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ORIGINAL PAPER

An integrated framework for municipal demand management and groundwater recovery in a water stressed area

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Abstract
Aiming at meeting future water demands in Palestine, an optimization model is developed to help Palestinian water planners to find the optimal combination of management alternatives that meet future demands of 2040 at minimal costs. The model considers three different options:(A) utilizing existing groundwater from groundwater resources; (B) conserving water through retrofitting the existing household water system; and (C) buying water from Mekorot company. A calibrated groundwater model is employed to investigate the combination of those management alternatives on groundwater recovery. The uniqueness of this study is its inclusiveness of several water demand and supply alternatives which have a direct impact on water demand and seawater intrusion recovery. Model results show several crucial outcomes: (1) a combination of supply and conservation alternatives for all districts to minimize cost;(2) retrofitting toilet and clothes washer should be given priority over retrofitting household shower and faucet for all districts in order to save on water use. Furthermore, when demand is reduced by 23% in 2018, through the implementation of conservation in conjunction with buying water from Mekorot and use of groundwater, the seawater intrusion reduced from 150 to 114 km^2 which indicates substantial aquifer recovery.

Keywords Demand management · Conservation · Optimization · Groundwater recovery · Palestine

Introduction

Water authorities and planners constantly developing new tools to find feasible and economic decisions to meet future water demands (Yazdani and Jeffrey 2012; Yamout and El-Fadel 2005; Al-Juaidi and Hegazy 2017a; Al-Juaidi and Hegazy 2017a, b). Managing water resources in high-density urban areas is difficult as managers try not only to meet future municipal demands but also to minimize associated costs of developing new water supply sources (Babel et al. 2005; Al-Juaidi 2017a; Al-Juaidi 2017b). As a result, management alternatives should be planned for to help decision-makers manage their available resources more efficiently. System analysis and optimization methods are useful tools to help water authorities see multiple options and flexibility of their management decisions (Ratnayaka et al. 2009; Al-Juaidi et al. 2009; Al-Juaidi et al. 2010; Al-Juaidi et al. 2011a; Al-Juaidi et al. 2011b; Al-Juaidi et al. 2014). Optimization models have been extensively used in water distribution systems and household conservations to find the optimal mixture of alternatives that minimizes costs of supply and demand management (Rosenberg et al. 2007; Roshani and Filion 2013; Alafifi 2014; Cahill et al. 2013). This study develops an optimization framework to help decision-makers and water authorities to find the least costly combination of supply and conservation options that is recommended to meet the 2040 future municipal demand for the Gaza Strip and West Bank districts under system constraints.

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Background and problem

Water supply and sanitation in the Palestinian districts are considered severely insufficient and controlled by Israel. Palestine has 16 districts, 11 districts located in West Bank and 5 districts located in the Gaza Strip (see Fig. 1). The average rainfall intensity in Southern and Northern Gaza is

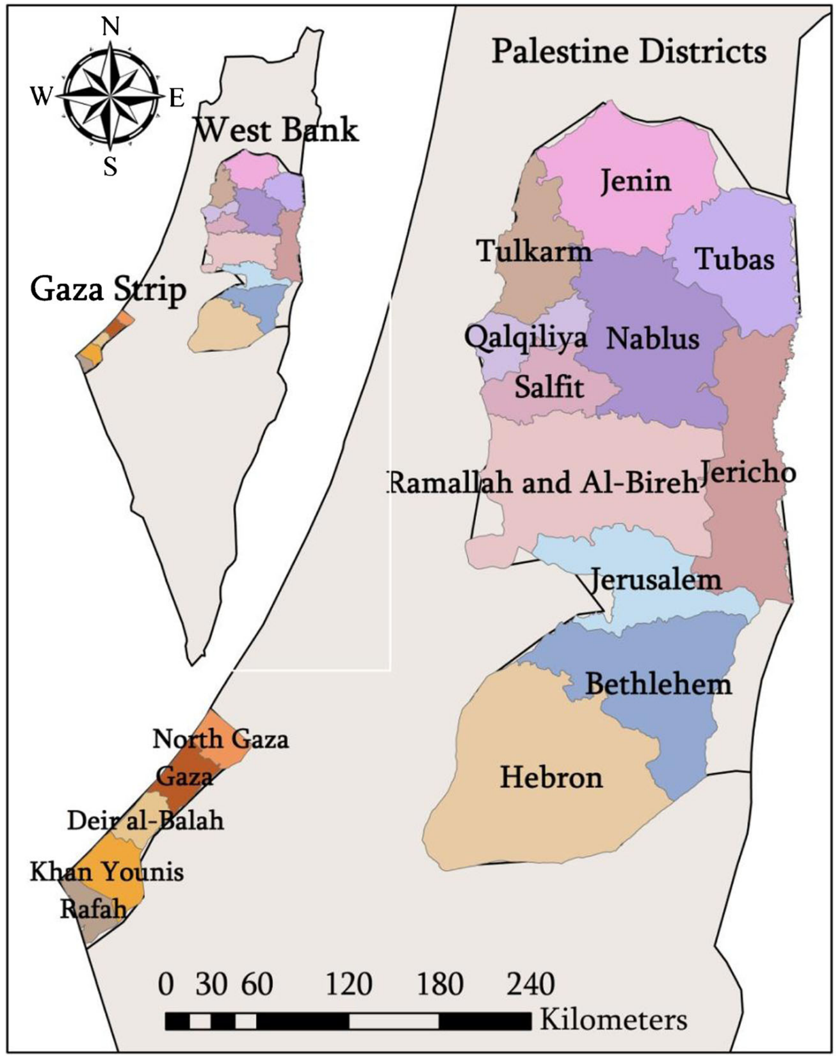


Fig. 1 Palestine districts

250 and 400 mm per year, respectively (Al-Juaidi 2018; Al-Juaidi et al. 2018). Water quality is worse in the Gaza Strip when compared with the West Bank. The Gaza Wars has caused severe damage to the infrastructure in the Gaza Strip. Water sector development in Palestine totally depends on external financing (Fatta et al. 2004; United Nations 2009; World Bank 2009).

The West Bank is a mountainous area, and the elevation ranges from 400 m below sea level in Jericho to 1000 m above sea level in Ramallah, Hebron, and Jerusalem. The rainfall intensity average is 600 mm per year. It varies from less than 100 mm per year in the east to 700 mm in the north and west. Groundwater is the primary water supply source. The renewable water quantity in the mountain aquifer varies from 590 to 690 million cubic meters (MCM), only from rainfall. Surface water is low and it is mainly from flooding water that is not captured by the stormwater system. Around 70 MCM is discharged from the dry valleys into the Dead Sea, and 20 MCM into the Mediterranean Sea. The West Bank districts do not have an access of water from the Jordan River (Fatta et al. 2004). The total water supply to the West Bank districts is around 98.0 MCM/year, with 26.0 MCM/year losses due to leakages in the distribution system (Nazer et al. 2008; PWA 2012; PCBS 2016).

The coastal aquifer is the main water source for the Gaza Strip districts. The aquifer drains from the east to the west, with low flow from the north to the south. Water quality in the Gaza Strip is poor and saline due to seawater intrusion. Seawater intrusion is caused due to over abstraction of water for illegal agricultural wells. The estimated recharge of the aquifer is around 55 mm per year, from the rainfall. The abstraction of water from the aquifer is around 160 mm per year. Mekorot is supplying Gaza district with 5 MCM per year. The total water supply to the Gaza Strip districts is around 94

MCM/year from the municipal wells only (PWA 2012; Fisher et al. 2005).

The rationale of this problem is that Palestinian districts are striving to continue on the development pace and therefore should utilize its available natural resources to continue providing such opportunities in the long run. Nonetheless, this has to be combined with the management's goal of minimizing associate costs. In addition, the 16 districts do not all have one individual water supplier. Mekorot supplies West Bank districts with a total of 40 MCM per year and 5 MCM for Gaza district (Fisher et al. 2005).

Desalination along the Mediterranean coast in the Gaza Strip is a potential new water source for the future. The Palestinian Water Authority (2015) suggests a large desalination unit of capacity 55 MCM per year in Gaza in addition to the two existing desalination units in Northern Gaza and Deir Al-Balah at 1.83 MCM per each district (Al-Juaidi et al., 2014).

Most water municipal suppliers at Palestinian districts are currently exceeding their water supply. Therefore, there is a need to explore different alternatives in order to meet projected future requirements. The complexity and variability of water supply and conservation options necessarily requires developing a model that is capable of capturing different inputs and simulate a variety of management alternatives.

The objective of this paper is to develop a tool that can help decision-makers in Palestine (Gaza Strip and West Bank) to assess and evaluate different alternative water resources management strategies and obtain the optimal combination of water supply and conservation options to meet projected water demands. Thus, an optimization model will be developed to help decision-makers answer the following question: What is the minimal cost combination of supply and conservation alternatives that is recommended to meet the 2040 future municipal demand under system constraints? In this study, a mixed integer linear programming optimization model is developed and applied to suggest best combination of water supply and conservation alternatives that minimizes costs of supply within the system's limitations.

Research methodology

Population statistics for 2015 were taken from the Palestinian Statistics Bureau website (PCBS 2015) and are presented in Table 1. Number of households was calculated based on the average household size in Palestine of 6.0 persons according to PCBS (2012) and PCBS (2015). Current water use data was collected from a variety of sources including Palestinian Water Authority (2015) and the Palestinian Bureau Statistical Census (2016). The historical records, from 1997 to 2015, showed that the average population growth rate for Palestine districts—Gaza and West Bank—was 3.0%. The population growth rate in 2015 for the Gaza Strip is 3.41%, while it is 2.59% for the West Bank governorates (PCBS 2016). Since the population growth rate for Gaza Strip and West Bank is decreasing over the years (1997–2015), the lowest growth rates of 2.59 and 3.41% observed in recent years were used for the projection for West Bank and Gaza Strip districts, respectively. Table 2 shows the future population projection for 2040. This study uses the population and municipal water use of 2015 as a baseline and attempts to meet the 2040 future demands of the 16 districts listed in Table 1.

Table 1 Demographic data of 2015 and 2040 population of Palestinian districts

Water-using entity	Population data	
	2015	2040
N. Gaza	377,126	872,067
Gaza	645,205	1,491,973
Deir Al-Balah	273,381	632,167
Khan-Younis	351,934	813,813
Rafah	233,490	539,923
Hebron	729,193	1,381,873
Bethlehem	221,802	420,331
Jerusalem	426,533	808,311
Ramallah	357,968	678,375
Jericho	53,562	101,504
Salfeit	72,279	136,974
Qalqiliya	113,574	215,230
Nablus	389,328	737,804
Tulkarem	185,314	351,183
Jenin	318,958	604,448
Tubas	66,854	126,693

Management alternatives

The Palestinian Water Authority (PWA) has few management alternatives to meet future water use. These alternatives can be categorized into two categories: (1) increase supply to meet future water use through (a) buying additional water from Mekorot and/or (b) developing local groundwater supplies and (2) conserve water use as managers can also enforce or subsidize conservation actions through retrofitting water appliances in households.

Increase supply

Buy additional water from Mekorot company Palestine districts purchase water from an Israeli water national company (Mekorot) who uses groundwater as the main source of water. Mekorot has its own groundwater wells in the Israeli

Table 2 Average annual water use of Palestinian districts (PWA 2012)

Water-using entity	Average use (2015) (MCM/year)	Average use (2040) (MCM/year)
N. Gaza	35.72	69.34
Gaza	46.18	103.70
Deir Al-Balah	25.13	49.50
Khan-Younis	26.30	57.67
Rafah	16.83	37.64
Hebron	22.73	63.40
Bethlehem	7.59	19.95
Jerusalem	12.49	36.28
Ramallah	12.08	31.0
Jericho	36.79	39.78
Salfeit	2.72	6.75
Qalqilya	3.37	9.70
Nablus	35.86	57.57
Tulkaerm	20.07	30.4
Jenin	14.39	32.18
Tubas	2.16	5.89

settlements. The Mekorot current supply to Palestinian districts is 45 MCM per year (Water Authority 2012), as shown in Table 3. Last year, Israel for the first time increased the previous amount of 5 MCM of water Israel sold to Gaza each year to 10 MCM. The Water Authority (2012) states that the cost of buying additional water for district already served by Mekorot is ($0.4/m^3), while the cost of buying additional water for districts not served by Mekorot is ($0.5/m^3).

Table 3 Existing municipal water and Mekorot supply

Water-using entity	Existing groundwater use (2018) (MCM/year)	Buying water from Mekorot (MCM/year)	Groundwater use after implementing conservation (MCM) (2018)
N. Gaza	15.0	0.0	9.7
Gaza	33.0	5.0	27.6
Deir Al-Balah	14.0	0.0	10.8
Khan-Younis	19.0	0.0	14.8
Rafah	13.0	0.0	9.6
Hebron	17.0	9.0	13.2
Bethlehem	9.0	8.5	6.8
East Jerusalem	5.0	5.0	4.1
Ramallah	10.0	6.5	6.8
Jericho	8.0	4.5	6.1
Salfeit	2.0	0.0	1.2
Qalqiliya	4.0	0.0	2.8
Nablus	4.0	3.0	2.7
Tulkaerm	11.0	0.0	7.3
Jenin	7.0	3.0	5.8
Tubas	3.0	0.0	2.1

Develop maximum local groundwater supply potential The amount of recharge for the Gaza aquifer is around 55 MCM/year. However, the amount abstracted from municipal well in Gaza Strip for all sectors is 94 MCM/year. Therefore, this study suggests to implement household retrofits in conjunction with buying water from Mekorot and use the local water source (groundwater) for sustainable development of the groundwater. The existing water supply of the Palestinian districts is considered the main water supply; however, Gaza district planned to construct a large desalination plant with a capacity of 55 MCM/year. Two more small desalination plants will be constructed for Deir Al-Balah and North Gaza with a 1.83 MCM capacity in each district (Metcalf and Eddy 2000). The Palestinian Water Authority is also planned to construct a conveyance line to transport desalinated water from Gaza district to Hebron with a capacity of 10 MCM/year. Further, Mekorot company has not reached its maximum supply limit; therefore, there is a potential for Mekorot to increase its supply to the maximum capacity (Water Authority 2012). The cost of developing available resources of groundwater is $1.2/m^3 according to PCBS (2016) and Metcalf and Eddy (2000). Rainfall is the main source of aquifer recharge, which was used in the analysis as the existing ground water from groundwater resources. In Gaza governorates, stormwater is used to recharge the aquifer through soak away units and in-site stormwater infiltration basins (Hamdan et al. 2011), and not all Palestinian districts have the same practice.

Conserve water use

The water supply in the Palestinian districts is significantly less than it is in many other countries around the world. The main sources of water in the Palestinian Territories are surface and groundwater. In the coming years, the population will grow with limited access to groundwater, and less water will be available for these people.

According to the PWA, when efficient water appliances are introduced, the annual water use per person is reduced from 20 to 25%. The water use in Gaza and West Bank is 90 and 75 L per day, respectively. After introducing efficient water appliance, the water use is expected to reduce to 68 and 57 L/capita.day in Gaza and West Bank respectively. The Palestinian Water Authority (2015) and Metcalf and Eddy (2000) suggest that Palestine, in general, is in need to develop a conservation program to reduce existing water demand by 25% in 2040. The costs and benefits of retrofitting water appliances (i.e., toilets, showerheads, clothes washers, and faucets) are explored according to the US EPA report. It intends to compare supply and conservation alternatives. The costs imitate annual costs of all retrofits per household (i.e., replacing two toilets, etc.) which are estimated mainly on dividing the one-time capital cost over the lifetime of the appliance plus the annual operational costs (US EPA 2005). For instance according to the US EPA (2015), retrofitting a toilet, a showerhead, a faucet, and a clothes washer requires an annual cost of $0.6, 0.9, 0.91, and 0.94 per cubic meter respectively. The corresponding annual savings from retrofitting one toilet, one showerhead, one faucet, and one clothes washer are 40 m^3, 4.0 m^3, 3.5 m^3, and 11 m^3 per year respectively.

Pre-model processing

All districts were tested using future projected demand and existing supply potentials. This was executed to establish which districts require interferences (i.e., supply or conservation actions) to meet future water requirements. Future demands were compared against existing supply potentials. Most of the Palestinian districts do not meet future 2040 demand using existing supply (see Fig. 2). Therefore, the model will center of attention on all districts and recommend interventions to meet 2040 demand. That is, all districts which are in shortage will be included for further analysis. Figure 2 outlines the 16 Palestinian districts under study. The base case of 2015 and future use of 2040 are depicted in red and green respectively. Surplus and shortages in MCM per year are shown in positive and negative values in the vertical axis. Few districts are only meeting 2016 demands such as Bethlehem, Salfeit, Tubas, and Qalqilya (Fig. 3). The Mekorot current supply to the Palestinian districts is considered to be 45 MCM/year.

Model development

Here, a mixed integer linear optimization model is developed to help decision-makers select the optimal combination of management alternatives to meet future water use at minimal costs. This model combines both integer (i.e., discrete) and continuous decision variables. Integer decisions describe number of households that the model will recommend to retrofit their water appliances (Alafifi 2014). However, the model will recommend continuous values for the supply increase actions required to meet future water use. The model development equations were all applied and solved using Lingo software (www.lindo.com). To develop the model, the following steps are followed.

Define decision variables

Decision variables are the variables within the system that managers have control over. These variables can either have continuous values, which mean it may take any real value, or an integer which means it only take zero (0) or one (1) values. Integer variables are used to describe whether an option should or should not be implemented (i.e., binary value), or how many of an option should be implemented (e.g., groundwater). In this model, there are two decision variables:

The level of implementation of supply actions $X_{sj,\ n}$

Where X_s is an index of supply action variables, i is either 1 for buying additional water or 2 for developing groundwater supply, and n is the district index (ranges from 1 to 16). These variables are continuous and can take any real number within the system boundaries.

The number of household retrofits for conservation actions $X_{cj,\ n}$

Where X_c is an index of conservation action variables; j is conservation action applied and can take the values of 1 for toilet, 2 for showerhead, 3 for faucet, and 4 for clothes washer; and n is the district index (ranges from 1 to 16). These variables are integers as they can only take discrete numbers ranging from 0 to the number of households in each district.

Define objective function

The objective of this optimization model is to minimize the costs required to meet future water use. Therefore, both supply

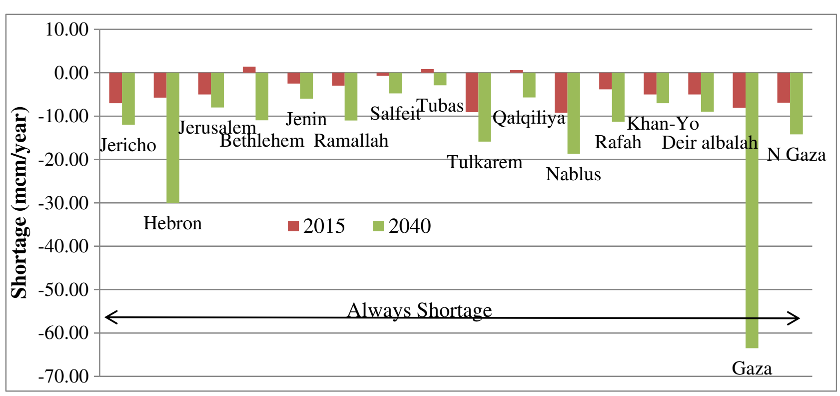


Fig. 2 Water shortage and surplus classification of the Palestinian districts

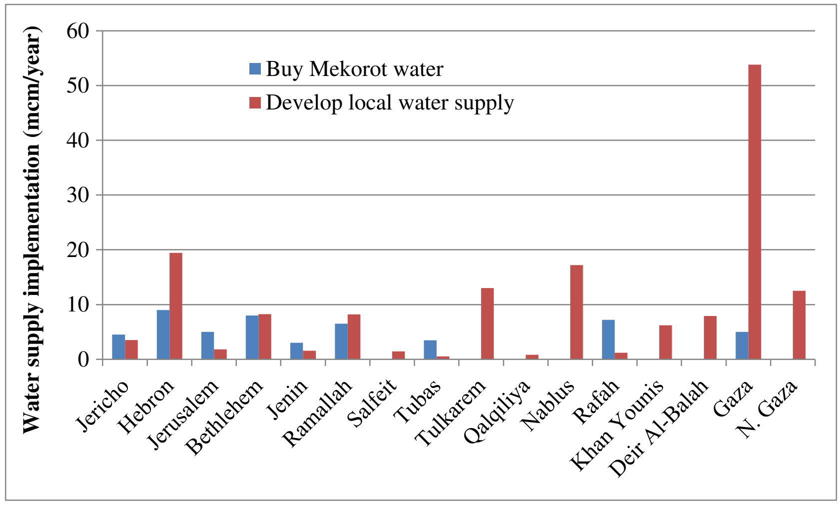


Fig. 3 Computed water supply implementation actions for 2040

and conservation action costs need to be minimized. The following function defines the objective of this model:

Min Z = sum of costs of supply action + costs of conservation actions

$$Z = \sum_{i=1}^{2} C_{\mathrm{si,n}} \times X_{si,n} + ^{\mathrm{si,n}} \sum_{j=1}^{4} C_{\mathrm{cj,n}} \times X_{\mathrm{cj,n}}, \forall_{\mathrm{n}} \quad (1)$$

where $X_{\mathrm{si,\ n}}$ is the level of implementation of supply action i for district n, $X_{\mathrm{cj,\ n}}$ is the number of conservation retrofits of conservation action j for district n, C_{si} is the annual costs of implementing supply action i for district n, $C_{\mathrm{cj,\ n}}$ is the annual costs of implementing conservation action j for district n, n is an index for districts, i is an index of supply actions, and j is an index of conservation actions.

System constraints

The optimization model is limited by a set of constraints that bound its decision variables. The system follows the following set of constraints.

Conservation actions need to be integers $X_{\mathrm{cj,\ n}}$

Conservation actions in this model are appliances retrofits. It is assumed that houses can either retrofit all appliances of the same type or none; the actions have to be defined as integers.

Number of conservation actions has to be equal to or less than number of households in each district

$$X_{\mathrm{cj,n}} \le H_{\mathrm{j,n}}, \forall_{\mathrm{n}} \quad (2)$$

where $H_{\mathrm{j,\ n}}$ is the number of households for each n district for each conservation action j

Develop groundwater supply actions need to be less than or equal to upper limits

$$X_{\mathrm{s2,n}} \le H_{\mathrm{s,n}}, \forall_{\mathrm{n}} \quad (3)$$

where $H_{\mathrm{s,\ n}}$ is upper limit capacity for each n district supplier.

Sum of "Buy additional water" actions has to be less than or equal to Mekorot upper limit

$$\sum_{n=1}^{11} X_{\mathrm{n}} \le Mek_{\mathrm{u}}, \forall_{\mathrm{n}} \quad (4)$$

where Mek_{u} is the upper limit to the Mekorot supply source.

Supply and conservation actions have to meet annual shortage for each district

$$\sum_{i=1}^{2} X_{\mathrm{si,n}} + \sum_{j=1}^{4} X_{\mathrm{cj,n}} \ge S_{\mathrm{n}}, \forall_{\mathrm{n}} \quad (5)$$

where S_{n} is the 2040 shortage for each district n.

Results and discussion

The model shows that all districts were capable of meeting 2040 future water use requirements using a combination of the supply and conservation alternatives within the system constraints. Results show that neither supply nor conservation actions alone are recommended to meet future demand. The results always recommend a combination of both options in order to keep costs at minimal levels. The results also show that the minimum cost to meet future water demand for all districts is $46 million. This can be broken down and can also be illustrated using percentages as shown in Fig. 4 and Table 4. Table 3 shows the groundwater use for the existing situation and after implementing water conservation and buying water from Mekorot for all districts. Results show that the groundwater withdrawal for all Palestinian districts has reduced about 24% when after implementing water conservation (see Table 3). In the Gaza Strip districts, groundwater use was reduced by 22%, from 94 to 72.5 MCM in 2018.

Supply actions

The results also recommend that districts which are already buying water from Mekorot buy additional water from this supplier. This is mainly because costs of purchasing extra water are lower ($0.4/m^3) than the costs for the other districts which will start to purchase water from Mekorot with a cost of $0.5/m^3.

The results also recommend districts to use both supply alternatives for all districts (see Fig. 3). It shows that all districts have exhausted the least costly option (buying water) first and then recommended developing groundwater supply (see Fig. 3). For instance, the model has already used most of the Mekorot water available and therefore recommended developing more groundwater supply to meet future use. Figure 4 shows the percentage of supply and conservation action cost for each district to meet future demand of 2040.

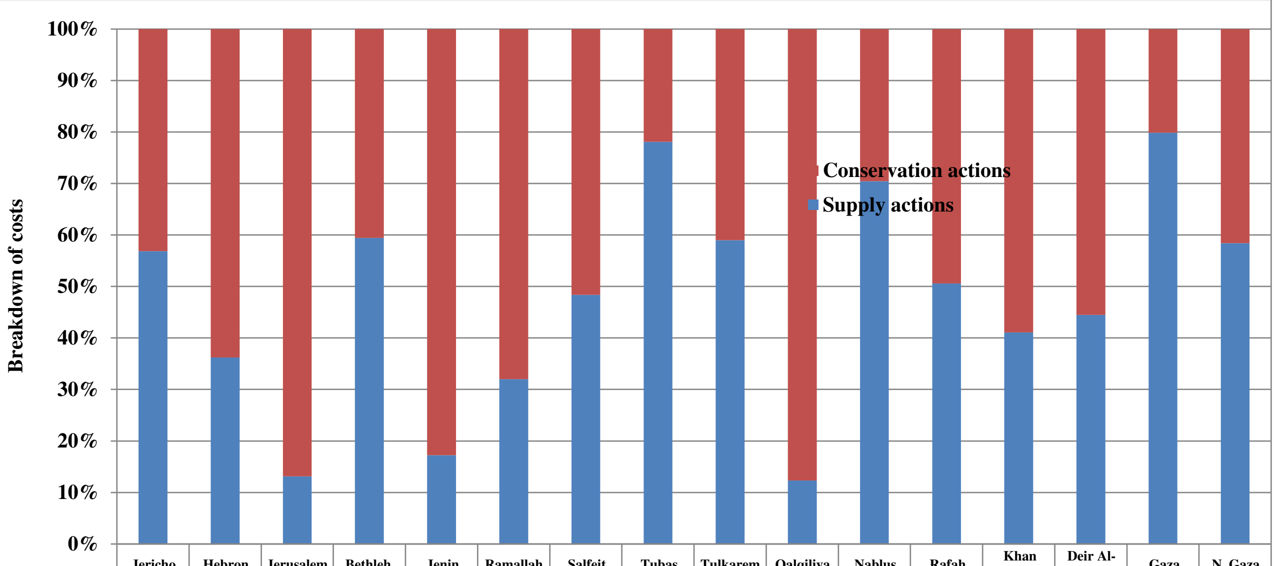
It is noticed from the results that most of the districts need to implement conservation to achieve minimum cost and meet future demand.

Conservation actions

The results recommend retrofitting toilets and clothes washers for all households in all districts, because of the high savings potentials and low costs associated with toilet retrofitting. Table 4 shows the cost combination of conservation and supply actions. The results also recommend retrofitting showerheads and faucets, but not for all households. The results also suggest prioritizing retrofitting toilets and clothes washers in all households for all districts. This is primarily because the annual savings on water of toilet and clothes washers are larger than faucet and showerhead. For instance, in Rafah district, the number of households to retrofit toilet and clothes washer is 11,792 households, while the number of households to retrofit the showerheads and faucets is 4309 households.

Impact of water conservation on energy cost savings

After finding the number of houses per district which considered retrofit to save water, the amount of water that could be saved from replacing old to new appliances (e.g., retrofitting) can be obtained. Since the cost of delivering one cubic meter cost is $1.2, the amount of water saved from retrofitting is 29.3 MCM per year for 2040, which converted to energy cost saving of $35.1 million per year.



	Jericho	Hebron	Jerusalem	Bethleh.	Jenin	Ramallah	Salfeit	Tubas	Tulkarem	Qalqiliya	Nablus	Rafah	Khan Younis	Deir Al-Balah	Gaza	N. Gaza
Conservation actions	1501580.0	22239920.0	7543990.0	3148090.0	4050330.0	9359000.0	732360.0	627610.0	5215560.0	1890320.0	4581680.0	3988890.0	6077880.0	4688140.0	12056820.0	7047390.0
Supply actions	1978225.0	12633788.5	1142326.5	4608655.5	845076.0	4407926.5	686077.0	2236582.5	7503079.0	266339.0	10927304.0	4086551.8	4236694.0	3758104.3	47826339.6	9903987.8

Fig. 4 Percentages of supply and conservation action costs in US$ for each district to meet future demand of 2040

Table 4 Breakdown of costs for Palestine districts to meet future water demands

Breakdown of costs	Supply actions (US$)	Conservation actions (US$)	Total (US$)
Jericho	1,978,225.0	1,501,580.0	3,479,805.0
Hebron	12,633,788.5	22,239,920.0	34,873,708.5
Jerusalem	1,142,326.5	7,543,990.0	8,686,316.5
Bethlehem	4,608,655.5	3,148,090.0	7,756,745.5
Jenin	845,076.0	4,050,330.0	4,895,406.0
Ramallah	4,407,926.5	9,359,000.0	13,766,926.5
Salfeit	686,077.0	732,360.0	1,418,437.0
Tubas	2,236,582.5	627,610.0	2,864,192.5
Tulkarem	7,503,079.0	5,215,560.0	12,718,639.0
Qalqiliya	266,339.0	1,890,320.0	2,156,659.0
Nablus	10,927,304.0	4,581,680.0	15,508,984.0
Rafah	4,086,551.8	3,988,890.0	8,075,441.8
Khan-Younis	4,236,694.0	6,077,880.0	10,314,574.0
Deir Al-Balah	3,758,104.3	4,688,140.0	8,446,244.3
Gaza	47,826,339.6	12,056,820.0	59,883,159.6
N. Gaza	9,903,987.8	7,047,390.0	16,951,377.8
Total	117,047,057.0	94,749,560.0	211,796,617.0

Sensitivity analysis

In the sensitivity analysis, there are two kinds of constraints, the ones which are binding (i.e., have no slack) and which are not binding (i.e., have a slack value). Sensitivity analysis helps water authorities find the optimal solution to potential changes in the system, when altering the values of the binding constraints. This is helpful for water managers to see the flexibility of the optimal solution to potential changes in the constraints which leads to finding trade-offs and alternatives in the system. The following constraints are binding: (1) upper limits of groundwater supply and (2) the Mekorot maximum capacity. The model tried all available water to achieve optimal decision.

All water is used primarily because of inappropriate use of old household appliances. Therefore, Mekorot water is increased by 50% to increase water supply. In other words, the future Mekorot supply is 67.5 MCM/year. After relaxing the constraint (4) by increasing Mekorot future supply, the objective function cost was reduced ($43.7 million). Figure 5 shows the new combination of supply alternative for each district. It can be seen that some districts are using the whole Mekorot water and save some of their groundwater supply for future use. Comparing this with the original optimal solution shows some districts (e.g., N. Gaza, Nablus, Hebron) no longer need to use their groundwater supply for future use and can instead buy it from Mekorot. This may refer to the lower cost of buying water from Mekorot ($0.5/m^3) when compared with

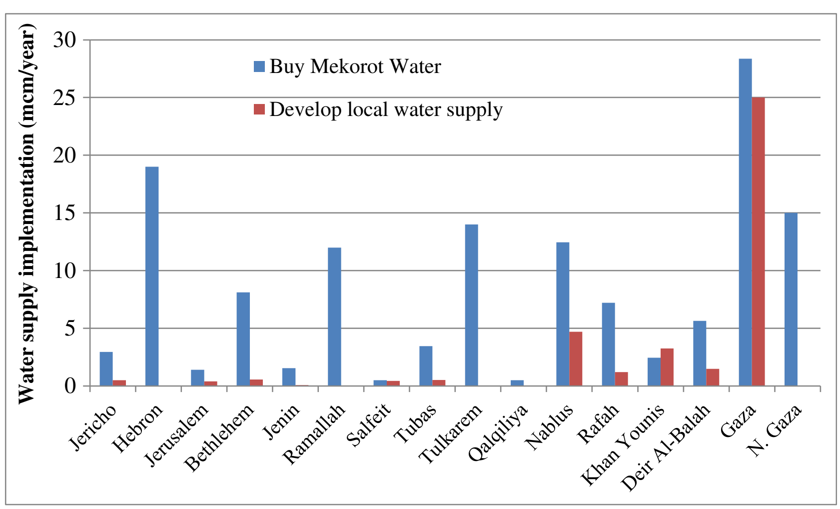


Fig. 5 Sensitivity analysis of the level of water supply implementation for each supply action

treat and deliver brackish groundwater ($1.1/m^3). This option seems more sustainable for future use and likely be more acceptable to the public rather than exhausting their groundwater resources.

Groundwater recovery evaluation in the Gaza Strip

The optimization analysis showed the average quantity of groundwater that can be reduced due to water conservation in the Gaza Strip 21.5 MCM/year in 2020. The total abstraction from the Municipal wells in the Gaza Strip is 79 MCM/year. Therefore, the optimization analysis using the mixed integer method showed that the groundwater abstraction can be reduced by 27% compared with the existing use. The calibrated groundwater model by Saleh (2007) was employed to explore groundwater levels and seawater intrusion as a result of groundwater abstraction reduction. The model established various relationships between the abstraction from agricultural and municipal wells on Gaza groundwater elevation and seawater intrusions. Figure 6 shows the relationship between the areas with water levels below the mean sea level (MSL) percentage of reduction in municipal pumping percentage for the Gaza Strip (Saleh 2007). After reduced abstraction in municipal by 23%, the area of groundwater levels below the mean sea level decreases to 36 km^2 (from 150 to 114 km^2). This indicates that municipal wells positively reduced the seawater intrusion.

Summary and concluding remarks

Water resources managers need tools for informed decision-making and evaluation of the best possible alternatives to manage scarce resources. In order to meet future water demand, managers need to account for all possible supply and conservation options and choose the optimal combination of these alternatives that minimize cost. The sixteen Palestinian districts are increasingly growing and therefore need plans for their available water resources.

In this study, two water supply and four conservation alternatives were tested in a mixed integer system optimization model. Supply options include buying additional water units from Mekorot and further developing groundwater supply sources. Conservation alternatives include retrofitting household water appliances (i.e., toilets, showerheads, faucets, and clothes washers). Costs and savings of all alternatives were integrated into the optimization model and the optimal solution was obtained considering all system constraints.

The study suggests that neither supply nor conservation actions alone are not sufficient to meet future demand. A combination of alternatives is always recommended in order to keep the cost at a minimal level of $211.7 million per year for 2040. These results suggest that districts which are already buying water from Mekorot should buy additional water units to meet future demand. While the districts are not currently buying water from Mekorot, they should further use their groundwater water supply sources (e.g., Tulkarem). Therefore, districts should consider re-allocation water between districts, based on their demands and cost of Mekorot and groundwater sources development. The sensitivity analysis shows some districts (e.g., Jenin, Qalqiliya) should only buy water from Mekorot, with no further development of their groundwater supply sources for future water use. Therefore, households in all districts should retrofit their toilets and clothes washers in order to save on water use. District managers can potentially reduce the costs of meeting future water use if Mekorot increased its supply potentials at a reduced cost. Also, this study shows Gaza aquifer recovery through the reduced area below MSL (i.e., seawater intrusion) after findings of new demand combinations such as conservation jointly with using groundwater and buying water from Mekorot. In conclusion, this study provides a tool for Palestinian decision-makers to explore the best combination of water supply and demand management and reflects on a thoughtful understanding for better water allocation and management in the planning horizon.

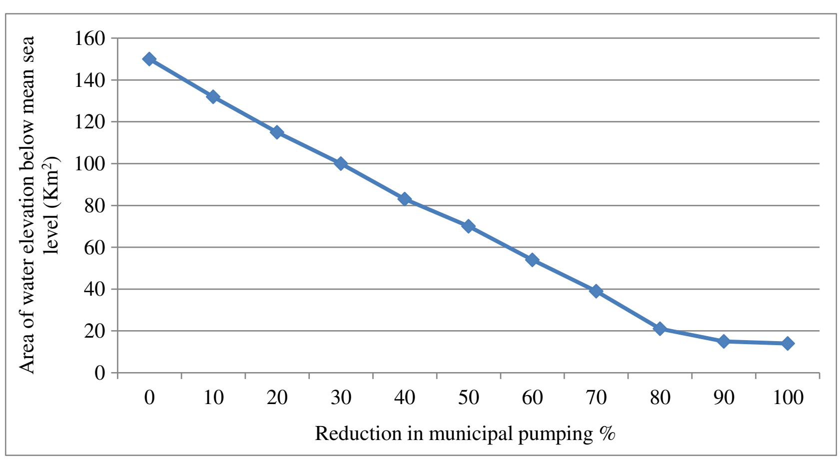


Fig. 6 Relationship between the area that has negative head and the reduction in municipal pumping

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