International Journal of Water Resources and Environmental Engineering Vol. 3(12), pp. 266-282, 21 November, 2011
Available online at http://www.academicjournals.org/ijwree
DOI: 10.5897/IJWREE10.030
ISSN 1991-637X ©2011 Academic Journals

Full Length Research Paper

Water management with wastewater treatment and reuse, desalination, and conveyance to counteract future water shortages in the Gaza Strip

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Accepted 14 October, 2011

Groundwater is the only freshwater source available for the Gaza Strip of Palestine, but Gaza groundwater is heavily polluted from agricultural activities and seawater intrusion. Water resource planners therefore have to find innovative alternate sources of water to minimize existing and future deficits. Possible management options include the use of treated wastewater (TWW), desalination, and conveyance of water between locations based on the demand. However, these options require significant funding and therefore, economic evaluation. Sophisticated economic and mathematical tools are now available that allow such analyses. A water allocation system model was used to economically evaluate various options for the projected water demands in 2010, 2020, and 2030. Results show that the use of TWW in agriculture can significantly increase net benefits and reduce water prices. However, any reduction in groundwater pumping can impact net benefits and increase water prices if additional supply is not found. Similar observations were made with the shadow value of water. However, water deficits cannot be accommodated with the existing supply including the use of TWW in agriculture. A combination of TWW use and desalination can increase the supply in an economically competitive manner while reducing groundwater pumping to minimize seawater intrusion. The increased net benefits and profits derived from such supply enhancements surpass the costs to rebuild and maintain the required infrastructure for the Gaza Strip.

Key words: Water allocation, wastewater reuse, desalination, conveyance, sustainable water management, economic benefits, the Gaza Strip.

INTRODUCTION

The primary competing uses for water are typically agriculture followed by domestic, industry, recreational, and more recently, environmental preservation. The proper distribution of water among these sectors requires careful planning and management. Sustainability of water resource and an equitable distribution of available water drive much of this planning (Huber Lee, 1999; McCarl et al., 1999; Orr and Colby, 2004; Loehman and Becker, 2006). Finding sustainable solutions for water stressed regions is an important focus of water resources planners and policy makers. To sustainably manage water, water allocations must be socially fair for both current and future populations (Huber Lee, 1999; Gillig et al., 2001; Loehman and Becker, 2006). The main goal of regional water managers is to develop spatial and temporal policies or suggest the efficient use of scarce water supplies for meeting ever increasing water demands. Integrating engineering, economic, social, and political considerations is crucial for this process (Perry, 1999; Rosenberg, 2008).

Water is not scarce in terms of quantity for those countries bordering a coast such as the Gaza Strip, Palestine. Coastal regions have the option of producing

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freshwater through desalination. For example, the approximate cost of desalination along the Mediterranean coast of the Gaza Strip is about \$0.50 to 0.60 /m^3 in 2005 (Metcalf and Eddy, 2000; Fisher et al., 2002; Al-Agha and Mortaja, 2005). Costs are even greater for land-locked countries due to desalination and conveyance to the point of use. Given the different options to produce more water, two points of interest become into attention in planet wide perspective; first, water scarcity is a matter of cost and value, not merely of quantity. Second, the value of water should be for free (is not an economic good) as what most of the people thinking in the Gaza Strip. The question might be posed as to how to place a value on water as a necessity for life, and, whether water prices should be based on the direct costs of provision (extraction, treatment, conveyance) to consumers, as water is a natural resource and a right. Both views are controversial and may be wrong (Fisher et al., 2005). Irrespective of the importance of water, it is unreasonable to value water at more than the cost of production and delivery. Therefore, desalination represents the upper bound of the value of water.

In addition to the cost of provision, demand also plays an important role among water uses. For example, if a user is willing to pay any asking price for water, then coastal countries can produce desalinated water and export to users irrespective of the distance or cost of production. Yet, there is an upper bound to the price that users are willing to pay. Most land-locked countries do not import desalinated water from coastal regions due to the high costs (Fisher et al., 2005).

On the other hand, the value of water does not merely consist of direct costs, such as extraction, treatment, and conveyance. Consider a scenario of a lake community where the water supply is abundant. With increasing population growth, there will be a time at which the renewable water from the lake will not be sufficient to address the needs of the population. At such a time, the value of water becomes more than zero because the population will be willing to pay for water given the short supply (Gibbons, 1986; Giordano et al., 2004; Fisher et al., 2005).

In this paper, an upper bound of water value will be the desalination cost of \$0.60/m^3 in the Gaza Strip in 2005. The actual value of water will be calculated from a systems analysis which considers the costs and benefits from different water use sectors that use groundwater and treated wastewater (TWW). The shadow value of water is the price that a buyer who values additional water the most would be willing to pay to obtain that additional water, given the optimal water flow conditions.

Water resources planning and management in regions with limited supply should consider long term goals and consequences of all potential options to ensure sustainable resource use. The Gaza Strip of Palestine is a good example where unmanaged groundwater withdrawals from the coastal aquifers have caused seawater intrusion, poor water quality, deterioration of valuable land due to high salinity, and large areas with the water table falling below mean sea level. To minimize these impacts, science based water resources planning and management that considers reduced groundwater pumping, desalination, reuse of TWW, and conveyance is needed to identify sustainable practices. An important part of this analysis is to consider the economics of water development in the overall planning framework.

Several earlier studies discussed the treatment of water as an economic commodity (Gibbons, 1986; Rogers and Fiering, 1986; Rosegrant, 2008; Sekler, 1996; Rogers, et al., 1998; Perry, 1999; Draper et al., 2003), but typically this approach has not been applied in real-life scenarios. There are, however, a growing number of examples of economic analyses in water resources management. Rogers (1993) studied the Ganges-Brahmaputra basin in the context of value of cooperation between India, Nepal, and Bangladesh, using a fixed supply and a single water type. Bhatia et al. (1994) modeled the industrial sector in Jamshedpur, India, and the impacts of both water tariff and effluent disposal charges. Huber Lee (1999) presented an inter-temporal model for sustainable management of the Gaza coastal aquifer. Huber Lee (1999) modeled groundwater hydrology and salt transport, as well as the economics of water allocation and agricultural water use. Fisher (1995), Fisher et al. (2002), and Fisher et al. (2005) modeled the agricultural, industrial, and domestic sectors of Israel, Jordan, and Palestine, to determine the value of water in these disputed countries.

Many studies have discussed the public health implications related to the use of TWW in agriculture and how TWW can help reduce stress on freshwater supplies (Afifi, 2006; Al-Juaidi et al., 2010). In sustainable water resources planning in water deficit regions, this discussion of public health impacts due to the use of TWW in agriculture should be addressed. In a previous work, Al-Juaidi et al., (2010) identified the potential health risk impacts of using TWW in irrigated agriculture in the Gaza Strip and the corresponding costs and benefits to the agricultural sector.

In the Gaza Strip, water is limited and already saline. The Gaza Strip faces serious issues with seawater intrusion and aquifer contamination from illegal discharging of untreated wastewater (Afifi, 2006; Al-Agha and Mortaja, 2005; Agha, 2006; Al-Juaidi et al., 2010). Water managers in the Gaza Strip are developing new tariff structures to cover the true cost of providing water. They are also implementing policies to reduce water losses to 20% of the gross water supplied and these approaches include improved metering, leak detection, and network rehabilitation. In addition, Palestinian water managers are trying to encourage the use of treated wastewater (TWW), brackish water, and harvested water in agriculture. Managers are holding workshops and public awareness programs for homeowners and farmers on water conservation, use of brackish water, and the use of TWW in agriculture (Al-Yaqubi et al., 2007; Metcalf and Eddy, 2000).

Despite these actions, Palestinian water managers face numerous challenges. First, water supply is limited, demand exceeds supply, much of the supply is saline or brackish, and supplies are becoming more saline. For example, nearly the entire Gaza Strip supply is saline due to the over abstraction from the Gaza aquifer causing seawater intrusion. The only freshwater supply is a relatively small 5 million cubic meters (MCM) per year delivery from Israel to Gaza City by pipe. Second, in Gaza, saline water use is extensive. However, in Gaza, authorities consider this saline water supply as a part of the fresh water supply thereby ignoring the reduced economic benefits and the additional costs that users incur to use saline groundwater. Third, there is no coordination among Palestinian institutions to forecast water demands, monitor, and license or regulate wells, administer water rights, price water, protect water quality, or systematically plan and develop system infrastructure (Al-Juaidi et al., 2010). There has been little consideration given to what desalination, waste-water treatment, and conveyance infrastructure may be needed (or could be avoided), and how water may be more beneficially allocated among sectors and districts. Fourth, the Israeli occupation and political unrest have exacerbated all of the above problems.

To help evaluate some of the deficiencies of the water allocation programs discussed earlier in an economically competitive manner. This paper assesses the economic viability and provides economic knowledge of improved water management options suitable for water deficit regions. This paper evaluate the issues of manage water deficit in the context of economics and social welfare. This paper provide economic knowledge from evaluating different water supply options that could reduce aquifer deterioration from sea water intrusion and dumping untreated wastewater into Gaza aquifer. Options include reduced groundwater pumping, desalination, use of TWW in agriculture, and conveyance. The proposed methodology will be demonstrated to the Gaza Strip, Palestine. The specific research questions addressed by this work are (1) how are the urban and industrial sectors affected when TWW is used in agriculture? (2) Will a reduction in groundwater pumping without the use of TWW have detrimental effects on supply and economic benefits? (3) What supply enhancement options are available to reduce future water deficits? And (4) what are the competitive economic benefits of these improved options?

METHODOLOGY

This work uses the water allocation model proposed by Fisher et al. (2005) and the details are given in the next section. The water allocation model maximizes the net benefits by allocating water to the different sectors and districts based on demand. Associated with these allocations is a system of shadow values of water in different locations. There are two fundamental concepts in a water allocation model. First, water scarcity provides a value for water. As water scarcity increases, consumers are willing to pay relatively higher prices for small amounts of water. Water becomes less valuable when it is abundant. Second, a social value for water gives governments the incentive to subsidize. In countries where agriculture is not profitable but socially and politically desirable, the government may subsidize water for agriculture. This action will allow delivering water to farmers at a lower price (Fisher et al., 2005). The water allocation model explicitly considers these social values.

Description of the water allocation model

In this work, the economic value of water reflects the benefit from use, costs to procure, treat, and convey water to the point of use. Costs of seawater desalination plus conveyance to the point of use determine the upper bound value of water as this is the most expensive option in water deficit regions such as the Gaza Strip, Palestine. The water allocation system model utilized herein (Fisher et al., 2005) is a steady-state, deterministic optimization model for a single-year. The model maximizes annual net benefits from water use subject to physical and sociopolitical constraints on water availability, use, reuse, conveyance, and price policies that tax or subsidize certain water uses. The net benefit is the area between the demand and cost curves (Figure 1). The optimal allocation is the quantity, *q** in Figure 1 (assuming there are no binding constraints). In the case of the Gaza Strip, constraints are specified for different districts and water-use sectors. For example, the quantity demanded must balance with the water extracted from local sources, imported from and exported to other districts, and the use of TWW that cannot otherwise be put to an economical use. Appendix A presents the mathematical formulation of the water allocation system model.

Mathematical formulation

The mathematical formulation presented in Appendix A studies the costs and benefits associated with water supply and demand across multiple water use sectors in each demand district. The analysis assumes the entire region, in this case the Gaza Strip, as a single integrated system consisting of five demand districts and each district has different water use sectors. The water use sectors considered in the analysis are agriculture, urban, and industrial. Net benefit (Z, Equation A1 in Appendix A) is estimated as the benefit of water demanded (from water related services) minus the cost to supply the demanded water. Benefits are the first term in Equation A1 and calculated as the area under the inverse demand or willingness to pay curve. The remaining objective function terms represent costs of local water supply, desalination, wastewater treatment, and conveyance of fresh and TWW between districts. The inverse demand curve describing benefits assumes constant elasticity and is represented as:

$$P_i = \beta_i \times Q_i^{\alpha_i} \quad (1)$$

where P_i is the price ($/m^3); Q_i is the quantity demanded (m^3); β_i is a dimensionless parameter that indicates the position of the demand curve and allows exploration of the effects of greater or lesser demands for district *i;* and α_i is the dimensionless exponent whose inverse (1/ α_i) is the price elasticity of demand in district *i*. Price elasticity of demand is defined as the percentage change in

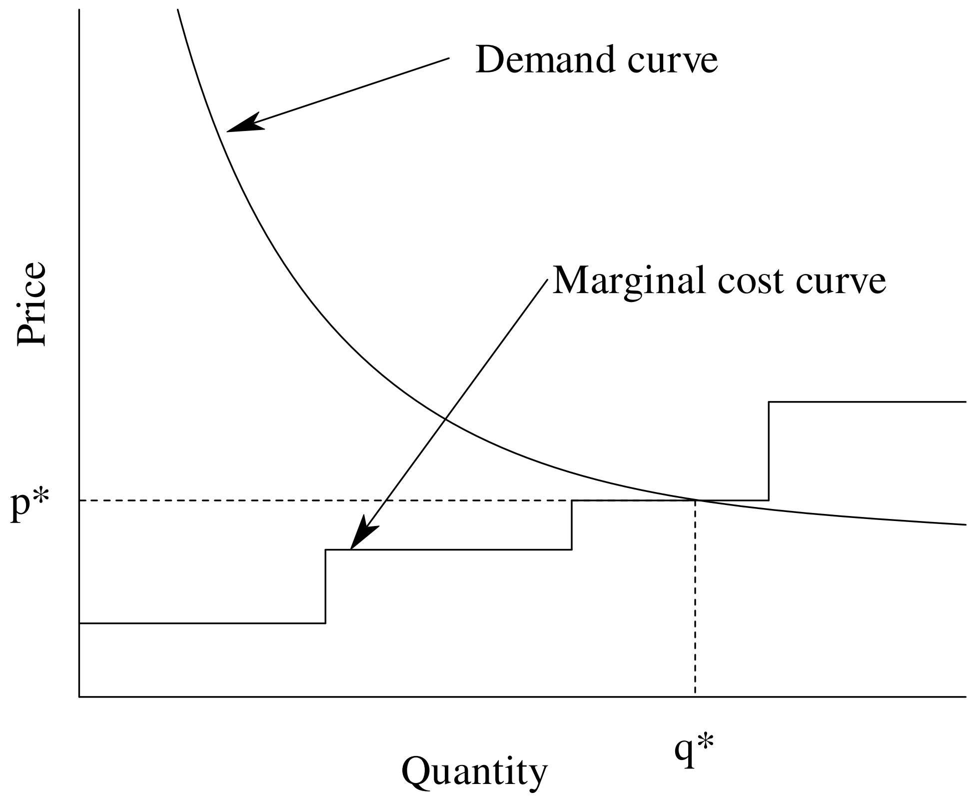

Figure 1. Demand and cost curves for net benefit evaluation (Fisher et al., 2005).

quantity induced by a 1% change in price and it is a measure of the sensitivity of quantity demanded to the change in price.

The literature on price elasticity of demand for urban and industrial water use is extensive (Espey et al., 1997; Gibbons, 1986; Fisher et al., 2005). The value of price elasticity of demand for Palestine is -0.6 for urban use, -0.33 industrial, and -0.5 agricultural uses (Fisher et al., 2005). The specification of demand here does not specify a fixed quantity to be used. Rather, the focus is how benefits change with different quantities of use. Water demand functions were estimated for the Gaza Strip for 2010, 2020, and 2030 using data collected from a variety of sources (Huber-Lee, 1999; Metcalf and Eddy, 2000; PWA and SUSMAG 2003; Fisher et al., 2005; MoP, 2005; PCBC, 2005).

The estimates of water consumption from different water sources including groundwater and return flows for each water district and sector are given in Table 1. Table 1 provides the base year use (consumption) across demand years. For example, the estimate of the coefficient of inverse demand curve B_{id} for 2030 is the base year use of 2030 over the base year use of 2020.

Demand and supply

The water balance for freshwater is given in Equation (A2) of Appendix A. The amount of fresh water consumed in any location must equal the sum of water extracted from the location, desalinated quantity, and water brought from other locations minus the amount conveyed to other locations or lost to leakage.

The TWW balance is similar to freshwater (Appendix A, Equation (A3)). In this case, the amount of water consumed in any location must equal the amount produced there plus the amount imported from other locations minus the amount conveyed to other locations. The water available for treatment is assumed to be available from urban and industrial sources only. In this work, it is assumed that a maximum of 2/3 of the total urban and industrial water use is available for treatment and reused in agriculture (Metcalf and Eddy, 2000; Fisher et al., 2005). Presently, the Gaza Strip has three wastewater treatment plants (WTPs) that are not functioning well. In the proposed scenarios, new WTPs will be assumed to be constructed to produce adequate quality TWW without relying on existing WTPs.

The economic evaluation will address the water resources management of the Gaza Strip in two parts. In Part 1, the economic benefits of using TWW and a reduction in groundwater pumping to allow aquifer recovery are evaluated. In Part 2, the analysis is extended to include supply enhancement options to reduce the increasing water deficit. The additional options considered include desalination, increase TWW output, and conveyance of water between different districts. Finally, we evaluate the required institutional changes to implement the proposed supply enhancements, their costs, and compare the costs against net benefits.

Description of study area

The Gaza Strip is 40 km long and approximately 9 km wide and located between the Negev Desert, Israel and Mediterranean Sea. The Gaza Strip depends on water from the coastal aquifer that runs from the border of Egypt to Haifa in Israel. The aquifer drains from east to west, with negligible north-south flows. The Gaza coastal aquifer is presently being overexploited by agricultural pumping, with total pumping exceeding the total recharge. The Gaza Strip has a semi-arid climate. There are two well-defined seasons: the wet season from October to March and the dry season from April to September. Peak months for rainfall are December and January.

Table 1. Projected of water use (consumption) of the Gaza Strip for 2010, 2020, and 2030.

District	Water use (MCM/year)		
	2010	2020	2030
Urban			
Gaza North	11.3	15.91	20.22
Gaza	26.84	37.81	46.87
Deir al-Balah	11.22	15.8	22.81
Khan-Younis	15.48	21.81	27.53
Rafah	8.24	11.61	16.72
Industrial			
Gaza North	1.1	1.49	2.43
Gaza	2.7	3.53	5.62
Deir al-Balah	1.1	1.48	2.74
Khan-Younis	1.6	2.04	3.3
Rafah	0.8	1.08	2.01
Agricultural			
Gaza North	22	19.1	19
Gaza	28	26.4	25
Deir al-Balah	15	13.3	14
Khan-Younis	14	12.2	11
Rafah	9	8	8

The long term mean annual rainfall is 325 mm/year, and it decreases from north to south. The mean temperature varies from 12 to14ºC in January to 26 to 28ºC in June. Evaporation measurements have clearly shown that the long term average open water evaporation is approximately 1,300 mm/year. The maximum evaporation rate of 140 mm/month occurs in June, July, and August, and the minimum is around 70 mm/month during winter.

The Gaza Strip is an interesting case study for many reasons. The region faces serious issues with seawater intrusion, as well as aquifer contamination from agricultural and urban wastes (Afifi, 2006; Agha, 2006). The Gaza Strip is densely populated with a population growth rate of 3.2%. The majority of the population has relatively low income, while the region has a highly uncertain political situation. Political uncertainty has contributed to ineffective political institutions, particularly to manage natural resources such as water. Given the small area in combination with the existing political and social unrest, it is not surprising that environmental quality is rapidly deteriorating. There is widespread groundwater contamination, and over-pumping of the aquifer has led to seawater intrusion (Yakirevich et al., 1998; Metcalf and Eddy, 2000; Melloul and Collin, 2000; Qahman, 2004; Weinthal et al., 2005; Agha, 2006).

The Gaza Strip is divided to five districts known as *Gaza,* North Gaza, Deir Al-Balah, Khan Younis, and Rafah (Figure 2). The population is expected to be 1,557,000 and 1,993,100 in 2010 and 2020, respectively. The population distribution is about 15.4% in North Gaza, 36.7% in Gaza, 15.3% in Deir-al-Balah, 21.1% in Khan-Younis, and 11.2% in Rafah.

The total agricultural area of the Gaza Strip is about 16,650 ha. Previous studies have indicated that the agricultural sector is the largest consumers of water in the Gaza Strip (Issac, 2000; Khalil et al., 2003; Afifi, 2006). However, this percentage has decreased and will continue to decrease with increasing population. Presently, water is considered as a "free good" by farmers, without subject to metering or pricing. Farmers pay only the water pumping cost which is less than \$0.05 /m^3.

Table 1 shows projected water consumption across the years for the Gaza Strip district. Projected water uses for 2010, 2020, and 2030 (Huber- Lee, 1999; Metcalf and Eddy, 2000; PWA and SUSMAG, 2003) suggest that industrial use will stay small and not be more than 7% of the total use. On the other hand, urban use will likely increase in both amount and share from about 40% in 2010 to 59% in 2030. Given the limited land area especially for agriculture, agricultural water use will likely stay the same in volume but decrease in share.

Water supply

The Palestinian Water Authority (PWA), which is the government institution responsible for water resources, stipulates the maximum allowable groundwater extraction in each district (Metcalf and Eddy, 2000).

The total water availability in the Gaza Strip is about 145 MCM/year. This supply is distributed as 32, 46.5, 24.6, 25.9, and 16 MCM/year for North Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah, respectively. The price of water is \$0.33/m^3 for the urban and industrial sectors in 2010. The price of water for the agricultural sector is \$0.16 /m^3 in 2010 (Melloul and Collin, 2000; Fisher et al., 2005; Weinthal et al., 2005). Water pumping costs in 2010 are 0.033, 0.014, 0.018, 0.031, and 0.032 \$/m^3 for North Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah, respectively (Fisher et al., 2005; Melloul and Collin, 2000; Weinthal et al., 2005). Water supply is expected to remain the same for the years of 2020 and 2030 (Metcalf and Eddy, 2000).

Additionally, private water sellers provide 5 MCM/year to the Gaza district at \$0.40 per m^3. We assume that the available quantity of water to Gaza is 145 MCM/year and that each of the five districts can draw from the aquifer as a common pool resource (Metcalf and Eddy, 2000; Fisher et al., 2005). This quantity is

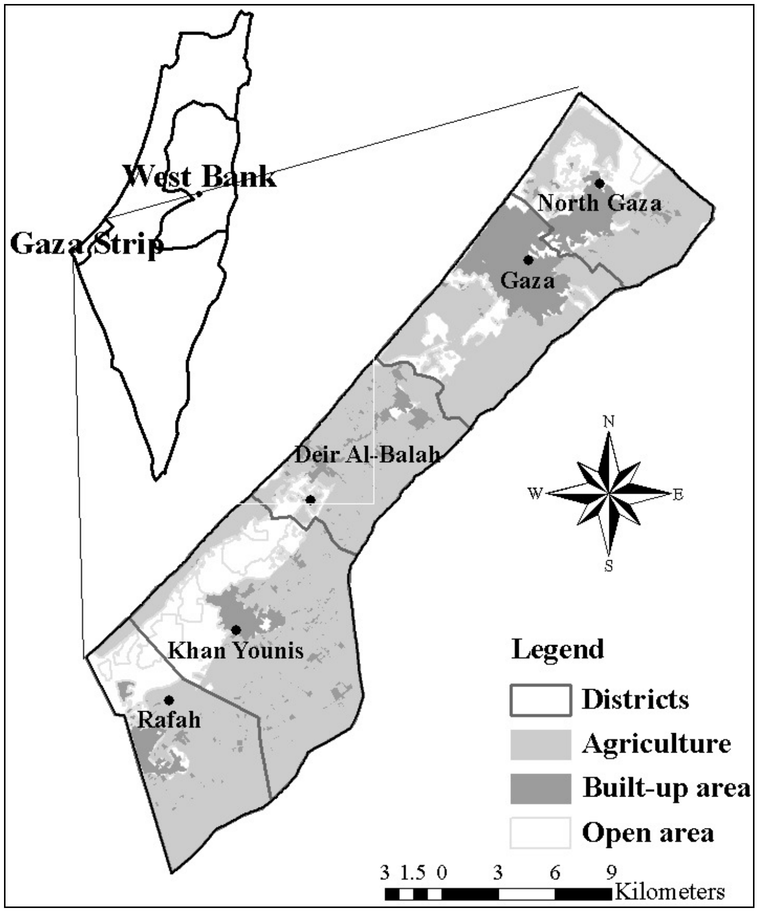

Figure 2. Layout of the Gaza Strip, Palestine showing the different water districts.

considered a reasonable value for long-term natural aquifer replenishment of the Gaza Strip (Metcalf and Eddy, 2000).

The Gaza Strip currently has no inter-district conveyance. Intra-district conveyance for industrial and domestic water use exists but suffers from serious problems related to illegal water uses and leakages. It is estimated that these losses from the system are close to 40% of the total water supply (Metcalf and Eddy, 2000; Fisher et al., 2005). This work will assume that the proposed infrastructure improvements will eliminate the existing leakages and will only account for system losses due to illegal water use at a rate of 20%.

The use of TWW in agriculture is low due to poor social acceptance. With the low chemical hazard and low quantities generated from the industry, there is no special treatment for industrial water, and this water is treated with urban wastewater in the same treatment plants.

RESULTS AND DISCUSSION

Use of TWW and reduced groundwater pumping

The first part of this study will evaluate if the use of TWW in agriculture is sustainable and economically attractive while considering some restriction on groundwater pumping to reduce seawater intrusion. The proposed scenarios are (1) existing conditions, that is, no reduction in groundwater pumping and no use of TWW; (2) existing conditions with the use of TWW for agriculture; (3) existing conditions with 50% reduction in groundwater pumping only; and (4) existing conditions with 50% reduction groundwater pumping and the use of TWW in agriculture.

In scenarios 1 and 3 when TWW is not used, only freshwater is available for agriculture. In other words, $PR_{max\,id}$ is set to zero in Equation (A7) of Appendix A and $QFRY_{id}$ in Equation (A1) becomes zero. In scenarios 3 and 4 when reduced pumping is considered, $QS_{max\,is}$ in Equation (A6) in Appendix A is reduced accordingly.

Use of TWW with existing groundwater pumping

Table 2 provides the results of Scenarios 1 and 2 for 2020 where groundwater pumping is maintained at existing levels but includes both the use, and non-use of TWW in agriculture. Table 2 shows that without the use of TWW, only 116 MCM/year of water is available (after allowing for leaks) from groundwater. Given the deficit, all

Table 2. Results of Scenarios 1 and 2 for the economic evaluation of TWW use with no reduction in groundwater pumping for 2020.

Item	Scenario 1 - No use of TWW (Base Case)					Total
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	
Net benefit ($millions)	--	--	--	--	--	--
Fresh water to urban sector (Q_{du}), MCM	17.0	34.0	15.0	16.0	9.0	91.0
Fresh water to industrial sector (Q_{di}), MCM	1.0	2.0	1.0	1.0	1.0	6.0
Fresh water to agriculture (Q_{da}),MCM	7.0	4.0	3.0	3.0	2.0	19.0
Urban water price ($/m^3)	0.26	0.35	0.32	0.48	0.41	--
Industrial water price ($/m^3)	0.26	0.35	0.32	0.48	0.41	--
Agricultural water price ($/m^3)	0.26	0.35	0.32	0.48	0.41	--
Shadow value of water ($/m^3)	0.21	0.27	0.26	0.38	0.38	--

Item	Scenario 2 - Use of TWW					
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	Total
Change in net benefit ($ millions)	1.0	1.0	1.0	2.0	1.0	6.0
Fresh water to urban sector (Q_{du}), MCM	24.0	37.0	18.0	19.0	11.0	109.0
Fresh water to industrial sector (Q_{di}), MCM	1.0	3.0	1.0	1.0	1.0	7.0
Fresh water to agricultural sector (Q_{da}), MCM	0.0	0.0	0.0	0.0	0.0	0.0
TWW from urban sector (QRY_u), MCM	11.51	9.00	5.0	6.0	4.0	35.5
TWW from industrial sector (QRY_i), MCM	0.57	0.12	0.95	0.68	0.11	2.43
TWW to agriculture ($QFRY_{na}$), MCM	12.08	9.12	5.95	6.68	4.11	38.0
Urban water price ($/m^3)	0.15	0.28	0.23	0.37	0.30	--
Industrial water price ($/m^3)	0.15	0.28	0.23	0.37	0.30	--
Agricultural water price ($/m^3)	0.10	0.10	0.10	0.10	0.10	--
Shadow value of water ($/m^3)	0.12	0.23	0.23	0.29	0.24	--

sectors and districts exhibit significant shortfalls of water. However, when TWW is introduced, the supply increases by 76 MCM/year due to the wastewater available from urban and industrial sectors. It should be noted that up to 2/3 of freshwater use in urban and industrial sectors is available for reuse as TWW. In this scenario, no freshwater is allocated to agriculture.

The net benefit increases when TWW is used in agriculture due to the availability of additional water in each district. As an example, the shadow values for North Gaza with and without TWW are $0.12 and $0.21 per m^3, respectively. The water prices of urban and industrial sectors decrease when the sector's wastewater is treated and reused in agriculture. Agricultural water prices also decrease as a result of TWW use in agriculture. The Gaza district, which always has the highest demand among all districts for each sector, showed the highest reduction in both shadow value and sector water prices. Overall, total net benefits increase by $6 million/year when TWW is reused in agriculture.

Reduction in groundwater pumping

Table 3 shows the results of Scenarios 3 and 4 where groundwater pumping is reduced by 50% in each scenario for 2020. With the reduction of groundwater pumping, the fresh water availability reduces to 58 MCM and this water is mostly allocated to urban and industrial sectors. The agricultural sector received only than 9 MCM/year without the use of TWW. With the use of TWW, the total supply of water to the agricultural sector increased by 32.7 MCM/year. Since the agricultural water demand is served by TWW, freshwater supplies to the urban and industrial sectors also increased by 9 MCM/year.

Table 3 shows that the change in net benefit from the base case decreases by $19 million/year when TWW is used while maintaining 50% reduction in groundwater pumping. Both urban and industrial water prices decreased by about 40% while the agricultural water prices decreased to about 10% of the price without the TWW due to the increased TWW supply of 32.7 MCM.

The sustainable yield of the Gaza aquifer is about 60 MCM/year (Metcalf and Eddy, 2000; Fisher et al., 2005). The reduced groundwater pumping in Scenarios 3 and 4 allowed 58 MCM/year of freshwater from the aquifer, and this amount is close to the sustainable yield of the aquifer. If future pumping is continued at this rate, then recovery of the aquifer can be expected due to reduced seawater intrusion. However, the shadow value of water in both scenarios, including the scenario with the addition of TWW, remained higher than $0.60/m^3. Therefore, these results indicate that supply enhancements are needed to meet the demand while promoting aquifer recovery in the presence of serious seawater intrusion.

Table 3. Results of scenarios 3 and 4 for the economic evaluation of TWW use with 50% reduction in groundwater pumping for 2020.

Item	Scenario 3 - No use of TWW					Total
	North Gaza	**Gaza**	**Deir al-Balah**	**Khan Younis**	**Rafah**	
Improvement in net benefits from base case ($ millions)	-7.0	-15.0	-6.0	-5.0	-3.0	-36
Fresh water to urban sector (Q_{du}), MCM	7.0	17.0	7.0	10.0	5.0	46.0
Fresh water to industrial sector (Q_{di}), MCM	0.5	1.0	0.5	0.5	0.5	3.0
Fresh water to agriculture (Q_{da}), MCM	3.0	2.0	1.0	2.0	1.0	9.0
Urban water price ($/m^3)	1.06	1.04	1.04	1.06	1.06	--
Industrial water price ($/m^3)	1.06	1.04	1.04	1.06	1.06	--
Agricultural water price ($/m^3)	1.06	1.04	1.04	1.06	1.06	--
Shadow value of water ($/m^3)	0.85	0.83	0.84	0.85	0.85	--

Item	Scenario 4 – Use of TWW					
	North Gaza	Gaza	Deir al-Balah	Khan Younis	Rafah	Total
Change in net benefits from base case ($ millions)	-4.0	-9.0	-3.0	-2.0	-1.0	-19
Fresh water to urban sector (Q_{du}), MCM	9.0	20.0	6.0	11.0	6.0	52.0
Fresh water to industrial sector (Q_{di}),MCM	1.0	1.0	1.0	1.0	1.0	6.0
Fresh water to agricultural sector (Q_{da}),MCM	0.0	0.0	0.0	0.0	0.0	0.0
TWW from urban sector (QRY_u), MCM	6.52	7.48	5.26	6.00	4.01	28.84
TWW from industrial sector (QRY_i), MCM	0.73	1.64	0.69	0.68	0.10	3.84
TWW to agriculture ($QFRY_{na}$), MCM	6.82	9.12	5.95	6.68	4.11	32.68
Urban water price ($/m^3)	0.66	0.76	0.76	0.78	0.78	--
Industrial water price ($/m^3)	0.66	0.76	0.76	0.78	0.78	--
Agricultural water price ($/m^3)	0.28	0.10	0.10	0.10	0.10	--
Shadow value of water ($/m^3)	0.62	0.61	0.61	0.62	0.62	--

The most and least favorable scenarios for supply are Scenario 2 and 3, respectively. When the results of these two scenarios are compared, it is seen that the shadow values reduce significantly with the use of TWW and no reduction in groundwater pumping. For example, the most water demanding Gaza district sees a reduction from $0.83 to $0.23/m^3 which is over a 55% reduction. Still, the shadow values in all districts are higher than $0.60 per m^3, with Scenario 3 and Scenario 4, even after using TWW.

Tables 2 and 3 clearly indicate that for a given groundwater withdrawal, agricultural use of TWW provides significant economic benefits. The shadow value of water increases and net benefits decrease when pumping is constrained due to the higher scarcity of water. The prices of water in each sector decrease with the use of TWW, especially in the agricultural sector while increasing the net benefits. Districts such as Gaza and Rafah showed significant increase in net benefit.

The shadow values for the base case scenario for Gaza and Rafah districts in 2010, 2020, and 2030 are around $0.20, $0.30, and $1.54 /m^3, respectively. The shadow values for the base case scenario including a 50% reduction in pumping for Gaza and Rafah districts in 2010, 2020, and 2030 are around $0.60, $0.85, and $3.87 /m^3, respectively. These two districts had the highest and lowest demands. As discussed earlier, the shadow value of water increased in both districts with reduced groundwater pumping. Most importantly, the shadow value increased with time in both districts due to the higher demand with time. Also the difference between the shadow value with and without groundwater pumping also increased with time in both districts indicating that increased demand with time produce a higher rate of shadow value increase.

Reuse of TWW has a positive economic impact on the water supply of the Gaza Strip. However, this gain is reduced when groundwater pumping is reduced. The shadow values of water can be kept below $0.60 per m^3 only when both TWW is used, and groundwater pumping is maintained at the same levels.

Options for water supply enhancements

As discussed earlier, TWW reuse for agriculture did not reduce the shadow value of water below $0.60/m^3 as demands grew but supplies remained the same. Moreover, the shadow value of water increases in 2020 and 2030. Furthermore, the shadow value of water differs by district. These factors necessitate the search for new and additional water resources. The proposed management actions in this study are (a) desalination; (b) increasing the number of WTPs; and (c) water conveyance systems between districts. For the purpose of this study, the following management options were

Table 4. Shadow value SV ($\$/m^3$) and change in net benefit ($ million per year) relative to base case for 2030.

Option	North Gaza		Gaza		Deir Al-Balah		Khan-Younis		Rafah		Total change
	Change in net benefit	SV	Change in net benefit	SV	Change in net benefit	SV	Change in net benefit	SV	Change in net benefit	SV	
1	--	1.54	--	1.52	--	1.53	--	1.54	--	1.54	--
2	6.0	1.18	9.0	1.16	4.0	1.17	5.0	1.18	3.00	1.18	27.0
3	-6.0	3.77	-30	3.75	-9.0	3.75	-10.0	3.76	-7.0	3.77	-62.0
4	2.0	0.62	9.0	0.60	2.0	0.60	1.0	0.62	2.0	0.60	16.0
5	1.0	1.82	4.0	0.60	1.0	1.81	0.0	1.82	0.0	1.82	6.0
6	1.0	0.87	4.0	0.60	1.0	0.85	2.0	0.87	2.0	0.87	10.0

1. Base case (Existing situation) - no constraint on pumping and no use of TWW
2.Use of TWW by adding five WTPs and the capacity of each unit are 20, 40, 25, 15, 15 MCM/year for North Gaza, Gaza, Deir Al-Balah, Khan-Younis, and Rafah, respectively.
3. Option 2 + 50% reduced pumping.
4. Option 3 + desalination unit in each district with an individual capacity of 15 MCM/year.
5.Option 3 + one desalination plant each in North Gaza and Deir Al-Balah districts with an individual capacity of 1.83 MCM/year and one unit of capacity 54.8 MCM/year in the Gaza district.
6. Option 5 + two conveyance pipelines to distribute water from the Gaza to Khan-Younis district and from Gaza to Rafah district. The maximum capacity of each line will be 10 MCM/year.

developed in combination of the three actions proposed earlier:>

Option 1: Base case (existing situation) - no constraint on pumping and no use of TWW.
Option 2: Use of TWW by adding five WTPs and the capacity of each unit are 20, 40, 25, 15, 15 MCM/year for North Gaza, Gaza, Deir Al-Balah, Khan-Younis, and Rafah, respectively.
Option 3: Option 2 + 50% reduced pumping. The basis for this reduction is that in the Gaza Strip, the total water use is 140 MCM/year, but the recharge of the Gaza coastal aquifer is 60 MCM/year or 43% of use. Similar results are available for the West Bank as well.
Option 4: Option 3 + desalination unit in each district with an individual capacity of 15 MCM/year.
Option 5: Option 3 + one desalination plant each in North Gaza and Deir Al-Balah districts with an individual capacity of 1.83 MCM/year and one unit of capacity 54.8 MCM/year in the Gaza district.
Option 6: Option 5 + two conveyance pipelines to distribute water from the Gaza to Khan-Younis district and from Gaza to Rafah district. The maximum capacity of each line will be 10 MCM/year.

It should be noted that some of these options were previously proposed by the PWA but were not studied for economic viability. In this work, the economic viability will be evaluated using net benefit and shadow value. Since the addition of desalination plants and/or WTPs can increase the supply of freshwater to all sectors and TWW for agriculture, these options include a 50% reduction in groundwater pumping.

Shadow value of water

Table 4 shows the shadow value of water in 2030 to the supply enhancement options discussed earlier. The shadow values in the existing scenario are around $\$1.54/m^3$ and these values decreased with the introduction of the five WTPs in Option 2 to about $\$1.18/m^3$. The obvious reason is the increased availability of water to agriculture while the freshwater supply available to other sectors increased. However, the shadow prices increased more than threefold from Option 2 to Option 3 due to the reduction in groundwater pumping by 50%. The reason is the reduced supply of freshwater while additional TWW from the new plants can be used for agriculture only. It should be noted while an increase in TWW supply helped reduce the shadow value of water, the most sensitive change was observed with the constrained pumping in Option 3. The increase in shadow value between Options 2 and 3 is much larger than between Options 1 and 2. Hence it is obvious that any constrained pumping will have a large impact that may not be corrected with the use of TWW only.

Following the same discussion, Option 4 shows even more drastic changes in shadow value with the introduction of desalination consisting of five units. The reduction in shadow value between Options 3 and 4 is much higher than the increase in shadow value between Options 2 and 3. Therefore, the results suggest that the large impact produced by constrained pumping can be successfully mitigated using desalination. In Option 4 with desalination, constrained pumping and the use of TWW, the shadow value of water is around $\$0.60/m^3$ across all districts.

Option 5 which installed one large desalination plant in the Gaza district and two smaller desalination plants in North Gaza and Deir Al-Balah districts did not help to reduce the shadow value except in the Gaza district. In Option 6 which introduces two conveyance lines to the desalination plant configuration in Option 5, shadow values decrease in districts (Khan Younis and Rafah) that received water and remained $0.60/m^3 in the Gaza district that provided water. Even under this option, the shadow value in other districts remained as high as $0.87 per m^3.

Change in net benefits

Table 4 shows the change in net benefit from the base case for 2030. The results are similar to the results obtained for shadow value. The introduction of five WTPs increased the net benefits in all districts especially in the Gaza district where the demand is highest. The total net benefits increased by $27 million/year between the existing and Option 2. However, the reduced groundwater pumping in Option 3 reduced the net benefits significantly in all districts due to the reduction of freshwater supply. In Option 3, the total net benefits decreased by $62 million per year. The major recovery of net benefits in all districts occurred in Option 4 with five desalination units. This recovery was highest in the Gaza district and less in other districts. The improvement in net benefits with Option 4 over the base case is $16 million/year. In Option 6, where three desalination plants and a conveyance line are considered, the change in benefits is $10 million which is lower than $16 million when five desalination units are considered.

Water prices

Urban water prices are affected when the freshwater supply is affected. Any increase in WTPs cannot directly improve the urban water supply, because TWW is used in agriculture only. Also, any option that reduces groundwater pumping also showed an increase in urban water prices due to the reduced availability of freshwater.

Figures 3 and 4 shows the comparison of urban and agricultural water prices for major scenarios considered so far in this work. These include the existing conditions (no use of TWW and no reduction in groundwater pumping), construction of five desalination units and five WTPs with a 50% reduction in pumping, and construction of three desalination units and five WTPs with a 50% reduction in pumping.

As shown in Figure 3, the urban water prices were lowest with both desalination plants of capacity 15 MCM and TWW in each district. In addition, the urban water prices were the lowest with a large desalination plant of 54.8 MCM in the Gaza district. The agricultural water prices decreased dramatically when TWW was used in agriculture including 5 desalinations due to the availability of more water. Existing conditions (without TWW) produced the highest agricultural water prices compared to all other options.

As shown in Figure 4, the existing conditions produced agricultural water prices of $1.93, $1.9, $1.91, $1.92, $1.92/m^3 for N.Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah, respectively. These agricultural water prices decreased to $0.18, $0.10, $0.10, $0.10, and $0.10/m^3 for North Gaza, Gaza, Deir al-Balah, Khan-Younis, and Rafah districts, respectively, with the introduction of WTP and 5 desalinations in each district with Option 4.

Benefit comparison

Table 5 summarizes the changes in net benefits from the base case for different combinations of desalination, use of TWW, and groundwater withdrawal levels for 2020 and 2030. The results show few interesting details. First, when the freshwater supply is not increased with desalination, net benefits reduce with time due to increasing demands. As desalination is introduced and desalination capacity is increased, the net benefits increase between options as well as with time. As expected and similar to previous observations, addition of TWW for agriculture always helps to improve net benefits irrespective of the capacity of desalination. Second, the reduction in groundwater pumping has a large sensitivity on net benefits. For example, net benefit change can vary from $3 to $-32 million/year when pumping is reduced by 50% in 2020 with three desalination units. On the other hand, this impact can be softened with the use of TWW, which makes the change in net benefits vary from $-32 to $-17 million/year. For the purpose of economic viability, maintaining the status quo for groundwater pumping is attractive, but at the cost of long term impacts to the freshwater supply of Gaza aquifer.

Infrastructure development and benefits

The work conducted so far addressed the economic benefits and limitations of various supply enhancements options suggested by Metcalf and Eddy (2000), PWA (2003), and PWA and CDM (2003) to address future water deficits in the Gaza Strip up to 2030. Each option considered fixed (specified) infrastructure capacities. However, model results show water scarcity will likely persist, (shadow values in several districts are above the desalination cost of $0.60/m^3) and suggest that expanded supply enhancements may be warranted. We now consider an optimization methodology that identifies the appropriate infrastructure capacity for future improvement to economic viability by maximizing net benefit. Since desalination and the use of TWW and freshwater transport among districts were identified as the best options with some consideration to reduce groundwater pumping to limit seawater intrusion, these options were further analyzed here, it is important to find the best combination from the different approaches of desalination, wastewater treatment and reuse,

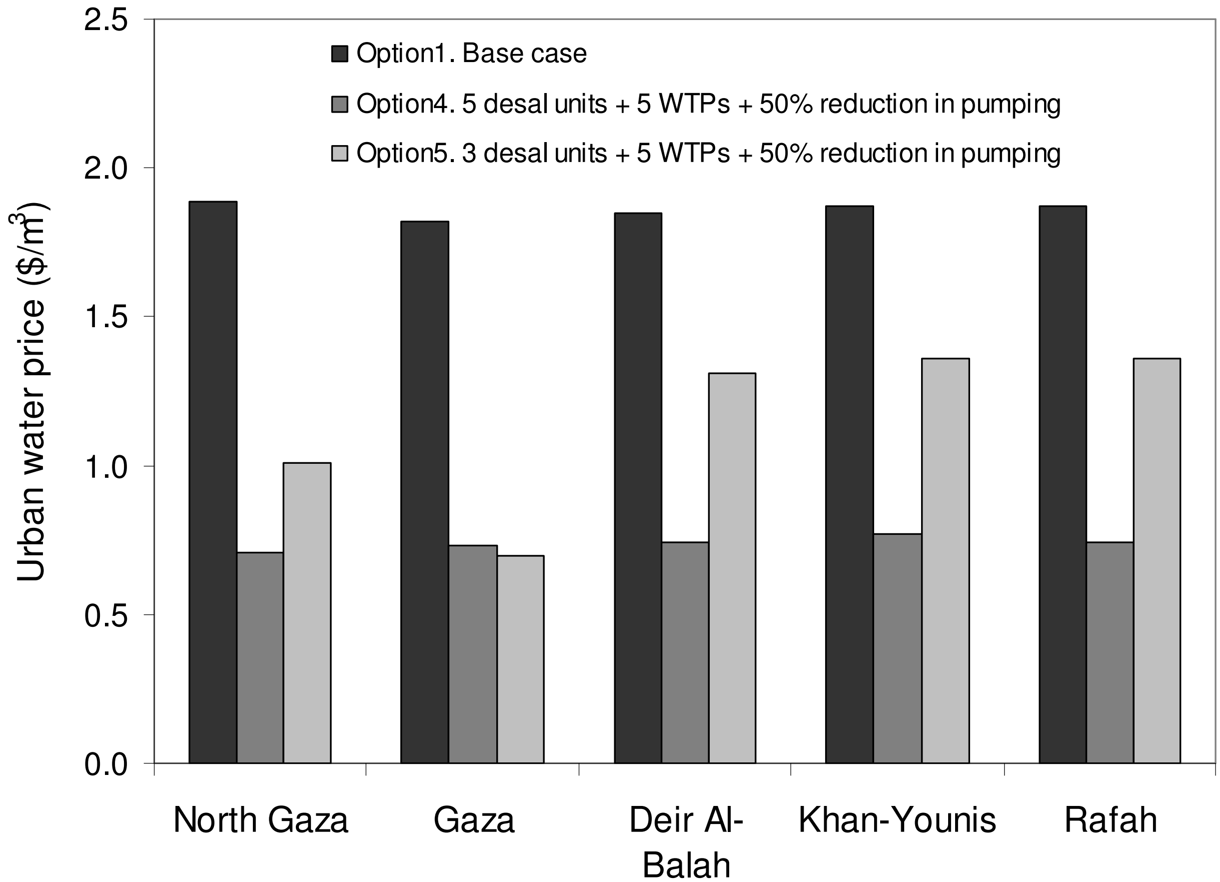

Figure 3. Predicted urban water prices in 2030 for base case, supply enhancements options of (5 desal units + 5 WTPs with 50% reduction in pumping) and (3 desal units + 5 WTPs with 50% reduction in pumping).

conveyance of fresh water between districts and reduced groundwater withdrawal from the Gaza aquifer while addressing benefits. A simulation was conducted with a higher Upper bound of 1000 MCM set for each desalination, wastewater treatment plants, and conveyance of fresh water between districts to find the optimal desalination, WTPs, and conveyance capacity required in each district. These simulations consist of reducing the groundwater pumping from the base case conditions in 2030 (Table 6).

A discount rate of 5% was used to calculate the present value of profit from annual net benefits computed from the optimization analysis and the capital costs for the proposed new infrastructure. The estimated capital costs were $2.72 million in 2010 to add 1 MCM per year of desalination capacity (Metcalf and Eddy 2000; PWA 2003; PWA and CDM 2003). A cost of $1.2 million is required to expand the treatment wastewater capacity by1 MCM per year (Metcalf and Eddy 2000; PWA 2003; PWA and CDM 2003).

The results in Table 6 show few interesting features. As groundwater pumping is reduced to promote aquifer recovery (and reduce seawater intrusion), more desalination is needed to maximize net benefit. With the reduced freshwater supply due to reduced pumping, the maximum amount of wastewater produced and available for reuse is reduced given the cutoff ratio of 2/3. As groundwater pumping is reduced, therefore, less TWW is available for agriculture. The conveyance capacity is zero in for all scenarios due to the availability of water from desalination and treated wastewater. Given the increased cost of desalination with reduced pumping, the net benefits gradually reduce. Once the capital cost of infrastructure, especially for desalination is included, the profits reduce with reduced groundwater pumping. A reduction in groundwater pumping approximately above 50% may introduce negative profits in supply enhancement.

The sustainable yield of the Gaza aquifer is around 60 MCM/year. It is seen that if groundwater pumping is reduced to this level, the net benefit is at the minimum from all scenarios and the profit is negative at $56 million. Metcalf and Eddy (2000) estimated the total operating budget of $4.7 million/year for the Palestinian institutions involved in implementing and regulating wastewater treatment and reuse for 2010. This budget is many times smaller than the profit predicted by this analysis. These results should therefore motivate and potentially fund

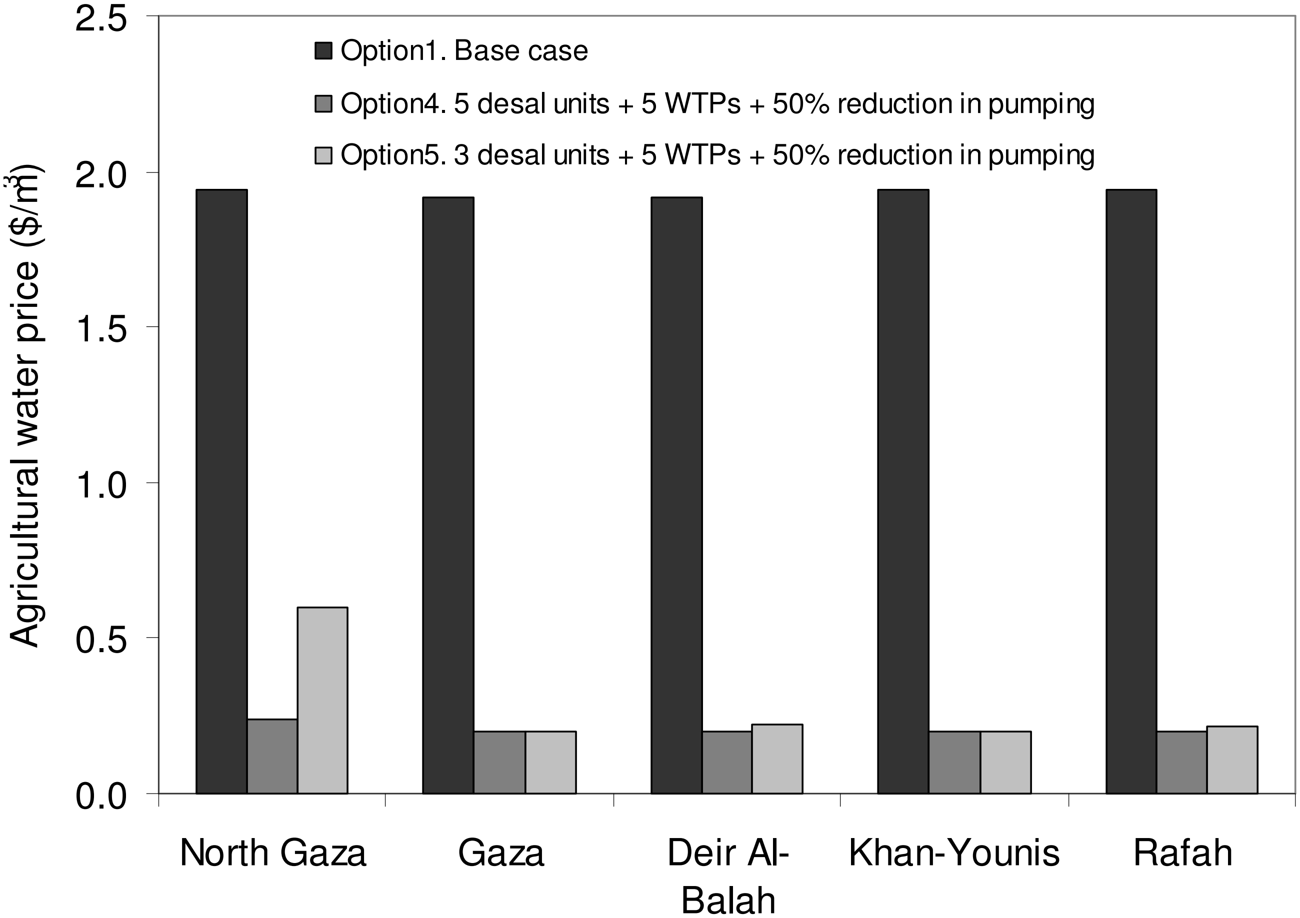

Figure 4. Predicted agricultural water prices in 2030 for base case, supply enhancements options of (5 desal units + 5 WTPs with 50% reduction in pumping) and (3 desal units + 5 WTPs with 50% reduction in pumping).

Table 5. Computed annual net benefits with different management options for supply enhancement.

Year	Option		Change in net benefit from base case ($ millions/year)	
	Desalination plants[1]	Reduction in pumping (%)	Without TWW	With TWW
2020	No	0	0	6
		50	-36	-19
	3	0	3	10
		50	-32	-17
	5	0	5	12
		50	-23	-9
2030	No	0	0	27
		50	-115	-62
	3	0	23	37
		50	-24	6
	5	0	24	38
		50	3	16

[1]Five desalination plants consist of one in each district with a capacity of 15 MCM/year. Three desalination plants consist of two desalination plants for North Gaza and Deir al-Balah with individual capacity of 1.825 MCM/year and one desalination plant for Gaza district with a capacity of 54.75 MCM/year.

Table 6. Results of the optimization and economic analyses to evaluate the infrastructure developments for 2030 with unconstrained capacities for desalination, wastewater treatment, and conveyance infrastructure. The discounted rate used is 5%.

Item	Reduction in groundwater pumping (%) and corresponding freshwater supply (MCM/year)			
	0% (145 MCM)	38% (90 MCM)	50% (72.5MCM)	58% (60MCM)
a. Improvement in annual benefits from base case ($ million/year)	36	21	17	12
b. Predicted total desalination capacity (MCM/year)	0	20	26	62
c. Predicted total wastewater treatment capacity (MCM/year)	75.8	47	37.6	30.7
d. Total conveyance capacity (MCM/year)	0.0	0.0	0.0	0.0
e. Present value of annual net benefits ($ million)	449	262	212	150
f. Capital costs of infrastructure in (b,c,d) ($ million)	90.9	110.8	115.8	205.5
g. Profit ($ millions)	357.6	150.8	95.9	-55.9

both the institutional improvements and wastewater produced the highest reduction in agricultural water prices. The results also indicate that an appropriate optimization methodology can identify the best design volumes of desalination and TWW with a reduction in groundwater pumping to minimize seawater intrusion. Therefore, water resources development and planning in water deficit regions such as the Gaza Strip should not sacrifice environmental goals to increase supply because both supply and environmental goals can be achieved in an economically competitive manner.

Conclusions

Most water deficit regions are stressed from lack of adequate water due to increasing demands from population growth alone. Climate change may further impact the water deficits in most parts of the world. Therefore, water cannot be treated as a “free” good and instead, managers must consider the actual costs to develop and deliver water to users, plus the benefits derived from use. In managing water, planners and policy makers may need to develop alternative water sources when the supply is limited but demands are increasing. The Gaza Strip, Palestine is a classic example experiencing these issues together with groundwater quality deterioration due to excessive pumping from the coastal aquifer. In addition, the population growth in the region is well above the regional and global averages, while experiencing significant political unrest.

In such regions, water planners need to develop other sources of water, while ensuring water from these sources is delivered in an economically efficient manner. Sophisticated economic and optimization tools can be readily used in these situations to assess the applicability of different management options. In this work, the Water Allocation System Model of Fisher et al. (2005) was used to find the applicability of using TWW in agriculture to reduce the stress on freshwater supply. The work was extended to include new sources of water through desalination and the introduction of a water conveyance system between different water districts to assess the best management options to satisfy the demands in 2020 and 2030. Different management options were evaluated using the net benefit and shadow value of water in each sector. The key findings are:

1. The shadow value of water and water availability are inversely proportional. The use of TWW in agriculture in water deficits regions such as the Gaza Strip has a large impact on the overall availability of water. The reason is that TWW use in the agricultural sector allows the previously allocated freshwater to agriculture to be reallocated for urban and industrial sectors.
2. The urban and industrial sectors benefit significantly when their wastewater is treated and reused in agriculture. Reuse TWW in the agricultural sector also reduces the prices of urban and industrial water and also increases the supply for agriculture.
3. Benefits of using TWW increase over time as demands increase and water become scarcer. In the case of the Gaza Strip, however, the shadow value of water does not fall below $0.60/m3 with the use of TWW only.
4. In the Gaza strip, the use of TWW alone is not sufficient to increase the supply and be economically competitive. Additional supply enhancements such as desalination combined with the use of TWW should be seriously considered.
5. The design of the most effective supply enhancement options needs careful analysis. The example from the Gaza Strip shows that a fixed volume based desalination and TWW is not the most appropriate design. The results show that planned desalination plants may be oversized and TWW plants undersized. The results show additional net benefits are possible with proper sizing and that these options are still economically viable with reduced (more sustainable) groundwater pumping.
6. This work also showed that conveyance of water from districts with low demand to districts with high demand can help reduce the shadow value of water and make the system more economically competitive. In regions where the demand varies spatially, conveyance of water should be seriously considered.

7. In regions such as the Gaza Strip where seawater intrusion is a serious issue, the impacts of reducing groundwater withdrawal can only be minimized when alternative options such as desalination and TWW are simultaneously considered.
8. Transferring water among districts reduces the shadow value of water of districts receiving water while not significantly affecting the shadow value of water in districts providing this water.
9. The additional net benefits and profits achieved from the proposed options can also finance the institutional capacity building and other costs to manage and oversee implementation of options, such as the use of TWW in agriculture.

In summary, the proposed methodology consisting of systems and economic analyses with appropriate mathematical models allows a systematic approach to address sustainable water resources management in a water deficit region using desalination, TWW, and conveyance. The knowledge and insight gathered from this work can be easily incorporated in other regions similar to the Gaza Strip where water is scarce, population growth rate is high, and water quality issues are serious.

ACKNOWLEDGMENTS

Dr. Ahmed Al-Juaidi was supported by the Inland Northwest Research Alliance (INRA) Foundation graduate research fellowship. The authors thank the three anonymous reviewers for comments on earlier draft.

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APPENDIX A

The water allocation system model is an optimization program (Fisher et al., 2005). The mathematical representation of this model is given below:

Objective function:

$$Max\ Z = \sum_i \sum_d \left(\frac{B_{id} \times (QD_{id} + QFRY_{id})^{\alpha_{id}+1}}{\alpha_{id}+1} \right) - \sum_i \sum_s (QS_{is} \times CS_{is}) - \sum_i \sum_j (QTR_{ij} \times CTR_{ij}) - \sum_i \sum_j (QRY_{ij} \times CR_{ij})$$
$$- \sum_i \sum_j (QTRY_{ij} \times CTRY_{ij}) - \sum_i \sum_j \left[CE_{id} \times (QD_{id} + QFRY_{id}) \right] \quad \text{(A1)}$$

Subject to:

$$\sum_d QD_{id} = (\sum_s QS_{is} + \sum_j QTR_{ji} - \sum QTR_{ij}) \times (1 - \mathrm{LR}_i) \qquad \forall i \quad \text{(A2)}$$

$$\sum_d QD_{id} = (\sum_s QS_{is} + \sum_j QTR_{ji} - \sum QTR_{ij}) \times (1 - \mathrm{LR}_i) \qquad \forall i \quad \text{(A3)}$$

$$\sum_d QFRY_{id} = \sum_d QRY_{id} + \sum_j QTRY_{ji} - \sum_j QTRY_{ij} \quad \forall i \quad \text{(A4)}$$

$$QRY_{id} = PR_{id} \times (QD_{id} + QFRY_{id}) \quad \forall i, d$$

With the following bounds:

$$(QD_{id} + QFRY_{id}) \geq \left[\frac{P_{\max}}{B_{id}} \right]^{1/\alpha_{id}} \quad \forall i, d \quad \text{(A5)}$$

$$QS_{is} \leq QS_{\max\ is} \quad \forall i, s \quad \text{(A6)}$$

$$PR_{id} \leq PR_{\max\ id} \quad \forall i, d \quad \text{(A7)}$$

$$P_{id} = B_{id} \times (QD_{id} + QFRY_{id})^{\alpha_{id}} \quad \text{(A8)}$$

Indices

i - District,
d - Demand type (urban, industrial, or agricultural),
s - Supply source or steps

Parameters

B_{id} - Coefficient of inverse demand curve for demand d in district i (dimensionless)

α_{id} - Exponent of inverse demand function for demand d in district i (dimensionless)

CE_{id} - Unit environmental cost of water discharged by demand sector d in district i in ($/m^3$)

CR_{id} - Unit cost of TWW supplied from sector d in district i in (\$/m^3),

CS_{is} - Unit cost of water supplied from groundwater supply step s in district i (\$/m^3)

CTR_{ij} -Unit cost of transport fresh water from district i to district j (\$/m^3)

$CTRY_{ij}$ - Unit cost of transport TWW from district i to district j (\$/m^3)

LR_i - Loss rate in district i (dimensionless)

$QS_{\max is}$ - Maximum amount of water from supply s in district i (MCM)

$PR_{\max}$ - Maximum percent of water from demand sector d that can be treated (recycled) in district i in (M CM)

$P_{\max\ id}$ -Maximum price on the demand curve from sector d in district i in (MCM)

P_{id} - Shadow price of water for demand sector d in district i (computed) (\$/m^3)

Decision variables

Z - Net benefit from water in million dollars,

QD_{id} - Quantity demanded by sector d in district i in (MCM),

QS_{is} - Quantity supplied by source s in district i in (MCM),

QTR_{ij} - Quantity of freshwater transported from district i to district j in (MCM),

QRY_{id} - Quantity of TWW supplied from sector d (M&I) in district i in (MCM),

$QTRY_{ij}$ - Quantity of TWW transported from district i to district j in (MCM),

$QFRY_{id}$ - Quantity of TWW supplied to use d (agriculture) in district i in (MCM),

PR_{id} - Percent of TWW from sector d (used in agriculture) in district i in (MCM)