Desalination and Water Treatment
www.deswater.com
doi:10.5004/dwt.2017.20435

72 (2017) 13–21
April

Economic analysis of brackish-water desalination used for irrigation in the Jordan Valley

Tala H. Qtaishat[a], Emad K. Al-Karablieh[a], Amer Z. Salman[a], Mohammad A. Tabieh[a], Hussain F. Al-Qudah[a], Nayef Seder[b]

[a]*Department of Agricultural Economics and Agribusiness, School of Agriculture, The University of Jordan, Amman 11942, Jordan, email: t.qtaishat@ju.edu.jo (T.H. Qtaishat), karablie@ju.edu.jo (E.K. Al-Karablieh), asalman@ju.edu.jo (A.Z. Salman), m.tabieh@ju.edu.jo (M.A. Tabieh), halqudah@ju.edu.jo (H.F. Al-Qudah)*
[b]*Freelance consultant, email: nseder@hotmail.com*

Received 16 August 2016; Accepted 12 December 2016

ABSTRACT

The financial profitability is one of the main factors that play a role in the decision to adopt this technology. More than 50 brackish water desalination plants have been installed by farmers in the Jordan Valley for irrigation purposes. In all plants, reverse-osmosis technology is applied. The plants' capacities are 360 to 2400 m³/d. The total water abstracted is about 11.7 MCM, whereas the total desalinated amount reaches 7.7 MCM while the brine discharge is about 4.1 MCM. Brackish water, having salinity between 1300 and 7000 ppm with an average of 3150 ppm. Desalinated waters have a salinity between 50 and 800 ppm, averaging 195 ppm. The facilities are generally in operation 24 h/d in the summer and 12 h/d in the winter. The only energy source used to run these plants is the electric power grid. Desalinated water is then diluted to a salinity of about 700 ppm (400–1000 ppm). Irrigation water is applied, in particular, for bananas, strawberries, and dates. Those crops have a high market value. The average investment cost per cubic meter for the installed capacity of the desalination plants ranges between $124/(m³/h) for small plants and $63.5/(m³/h) for large plants; the average is $89/(m³/h). The average desalination cost is $0.38 per cubic meter. The results show that large desalination plants have a lower desalination cost ($0.33/m³) compared with small ones that have an average desalination cost of $0.48/m³.

Keywords: Cost-effectiveness analysis; Desalination cost; Irrigation; Jordan Valley

1. Introduction

Water scarcity in Jordan is a significant and well-documented problem that continues to worsen with the increasing demand due to high population growth, hosting several fluxes of refugees, economic-development needs, and climate change [1]. Jordan's population has increased from 6.1 million in 2010 to around 9.71 million in the middle of 2016 [2]. The huge increase, despite the lower local growth rate of 2.2%, is attributed to the influx of refugees from other countries, mainly from Iraq and Syria. The expanding population creates enormous pressure for the already scarce and depleted water resources.

Jordan's renewable water resources are limited and insufficient to meet national demand. There are growing signs of apparent overuse for an increasing number of watersheds and aquifers. The fresh-water share per capita per year has fallen from 500 m³ to 140 m³ in the 1975 and 2010, respectively [3]. In 2016, Jordan's annual renewable resources of less than 100 m³/capita are far below the global threshold of severe water scarcity (500 m³/capita). Given the water-security threat to Jordan that is posed by water

*Corresponding author.

shortages, water security has become a major domestic issue as the population increases rapidly with refugees entering the country because of conflict in neighboring countries, including a new influx from Syria that is estimated to have 2.72 million people. By the end of December 2015, about 1 million refugees from various countries were registered [3].

Irrigation uses just over half the currently available supply, around 504 MCM, although these figures may underestimate both irrigation use and total water use for various reasons. Domestic use ranks second, around 428 MCM, while industrial use is currently around 39 MCM, which is less than 5% of the total supply but is expected to grow. The Ministry of Water and Irrigation (MWI) updated its strategy to hold agricultural water use at 700 MCM in the future, so a strong challenge will be to generate a great deal more value from utilizing that amount of water (MWI, 2016b).

Based on these factors, Jordan has no choice but to embrace desalination for four reasons. First, the nation is facing a rapidly depleting groundwater resource, especially fossil water, without any form of replenishment [4]. Second, stream flow in the major rivers has declined as a consequence of drought, reduced rainfall, and draw down from neighboring countries [5]. Third, the nation is faced with a rapidly growing population that is accompanied with refugees coming to the country. Fourth, the nation has a larger irrigation-reliant agricultural sector than it did in the past; there are very few options to augment the supply with existing sources.

Brackish-water desalination is still a costly water-supply option compared to natural water resources (e.g., ground- or surface water). The financial profitability is one of the main factors that play a role in the decision to adopt this technology, along with other factors such as feed-water characteristics, water quality, plant capacity, plant reliability, concentrate disposal, space requirements, operation and maintenance, and energy availability [6].

In Jordan, desalination is receiving considerable attention from scientists, resource planners, policy-makers, and other stakeholders [7]. Desalination is not a new technology; in fact, studies from centuries ago discussed how Mediterranean and Near East civilizations distilled drinking water from seawater [8]. Desalinating water in Jordan can be a technically and economically efficient option to produce additional quality water [9]. Desalination of Red Sea water with reverse osmosis (RO) and brackish-groundwater desalination with nano-filtration could be technically viable as well as economically feasible [10]. Using desalination technologies in Jordan is quite new when compared to the Gulf States where it has been used since 1957, but interest is growing as conventional water resources become fully allocated. Today, desalination is primarily utilized by the industrial and tourism sectors because of the high cost of seawater desalination. Using desalination for other purposes (agriculture and municipal) will depend on technological improvements that result in reduced overall and marginal costs.

According to the new water strategy (2016–2025), brackish water, either for direct use or after desalination, appears to offer the highest-potential non-conventional means of augmenting the country's water resources [11]. Adopting non-conventional sources (desalination) for water-supply reinforcement is necessary in the near future for Jordan to sustain its development [12]. Hydropower and solar technologies are the most-effective non-conventional energy resources for water desalination. A water shortage occurs most at places of high solar radiation. The shortage usually peaks during the hot summer months with maximum solar radiation. Hence, solar desalination could be one of the most successful applications of solar energy for most of the hot-climate countries that have limited fresh-water resources.

Therefore, analyzing the cost of water desalination is essential to understand whether the process is feasible to produce a water resource that could be used as a substitute for fresh-surface and groundwater resources in areas with water shortages. Desalination could double or triple the cost of fresh-water production. A recent report about the cost of irrigation water in the Jordan Valley indicates that the JVA needs significant tariff increases to strengthen its financial sustainability [13]. Water prices are very low, especially relative to the agricultural water's value. In the Jordan Valley, farmers pay a water price of just \$0.017/m^3; this low price provides no incentive for efficient water use [14,15].

The main objective is to analyze the costs of brackish-water desalination used for irrigation purposes and to understand whether the process is feasible to produce a water resource that could be used as a substitute for surface- and groundwater resources in areas with water shortages. This study presents a broader perspective for the cost analysis of desalinating brackish water that is used for irrigation purposes at the regional scale (Jordan Valley); the research addresses problems, both short and long term, related to the economic feasibility of desalination plants. The results can be used by water authorities and communities to optimize desalination processes based on experiences from other regions and countries.

2. Jordan's experience with desalination

The most-promising long-term solution for Jordan's water problems is desalination [16–19]. The main project regarding desalination is the Red Sea-Dead Sea Canal project. Early in 2015, Jordan Palestinian Authority and Israel signed an agreement for this project [11]. Jordan's national water-strategy projects for 2016–2025 is an additional amount of 85 MCM in the first stage (2017–2021); then in the second stage, an additional 135 MCM desalted water will be realized for the period of 2021–2025 with the Red Sea-Dead Sea Canal project [11]. According to estimates by [17, 18], the additional freshwater supply from the Red Sea-Dead Sea Canal could reduce the domestic and irrigation water deficit in the Jordan Valley to zero, even with increased water demand and reduced water availability for the climate-change scenario.

Jordan is not a traditional desalination country. Jordan already has a number of public desalination plants. There are two major sources for desalination. The first one is the brackish water that is available throughout the country, and the second one is seawater at the Gulf of Aqaba [20]. There are 20 public desalination plants out of 44 water treatment plants. About 70 MCM of water is desalinated annually, and the 6 plants under construction will desalinate about 10 MCM of water annually. All the plants are or will be run by WAJ to treat saline water for the drinking-water supply. The units are all of a small size compared to the plants in the Gulf Region. Currently, the Abu Ezzeghan desalination plant produces around 11–12 MCM annually. The most recent, large, major desalination plant is Zara Ma'in which was constructed in 200 and produces around 36–50 MCM/y. Additionally, there are several small to mid-size water-desalination plants operating in Jordan that produce no more than 10 MCM/y; these desalination plants include Karamah Dam, with a capacity of 1 MCM/y; Faisal nursery wells, with a capacity of 2.3 MCM/y; and Bereen wells, with a capacity of 1.8 MCM/y [21].

In the future and in addition to the Red-Dead sea project, there are plans to expand and construct small to mid-size desalination plants with the potential of increasing the desalinated quantity of water by around 1 MCM annually for the next 5 years. Additionally, there are plans to develop a desalination plant in Aqaba; the plant has two phases, each having a capacity of 5 MCM annually, with a total cost estimated at $50 million [1].

Brackish water is available in the South of Ghor between Dier Alla and the Dead Sea; this water has a salinity of about 3,000–7,500 ppm and a potential yield of about 60 MCM/y. Other sources are the saline springs east and west of the Jordan Valley; they have a capacity of about 10 MCM/y. The brackish water that is distributed all over the country is estimated at about 100 MCM [22]. Water resource-management studies indicate that there is a maximum of 80 MCM of water that can be used in the Jordan Valley [23,24]. However, it is very difficult to exploit these resources due to the country's topography; the distance between these scattered resources; the need for special treatment to remove some chemicals, such as manganese, sulfates, and iron; as well as the need to remove gases, such as hydrogen sulfide. Finally, the main problem is disposing the brine which can cause environmental problems. These scattered resources can supply desalinated water for small communities by using solar energy and/or wind power [17].

2.1. Desalination as a source for irrigation

Water quality can be looked at in several ways. Poor water quality, for instance, can limit the crops that a farmer can grow or reduces water-use efficiency. Therefore, water quality is multi-dimensional because the water includes a concentration of certain chemicals, a level of salinity, a concentration of bacteria and organic matter, as well as temperature [25].

Surface water is used in the Jordan Valley; this water appears, overall, to be of acceptable quality. The area faces important problems with salinity and bacteriological contamination of a localized nature which, due to impacts on human health and agriculture, are of strategic significance [26]. Regarding groundwater, evidence suggests a simultaneous trend of declining water tables and increasing salinity for most aquifers, resulting in higher extraction costs (in terms of pumping as well as accelerated well replacement). Due to the increasing problem of water shortages in the Jordan Valley, utilizing brackish water, which was once not an attractive option, has gained prominence. The cost per unit of desalinated water has been dropping as advances are made with desalination technology. Introducing innovations that could allow the use of brackish or saline water for irrigation, without needing prior treatment, is an attractive concept for Jordan [15].

In the past, the high cost of desalination and the energy required for the process were major constraints for the large-scale production of freshwater from brackish waters and seawater [16]. Desalinated water is becoming more competitive for urban uses because desalination costs are declining while the costs for surface water and groundwater are increasing. Desalination costs have dropped significantly during the past decade due to technological advances. This reduction has increased the attractiveness of desalination as a means to address water-supply shortages. In 2004, the World Bank and BNWP reported that, in the Jordan Valley, there is small-scale brackish-water desalination. Twenty-one stations deliver water that is destined largely for irrigation use. These stations are located north of the Dead Sea and are privately owned.

Desalinated brackish waters and seawater are not used worldwide for irrigated agriculture because of the cost. In some countries, this water is used for high-value horticultural cash crops. Because irrigated agriculture does not require the strict standards that apply for drinking water, opportunities appear to exist for blending high-quality desalinated water with lower-quality waters. In this way, the final cost for a cubic meter of irrigation water can be reduced.

Utilizing desalinized water as a source of irrigation water for agriculture is on the rise. Because it is estimated that irrigation is responsible for 87% of the global water consumption, the current freshwater resources may soon be insufficient to meet the growing demand for food. Technological advances have made desalination an economically feasible solution for high-return agriculture. Replacing saline irrigation water with desalinated water is anticipated to increase yields because of reduced salinity stress and to allow for drastic decreases in the amount of water that is used to leach salts from the root zone. Therefore, desalination has, in fact, become a real option for planners, decision-makers, and growers in many countries.

Reintroducing beneficial nutrients to desalinated water that is destined for agriculture can be accomplished in one of three ways: (i) the nutrients can be added at the desalination plant as part of the post-treatment processing; (ii) they can be added by farmers as fertilizers; or (iii) they can be added by blending the desalinated water with saline water.

3. Literature review

As reported by [27], since the late 1990s, desalination markets have grown significantly, with seawater reverse osmosis (SWRO) spirally wound membranes becoming established as the main technology employed for large-scale industrial and municipal applications [27]. These high growth rates continue to accelerate. The market has been driven slightly by the increased water demand, but more significantly by technological advances and the reduction in desalination costs over time [28]. Capital and operational costs are the main factors that determine the price of the final product (desalinated water), and in many cases, the high anticipated costs hinder desalination investments. Over the past 20 years, technological advances have significantly reduced the cost to produce water using desalination [29]. Desalinated-water operating costs have fallen over the last 20 years, from an average of $1.25–1.50/m^3$ for treated water in the early to mid-1990s to less than $0.75/m^3$ today. This ongoing cost reduction is driven both by technical process improvements that lower operating costs and by improvements with the manufacturing practices. The latter has significantly lowered the initial capital investment that is required to build a desalination plant.

Water desalination in Jordan can be a technically and economically efficient option to produce additional quality water [9]. Desalination of Red Sea water with reverse osmosis (RO) and brackish groundwater desalination with nano-filtration could, technically, be viable and economically feasible [10]. A recently constructed, large-scale plant in Tampa Bay, Florida, USA, reported costs as low as $0.60/$m^3$ [30] for medium salinity RO while in Ashkelon, Israel, and in Singapore, large-scale SWRO plants produced water for around $0.55/$m^3$ [31,32] reported slightly higher costs for large-scale seawater membrane and distillation plants with the unit cost of water in a range from $0.80–1.00/$m^3$ [31] used past data to forecast the current costs for brackish water RO (BWRO) and sea water RO (SWRO), predicting that, in the near future, the costs will be somewhere in the range of $0.07–0.08/$m^3$ for BWRO and $0.42–0.48/$m^3$ for SWRO.

Many studies have handled the cost aspects of establishing and operating desalination plants. The economic aspects of desalination are the major factor that determines its effectiveness in the short and long term [33–35].

4. Cost of desalination

The desalination cost is a vital aspect to consider. Desalination is still a costly water-supply option compared to natural water resources (e.g., ground- or surface water), but it may soon be a competitive alternative, even in non-water-stressed regions. The desalination cost depends on different factors. The most important one is the type and stage of development where the technology is being used, and the cost for the energy consumed in the process.

Desalination can become a real solution for Jordan's growing water-scarcity problem if new technologies are adapted to reduce the process' major cost components. The high cost of traditional desalination is driven by the price of energy for high-pressure systems as well as the capital cost of high-pressure pumps and seals. Today, the recovery of capital and electric power can be as much as 73% of the cost for desalinated water. The most important issue that hinders the expansion of desalination from a secondary water-supply source to a primary water-supply source is the high cost. Technological advances continue to fine-tune desalination with the goal to make it more cost-effective. Once a desalination project can solve this problem, desalination will be poised to become a significant source of drinking water for Jordan. With desalination in the mix, municipalities and water facilities will be able to reduce their dependence on such finite freshwater sources as groundwater and spring-fed reservoirs.

The cost of desalination varies greatly from country to country and from one facility to another one. Several factors, such as the plant type; the plant size; the influent's salt concentration; energy prices; geographical, socioeconomic, and environmental conditions; regulations about establishing and operating desalination plants; and the location where the water is transported, affect the cost. Due to the lack of detailed data and a common method for cost estimation, it is hard to make a direct comparison about the desalination costs for different countries and regions or to compare the costs for different facilities [36].

The major cost elements for desalination plants are capital cost (CAPEX) and annual operating costs (OPEX). The capital cost covers the expense of purchasing equipment, auxiliary equipment, and land as well as the installation charges [37]. The annual operating cost represents the total yearly costs of owning and operating a desalination plant, including the amortization or fixed charges, operating and maintenance costs, energy costs, and membrane-replacement costs. This cost study is only for isolated plant cases and does not include distribution. The combined environmental impact of desalination includes on- and off-site pumping.

The costs of desalinating water and the final water prices can vary significantly due to changing capital costs or interest rates. Moreover, operation and maintenance (O&M) costs can vary during a desalination plant's lifetime due to changes for the input costs or the lifetime of major equipment.

One cost-effective example is an installation in Singapore. During its first year of operation in 2013, the cost of desalinating water was as low as $0.45/$m^3$. [31] estimated the costs for brackish water to be in the range of $0.07–0.08/$m^3$ and the costs of seawater to be $0.50–0.70/$m^3$, including capital and operating costs. The range reflected economies of scale due to the plant's size. In 2010, the prices ranged from $0.2–1.2/$m^3$ for desalinated brackish groundwater and $0.3–3.2/$m^3$ for desalinated seawater [38,39].

5. Methods and data

Primary data were the initial investment costs, operational costs, working hours, plant capacity, inflows, and outflows. Water salinity was measured during the researchers' field visit from 50 private desalination plants. These 50 desalination plants desalinate brackish water for irrigation purposes in different locations in Jordan Valley representing different production systems. Each plant was unique in terms of the source water type and quality as well as the volume of water treated and the uses for the treated water. A structured questionnaire about the detailed cost breakdown was designed, pre-tested, and administered in the field for this purpose. Personal interviews were also conducted with farmers and plant operators. Four questionnaires were dropped from the analysis due to insufficient data. The study's analysis was based on information collected from for 46 farmers who have innovative desalination plants in the Jordan Valley. The Literature Review created the background for a discussion about the economics of desalination at the local level.

The first private unit to desalinate brackish water for irrigation purposes started operating in 1996. All plants are constructed and run privately by farmers. For all plants, reverse osmosis technology is applied. Today, more than 50 brackish water desalination plants have been installed by farmers in the Jordan Valley for irrigation purposes (Fig. 1). The plants' capacities are 360 to 2400 m³/d (a total capacity of almost 14 MCM/y). The total water abstracted is about 11.7 MCM, whereas the total desalinated amount reaches 7.7 MCM while the brine discharged is about 4.1 MCM.

5.1. Cost-Effectiveness Analysis (CEA)

CEA is an analytical method used for assisting decision-makers to have rational, effective and economically grounded decision making. This analysis is mainly designed for judging different projects or measures on the basis of their economic costs and their effectiveness with respect to a specific objective [40].

The cost of something in terms of an opportunity foregone (and the benefits that could be received from that opportunity) or the most valuable foregone alternative is the value attributable to the cost savings from the next-best alternative service source (e.g., electricity or transportation). At-site or at-source valuation of intermediate goods includes the off-stream (agriculture or industry), in-stream (hydropower or transportation), and private and collective consumption of goods by households.

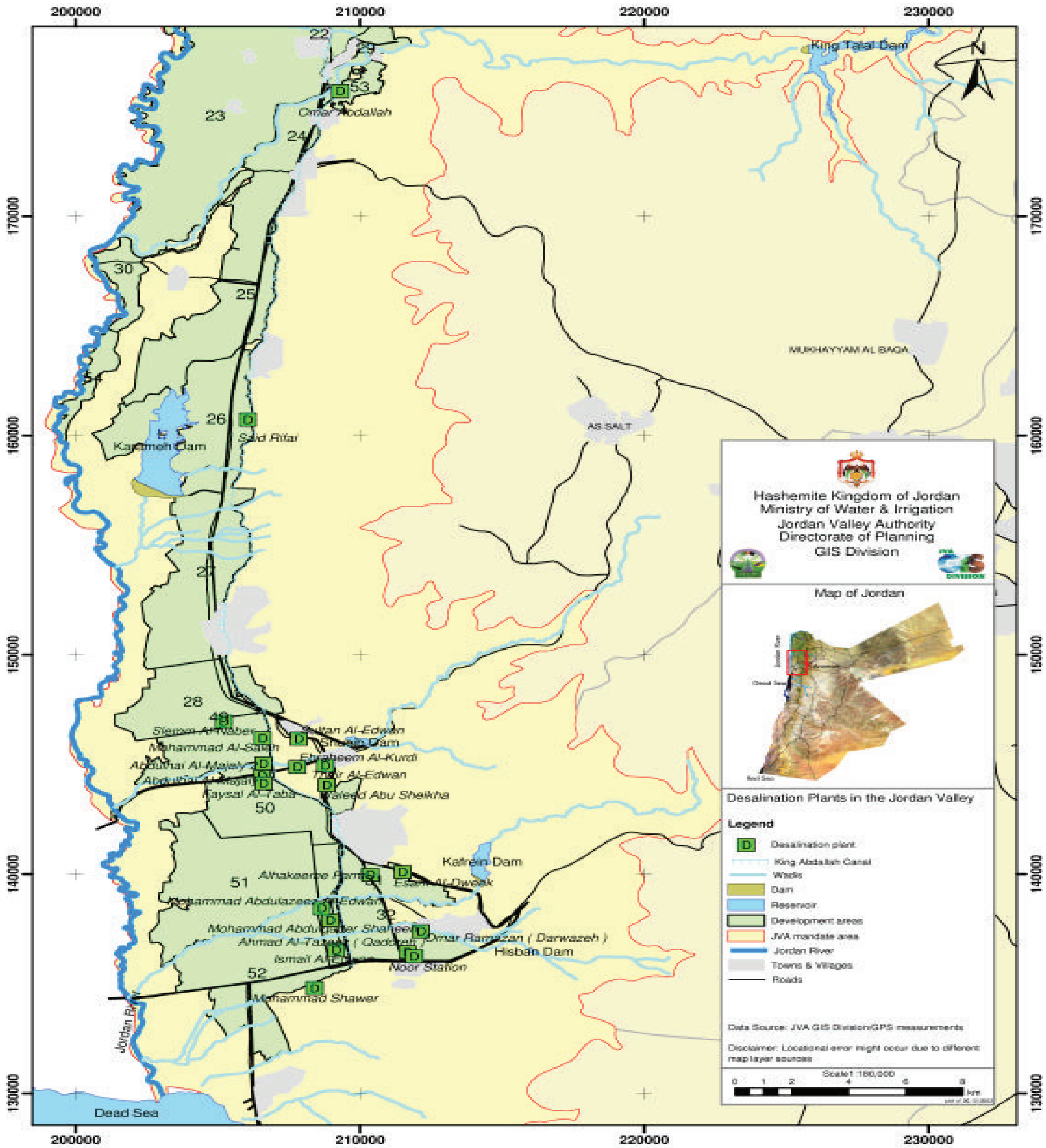

Fig. 1. Geographical distribution of private desalination plants in the Jordan Valley.

5.2. Total annualized economic cost (TAEC)

The full-cost present value, or the total annualized economic cost, is defined as follows [40]:

$$TAEC = \frac{rl_o(1+r)^t}{(1+r)^t - 1} + AOC \quad (1)$$

where l_o is the total capital cost, AOC is the annual operational cost, r is the interest rate or opportunity cost for capital, and t is the project's life span (20 y). The cost-effectiveness ratio is the average per-unit cost (average equivalent cost), that is, the TAEC divided by the average annual amount of expected physical benefit (B), e.g., the amount of water produced or saved by the policy option, action, demand management, etc.

$$AEC = \frac{TAEC}{B_q} \quad (2)$$

The final AEC results differ significantly according to the discount rate and the time horizon used to calculate the ratios [41]. For the already planned measures, the costs were estimated based on the initial feasibility studies or the expected project funding from the lending agencies. For all other measures, costs should be estimated according to local experts' knowledge or according to the cost data for similar measures. A common discount rate of 4–6% could be taken according to the European Commission and World Bank recommendations for social projects [42]. With the same logic, single-lifetime cycles were based on the demand for similar measures that was found in the local literature. Given the national water security, cost-effectiveness should not be the primary determinant in the decision-making process for brackish-water desalination [43–45].

6. Results and discussion

The 46 desalination plants are divided into 3 categories (small, medium, and large) according to plant capacity in m³/h as shown in Table 1. The Jordan Valley's desalination plants are divided by their capacities, sizes, and working hours. Table 3 shows the mean, the standard deviation for the capacities, and the working hours. The facilities are generally in operation 24 h/d in the summer and 12 h/d in the winter, with an average of 16.5 working h/d (Table 3).

AQ1

Table 1
Distribution of plant capacity and desalination working hours

Plant size	Capacity m³/h	No. of plants	Capacity/ m³/h		Working hours (h/d)	
			Mean	σ^2	Mean	σ^2
Small	15–29	11	19.73	2.28	18.55	5.66
Medium	30–49	21	35.62	6.53	15.19	4.00
Large	50–100	14	70.00	15.69	16.71	6.32
Total		46	42.28	21.80	16.46	5.25

Source: Survey data.

The only energy source used to run these plants is the electric-power grid.

Brackish water, having a salinity between 1300 and 7000 ppm, with an average of 3150 ppm is pumped from wells at depths between 100 and 150 m. Desalinated waters have a salinity between 50 and 800 ppm, with an average of 195 ppm. With full-capacity operation, the brine production reaches about 685 m³/h on an average salinity of 8038 ppm (3000 to 18,000 ppm). Desalinated water is then diluted to a salinity of about 700 ppm (400–1000 ppm). Irrigation water is applied, in particular, for bananas, strawberries, and dates. Those crops have a high market value (cash crops). The total annual water abstraction is estimated with 11.7 MCM with an average of 254,943 cubic meters per plant; as the size of the desalination plant's capacity becomes larger, the water inflows and outflows increase. The analysis of variance does not show a significant difference between plant in the physical characteristic of water inflows and outflows (Table 2).

The costs of desalination vary significantly, depending on the plant's size and type, the source and quality of the incoming feed water, the plant's location, site conditions, qualified labor, energy costs, and the plant's lifetime. Lower feed-water salinity requires less power consumption and dosing of antiscale chemicals. A larger plant capacity reduces the water's unit cost due to economies of scale. Lower energy costs and a longer plant life reduce the cost for a unit of water.

Table 3 provides information about the initial and operational costs for each installed desalination unit capacity, and the estimated cost per cubic meter for installed capacity (the various sizes) of desalination plants in the Jordan Valley. The average investment cost per cubic meter of installed capacity for the desalination plants ranges between $124/(m³/h), with a standard deviation of $25 for small plants, $89 (m³/h) for medium RO plants, and $63 (m³/h) with a standard deviation of $14 for large plants. The weighted average-investment cost is $89 (m³/h).

The results of desalination costs per plant capacity are shown in Table 4. The average desalination cost is $0.38/m³. The results show that the large desalination plants have lower desalination costs ($0.32/m³) compared with small ones that have average desalination costs of $0.48/m³. The operational costs represent about 80% of the total desalination costs. The estimated cost is $0.48/m³, with a standard deviation of $0.21/m³ for small RO plants (15–19 m³/h), $0.37/m³ for medium RO plants (30–49 m³/h), and $0.32/m³ for large RO plants (50–100 m³/h). The weighted average is $0.38/m³ with a standard deviation of $0.18/m³.

There is a positive relationship between the total desalination cost and the total dissolved solid (TDS) removed from water salinity. When more salts have to be removed, the desalting process is more expensive (Fig. 2). One can roughly say that each 1,000 ppm of TDS removed from brackish water will cost about 14 US cent.

Furthermore, there is a negative relationship between the desalination cost and the plant capacity (Fig. 3). As the desalination plant's capacity increases, the desalination cost decreases, selecting the appropriate plant capacity relies on other factors, such as cultivated areas, the crop's water requirements, and the flow discharge for brackish sources.

The value of the water used to produce many Jordan Valley crops, including bananas, exceeds the cost of brack-

Table 2
Physical characteristics of water inflows and outflows as well as the annual water usage

Plant size	Unit	Small		Medium		Large		Total	
		Mean	σ^2	Mean	σ^2	Mean	σ^2	Mean	σ^2
Inflow-water salinity	ppm	2795	1073	3195	1722	3356	1792	3148	1596
Outflow-water salinity	ppm	112	79	227	162	214	209	195	167
Brine-water salinity	ppm	7284	2859	7508	3987	9426	3599	8038	3673
Irrigation-water salinity	ppm	700	185	717	160	691	182	705	169
Annual desalinated water	M^3/a	84,240	35,295	132,909	48,866	282,883	148,025	166,915	118,586
Annual brine discharged	M^3/a	49,091	22,656	64,097	25,975	154,517	71,750	88,028	62,565
Annual water abstraction	M^3/a	133,331	49,653	197,006	69,338	437,400	213,655	254,943	177,231

Source: Survey data.

Table 3
Average desalination capacity and estimated costs for the various sizes of the desalination plants in the Jordan Valley

Plant size	Unit	Small		Medium		Large		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Initial capital investment cost	$/plant	52,000	11,138	84,257	24,450	134,015	36,302	91,687	40,523
Monthly operational costs	$/month	2,427	576	3,095	537	4,267	433	3,291	867
Annual operation costs	$/year	29,130	6,916	37,143	6,447	51,198	5,192	39,505	10,408
Annual total costs	$/year	34,427	7,279	45,725	7,904	64,847	5,915	48,842	13,589
Investment cost per hour capacity	$\$/(m^3/h)$	124	25	89	14	63	14	89	28

Source: Survey data.

Table 4
Operation and fixed and total costs of desalination ($) per m^3

Plant capacity	Small		Medium		Large		Total	
Indicators	Mean	Std. D.	Mean	Std. D.	Mean	Std. D.	Mean	Std. D.
Operational costs	0.404	0.186	0.301	0.076	0.263	0.200	0.314	0.158
Total fixed costs	0.073	0.029	0.069	0.021	0.067	0.051	0.070	0.033
Total desalination costs	0.476	0.208	0.370	0.092	0.331	0.245	0.385	0.183

ish-water desalination ($0.33 to $0.476/m^3), making private investment in the water supply for such crops feasible and attractive to investors.

The recent results for water values in the Jordan Valley, using the residual imputation approach [15,46], show that the overall weighted average-water value for irrigation in the southern Jordan Valley was estimated at $0.86 m^{-3}. With regard to individual crops, cucumbers had the highest water values (about $6.18 m^{-3}), followed by strawberries ($6.05 m^{-3}). Bananas have among the highest water value ($0.90 m^{-3}). Dates have an average of $0.507 m^{-3}. [47] show that the weighted average for the farmers' maximum ability to pay for irrigation water in the Jordan Valley is estimated at $1.07 m^{-3}. The farmer's ability to pay for water used in a plastic house is $1.89 m^{-3} compared to $0.87 m^{-3} for an open field. The estimated value of desalinated brackish water is $0.83 m^{-3} while the average desalination cost is $0.39 m^{-3}. The result shows that the water value is twice the desalination cost of one cubic meter. Therefore, the current practice of brackish-water desalination by banana, date, and strawberry producers in the southern Jordan Valley is economically rational by installing RO units to irrigate cash crops (The average desalination cost is between $0.38 m^{-3}.) because the water value is 3–4 fold the desalination costs for one cubic meter of water. Thus, the desalination costs are justified by increased agricultural production, leading to higher farmers' incomes, in particular, and helping the country's economy as a whole.

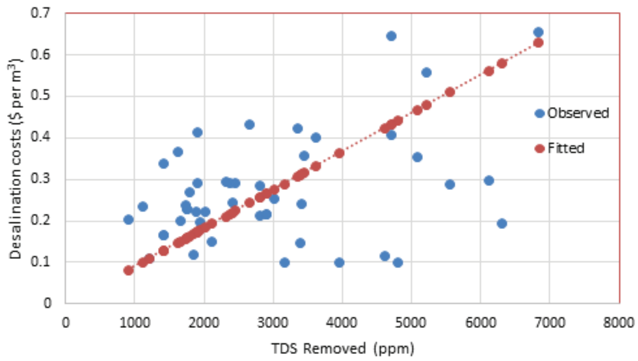

Fig. 2. Relationship between desalination cost and TDS removed.

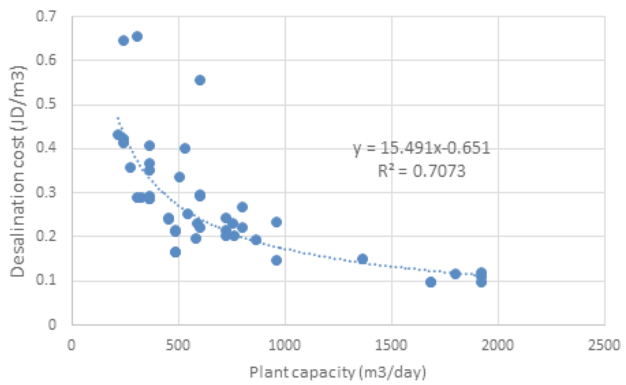

Fig. 3. Relationship between desalination cost and plant capacity.

The widespread of desalination plants appears to be a one-time investment with substantial long-term benefits, particularly for the agricultural sector.

7. Conclusion

Water desalination will be the only solutions for Jordan to bridge the gap between water supply and demand equation. The estimated economic value of desalinated brackish water is \$0.83 m^{-3} while the average desalination cost is \$0.39 m^{-3}. This estimated low cost of desalination of brackish water compared to sea water is due to lower TDS (3148 ppm) in local brackish water. The result shows that the economic water value is twice the desalination cost of one cubic meter. Therefore, the current practice of brackish-water desalination by agricultural producers in the Jordan Valley is economically rational by installing reverse osmosis units to irrigate cash crops. The increased use of brackish-water desalination would reduce the pressures on the need for surface- and groundwater and would have a positive impact in the reducing soil salinity because desalinated water would slowly dissolve and flush salts from the surface soils used for agricultural production.

Acknowledgments

The authors would like to express their gratitude to the German Ministry for Education and Research for funding this work which was done as a part of SMART-MOVE project.

References

[1] MWI, Ministry of Water and Irrigation, National Water Strategy 2016–2025: Water Sector Policies (2016), Ministry of Water and Irrigation, Amman, Jordan.
[2] DOS, Department of Statistics, Demographic Statistics, Department of Statistics (2016), Amman, Jordan.
[3] UNCHR, 2015 UNHCR Country Operations Profile–Jordan (2016), http://www.unhcr.org/pages/49e486566.html#.
[4] MWI, Ministry of Water and Irrigation (MWI), Annual Report (Water Policy), (2010), Amman, Jordan.
[5] M.J. Haddadin, A. Salman, E. Karablieh, The Role of Trade in Alleviating Water Shortage, in Water Resources in Jordan (Evolving polices for development, the environment and conflict resolution), (2006), Editor: Munther J. Haddadin, Resources for The Future, Washington D.C.
[6] UN, United Nations, Sectoral Water Allocation Polices in Selected ESCWA Members Countries: An Evaluation of the Economic, Social and Drought-Related Impact (2003), Economic and Social Commission for Western Asia, New York.
[7] T. Qtaishat, Water-supply augmentation options in water-scarce countries, Int. J. Water Resour. Environ. Eng., 4 (2012) 263–269.
[8] M. Abu Zeid, Desalination in Egypt Between the Past and Future Prospects, Newsletter of the Middle East Desalination Research Center, Watermark 9 (2000).
[9] B. Ammary, Wastewater reuse in Jordan: present status and future plans, Desalination, 211 (2007) 164–176.
[10] M. Afonso, J. Jaber, M. Mohsen, Brackish groundwater treatment by reverse osmosis in Jordan, Desalination, 164 (2004) 157–171.
[11] MWI, Ministry of Water and Irrigation, National Water Strategy 2016–2025: Water Demand Management Policy (2016b), Ministry of Water and Irrigation, Amman, Jordan.
[12] K. Alqadi, L. Kumar, Water policy in Jordan, Int. J. Water Resour. Develop., 30 (2014) 322–334.
[13] S. Taha, National Water Master Plan in Jordan, Conference of the water directors of the Euro-Mediterranean and South Eastern European countries (2006), Athens, Greece.
[14] A. Salman, E. Al-Karablieh, H-J. Regner, H-P. Wolff, M. Haddadin, Participatory irrigation water management in the Jordan Valley, Water Policy, 10 (2008) 305–322.
[15] International Resources Group (IRG) and E. Al-Karablieh, Water Valuation Study: Disaggregated Economic Value of Water in Industry and Irrigated Agriculture in Jordan United States Agency for International Development (USAID), (2012), https://usaidjordankmportal.com/system/resources/attachments/000/000/231/original/Water_Valuation_Study_-_Disaggregated_Economic_Value_of_Water_in_Industry_and_Irrigated_Agriculture_in_Jordan_-_2012_-_ISSP.pdf?1451226958.
[16] M.S. Mohsen, Water strategies and potential of desalination in Jordan, Desalination, 203 (2007) 27–46.
[17] A. Al-Omari, A. Salman, E. Karablieh, The Red Dead Canal Project: an adaptation option to climate change in Jordan, Desal. Water Treat., 52 (2014) 2833–2840.
[18] A. Al-Omari, E. Al-Karablieh, Z. Al-Houri, A. Salman, R. Al-Weshah, Irrigation water management in the Jordan Valley under water scarcity, Fres. Environ. Bull., 24 (2015) 1176–1188.
[19] J.F. Schyns, A. Hamaideh, A.Y. Hoekstra, M.M. Mekonnen, M. Schynsm, Mitigating the risk of extreme water scarcity and dependency: the case of Jordan, Water, 7 (2015) 5705–5730.
[20] Japan International Cooperation Agency (JICA), Final Report on Brackish Groundwater Desalination in Jordan (1995), Amman, Jordan.
[21] Ministry of Water and Irrigation (MWI), Annual Report (2015), Amman, Jordan.
[22] N. Hadadin, M. Qaqish, E. Akawwi, A. Bdour, Water shortage in Jordan–sustainable solutions, Desalination, 250 (2010) 197–202.
[23] World Bank, and BNWP (Bank-Netherlands Water Partnership), Seawater and Brackish Water Desalination in the Middle East, North Africa and Central Asia-Final Report Annex 3 Jordan (2004), DHV Water BV, the Netherlands BRL ingénierie, France.

[24] Japan International Cooperation Agency (JICA) and Ministry of Water and Irrigation (MWI), The Study on Water Resources Management in the Hashemite Kingdom of Jordan, Final Report (2001), Volume I: Main Report Part A, Water Resources Management Master Plan; and X: Summary Report.
[25] G. Carr, R.B. Potter, S. Nortcliff, Water reuse for irrigation in Jordan: perceptions of water quality among farmers, Agric. Water Manage., 98 (2011) 847–854.
[26] T.M. Abu-Sharar, E.K. Al-Karablieh, M.J. Haddadin, Role of virtual water in optimizing water resources management in Jordan, Water Resour. Manage., 26 (2012) 3977–3993.
[27] G. Pearce, Pre-treatment to seawater reverse osmosis: markets and experience, Filtr. Separ., 47 (2010) 30–33.
[28] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability, Desalination, 309 (2013) 197–207.
[29] T. Dabbagh, The management of desalinated water, Desalination, 135 (2001) 7–23.
[30] M. Wilf, Optimization of seawater RO systems design, Desalination, 138 (2001) 299–306.
[31] M.H.I. Dore, Forecasting the economic costs of desalination technology, Desalination, 172 (2005) 207–214.
[32] N.M. Wade, Distillation plant development and cost update, Desalination, 136 (2001) 3–12.
[33] B. Djebedjian, M. Mohamed, S. El-Sarraf, M. Abou Rayan, Evaluation of desalination and water transport costs (case study: Abu Soma Bay, Egypt), 9th International Water Technology Conference, IWTC(2005), Sharm El-Sheikh, Egypt.
[34] Y. Zhou, R.S.J. Tol, Evaluating the costs of desalination and water transport, Water Resour. Res., 41 (2005) 269–287.
[35] M.K. Wittholz, B.K. O'Neill, C.B. Colby, D. Lewis, Estimating the cost of desalination plants using a cost database, Desalination, 229 (2008) 10–20.
[36] E. Lapuente, Full cost in desalination: a case study of the Segura River basin, Desalination, 300 (2012) 40–45.
[37] H.M. Ettouney, H.T. El-Dessouky, R.S. Faibish, P. Gowin, Evaluating the economics of desalination, Chem. Eng. Prog., 98 (2002) 32–40.
[38] V.G. Gude, N. Nirmalakhandan, S. Deng, Renewable and sustainable approaches for desalination, Renew. Sustain. Energy Rev., 14 (2010) 2641–2654.
[39] L. Karagiannis, P. Soldatos, Water desalination cost literature: review and assessment, Desalination, 223 (2008) 448–456.
[40] S. Aulong, M. Bouzit, N. Dorfliger, F. Comair, E. Al-Karablieh, A. Salman, Integrating water balance and cost-effectiveness analysis for water management: an application in Jordan and Lebanon, 13th IWRA World Water Congress, 1–4 September (2008), Montpellier, France.
[41] B. Zanou, Decrease of Non-Point Water Pollution: A Practical Algorithm for the User-Friendly Presentation of the Cost-Effectiveness Comparison of Management Measures, European Water Association (EWA), 1 (2006) 1–20.
[42] European Commission, Guidance on the Methodology for Carrying Out Cost-Benefit Analysis, Working Document No. 4: The New Programming Period 2007–2013 (2006), Brussels. Available at: http://ec.europa.eu/regional_policy/sources/docoffic/2007/working/wd4_cost_en.pdf.
[43] S. Aulong, M. Bouzit, N. Doerfliger, Cost-effectiveness analysis of water management measures in two river basins of Jordan and Lebanon, Water Resour. Manage., 23 (2009) 731–753.
[44] S. Nortcliff, G. Carr, R.B. Potter, K. Darmame, Jordan's Water Resources: Challenges for the Future (2008), Geographical Paper No. 185, The University of Reading, United Kingdom.
[45] R.B. Potter, K. Darmame, S. Nortcliff, Issues of water supply and contemporary urban society: the case of greater Amman, Jordan, Philos. Trans. Royal Soc. A: Math. Phys. Eng. Sci., 368 (2010) 5299–5313.
[46] E. Al-Karablieh, A. Salman, A. Al-Omari, H-P. Wolff, T. Al-Assa'd, D. Hunaiti, A. Subah, Estimation of the economic value of irrigation water in Jordan, J. Agric. Sci. Technol., 5 (2012) 487–497.
[47] M. Tabieh, E. Al-Karablieh, A. Salman, H. Al-Qudah, A. Al-Rimawi, T. Qtaishat, Farmers' ability to pay for irrigation water in the Jordan Valley, J. Water Resour. Protect., 7 (2015) 1157–1172.