}^y$	Groundwater salinity at farm f in year y (mg/l)
ECT_c	Salinity-based yield reduction factor for crop c (mg/l)
$TWD_f{}^y$	Annual water demand for farm f (m^3)
WD_c	Water demand of crop c (m^3/ha)
$\varphi{}^y$	Regional salinity variation rate in year y
$TWA{}^y$	Total regional water abstraction in year y
SY	Aquifer safe yield MCM
A_{cfo}	Initial area under cultivation of crop c in farm f (ha)

Decision variables

Z	Net benefit in million dollars
A_{cf}	Area under cultivation of crop c in farm f (ha)

QD_{idq}	Quantity demanded by sector d in district i for quality q in MCM
QD_{is}	Quantity supplied by source s in district i in MCM
QTR_{ijq}	Quantity of freshwater transported from district i to district j for quality q in MCM
QRY_{iqd}	Quantity of treated wastewater from sector d (M&I) in district i for quality q in MCM
$QTRC_{ijq}$	Quantity of treated wastewater transported from district i to district j for quality q in MCM
$QTREC_{ijq}$	Quantity of treated wastewater transported from district j to district i for quality q in MCM
$QREC_{idq}$	Quantity of treated wastewater supplied to use d (agriculture) in district i for quality q in MCM
$QDES_{iq}$	Quantity of desalinated water supplied to all sectors d in district i for quality q in MCM
PR_{id}	Percent of treated wastewater from sector d (used in agriculture) in district i for quality q in MCM
P_{idq}	Shadow value of water for demand sector d in district i for quality q (computed) ($/m^3)

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